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A Methodology for the Quantitative Risk Assessment of the Road and Rail Transport of Explosives

by

Paul Anthony Davies

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Submitted in Partial Fulfilment of the Requirements
for the Award of

Doctor of Philosophy

of the Loughborough University of Technology

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A Methodology for the Quantitative Risk Assessment of the Road and Rail Transport of Explosives

by Paul Anthony Davies

ABSTRACT

Key Words: Risk, Hazard, Explosion, Explosives, Accidents, Transport, Injury, Damage.

A study was made of the hazard presented by, and the risks associated with, the road and rail transport of conventional explosives.

Its purpose was firstly to review the accident and transport environments associated with the carriage of hazardous goods and in particular conventional explosives. Secondly, to identify and assess those stimuli present in transport and accident environments which are liable to cause accidental initiation of explosives. Thirdly, to identify explosion consequence models suitable for the assessment of injury and damage suffered by roadside and railside populations as a result of explosion. Finally, to apply and develop a risk assessment methodology capable of identifying, quantifying, evaluating and monitoring individual and societal risks.

The study formulates a basic methodology for the assessment of transient hazards and more specifically, a methodology suitable for quantitative risk assessment of the road and rail transport of conventional commercial and military explosives.

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3. Those individuals at Fafnir Bearings, Wolverhampton, and The Polytechnic, Wolverhampton, who unknown to them set the path leading to this study.

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Note

This thesis is structured so that all tables and figures appear at the end of appropriate sections, chapters or appendices. Within chapters/appendices tables and figures are labelled consecutively by order of appearance. All references are listed at the end of appropriate chapters/appendices.

INTRODUCTION

1.0 INTRODUCTION

This study assesses the hazard of, and the risks from, the transport of conventional commercial and military explosives by road and rail. The aim of the study is to

1. review the accident and transport environments associated with the carriage of conventional explosives,

2. assess the sensitivity of explosives to accidental initiation and identify those initiation stimuli and accident/transport environments liable to introduce and cause accidental initiation,

3. describe and determine a methodology from which
   a. potential incidents can be assessed and quantified,
   b. explosion consequences can be quantified and evaluated,
   c. risks can be assessed, monitored and evaluated both qualitatively and quantitatively.

Data and discussion on both the road and rail accident and transport environments are given in Part A. Accidents, fires and explosives movements are reviewed together with historical events/incidents providing a complete appraisal of the environment under which explosives are conveyed. In addition, Appendix A reviews the regulations and laws governing the transport of explosives, and Appendix B details a number of historical accidents on both the roads and railways.

The sensitivity of explosives to a number of stimuli is addressed in Part B. Sensitivity and stimuli are discussed in relation to accidental initiation. Conditions conducive to accidental initiation, stimuli most likely to cause initiation and those explosives most vulnerable to initiation are identified.

Part C details the methodology developed for the assessment of the risks arising from the transport of explosives by road and rail (the general principles of the methodology are also applicable to the assessment of other hazardous goods). The methodology catalogues the essential items and data needed for such a risk assessment, together with a means by which data can be classified for ease of analysis and assessment. Incident sequence identification and quantification are detailed for fire and non-fire incidents and a number of illustrative examples given. Various means of evaluating explosion consequences are discussed and illustrated for blast, missile and thermal damage. The problems of estimating the numbers of individuals exposed to transport hazards are examined, and those most at risk identified. The difficulties in producing consequence evaluation models are discussed and a model suitable for transport environments and condensed phase explosions identified.

An overview of risk assessment is given in Part D. Historical background together with studies of particular interest is discussed. The advantages and disadvantages of risk assessment studies are detailed. A discussion is given on the acceptability of risks, means of expression and assessment sensitivity. In addition, a means of monitoring risk is identified in the form of hazard warning structure, and the merits and use of this system detailed with illustrative examples.

Application of the risk assessment methodology is demonstrated in Part E. Two illustrative examples are given, primarily in a simple delineative manner, thereby providing a guide to the identification and quantification of accidents liable to cause explosion, the quantification of explosion effects, monitoring of risks and sensitivity assessment.

Finally, a number of broad conclusions on the suitability of the methodology developed, and the assessment of transport hazards (road and rail) is drawn, together with a number of recommendations for further work.

PART A

2.0 THE RISKS OF EXPLOSIVES TRANSPORT

The risks from the processing and storage of hazardous materials at fixed installations are well documented and have been studied, assessed and quantified over the past decade in varying degrees of depth and approach. In comparison, less attention has been given to the risks from the transport of hazardous materials. However, the risks from transport operations have been acknowledged as requiring detailed assessment. The Health and Safety Commission (HSC) voiced there concern during the late 1970's culminating in the approval of recommendations by the Advisory Committee on Dangerous Substances (ACDS) to

> "[explore] the possibility of major hazard implications in the transportation of certain hazardous substances"[1]

Subsequently the HSC through the Health and Safety Executive (HSE) have instigated programs into the assessment of risks from the transport of hazardous materials. Quantified risk assessments are currently being undertaken by the ACDS sub-committee on major hazard aspects of the transport of dangerous substances[2] (1986 - to-date). Similar work, specifically for the hazard of transporting military explosives, is also being conducted for the Ministry of Defence by the Plant Engineering Group at The University of Technology, Loughborough.

It is thought here that the reason for delay in the assessment of transient risks is a combination of

a. attention being focused on fixed installations as a result of incidents, such as Flixborough in 1974,
b. the absence of major incidents on roads and railways in the UK.

There are of course other contributing factors. Historically the public have expressed little concern over the transport of hazardous materials. Only recently, as a result of pressure group activities, has public perception of transient risks been stirred enough to question the safety of transporting hazardous goods. Furthermore, individual risks to members of the public from hazardous transport operations tend to be much lower than those from fixed installations. This is due in part to the inherent mitigating feature associated with transient hazards, namely, that an accident has a certain likelihood of occurring at any point along a transport route. In addition, individual risks are low compared with societal risks. This can be illustrated by a simple example. Consider a shopping complex exposed to a transient hazard. During the daytime the complex is full of individuals exposed to the hazard. However, the majority of individuals only spend a fraction of the exposed day at the complex. Thus, although a sizeable population is continually exposed, individual exposure is low. As a consequence of the continual change in the individuals forming the exposed population, it is apparent that individual risks to members of the public are low compared with societal risks.

The number of deaths resulting from the transport of hazardous goods is said to be comparable with those occurring at fixed installations[3]. This fact is supported by data collected by Kletz and Turner[4] over a ten year period between 1970 and 1979. During this time 2486 fatalities were recorded world-wide as being associated with the oil and chemical industries. Over 40% of the total were associated with the transport of oil and chemical products. It is estimated here that between 2% and 3% of all world-wide transport accidents occur in the UK. The majority of the fatalities, it is assumed, are due to loading/unloading operations[3] with the remainder resulting from traffic accidents.

2.1 Road Transport

At any one time there are between 400,000 and 450,000 heavy goods vehicles (HGVs) legally registered in Great Britain. The population of HGVs by the end of 1986 totalled 435,000. It is estimated here that just over 1% of HGVs are designed to carry hazardous goods[3]. For the year 1986 this provides a total of 4785 such vehicles. Assuming these vehicles to be as accident prone as other HGVs, then during a typical year, such as 1986, we could expect approximately 150 injury accidents. From available literature it is apparent that HGVs designed specifically for the carriage of hazardous goods are less likely to be involved in accidents than other HGVs. This point is supported by factual data; between the years 1968 and 1976 only 19 fatalities were recorded in the UK as being associated with vehicles conveying hazardous chemicals[3]. Statistics published by the Department of Transport[5] illustrate that HGVs have a much lower rate of accident involvement than private motor cars. It follows that HGVs conveying

hazardous goods are likely to have an even lower accident rate. Some of the reasons for this are thought to result from the high standards of maintenance of such vehicles compared with other HGVs, regular vehicle inspections and the fact that drivers are specially trained not only to be proficient in driving but also to be aware of the risks involved in hazardous transport. A discussion on this topic is given by Withers[3]. He suggests that an accident rate of 0.25×10^{-6} accidents per mile which corresponds to 0.16×10^{-6} accidents per km is a good estimate for the transport of hazardous goods by road. This accident rate is approximately four times lower than the national HGV accident rate derived by the author (see Chapter 3.0, Section 3.1.1). It is suggested here that the general accident rate for HGVs conveying hazardous materials lies somewhere between 0.10×10^{-6} and 0.30×10^{-6} accidents per km. Assuming HGVs transporting hazardous materials travel 250 million km per year (i.e. approximately 1% of annual distance travelled by all HGVs) then the estimated range given here provides no more than about 75 injury accidents per year. This compares with 80 injury accidents per year estimated by Kletz[6]. The ratio of fatalities to all injury accidents[7] varies from between 0.018:1 and 0.025:1. As a consequence of this we could expect between 0.5 and 2 fatalities per year from the transport of hazardous goods. This estimate compares well with the rate of 2 fatalities per year suggested by Withers[3]. From data collected on fatal accidents involving the road transport of hazardous chemicals over a 13 year period from 1970 to 1982 Kletz[6] derives a figure of 1.2 fatalities per year. Unlike the figures derived by Withers and the author this figure excludes "ordinary road deaths". Only those fatalities where the load contributes in some way towards death are recorded by Kletz.

From the data given above it is suggested here that the majority of fatalities from the transport of hazardous materials are not attributable to the loads conveyed. However, as the remainder of this section illustrates large numbers of deaths, as a consequence of hazardous loads, have a likelihood of occurring in Great Britain as they have done in other industrialised countries.

The most horrific accident to-date involving the transport of hazardous goods occurred in Spain on 11 July 1978 near San Carlos de la Rapita. A tanker conveying 22000 litres (23.5 te) of liquid petroleum gas (LPG) developed a severe leak which resulted in the loss of large quantities of propylene. The ambient temperature on the day of the accident was reputed to be 28°C and this led to the rapid vaporisation of the liquid resulting in the formation of a dense cloud. Since propylene is heavier than air the cloud hugged the ground and was elongated over a distance of 300 m in the windward direction. Shortly after formation the gas cloud ignited and a violent explosion occurred. The cab was thrown over 100 m in one direction with the tanker shell breaking up into several pieces scattered some 75 m in the opposite direction. The blast appeared to go in an upward and windward direction. This is supported by the fact that a single storey building 75 m from the centre of the blast was completely demolished, whereas, a motorcycle some 20 m in the opposite direction was still standing, although burnt-out. Unfortunately the incident occurred on a coastal road alongside a busy campsite filled with holiday makers. Over 100 people were killed instantly from the direct effects of blast and/or radiation and a further 180 were burned, some so badly that they later died bringing the final death toll to 215[8].

It has been remarked upon by Marshall[8] that no vapour cloud explosion occurred at San Carlos. All blast damage resulted from hydraulic tank rupture and a number of small explosions as a result of gas penetration within buildings. Consequently, Marshall claims that a number of individuals probably died from cryogenic shock following LPG contact. Regardless of whether the incident was a vapour cloud explosion or simply a hydraulic rupture the root cause of the accident is still unclear. However, it is thought that the 10 mm tank shell failed due to a combination of metal fatigue and excessive internal pressure. Whether such an incident could occur in the UK is debatable. Stintons[9] account of the disaster clearly indicates that he personally is convinced that such an incident could occur. He cites that tankers in the UK are of similar construction and that similar transport codes are enforced. However, the inquiry found that the tanker had been over-filled by some 3% and that the pressure relief valves had been deactivated. In addition, the tanker had previously been used for the carriage of ammonia (hence the blocking off of the relief valves) which can cause embrittlement in certain metals and therefore increase the likelihood of fracture. These additional circumstances almost certainly aided the incidents occurrence and clearly indicate a poor compliance with the relevant transport regulations. It is suggested here that in the UK transport regulations are much more strictly enforced and adhered to, and therefore, the attributing factors outlined above are less likely to occur. This point is supported by the safety record in the UK compared with other European countries[6].

Only three serious incidents involving the road transport of LPG have occurred in the UK to-date, resulting in 2 fatalities. Both fatalities were associated with the incident at Hull in 1970. A flat bed truck conveying a pressurised vessel of LPG collided with brick work at the

entrance to a road tunnel resulting in the loss of propane and ultimately its ignition. The other two incidents both involved road tankers which is the usual way of transporting liquefied gases. During 1957 a road tanker filled with vinyl chloride was punctured. Fortunately the escaping liquid did not ignite and no one was injured. The third incident occurred in Aberdeen in the winter of 1974. A BOC road tanker loaded with 16000 litres of LPG collided with a motor car causing a large spillage of butane. Due to the freezing weather conditions only a small amount of the butane vaporised. However, ignition did occur but fortunately no injuries were sustained. It is apparent from the Spanish disaster described previously, that if the temperature on the day of the accident had been higher (i.e. occurred during the summer) the consequences could have been much worse.

As far as the transport of commercial/military explosives is concerned four serious incidents in the UK have been identified (after 1946). The first occurred on 12 October 1957 when a lorry conveying 3.5 tons of trinitrotoluene (TNT) caught fire causing its load to ignite and ultimately explode. The explosion occurred on the main Brecon to Abergaveny road and left a crater 15 ft deep and 42 ft wide. Fortunately no one was injured although two nearby cottages were damaged. The other three incidents all occurred during the 1980's. Both incidents on 15 September 1981 and 13 December 1982 involved military explosives. No explosion occurred in either incident and no casualties were sustained. However, both were serious enough to warrant exclusion zones during "clear-up" operations and the attendance of emergency service personnel and/or explosives experts. The first military incident closed 15 miles of the M4 motorway in Berkshire for 8 hours when a defective HGV brake drum overheated causing the engulfment of USAF "cluster bombs". In

comparison, the second military incident involved the collision of an RAF HGV, laden with air-to-surface missiles, with a commercial HGV on the A17 in Lincolnshire. The road was closed for 6 hours. However, by far the worst incident, in terms of casualties and damage, involved commercial explosives. On the 22 March 1989 at Fengate Industrial Estate, Peterborough, a 7.5 ton HGV laden with approximately 750 kg of commercial explosives caught fire causing its load to ignite and consequently explode. Surrounding buildings and vehicles were severely damaged and over 80 people injured. Unfortunately 1 fireman was killed.

The incidents described above, especially San Carlos 1978 and the explosion at Peterborough in 1989, highlight the hazard of transporting hazardous materials and the potential such operations have to inflict damage, injury and death. This study is primarily concerned with the transport of explosives and therefore incidents involving commercial and military explosives are detailed further in Appendix B.

Although the safety record in the UK, for the transport of hazardous goods compares favourably with other industrialised countries there are no grounds for complacency. It is apparent that multiple fatality incidents could occur in the UK as they have in the United States and many European countries. This view is supported by numerous authors[3,6,9]. However, in addition to the incidents described here, the most damning evidence that such incidents could arise has been provided by the police force[10]. During the spring of 1985 various police forces throughout the UK conducted indiscriminate spot-checks on vehicles conveying hazardous goods. It was found that a third of the vehicles inspected were in breach of the

Dangerous Substances (Conveyance by Road in Road Tankers and Tank Containers) Regulations 1981. The HSE who acted as observers during the checks found that most of the breaches were of a minor nature. However, some were so serious that further travel was prohibited. Such action was mainly taken as a result of corroded or leaking tanks. It is clear from the survey that many road hauliers and their drivers were ignorant of the regulations or chose to disregard them, as was concluded by the HSE.

2.2 Rail Transport

During 1986, which was a typical year on British railways, freight trains were involved in 324 accidents at a rate of 6.0×10^{-6} accidents per km. The author has estimated that the rate of "severe" accidents for freight trains is between 0.5×10^{-6} accidents per km and 0.7×10^{-6} accidents per km. A "severe" accident is classed here as an accident involving death, serious injury and/or extensive damage. The severe accident rate is based on a study, conducted by the author, of over 180 railway accident reports detailed by the Railway Inspectorate. Results from the study are discussed in chapter 4.0. It is estimated from the study that freight trains transporting hazardous goods account for between 15% and 30% of all severe freight train accidents, resulting in approximately 4 to 11 severe accidents per year. This estimate assumes that freight trains conveying hazardous goods are as likely to be involved in severe accidents as other freight trains. From the small number of accidents involving hazardous loads it can be argued that freight trains loaded with hazardous goods are less likely to be involved in severe rail accidents than freight trains conveying non-hazardous goods. However, there is little data to support this

argument and help quantify a scale of reduction. The majority of supporting factors tend to be qualitative, such as, improved maintenance compared with other freight wagons, regular wagon inspections and the strict enforcement of regulations and safe working practices.

One of the worst accidents to occur in the UK, in terms of injuries and fatalities, took place near Eccles, Greater Manchester, on 7 December 1984. A 15 wagon freight train loaded with 500 te of gas oil travelling between 10 mph and 15 mph was hit in the rear by a passenger train at a speed of approximately 50 mph. The rear wagon was thrown across adjacent track by the force of the impact and both trains derailed causing many coaches to overturn. Some of the wagons ruptured spilling their contents which ultimately ignited. Unfortunately 3 people were killed in the collision and over 60 injured.

In comparison, the derailment at 40 mph of a train laden with 835 te of petroleum spirit resulted in no fatalities or injuries although the local population had to be evacuated. The accident occurred on 20th December 1984 at Summit Tunnel, West Yorkshire. Due to excessive freedom of movement, caused by axle-box failure, the wheel-set on the fourth wagon lifted and climbed the rails as the train entered the tunnel. As a consequence of this, derailment of the following wagons occurred causing some to overturn and puncture. Fortunately the train crew were able to scramble to safety before the petroleum vapour, which had escaped from punctured wagons, ignited. The subsequent fire was not considered under control until four days later and the line remained closed for 8 months.

Incidents in the United States, Canada and other European countries have been much worse than those described above. On 10 November 1979 a train consisting of a mixed consignment of 106 wagons and tankers derailed in an industrial area of Mississauga, Canada[11,12]. Fire ensued almost immediately from leaking propane tankers, accompanied some ten minutes later by multiple explosions. The explosions were so fierce that one of the rail cars was thrown over 500 m demolishing all in its path. Fortunately no one was killed and only minor injuries were sustained by the emergency services. However, the explosions were so violent, the fires so intense and more importantly the risks from chlorine so great, that in excess of 230,000 people were evacuated from hospitals, hotels and private residences. The fire took 3 days to extinguish and the area was not considered safe until almost a week later. Obviously the emergency services were hampered in their operations due to the mixed consignment of the train, which included propane, butane, chlorine, caustic soda, styrene, toluene, furnace oil, terpolene and hydrochloric acid. As a result of this the fire services concentrated on containing the fire rather than extinguishing it, consequently vast amounts of specialised equipment brought to the scene were left unused.

Many similar incidents have occurred throughout the United States and Europe resulting in multiple deaths and injuries. By far the worst in terms of casualties occurred at Ludwigshaven, Germany in 1948. A rail tank car ruptured alongside a dimethyl ether processing plant causing a large explosion which resulted in over 2000 injuries and 200 deaths. On 25th January 1969 2 people were killed and almost 1000 injured when a train conveying LPG derailed at Laurel Mississippi, causing propane vapour to be released resulting in fire and explosion.

The United States National Transportation Safety Board reported in 1979[13] that between the years 1969 and 1978 56 fatalities were associated with the rail transport of hazardous materials, a rate of 4.6 per year. It is estimated that for every 43 train accidents on British railways (including train fires) 1 fatality is incurred[14]. Assuming that this fatality rate is the same regardless of train type, then it is estimated here that freight train accidents account for between 7 and 8 fatalities per year. Of these it is estimated that no more than about 2 are associated with freight trains conveying hazardous goods. As stated above, this estimate assumes that the number of fatalities per accident is the same regardless of train type. In reality, a large proportion of freight train accidents will be less severe and involve fewer individuals than say passenger train accidents. As a consequence of this it is suggested here that the number of fatalities from the transport of hazardous goods (on average) is less than 2 per year.

It should be noted that British and American fatality rates are not strictly comparable. The United States permit much larger quantities of hazardous goods to be conveyed per train load than British Rail, and the mixing of dangerous goods is common with less segregation, causing incidents to be more severe. In addition, United States railroad track is considered to be in a poor state of repair[6] and free shunting of tank cars persists (or did), although its use has caused many incidents. One such incident involved the puncture and subsequent explosion of a tanker laden with nitromethane killing 2 people in 1958. Furthermore, rail tankers used in the United States do not incorporate buffers with coupling equipment, they are heavier and their centres of gravity higher. All these factors, it is assumed, account for the increased number and severity of rail accidents in the United States

compared with the UK.

Unlike the conveyance of explosives by road, only two serious incidents have been identified for the conveyance of explosives by rail. Both incidents occurred at rail stations in built-up areas exposing large numbers of individuals. The first incident occurred at Chelmsford Station on 22 October 1969. A 27 wagon FT laden with more than 117 tons of military explosives derailed causing extensive track, signalling and platform damage. A hot axle box subsequently caught fire but was quickly extinguished. Both lines into the station were blocked and "clear-up" operations by the Armed Forces took over 7 hours to complete. The second incident occurred during the autumn of 1987 at Parkway Station, Bristol. An FT collided with another FT laden with ammunition causing it to derail close to a densely populated housing estate. Fortunately, neither incident incurred fatalities or was accompanied by explosion. However, public concern was aroused in each case by media attention, highlighting the propagation potential of such incidents to cause death, injury and damage to surrounding populations.

Although the safety record in the UK for transporting hazardous materials is exemplary compared with other industrialised countries, such as the United States, it is clear that there is a possibility, however small, that multiple fatality accidents could occur on British railways. In addition to the incidents described here, evidence to support this claim is given by the 14 accidents which occurred between 1970 and 1985 involving the puncture of one or more tank wagons[15]. It is interesting to note that fortunately none of the puncture incidents involved pressurised tankers containing hazardous chemicals. It is estimated[15] that the probability of pressurised chlorine

tankers being punctured in incidents of similar severity is no more than about 20%. There have also been numerous occasions where leaking valves and loose man-hole covers have resulted in fire and/or spillage of tank contents. Fortunately, the incidents have all been relatively small, even compared with other UK incidents, and only a few casualties have occurred.

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3.0. THE ROAD ACCIDENT AND TRANSPORT ENVIRONMENT

Risk assessments of the road transport of explosives and other hazardous materials require detailed information on the transport and accident characteristics of the vehicles used. The data and information presented within this chapter are applicable to the transport of goods by heavy goods vehicles (HGVs) on public highways in Great Britain. Particular emphasis is given to the transport of explosives and hazardous materials. The number of accidents, frequency of accidents, collisions, single vehicle accidents (SVAs), HGV types, road class, collision speeds, urban and rural areas/roads and impact position have all been analysed.

At present no common methods are used in the collection and analysis of transport statistics. Studies and published data tend to use varying definitions and nomenclature for urban and rural areas, HGVs, road class and accident severity etc.. Due to the multitude of data interpretation, such a mixture of classes and categorises presents problems in analysing and comparing data. Often only generalised conclusions can be drawn with any degree of confidence. Consequently much of the data provided in this chapter are taken or derived from Department of Transport statistics. The main reasons for this are diversity of information, general consistency (although not always) and availability.

There are two other large sources of available data, namely the Home Office and the Transport and Road Research Laboratory (TRRL). However, much of the data from such sources are not directly comparable with the data given here, or with other similar studies. For example, during

1976 TRRL conducted a study of 740 fatal HGV accidents. Information contained within the study is reasonably extensive, however, the sample is small and broad definitions are used. In addition HGVs are classed as vehicles having unladen weights in excess of 3 tons; whereas, within this report and most Department of Transport published statistics HGVs are taken as vehicles having unladen weights of not less than 1.5 tonnes. Similarly, a Home Office study into the transport of chemicals by road provides no distinction between road class or HGV type, the sample is small and only 36 of the 607 incidents are attributed to road accidents.

Although there are drawbacks with much of the published data and available statistics, most are useful in at least identifying and loosely quantifying areas of interest. Therefore, both of the studies mentioned above are detailed in this chapter.

No attempt has been made to differentiate between weather conditions, time of year or time of day. It is possible to produce accident rates accounting for these factors. However, it is considered here that the improvement in assessment accuracy is minimal unless the vast majority of movements all have the same characteristics (i.e. travel between certain set times, etc.). Finally it should be noted that all accident data within this chapter, unless otherwise stated, refer only to injury accidents. The criterion for reporting an accident is that personal injury has occurred. Hence, little or no data exist with respect to non-injury accidents and the true number of road accidents are not known. In addition, not all injury accidents are recorded. This is because the Department of Transport collate data from UK police forces and unfortunately not all injury

accidents are reported to the police. In a study of injury accidents conducted by TRRL[1] it is estimated that injury accidents involving car occupants, pedestrians and pedal cyclists are likely to be under-reported by 14%, 27% and 60% respectively. Comparison between police and hospital records reveals that serious road accidents (in terms of casualties) are less likely to be under-reported. It is assumed that all accidents involving fatalities are fully recorded.

Note:

The HGVs discussed in this chapter are illustrated in Appendix C.

3.1 Vehicular Accidents

During 1986 almost 15,000 HGVs were involved in road accidents in Great Britain, providing a total of 13,429 accidents, at a rate of 1 accident every 1.65 million km for the 221 x 10^8 km travelled. Assuming 1986 to be a typical year for accidents on British roads (there is no evidence to suggest otherwise) it is estimated that 85% of all HGV accidents result from collision with two or more vehicles, and that the remaining 15% are the result of single vehicle accidents (SVAs). The majority of accidents, 58%, are the result of collisions with private motor cars, a further 11% are caused by collisions with motorcycles and over 14% with HGVs, light goods vehicles (LGVs) and public service vehicles (PSVs). The second largest category of accidents is attributed to single vehicle accidents, which consist of accidents with pedal cyclists, pedestrians and collisions with stationary objects, such as, bridge parapets and lamp posts etc.. Over 59% of HGV vehicular accidents result in frontal impact, the remainder being split fairly evenly between side and rear impacts. Approximately 80% of all collisions in non-built-up areas occur at 30 mph or more, falling to 50% in built-up areas. In comparison, it is estimated that SVAs occurring at 30 mph or more account for 42% and 33% of SVAs in built-up areas and non-built-up areas respectively.

A little under 45% of all HGV accidents occur on built-up roads (BURs). However, the rate of HGV accidents on BURs is approximately 2.5 times greater than that associated with non-BURs. Accident rates also differ between HGV types. For example, the accident rate for a rigid 2-axle HGV on a BUR is given in Table F as 0.86 x 10^{-6} accidents per km. This compares with an accident rate of 1.28 x 10^{-6} accidents per km for an articulated 4-axle HGV over

identical road. Similarly, rates vary depending on the class of road, the "safest" roads, excluding motorways, being those designated as class A.

During 1986 the number of HGVs involved in accidents on British motorways[2] totalled 1531 providing an accident rate of 0.23×10^{-6} accidents per km travelled. This rate exemplifies the inherently safe characteristics of motorways compared with other roads. Non built-up roads have accident rates twice that of motorways and built-up roads a little over 4.5 times that of motorways. Approximately 29% of the annual distance covered by HGVs occurs on motorways. If such roads were as hazardous as other roads then about 4000 accidents could be expected to occur on motorways each year. It is apparent from the data given here that motorway travel is much safer than travel along other road types regardless of whether they are built-up or non-built-up.

With respect to motorway accidents, no data exist which distinguish HGVs by body type and/or axle configuration. In addition, much of the data within this chapter includes motorways in the non-BUR category. The Department of Transport suggest that errors which may result from the inclusion of motorways in the non-BUR category are minimal.

It is possible to produce accident rates which take account of vehicular position in relation to the road. For example, it is estimated that almost 6% of rigid HGV accidents on BURs occur at roundabouts, 14% at crossroads and over a third not at or within 20 m of a junction. In comparison, articulated HGV accidents on BURs produce similar accident proportions, except that almost 9% of accidents occur at roundabouts, highlighting the inferior

stability of articulated vehicles compared with rigid HGVs. Furthermore, accident rates can take account of accident severity with respect to casualties. For example, almost 60% of all fatalities resulting from HGV accidents occur on non BURs, whereas less than 10% occur on motorways. In addition, more casualties can be expected from articulated HGV accidents than from rigid HGV accidents. The severity and incidence of casualties can also be distinguished by accident type and colliding vehicle type. Casualties resulting from HGV accidents are detailed in Section 3.6, Tables N, O, P, Q and R.

3.1.1 Vehicular Accidents Involving the Transport of Explosives and Other Hazardous Goods

A total of 435,000 HGVs were registered up to the end of 1986[3]. Of these it is estimated by Withers[4] that only 1.1% were designed to carry hazardous goods. Hazardous goods are those substances designated as hazardous by United Nations classification and governed by the Classification, Packaging and Labelling Regulations 1984 (CPL UK). In essence, substances are considered hazardous if they are one or more of the following: explosive, flammable, toxic, radioactive, or likely to decompose to oxygen at elevated temperatures.

From the data given above, it is estimated here, that up to the end of 1986, there were approximately 4785 vehicles designed to transport hazardous goods. Assuming that such vehicles travel similar annual distances as any other HGVs and are as accident prone, then the data given in Section 3.6, Tables A, E and F can be used to estimate, the distance travelled, number of accidents and the accident

rate of such vehicles. These estimates are shown here in Table 1.

From the available literature it is apparent that HGVs designed to transport hazardous goods are not as accident prone as general HGVs. A discussion on this is given by Withers[4]. He suggests an accident rate of 0.25×10^{-6} accidents per mile which corresponds to 0.16×10^{-6} accidents per km. This general rate is almost 4 times less than the "all speed limits" rate of 0.62×10^{-6} accidents per km given in Table 1C. From the study conducted by the author on the transport of military explosives by road[5], the HGVs used by UK Armed Forces for the conveyance of explosives are considered to have accident rates between one tenth and one third of that attributed to national HGVs. The accident reduction proposed by Withers and that estimated by the author compare favourably and support the assumption that military HGVs and national HGVs transporting hazardous goods, with respect to the likelihood of accident involvement, are affected by similar mitigation. Table 2, given below, illustrates the effect of compensating for the known lower incidence of accidents for HGVs conveying hazardous goods. For comparative purposes both reducing factors, one tenth and one third, estimated by the author, are detailed.

The most common vehicles used to transport explosives are rigid 2-axle HGVs. These vehicles tend to have substantially lower accident rates than other HGVs, especially on built-up roads. It has been discussed here and in Chapter 2.0 that HGVs transporting hazardous goods are less likely to be involved in accidents than HGVs transporting non-hazardous goods. It is therefore sensible to assume that rigid 2-axle HGVs loaded with explosives have accident rates below that nationally attributed to

rigid 2-axle HGVs. Accident rates are thought to be appreciably less as a result of thorough vehicle maintenance, compliance with relevant regulations and codes of practice and driver training. In addition, it is thought that the fact that drivers appreciate the load being conveyed ensures their vigilance and attention and therefore, reduces their chances of accident involvement.

The mitigating features described above are clearly shown by the UK Armed Forces in their movement of military explosives. Vehicle maintenance is thorough and driver instructions strictly enforced[6]. Load and vehicle inspections are performed prior to and during transit and limits imposed on vehicle speeds and the distance to be kept from other road traffic[6]. It is somewhat uncertain as to how much these mitigating features reduce accident rates. However, the author has found evidence to suggest that HGVs conveying explosives under the control of UK Armed Forces may have accident rates between one tenth and one third of that given nationally for HGVs.

Between January 1970 and June 1987 Army HGVs used for the conveyance of military explosives, henceforth termed munitions vehicles (MVs), were involved in four injury accidents providing an average of 0.23 injury accidents per year. These accidents occurred in the Federal Republic of Germany. Not one single injury accident is known to have occurred in the UK between January 1970 and June 1987. The author has no knowledge of RAF or Naval MV injury accidents during this period.

Where no event or failure has occurred over the period of observation, it is a common statistical device to assume that one occurs just at the end of the period. It is postulated that between January 1970 and June 1987 one person was injured as a result of a vehicular accident during the road transport of munitions in 2-axle HGVs (MVs) on BURs. Assuming MVs travel a total of 1.04×10^6 miles per year and that 17% of this is on BURs[3] then the postulated accident rate is 0.06 injury accidents per year. Kletz et al[7] assume MVs to have accident rates half that of national rigid 2-axle HGVs. However, Kletz et al suggest that their assumption probably over-estimates MV accident rates, and that actual MV rates are much lower. The injury rate postulated here is one half of that found if the assumption used by Kletz et al is adopted (i.e. 0.06 compared with 0.12). This suggests that the doubts expressed by Kletz et al, regarding the magnitude of accident rate reduction, are well founded. As previously mentioned, it is thought here that MV accident rates are between one tenth and one third of the national HGV accident rates. Assuming a value of 20% the annual MV injury accident rate on BURs approximates to 0.049. This estimate is supported here by reference to data collected on Armed Forces "B" vehicle accidents[8,9]. Vehicles classed as "B" are "soft-skinned" wheeled vehicles[10], such as, cars and general-purpose vans and lorries. The category includes vehicles employed to transport munitions.

Between 31 March 1985 and 31 March 1986 United Kingdom Land Forces (UKLF) "B" vehicles were involved in 4213 road accidents at a rate of 1.43×10^{-6} accidents per km travelled. The corresponding rate for regular Army "B" vehicles over 4 ton was 1.86×10^{-6} accidents per km travelled. Munitions vehicles are classed here as rigid 2-axle HGVs and the vast majority of these are included in the "over 4 ton" category.

The above rates are for all accidents over all classes of road within the UK. From data received through the Logistics Executive[8] approximately 8% of all tri-service worldwide transport accidents involve injury. Thus, it is estimated here that UKLF "B" vehicles over 4 ton have an injury accident rate of 1.5×10^{-7} accidents per km. National rigid 2-axle HGVs in Great Britain have a BUR injury accident rate of 0.86×10^{-6} accidents per km. This rate is approximately 40% greater than the accident rate for all HGVs over all classes of road (see Section 3.6, Table F). Assuming this increase is applicable to "B" vehicles then on BURs UKLF "B" vehicles over 4 ton have an injury accident rate of 2.1×10^{-7} accidents per km travelled on BURs.

As mentioned earlier national HGVs transporting hazardous goods tend to have lower accident rates than HGVs transporting non-hazardous goods. It is commonly accepted that MVs have lower accident rates than general UKLF vehicles. The reduction is somewhat uncertain. It is suggested here that the divide between national HGVs transporting general goods and those transporting hazardous goods is much greater than that between general UKLF vehicles and MVs. This is supported by the lower incidence of accidents to UKLF "B" vehicles over 4 ton (1.5×10^{-7} accidents/km) as opposed to national HGVs (0.62×10^{-6} accidents/km, see Section 3.6, Table F). As a consequence of this it is assumed that MVs have accident rates approximately 30% less than general UKLF "B" vehicles over 4 ton. From this assumption it is thought that MVs are involved in 0.04 injury accidents per year on BURs (0.14×10^{-6} accidents/km) (compared with 0.049 injury accidents per year estimated solely from national HGV data).

It is envisaged that a similar deviation of accident rates exists between national HGVs transporting explosives (and other hazardous goods) and those national HGVs not conveying such cargo's. The estimates given here for MV injury accidents on BURs are derived from different data sources (i.e. 0.049 and 0.04 injury accidents per year). However, they compare favourably lending support to the argument for accident rate reduction when assessing HGVs involved in the transport of explosives and other hazardous goods.

Table 1: Distance travelled, number of accidents and frequency of accidents of HGVs designed to transport hazardous goods: Great Britain 1986

See note.

1A: Distance travelled

Kilometres x 10^8		
All speed limits	Non-BUR	BUR
2.39	1.77	0.62

1B: Number of accidents

Number of accidents		
All speed limits	Non-BUR	BUR
148	81	67

Table 1: continued

1C: Frequency of accidents

Frequency of accidents x 10^{-6} per km		
All speed limits	Non-BUR	BUR
0.62	0.46	1.08

Note:

a. Data refer to HGVs conveying hazardous goods assuming accident rates are the same as for HGVs conveying non-hazardous goods.
b. Injury accidents only.

Table 2: Number and frequency of HGV accidents designed to transport hazardous goods: Modified to accommodate the known lower incidence of accidents compared with other HGVs: 1986

2A: Number of accidents

Number of accidents		
All speed limits	Non-BUR	BUR
15 - 48	8 - 27	7 - 22

2B: Frequency of accidents

Frequency of accidents x 10^{-6} per km		
All speed limits	Non-BUR	BUR
0.06 - 0.21	0.05 - 0.15	0.11 - 0.36

Table 2: continued

2C: Comparison between HGVs transporting hazardous and non-hazardous goods

Relative frequency of accidents	
Hazardous	Non-Hazardous
0.1 - 0.33	1

2D: Comparison between MVs and UKLF vehicles

Relative frequency of accidents	
MVs	UKLF[a]
0.6 - 0.8	1

Note:

a. UKLF "B" vehicles over 4 ton.
b. Accident rates for Tables 2C and 2D refer to all speed limits .

3.2 Collision Speeds of Heavy Goods Vehicles: Impact Speed Study

Estimating the speed of road vehicle collisions has until recently been entirely based on professional judgements formed by reference to travel speed surveys and accident investigations. For example, during the summer of 1983 the Department of Transport conducted a survey of vehicle speeds on non built-up roads. Speed measurements were taken on flat straight roads free from junctions, roadworks and other causes of traffic congestion. As a consequence of this, vehicle speeds were only restricted by road speed limits and the speeds at which drivers chose to travel. On single carriageway roads mean HGV speeds were 41 mph for rigid HGVs and 42 mph for articulated HGVs. These mean speeds compare with 48 mph and 49 mph, and 56 mph and 60 mph for rigid and articulated HGVs on dual carriageway roads and motorways respectively. It is perhaps surprising to note that articulated HGVs have greater mean speeds than rigid HGVs, but not surprising to find that the percentage of HGVs exceeding permitted speed limits range from 30% for rigid HGVs on motorways to 60% for articulated HGVs on single carriageway roads. The survey is detailed in Table 3. The Transport and Road Research Laboratory (TRRL) suggest that vehicle speeds in built-up areas are governed by traffic conditions, which are controlled by parking restrictions, junctions, traffic lights, roundabouts and crossings, etc.. From data supplied by Duncan[11] it is estimated that the mean speed of HGVs through large and small towns (population less than 30,000) is 23 mph and 14 mph respectively. Vehicle speeds, however, vary depending on the time of day and hence traffic density. During "peak" periods mean vehicle speeds tend to fall by between 1 mph and 3 mph. The data supplied by Duncan relate to actual vehicle motion and no account is taken of vehicle stoppages, although almost 11% of accidents occur when

vehicles are stationary[12] (i.e. 5.3% of accidents occur whilst vehicles are parked and 5.3% whilst vehicles are stationary in traffic).

Obviously only poor estimates of actual HGV collision speeds can be made from speed surveys, such as those described above. In addition, only marginal improvement in collision speed estimates is found by reference to accident investigations, which are based on vehicular damage and the measurement of skid marks, etc.. However, with the introduction of tachograph charts in 1974 and compulsory implementation for all HGVs in 1981[13,14] it is now possible to obtain accurate impact speeds for HGVs.

Essentially tachograph charts record the time, speed and distance of a vehicles journey. Tachograph analysis[15] has become an integral part of accident investigation and is performed by specially trained police and forensic science personnel. The detail provided by the recordings is often used as evidence in court cases supplementing eye witness accounts and data collected at the scene of accidents.

Impact speed data for HGVs have been collected by the author with the help of the Metropolitan Police Forensic Science Laboratory[16] (MPFSL). Over 110 tachograph based reports have been studied covering the years 1978 through to 1982. These tacho-graph reports form the basis of the impact speed study (ISS). MPFSL were the first to introduce tachograph analysis in the UK, as a consequence of this early reports cover various locations throughout Britain. However, with the increase nationally in facilities and staff trained specifically in tachograph analysis most of the latter reports relate to the Metropolitan Borough of London.

The data presented here are considered a biased sample of HGV impact speeds. This is because each report is part of an accident investigation which either involves serious casualties and/or police enquiries and/or court proceedings. No attempt has been made to compensate for the known conservatism.

Table 4 illustrates HGV accidents with respect to impact speed, location and accident type. Tables 5 and 6 use the data in Table 4 and distinguish between vehicular collisions (collisions between vehicles - excluding collisions with motorcycles) and single vehicle accidents. Actual impact speeds for vehicular collisions in built-up areas are recorded in Table 7. The sample of impact speeds given in Table 7 appear to be normally distributed (see Figure 1). Using the usual formula the distribution of HGV impact speeds in built-up areas is shown in Figure 2.

Key to Tables 4, 5 and 6 (ISS)

A - accident (impact position undetermined)
F - frontal impact of HGV
H - head-on collisions
MC - collision with motorcycle
PED - collision with pedestrian
PC - collision with pedal cyclist
R - rear impact of HGV
S - side impact of HGV
SVA - single vehicle accident

Table 3: Speed of heavy goods vehicles on non built-up roads: Department of Transport vehicle speed survey: 1983

3A: Single carriageway

HGV type	mean speed (mph)	speed limit (mph)	% over limit
Rigid	41	40	55
Articulated	42	40	60
All HGVs	41	40	56

3B: Dual carriageway

HGV type	mean speed (mph)	speed limit (mph)[a]	% over limit[b]
Rigid	48	40	87
Articulated	49	40	92
All HGVs	48	40	89

Note:

a. New speed limit 50 mph, 23 March 1984
b. With respect to new speed limit - 37% rigid, 46% artic.

Table 3: continued

3C: Motorways

HGV type	mean speed (mph)	speed limit (mph)[a]	% over limit
Rigid	56	60	30
Articulated	60	60	50
All HGVs	58	60	39

Note:

a. Unladen weight less than 3.05 te speed limit is 70 mph.

Table 4: HGV impact speeds: All accidents

4A: Built-up areas

Impact speed (mph)	Accidents	No
0 - 9	3F MCS	4
10 - 19	3H A 2SVA MCH PC 2PED	10
20 - 29	2H 7F S 9SVA MCS 2PED	22
30 - 39	H 6F S 4A 2SVA MCH PC 3PED	19
40 - 49	H 3F A 4SVA 2PED	11
50 - 60	2F	2
60+		--
Total		68

Table 4: continued

4B: Non built-up areas

Impact speed (mph)	Accidents	No
0 - 9	S SVA	2
10 - 19	H S 3SVA	5
20 - 29	A 2SVA	3
30 - 39	2H F R A 2SVA PC	8
40 - 49	3H 5F A SVA PC	11
50 - 60	2F	2
60+	F	1
Total		32

4C: Motorways

Impact speed (mph)	Accidents	No
0 - 9	-	-
10 - 19	-	-
20 - 29	H F MCR	3
30 - 39	H SVA	2
40 - 49	2F SVA	3
50 - 60	F R 2SVA	4
60+	SVA	1
Total		13

Table 5: HGV impact speeds: Vehicular collisions

Impact Speed (mph)	Accidents					
	BUA	No	Non-BUA	No	M-WAY	No
0 - 9	3F	3	S	1		
10 - 19	3H A	4	H S	2		
20 - 29	2H 7F S	10	A	1	H F	2
30 - 39	H 6F S 4A	12	2H F R A	5	H	1
40 - 49	H 3F A	5	3H 5F A	9	2F	2
50 - 59	2F	2	2F	2	F R	2
60+		--	F	1		
TOTAL		36		21		7

Note:

a. Excludes accidents with motorcycles.

Table 6: HGV impact speeds: Single vehicle accidents

Impact Speed (mph)	Accidents					
	BUA	No	Non-BUA	No	M-WAY	No
0 - 9			SVA	1		
10 - 19	2SVA 2PED	4	3SVA	3		
20 - 29	9SVA 2PED	11	2SVA	2		
30 - 39	2SVA 3PED	5	2SVA	2	SVA	1
40 - 49	4SVA 2PED	6	SVA	1	SVA	1
50 - 59					2SVA	2
60+					SVA	1
TOTAL		26	9		5	

Note:

a. Includes accidents with pedestrians.

Table 7: Sample of HGV impact speeds: Vehicular collisions in built-up areas

Impact Speed (mph)					
4	4	9	16	19	19
19	22	23	24	25	26
27	27	28	28	29	30
31	34	35	35	36	36
36	36	37	37	39	40
42	44	44	48	55	57

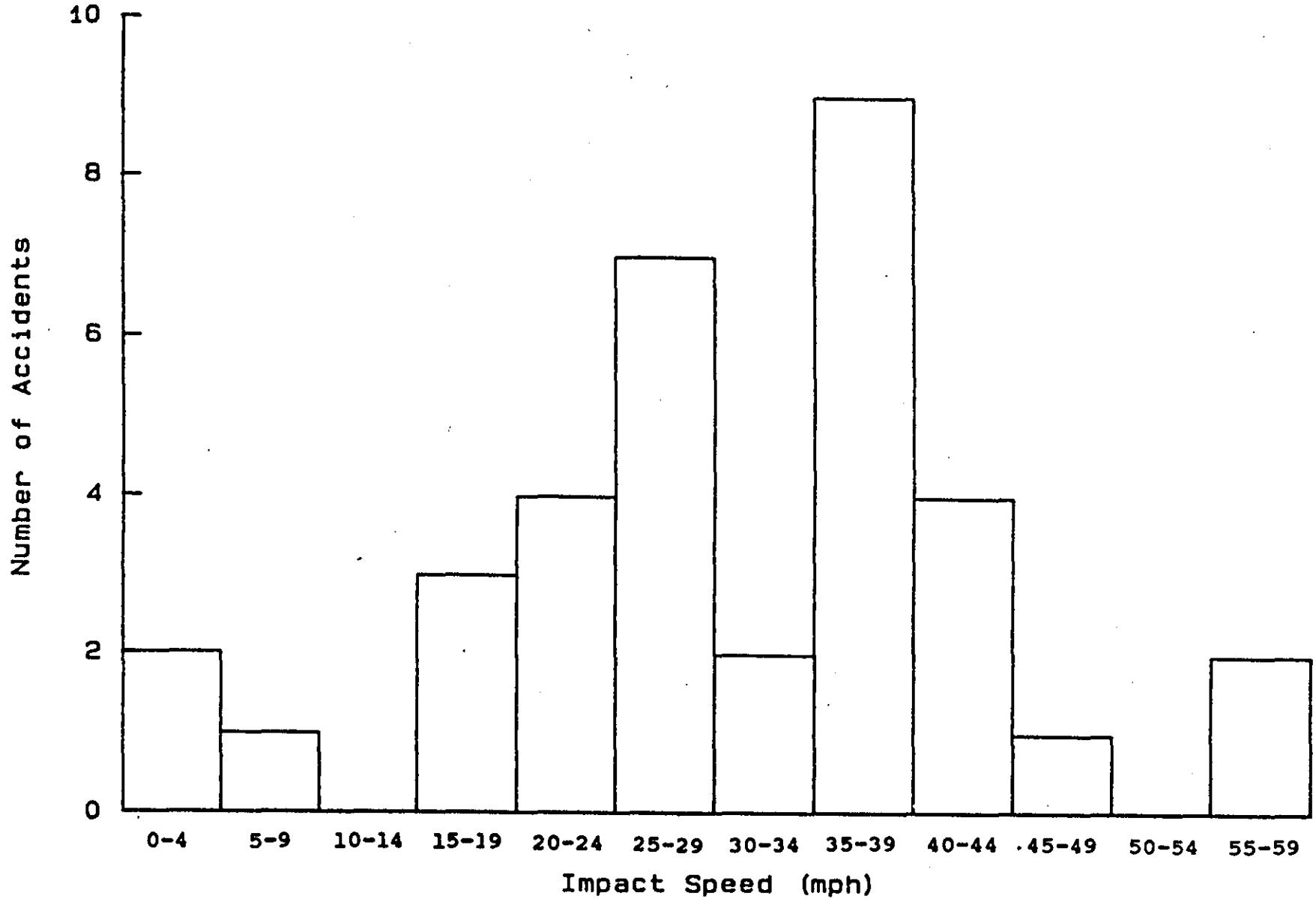

Figure 1: HGV vehicular collisions in built-up areas

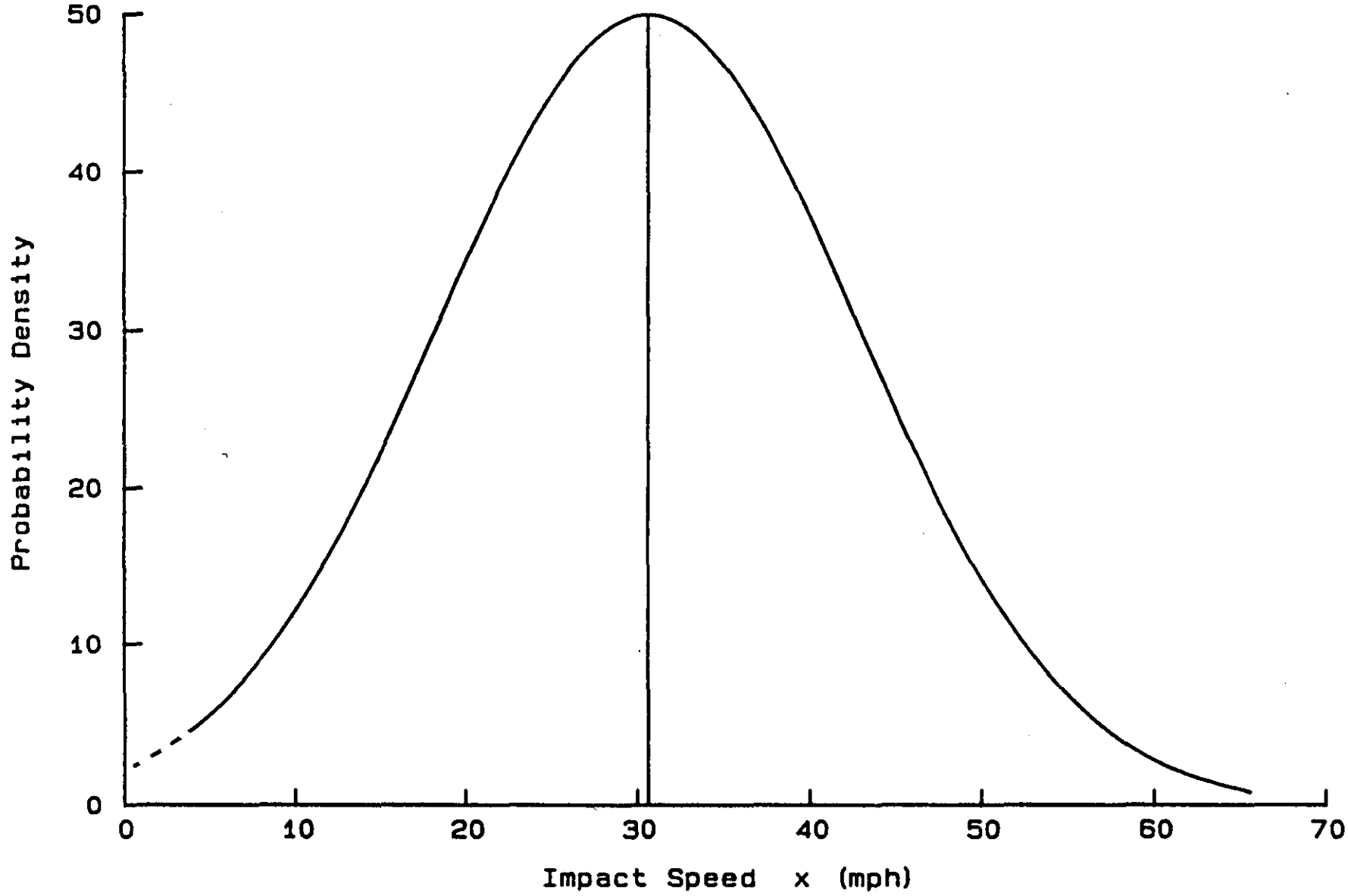

Figure 2: Distribution of HGV impact speeds for vehicular collisions in built-up areas

3.3 Vehicle Fires

During 1986 the fire brigade attended 7212 van and lorry fires[17]. Van and lorry fires accounted for 4634 and 2578 fires respectively. Not all of these were on the public highway. However, no data are available to quantify the number of fires on the public highway, but it is thought that the vast majority would have been. Due to lack of detail, and so as to estimate the incidence of vehicle fires it is assumed here that all van and lorry fires occur on the public highway.

From data released by the Home Office[17] a total of 71 van and lorry fires were caused by crash or collision during 1986. Of these 19 were attributed to lorry crash fires. Over the same period lorry non-crash fires totalled 2559.

When recording fire incidents the fire services use the term "lorry" to describe all vehicles which have a commercial chassis and/or a separate personnel and load compartment/area. For example, an HGV consisting of a cab with a flat-bed load area or tank compartment is classed as a lorry. From discussions with the London Fire and Civil Defence Authority[18] and the Cleveland County Fire Brigade[19] it is assumed here that a lorry corresponds to a heavy goods vehicle (HGV).

Assuming that HGVs travel[20] a total of 221×10^8 km per year, then during 1986 it is estimated here that HGVs were involved in 2559 non-crash fires at a rate of 0.12×10^{-6} fires per km. It follows that 19 HGVs were involved in crash fires over the same period at a rate of 0.09×10^{-8}

fires per km.

The rates given above are general rates for all HGVs over all speed limits. The estimates assume that crash and non-crash fires are as likely to occur on BURs as on non-BURs and that these likelihoods are the same regardless of HGV type. However, both crash and non-crash fire rates vary with respect to vehicle type, time and location. Unfortunately no data are readily available to categorise non-crash fires by vehicle type. Location, however, can be examined by the estimation of the distance travelled on particular roads combined with the mean HGV speeds associated with these roads (see Section 3.6, Table A - mean HGV speeds are detailed in Section 3.2). For example, the mean speeds of HGVs are governed by traffic conditions. The mean speed[11] of HGVs on BURs is 23 mph and on non-BURs it is assumed here to be 45 mph. Assuming HGVs travel 221 x 10^8 km per year, that 25% of this is on BURs and that a direct relationship exists between the incidence of non-crash fires and the time spent on BURs, then it is estimated here that 40% of HGV non-crash fires occur on BURs. This compares with almost a half of all HGV crash fires occurring on BURs (46%). HGV crash fires categorised by axle configuration, body type and location are detailed in Section 3.6, Tables S and T.

The causes of HGV non-crash fires are as numerous as they are frequent. Approximately 70% are attributed, at least in part, to poor vehicle maintenance. Such fires tend to be the result of fuel leaks, electrical faults and overheating, etc.. Surprisingly almost 14% of non-crash fires are the result of arson and 6% smokers negligence. Compared with non-crash fires the vast majority of crash fires are caused by the spillage and subsequent ignition of fuel. Non-crash fire causes are summarised in Section 3.6,

Table U.

It is considered here that the chances of fire resulting from one of the above causes, especially arson and smokers negligence are substantially lower for HGVs conveying explosives (and other hazardous goods) than HGVs conveying non-hazardous goods. This is because vehicles are rarely left unattended, smoking is strictly controlled (and actively discouraged) and vehicle maintenance is generally attributed greater importance[6].

The greatest threat to explosives and other thermally sensitive goods is the spread of fire causing vehicle, and in particular, load compartment engulfment. Vehicle engulfment is dependent upon a multitude of factors. First aid fire-fighting may be undertaken by those accompanying the vehicle or by other road users. Such action, however, relies to a large extent on the availability of fire-fighting equipment. Fires occurring in load compartments, or other areas where sight is restricted, may not be discovered until they are well established. Tyre fires are notoriously difficult to extinguish. In addition some delay may occur in the notification of the fire services. Obviously delays of this kind reduce the chances of rapidly controlling and extinguishing vehicle fires. Additionally, it is not uncommon for those within the immediate vicinity of a vehicle fire to refrain from first aid fire-fighting. Such "in-action" may be due to lack of equipment, injury or the need for evacuation as a result of engulfment (or imminent engulfment) of a hazardous load. In such instances, the only source of emergency action is that of the fire services. However, upon their arrival at the scene the vehicle may already be engulfed.

Vehicle engulfment is also affected by cause and location of fire. For example, vehicle fires caused by fuel tank rupture burn much more fiercely than isolated electrical fires. The location of fire on vehicles not only affects the likelihood of engulfment (i.e. relative position with respect to fuel or readily combustible materials) but also affects fire fighting procedure. For example, a fuel fire near to a load liable to explode requires greater caution by fire fighting personnel than a fire confined to a HGV cab. In certain circumstances the location of the vehicle may also affect fire fighting procedure and effectiveness (i.e. narrow roads, multiple accidents, injured persons and the distance from and vehicle position with respect to fire hydrants, densely populated areas, and chemical plants etc.).

There is a lack of detailed information on the causes of engulfing fires. In addition there are no data on the likelihood of engulfment given a fire of known cause. It is considered here that for HGVs conveying explosives the likelihood of engulfment given a non-crash fire is less than that for HGVs conveying non-hazardous goods. In addition to the points raised above vehicles used for the carriage of explosives are fitted with quick release fuel cut-off valves and most have additional fire proofing protection between the load compartment and surrounding vehicle. A review of vehicle features and regulations which affect the likelihood of fire and engulfment are given in Section 6.5.2 and Appendix A.

For HGVs not conveying hazardous goods, it is estimated here that about 20% of all non-crash fires subsequently become engulfing and that for HGVs conveying hazardous goods the proportion is substantially less than this (i.e. between 5% and 15%). These estimates are based on

assumptions used in the assessment of munition vehicle (MV) fires, conducted by the author for the Ministry of Defence[5]. It is estimated that the probability of engulfment given a fire caused by arson, smokers negligence, electrical faults, oil/petrol and unknown causes is 0.40, 0.05, 0.10, 0.15 and 0.10 respectively. Based on these assumptions 16% of all HGV (national) non-crash fires are considered to be engulfing. Ignoring arson and smokers negligence as causes of fire (for the reasons given previously) the probability of engulfment given a non-crash fire for MVs is estimated to be 5%. These estimates compare well with the estimate implied by North[20] that between 20% and 30% of all private motor vehicle fires are engulfing. This is because compared with private motor vehicles it is generally agreed that HGVs are less likely to become engulfed and that this likelihood diminishes further for HGVs conveying hazardous goods.

Between January 1970 and June 1987 Army MVs were involved in 7 non-crash fires and 1 crash fire[22]. Only three fires involved injury, all of which were non-crash fires occurring in the Federal Republic of Germany. In comparison, RAF MVs were involved in 3 non-crash fires between 15th September 1981 and 1st May 1986. All the RAF MV fires occurred on British roads and no casualties were reported[23]. No data have been made available on the incidence of naval MV fires.

The data given above on MV fires, and that data detailed in Appendix B, are not strictly comparable with data given here on national HGV fires. This is a direct result of the means by which the Ministry of Defence and the Department of Transport collect and record data. Statistics on national HGV fires are collated by the Home Office through data supplied by the fire services. All vehicle fires

attended by the fire services are recorded and reports made available to the Home Office. The attendance of the fire services, in most cases, only occurs when vehicle fires cannot be extinguished by those at the scene or there is a possibility that the fire may spread and/or endanger life. It should be noted that the fire services attend all fires on request regardless of severity. However, it is suggested here that only a small proportion of all vehicle fires attended by the fire services are trivial. Therefore, the majority of recorded incidents are fires considered to be "serious" or "non-trivial" in terms of severity, life and property. In comparison, the majority of MV vehicle fires, whether trivial or not, are recorded. In addition, unlike MV fire data a large proportion of fires recorded by the Home Office include HGV fires caused by arson and smokers negligence adding to the already present disparity between the two sets of data.

From the foregoing it is not possible to estimate the incidence of MV fires or make strict comparisons with national HGVs. However, the qualitative factors discussed above are useful in adjusting estimates based on national HGV data.

3.4 Movements of Explosives

The road movement of explosives can be chiefly divided into those explosives conveyed for commercial purposes and those conveyed by the Armed Forces (including Ministry of Defence establishments). As a result of the need for commercial confidentiality and military secrecy data on explosives movements are scarce and limited. Consequently only a broad description of explosives movements can be

given here.

It is estimated that HGVs conveying commercial explosives travel between 3×10^6 km and 4×10^6 km per year. A large proportion of the distance is covered by specially equipped rigid 2-axle HGVs. These vehicles are mainly used for secondary movements from storage/distribution depots to customers, and account for between 50% and 70% of all movements. In comparison the majority of primary movements, which consist of explosives transfers between depots, and factories and depots, involve articulated 4-axle HGVs. However, it is estimated that approximately 20% to 40% of primary movements are made by rigid 2-axle HGVs. For the distances quoted here it is thought that loaded vehicle kilometres account for between 50% and 65% of all vehicle kilometres. In comparison, the vast majority of military movements involve rigid 2-axle HGVs similar in construction to those used commercially. Loaded military movements cover between 1×10^6 km and 2×10^6 km per year. It is known that both commercial and military movements avoid, wherever practicable, built-up areas and use main trunk roads and motorways. The distance travelled through built-up areas is obviously route dependent, but it is thought that between 5% and 20% of total annual MV distance is covered on roads passing through BUAs.

3.5 Review of Accident Studies

Two reports have been found which are of particular interest to this study. The first report, issued by TRRL, details fatal accidents involving HGVs, and the second, issued by the Home Office, details incidents involving dangerous chemicals. Both reports have been compiled without the intention that their contents may be used for hazard assessments. However, the information they contain is useful for this purpose, if only as a general guide to the frequency of events. Although both surveys are useful in identifying areas of concern, detailed data with respect to road accidents, axle configuration, body type and road class are not recorded. A bibliography of accident studies and other useful data are given at the end of this section.

Fatal Accidents in Great Britain in 1976 Involving Heavy Goods Vehicles

Riley, B.S. and Bates, H.J. (1980). SR 586. Transport and Road Research Laboratory, Crowthorne, Berkshire.

The report is based on data collated from 740 fatal HGV accidents recorded by the police during 1976. All accidents occurred on British roads. The main aim of the study is to formulate a basis for the selection of safety developments and transport policies.

Heavy goods vehicles are classed as vehicles having unladen weights in excess of 3 tons. Axle configurations of vehicles are ignored and the only mention of body type refers to the fact that 54% of the 812 vehicles are rigid and 43% articulated. However, the data collated suggest

that rigid HGVs are under-represented in the sample.

Road class is highlighted, indicating that 65% of accidents occur on A class roads and approximately 8% on motorways. This compares well with the data given in Section 3.6 that about 68% of accidents occur on A class roads and 11% on motorways.

The report was compiled prior to the introduction of built-up and non built-up road classification. However, the report states that 43% of accidents occur in built-up areas, and that three quarters of these occur on roads subject to a 30 mph speed limit.

Accidents involving no more than two vehicles account for 85% of all accidents, whereas three or more vehicle accidents account for 5% of the total. This compares with approximately 78% and 22% respectively, using the data compiled within Section 3.6.

Eight HGVs caught fire, all due to impact. This figure indicates that the crash-fire rate of fatal HGV accidents is approximately twice that expected from all HGV road accidents.

Although rigid vehicles are under-reported the data support the general assumption that articulated HGVs are much more likely to roll-over when involved in accidents than rigid HGVs. Two thirds of roll-overs involve articulated HGVs (from a sample of 40). It is interesting to note that half of all the roll-overs are associated with single vehicle accidents (SVAs), and that these account for

some 70% of all SVAs.

Finally, recording of load movement and load shedding, which is often neglected or only briefly mentioned in most reports is well documented. Of the 812 HGVs, 58 shed their load and 30 experienced load movement. It should be noted that only 1 HGV shed its load and 5 experienced load movement prior to impact. The data suggest that 50% of all shedding and load movement occurs as a result of collisions between HGVs, illustrating the ferocity of these accidents.

Incidents Involving Dangerous Chemicals

Home Office Survey for the years 1977 and 1980.

During 1980 the Fire Department of the Home Office conducted a survey of road incidents involving the transport of "dangerous chemicals". The survey was undertaken in order to supplement a similar study by the Scientific Advisory Branch of the Home Office, which was curtailed in 1977 due to the Fireman's strike of that year.

The 1977 survey covers a period of 9 months and records 250 incidents arising from the transport of hazardous freight on British roads (out of a total of 304 incidents). Only 6 fatalities are recorded, all of which are associated with road accidents. Non-fatal casualties total 110, 41 resulting from road accidents and 69 resulting from involvement with chemicals in transit.

Five fires are recorded although incidents involving fumes total 124. Spillage of vehicle loads occurs in 260 cases; 109 being spills of up to 10 litres, another 109 between 10 and 210 litres and 42 incidents in excess of 210 litres.

Over 80% of all incidents are caused by mechanical defects. Less than 20% of incidents are the result of traffic accidents. Unfortunately, traffic accidents are not detailed.

In comparison 609 incidents are recorded in the 1980 survey, of which 15 are the result of fire. Thirty nine percent of road transport incidents occur on the public highway, of these only 36 are due to traffic accidents, a mere 15%.

Incidents are recorded by location; approximately 72% occur in urban areas, 25% in rural areas and 3% of locations are not known. The number of incidents in urban areas is considered excessive compared with national accident data which indicate that between 45% and 60% of all HGV accidents occur in built-up areas.

3.5.1 Bibliography of studies and sources of reference on HGV collisions and fires (excluding sources referenced)

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3.6 HGV Accident and Transport Data

Notes to tables

Table H

Proportions have been derived using vehicle involvement rates given in Table G and the number of vehicles involved by road class given by the Department of Transport[3].

Table I

Accident frequencies have been derived using the data given in Tables A, C, E and H.
e.g. HGV, rigid, 2-axle, non-BUR, class A road.

Accident frequency

= (number of accidents) / (vehicle kilometres)
= $(0.76 \times 3482) / (0.87 \times 87 \times 10^{8})$
= 0.35×10^{-6} accidents/km

Table J

Accident frequencies have been derived using the data given in Tables D2, D3, and I.

e.g. Accident between a rigid 2-axle HGV and a pedal cycle on a class A road.

Accident frequency

= proportion of PC accidents x frequency of HGV accidents
= $(0.086 \times 0.852) \times (0.84 \times 10^{-6})$
= 0.06×10^{-6} accidents/km

Two vehicle, and three or more vehicle accidents have been combined to give 85.2% of all HGV accidents. The vehicle combinations of accidents involving three or more different vehicles have not been considered due to lack of data. Hence, it is assumed that the relative proportions of vehicle combinations given in Table D3 are representative of all accidents, regardless of the number of vehicles involved. Similarly the relative proportions hold good regardless of road class.

Table K

See notes to Table J.

Table A: Distance travelled by road type, body type and axle configuration: 1986

HGV type	Distance (10^8 km) All speed limits	Non-BUR	BUR
Rigid			
2-axle	131	87	44
3-axle	11	8	3
4-axle+	10	8	2
Articulated			
3-axle	6	5	1
4-axle	41	36	5
5-axle+	18	17	1
All HGVs*	221	165	56

Note:

a. * includes axle configuration not reported.
b. Non-BUR includes motorways.

Source: Department of Transport[20]

Table B: Number of HGVs involved in accidents by road type, body type and axle configuration: 1986

HGV type	All speed limits	Non-BUR	BUR
Rigid			
2-axle	7660	3672	3988
3-axle	1345	714	631
4-axle+	1120	657	463
Articulated			
3-axle	730	447	283
4-axle	2118	1444	674
5-axle+	1188	872	316
All HGVs*	14773	7958	6815

Note:

a. * includes axle configuration not reported.
b. Non-BUR includes motorways.

Source: Department of Transport[20]

Table C: Proportion of HGVs involved in accidents by road class: 1986

Road class	Non-BUR	BUR
A	76	60
B	10	11
Other	14	29
Total	100%	100%

Note:

a. Data excludes motorways.

Source: Department of Transport[20]

Table D: Number of HGV accidents by the combination of vehicles involved: 1986

D1: Two vehicle and single vehicle accidents

Accident involving	Number of accidents	Proportion of accidents
Car	5271	50.4
MC	1012	9.7
Coach or Bus	186	1.8
LGV	594	5.7
HGV	529	5.1
Pedal cycle	723	6.9
Pedestrian	1104	10.6
SVA	890	8.5
Other	137	1.3
Total	10446	100.0%

Note:

a. MC includes combinations.

Source: Department of Transport[20]

Table D: continued

D2: Two vehicle accidents only

Accident with..	Proportion of accidents
Car	62.4
MC	12.0
Coach or Bus	2.2
LGV	7.0
HGV	6.3
Pedal Cycle	8.6
Other	1.5
Total	100.0%

Note:

a. Data is for two vehicle accidents only.
b. MC includes combinations.

Source: Department of Transport[20]

Table D: continued

D3: All accidents

Accident involving	Number of accidents	Proportion of accidents
SVA	1994	14.8
Two vehicles	8452	63.0
Three or more vehicles	2983	22.2
All accidents	13429	100%

Source: Department of Transport[20]

Table E: Number of HGV accidents by road type, body type and axle configuration: 1986

HGV type	All speed limits	Non-BUR	BUR
Rigid			
2-axle	7264	3482	3782
3-axle	1275	677	598
4-axle+	1062	623	439
Articulated			
3-axle	692	424	268
4-axle	2009	1370	639
5-axle+	1127	827	300
All HGVs	13429	7403	6026

Note:

a. Non-BUR includes motorways.
b. During 1986 14161 HGVs (excluding axle configuration not reported) were involved in 13429 accidents. The ratio of accidents to vehicles involved is 0.948:1. Using this ratio the number of accidents during 1986 can be estimated for HGVs by road type, body type and axle configuration. It is assumed that the ratio is constant regardless of HGV type and road type.

Table F: Frequency of HGV accidents by road type, body type and axle configuration: 1986

HGV type	Frequency (accidents/10^6 km) All speed limits	Non-BUR	BUR
Rigid			
2-axle	0.55	0.40	0.86
3-axle	1.16	0.85	2.00
4-axle+	1.06	0.78	2.20
Articulated			
3-axle	1.15	0.85	2.68
4-axle	0.49	0.38	1.28
5-axle+	0.63	0.49	3.00
All HGVs	0.62	0.46	1.08

Note:

a. Non-BUR includes motorways.
b. Accident frequencies are derived from data given in Tables A and E.

Table G: HGV involvement rates by road class: 1986

Road class	Involvement rate x 10^{-6} Non-BUR	BUR
A	0.57	1.19
B	1.15	1.21
Other	1.30	1.28
All roads	0.48	1.22

Note:

a. Involvement rate is per km.
b. Non-BUR includes motorways.

Source: Department of Transport[20]

Table H: Proportion of distance travelled by HGVs by road class: 1986

Road class	Non-BUR (%)	BUR (%)
A	87.0	61.0
B	6.0	11.5
Other	7.0	27.5
All roads	100.0%	100.0%

Note:

a. Data excludes motorways.

Table I: Frequency of HGV accidents by body type, axle configuration and road class: 1986

HGV type	Frequency x 10^{-6} per km					
	Non-BUR			BUR		
	A	B	Other	A	B	Other
Rigid						
2-axle	0.35	0.70	0.80	0.84	0.86	0.90
3-axle	0.74	1.48	1.69	1.95	1.98	2.09
4-axle+	0.67	1.35	1.55	2.14	2.19	2.30
Articulated						
3-axle	0.74	1.48	1.69	2.62	2.67	2.81
4-axle	0.33	0.66	0.76	1.25	1.28	1.34
5-axle+	0.43	0.85	0.97	2.91	2.99	3.14
All HGVs	0.66	1.32	1.51	1.05	1.08	1.13

Note:

a. Data excludes motorways.

Table J: Frequency of HGV accidents on BURs by body type, axle configuration, road class and the combination of vehicles involved: 1986

J1: Car, MC and coach or bus

HGV type	Frequency x 10^{-6} per km								
	Car			MC			Coach or Bus		
	A	B	Other	A	B	Other	A	B	Other
Rigid									
2-axle	0.45	0.46	0.48	0.09	0.09	0.09	0.02	0.02	0.02
3-axle	1.04	1.05	1.11	0.20	0.20	0.21	0.04	0.04	0.04
4-axle+	1.14	1.16	1.22	0.22	0.22	0.24	0.04	0.04	0.04
Artic.									
3-axle	1.39	1.42	1.49	0.27	0.27	0.29	0.05	0.05	0.05
4-axle	0.66	0.68	0.71	0.13	0.13	0.14	0.02	0.02	0.03
5-axle+	1.55	1.59	1.67	0.30	0.31	0.32	0.05	0.06	0.06
All HGVs	0.56	0.57	0.60	0.11	0.11	0.12	0.02	0.02	0.02

J2: LGV, HGV and pedal cycle

HGV type	Frequency x 10^{-6} per km								
	LGV			HGV			Pedal Cycle		
	A	B	Other	A	B	Other	A	B	Other
Rigid									
2-axle	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.06	0.07
3-axle	0.12	0.12	0.12	0.11	0.11	0.11	0.14	0.14	0.15
4-axle+	0.13	0.13	0.14	0.11	0.12	0.12	0.16	0.16	0.17
Artic.									
3-axle	0.16	0.16	0.17	0.14	0.14	0.15	0.19	0.20	0.21
4-axle	0.07	0.08	0.08	0.07	0.07	0.07	0.09	0.09	0.10
5-axle+	0.17	0.18	0.19	0.16	0.16	0.17	0.21	0.22	0.23
All HGVs	0.06	0.06	0.07	0.06	0.06	0.06	0.08	0.08	0.08

Table K: Frequency of HGV single vehicle accidents by body type, axle configuration and road class: 1986

K1: Built-up roads

HGV type	Frequency x 10^{-6} per km								
	SVA (no ped.)			SVA (ped.)			Total SVA		
	A	B	Other	A	B	Other	A	B	Other
Rigid									
2-axle	0.05	0.05	0.06	0.07	0.07	0.07	0.12	0.12	0.13
3-axle	0.12	0.12	0.13	0.15	0.15	0.16	0.27	0.27	0.29
4-axle+	0.13	0.13	0.14	0.17	0.17	0.18	0.30	0.31	0.32
Artic.									
3-axle	0.16	0.17	0.18	0.20	0.21	0.22	0.36	0.38	0.40
4-axle	0.08	0.08	0.08	0.10	0.10	0.10	0.18	0.18	0.18
5-axle+	0.18	0.19	0.20	0.23	0.23	0.24	0.41	0.42	0.44
All HGVs	0.07	0.07	0.07	0.08	0.08	0.09	0.15	0.15	0.16

K2: Non built-up roads

HGV type	Frequency x 10^{-6} per km								
	SVA (no ped.)			SVA (ped.)			Total SVA		
	A	B	Other	A	B	Other	A	B	Other
Rigid									
2-axle	0.02	0.04	0.05	0.03	0.05	0.06	0.05	0.09	0.11
3-axle	0.05	0.09	0.11	0.06	0.11	0.13	0.11	0.20	0.24
4-axle+	0.04	0.08	0.10	0.05	0.10	0.12	0.09	0.18	0.22
Artic.									
3-axle	0.05	0.09	0.11	0.06	0.11	0.12	0.11	0.20	0.24
4-axle	0.02	0.04	0.05	0.03	0.05	0.06	0.05	0.09	0.11
5-axle+	0.03	0.05	0.06	0.03	0.07	0.08	0.06	0.12	0.14
All HGVs	0.04	0.08	0.09	0.05	0.10	0.12	0.09	0.18	0.21

Table L: Impact position of HGVs by the combination of vehicles involved

Impact Position	Proportion of impacts				
	Car	MC	LGV	HGV	All vehicles
Frontal	66	41	63	53	59.4
Side	16	31	9	15	18.6
Rear	14	26	28	24	18.1
Other	4	2	0	8	3.9
Total	100%	100%	100%	100%	100.0%

Source: Riley, B.S. and Bates, H.J. (1980). Fatal accidents in GB in 1976 involving HGVs. SR 586. Transport and Road Research Laboratory, Crowthorne, Berkshire.

Table M: Proportion of HGV accidents by body type and junction type: 1986

Junction type	Rigid Non-BUR	Rigid BUR	Articulated Non-BUR	Articulated BUR
roundabout	3.4	5.5	5.0	8.9
T or staggered	13.7	36.0	10.0	32.9
Y junction	1.3	1.7	1.1	1.4
crossroads	4.2	13.6	3.1	12.5
multiple	0.5	1.7	0.5	2.7
slip road	2.7	0.5	4.1	1.3
private entrance	5.0	5.0	3.0	5.2
other	1.0	1.6	1.0	2.1
not at or within 20m of junction	68.2	34.4	72.2	33.0
Total	100.0%	100.0%	100.0%	100.0%

Source: Department of Transport[20]

Table N: Number of casualties involving HGVs by road type: 1986

Road type	Fatalities	All casualties
BURs[a]		
A roads	205	4926
B roads	34	933
Other roads	74	2316
All roads	313	8175
Non-BURs[a]		
A roads	451	6452
B roads	34	838
Other roads	37	1095
All roads	522	8385
All speed limits		
Motorways	73	1888
A roads	656	11378
B roads	68	1771
Other roads	111	3411
All roads	908	18448

Note:

a. Excludes motorways.

Source: Department of Transport[2]

Table O: Proportion of casualties resulting from HGV accidents by road type: 1986

Road type	Fatalities (%)	All casualties (%)
BURs[a]	34.5	44.3
Non-BURs[a]	57.5	45.5
Motorways	8.0	10.2

Note:

a. Excludes motorways.

Source: Department of Transport[2]

Table P: Number of HGV occupant casualties by road type: 1986

P1: Drivers

Road type	No. fatalities	No. casualties
BURs	8	773
Non-BURs	53	1987
All speed limits[a]	61	2760

P2: Passengers

Road type	No. fatalities	No. casualties
BURs	8	205
Non-BURs	14	354
All speed limits[a]	22	559

P3: All casualties

Road type	No. fatalities	No. casualties
BURs	16	978
Non-BURs	67	2341
All speed limits[a]	83	3319

Note:

a. Includes speed limit not reported.

Table Q: Number of HGVs involved in injury accidents by road type, body type, and axle configuration: 1986

Q1: Rigid HGVs

Road type	No. of vehicles Involved Fatal accidents	All accidents
2-axle		
BUR	164	3988
Non-BUR	239	3672
All speed limits[a]	403	7660
3-axle		
BUR	32	631
Non-BUR	41	714
All speed limits[a]	73	1345
4-axle+		
BUR	25	463
Non-BUR	50	657
All speed limits[a]	75	1120
All rigid HGVs		
BUR	221	5082
Non-BUR	330	5043
All speed limits[a]	551	10125

Note:

a. Includes speed limit not recorded.
b. Excludes axle configuration not reported.

Source: Department of Transport[2]

Table Q: continued

Q2: Articulated HGVs

Road type	No. of vehicles Involved Fatal accidents	All accidents
3-axle		
BUR	15	283
Non-BUR	35	447
All speed limits	50	730
4-axle		
BUR	39	674
Non-BUR	127	1444
All speed limits	166	2118
5-axle+		
BUR	15	316
Non-BUR	83	872
All speed limits	98	1188
All artic. HGVs		
BUR	69	1273
Non-BUR	245	2763
All speed limits	314	4036

Note:

a. Includes speed limit not recorded.
b. Excludes axle configuration not reported.

Source: Department of Transport[2]

Table R: Casualties resulting from HGV accidents with respect to vehicle(s) involved: 1986

Vehicle type	No. Fatalities[a]	No. Casualties[a]
HGV	24	672
LGV	-	137
Bus/coach	-	47
Car	4	622
Motorcycle[b]	-	17
Pedal cycle	1	8
SVA	32	1045
SVA[c]	171	1184
Other[d]	28	747

Note:

a. Excludes pedestrian casualties.
b. Includes scooters and mopeds.
c. Pedestrians hit by HGVs.
d. Includes any other vehicles, motorcycle combinations and accidents involving 3 or more vehicles.

Source: Department of Transport[2]

Table S: Estimated number of HGV crash fires by road type, body type and axle configuration: 1986

HGV type	All speed limits	Non-BUR	BUR
Rigid			
2-axle	10	5	5
3-axle	2	1	1
4-axle+	1	1	1
Articulated			
3-axle	1	1	0
4-axle	3	2	1
5-axle+	2	1	0
All HGVs	19	11	8

Source: Nyman, M.[17]

Table T: Estimated frequency of HGV crash fires by road type, body type and axle configuration: 1986

HGV type	Frequency (fires/10^8 km) All speed limits	Non-BUR	BUR
Rigid			
2-axle	0.08	0.06	0.12
3-axle	0.16	0.12	0.28
4-axle+	0.15	0.11	0.31
Articulated			
3-axle	0.16	0.12	0.38
4-axle	0.07	0.05	0.18
5-axle+	0.09	0.07	0.42
All HGVs	0.09	0.06	0.15

Note:

a. Non-BUR includes motorways.
b. Crash-fire frequencies are derived from data given in Tables E, F and N.

Table U: Number of lorry non-crash fires by cause: 1986

Cause	Number	Proportion (%)
Deliberate	352	14
Smokers materials	147	6
Electrical	720	28
Oil, petrol/other fuel	1044	41
Sparks	31	1
Overheating	24	1
Other/unknown	241	9
Total	2559	100

Source: Nyman, M.[17]

Table V: Proportion of all goods vehicles by gross vehicle weight (GVW) on British roads: 1985

Gross vehicle weight (te)	Proportion of all goods vehicles (%)
under 20	70
20 - 22	3
22 - 24	3
24 - 26	2
26 - 28	2
28 - 30	4
30 - 32	6
32 - 34	4
34 - 36	2
36 - 38	3
38+	1

Source: JMP Consultants[24]

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4.0 THE RAIL ACCIDENT AND TRANSPORT ENVIRONMENT

Risk assessments of the rail transport of explosives and other hazardous materials require detailed information on the transport and accident characteristics of the vehicles and wagons used. The data and information presented within this chapter are applicable to the transport of goods by freight trains (including freightliners) operated by British Rail (BR). Particular emphasis is given to the transport of explosives and other hazardous materials. The number of accidents, frequency of accidents, collisions, derailments, fires, accident speeds, locomotive/wagon types and commodities transported, are all analysed. In addition, those accidents considered to be the greatest threat to the integrity of conveyed goods are identified.

Over 180 railway accident reports, published by the Railway Inspectorate, have been studied by the author. Those of interest here (i.e. freight train accidents) have been used to devise a means of assessing accident severity. An accident severity index has been developed and appears to be useful in quantifying the severity of freight train accidents.

No attempt has been made to differentiate between weather conditions, time of year or time of day. It is possible to produce accident rates accounting for these factors. However, it is considered here that improvement in assessment accuracy is minimal (unless the vast majority of movements are conducted at the same time every day and only during the summer months, etc.).

It should be noted that unless otherwise stated all data refer to accidents reported by the Railway Inspectorate. The criterion for reporting an accident tends to change as new equipment and working practices are introduced. However, the accident frequencies presented within this chapter are unlikely to be greatly affected by minor changes in the classification and recording of freight train accidents.

Much of the data presented in the following sections are taken from, or based on, data recorded by the Railway Inspectorate for the year 1986. Compared with other years 1986 is typical of the transport and accident environment found on British railways during the 1980's and will probably remain so for the early part of the 1990's.

4.1 Freight Train Accidents and Fires

Freight train (FT) accidents essentially consist of collisions, derailments and fires. During 1986 FTs travelled a total of 54 x 10^6 km on British railways and were involved in 324 accidents[1], providing a rate of 1 accident every 167,000 km travelled. Unfortunately, available statistics do not detail the number of accidents which occur in built-up areas, and Railway Inspectorate accident reports lack clarity when describing accident locations. However, from the freight train accident (FTA) survey, conducted by the author and detailed in Section 4.2, it is estimated that 10% of British rail track (38,053 km open to traffic[2] at the end of 1986) is within built-up areas (BUAs). As a consequence of this it is estimated that between 10% and 30% of all FT accidents occur on rail track within BUAs.

No data have been found to support the general consensus that FTs conveying hazardous goods are less likely to be involved in accidents than FTs conveying general goods. Thus, it can be argued that, per km, the rate of FT accidents is the same regardless of load conveyed.

4.1.1 Collisions

During 1986 the number of FT collisions[3] totalled 113, providing 1 collision every 478,000 km travelled. From a study of over 90 train collisions published by the Railway Inspectorate, and from the FTA survey detailed in Section 4.2, collisions involving rolling stock are generally considered to be the most severe FT collisions, in terms of deaths, injuries and property damage. Of the 113 collisions during 1986 only 19 involved collisions with other rolling stock. Thus, from these figures it can be inferred that severe collisions account for approximately 17% of all FT collisions and a mere 6% of all FT accidents. Of these collisions approximately 42% involve other FTs, 53% empty coaching stock (ECS) and 5% passenger trains (PTs).

The collision at Dingwall on 5 November 1973 serves to illustrate the severity of collisions between rolling stock. A freight train consisting of a diesel locomotive, brake van and 14 freight vehicles, some loaded with whisky, having a total weight of 467 tons, collided head-on with a stationary passenger train at approximately 20 mph. Extensive damage was caused to both locomotives and three leading FT wagons derailed resulting in the loss of their contents. Subsequently a number of whiskey barrels ruptured causing a large spillage. All coaches of the PT suffered minor damage injuring 6 members of the public and 2 railway

staff.

Accidents similar to the collision described above illustrate the severity of collisions between trains having relatively low impact energies (i.e. closing speed, momentum and tonneage). If the train had been carrying a hazardous substance the consequences of the accident could have been much worse. Train speed, momentum and tonneage is discussed further in Section 4.4.

From a review of FT collisions conducted by Taig[4] approximately 65% of all FT collisions with rolling stock are thought to be either "head-on" or "rear-on" collisions. This figure compares well with the figure derived from the FTA survey that 70% of all FT collisions are either frontal or rear impacts (see Section 4.2). Taig's estimate is based on a much larger sample of FT collisions than that given by the FTA survey. This is because only those collisions which have been formally investigated by the Railway Inspectorate and reports published are included in the FTA survey. However, Taig's figure tends to augur well for the validity of the FTA survey. From the survey it is estimated that of the frontal/rear collisions 40% are head-on, 40% are frontal impacts with the rear of other trains (i.e. front-rear collisions) and 20% are rear impacts with the front of other trains (i.e. rear-front collisions). The remaining FT collisions with rolling stock are split between side impacts and glancing impacts. The FTA survey, together with the data collected by Taig[4] suggest that 10% and 25% of all FT collisions with rolling stock are side impacts and glancing impacts respectively.

Accidents involving buffer stops[3] totalled 55 during 1986. Most of the collisions occurred at impact speeds of 10 mph or less. It is suggested here that the vast majority of buffer stop collisions are unlikely to pose a significant threat to the integrity of wagons or their loads. Since the beginning of 1987 the Railway Inspectorate have ceased recording buffer stop collisions, emphasising the minor nature of such impacts. However, buffer stop accidents are the largest single source of FT collisions and most occur in BUAs (i.e. at railway stations and terminals, etc.). A collision of this type occurring at high speed to a train conveying flammable, toxic or explosive substances could conceivably result in a major incident with multiple fatalities. No such accidents have been identified by the author on ordinary surface track. This is not to say none have occurred. It should be noted that buffer stop collisions resulting in casualties have occurred on the London Underground, one of particular note being the accident at Moorgate in 1975.

A little over 5% of all FT collisions during 1986 were the result of collisions at level crossings[1]. For all rolling stock, over the same period, 44 accidents occurred on protected level crossings, 23 of which involved collision with road vehicles[1]. The corresponding figures for unprotected crossings are not known. However, from these data it can be argued that approximately half of all FT collisions on level crossings involve road vehicles, the remainder being collisions with barriers, pedestrians and rail debris, etc.. Information contained within the Railway Safety Report 1986[1] indicates that over 3/4 of all collisions with road vehicles on level crossings involve frontal collision of the train (i.e. 78% of incidents are the result of train impact with a vehicle obstructing the crossing). In comparison, less than a 1/4 of such collisions involve side collision of the train (i.e. 22% of

incidents are the result of road vehicle impact with a train travelling over the crossing).

It is possible for a large motor vehicle at a level crossing to cause structural damage and endanger life and loads under conveyance. However, such accidents, concluded from the FTA survey and other accident reports, are generally not severe enough to cause extensive train/track damage, effect the integrity of conveyed goods and/or cause multiple fatalities. The rail accident at Whittlesea level crossing on 8 May 1972 between an FT and a heavy goods vehicle (HGV) serves to support this statement. A laden HGV, having a gross weight of 23.5 tons, was hit at 30 mph by an FT consisting of 30 loaded 21 ton hopper wagons. The gross weight of the train was over 790 tons. No derailment of the train occurred and no damage was caused to the track. Fortunately, the driver of the HGV sustained only minor injuries.

Freight train collisions also involve impacts with animals and miscellaneous obstacles/projections. During 1986 almost 30% of all FT collisions were the result of such impacts[3]. The vast majority of these accidents are, however, relatively minor compared with rolling stock collisions. Animals hit by trains rarely cause serious damage (to the train) and obstacles placed maliciously or otherwise on the track, are unlikely to be of sufficient mass to cause incidents which could endanger the train or its load. However, it is not unknown for trains to derail as a result of objects placed on the track (see Section 4.1.2).

The primary causes of freight train collisions are not specifically recorded by the Railway Inspectorate. However, assuming (in the absence of other data) that the primary causes of train accidents are the same for all current train types (except accidents resulting from the irregular opening of doors by the public) then it is estimated here that 65% of all collisions are the result of staff error. Most of these accidents are caused by train crew, especially the "engine-men" (almost 50% of all staff errors). In comparison, irresponsible acts by the public account for 31% of all collisions, a staggering 67% of these due to malicious acts. Only about 4% of accidents are thought to result from mechanical/electrical defects of trains, signalling equipment or track.

4.1.2 Derailments

Derailments of FTs on British railways[3] totalled 158 during 1986, providing 1 FT derailment every 342,000 km travelled. Although FT derailments account for approximately 50% of all FT accidents, judging from the small number of official reports published by the Railway Inspectorate regarding FT derailments, it can be judged that generally FT derailments are not as severe as FT collisions. The number of FT derailments included in the FTA survey is small, and therefore, it is difficult to make quantitative judgements on the proportion of fires, subsequent over-turning and casualties associated with FT derailments. However, the data collected illustrate that most derailments occur at speeds in excess of 35 mph, wagons can run derailed for several miles without over-turning and that spillage of wagon contents can occur and fire may result.

From a review of FT derailments conducted by Taig[4] approximately 64% of unprotected lines are blocked per derailment, and of these, 4% lead to subsequent collision with rolling stock. This provides 1 derailment followed by collision every 13.4 million km, hence 4 accidents of this type annually. Taig also concludes that 4% of FT derailments subsequently collide with objects off the track, providing about 6 such accidents per year.

Railway Inspectorate (RI) accident reports indicate that derailments followed by subsequent collision with rolling stock are by far the worst FT derailments, in terms of expected casualties and property damage. From the FTA survey one RI accident report illustrates this point. On 8 March 1969 an FT consisting of a locomotive, brake van and 57 wagons loaded with coal derailed at approximately 35 mph. The FT was hit by an on-coming passenger train resulting in over 40 injuries and 2 deaths. Forty one of the FT wagons derailed and many were damaged beyond repair. However, it is clear from RI accident reports that the majority of FT derailments are not as severe as the one described here. Derailments are often associated with wagons running derailed for several miles before being rectified and thus, little or no damage to the train, track or signalling occurs. One such derailment occurred on 16 June 1973 at Berkhamstead. The 14th wagon of a 15 wagon freightliner derailed at approximately 60 mph and ran derailed for over 3 miles. No casualties or damage to the train, track or signalling occurred.

Derailments involving fire are much more likely to occur to freight trains conveying flammable or explosive substances. However, regardless of the load being conveyed a simple "wheel-set" derailment is unlikely by itself to result in fire. It is suggested here and supported by RI

accident reports that fire is much more probable when derailment is accompanied by over-turning and/or collision. One such derailment which was accompanied by fire occurred on 3 March 1983 near Warrington. An FT consisting of 14 tank wagons loaded with gas oil derailed. Subsequently one of the derailed wagons collided with a post supporting over-head electricity cables and fire ensued. Fortunately none of the staff present were injured and the fire was quickly extinguished.

As with collision incidents the primary causes of FT derailments are not specifically recorded by the Railway Inspectorate. However, assuming that the primary causes of train derailments are the same regardless of rolling stock type, then the primary causes of FT derailments can be estimated. Thus, based on 1986 data it is suggested here that about 56% of all FT derailments result from staff error. It is thought that such errors occur as a result of excessive speed at junctions, crossings and curved track. Technical defects account for approximately 38%, and obstacles placed on the track about 6% of all FT derailments. Derailments caused by technical defects are largely the result of worn equipment, such as, wheel-sets and track. The majority of derailments caused by objects lying on the track are the result of adverse weather conditions. However, a sizeable proportion of such derailments (approximately 38%) are caused as a result of malicious acts by the public.

4.1.3 Fires

Fires which do not result from train collision or derailment are referred to here as non-crash fires and those as a result of collision or derailment as crash fires. Train accidents are classed by the Railway Inspectorate as either collisions, derailments or fires. A collision or derailment involving subsequent fire is classed as a collision or derailment accident. Therefore, FT fires recorded by the Railway Inspectorate refer to non-crash fires.

Non-crash FT fires, as recorded by the Railway Inspectorate, are those extinguished by, or requiring the attendance of, the fire services[5]. As a consequence of this it can be argued that all such fires have the potential to cause serious train damage and/or endanger life and/or endanger the load under conveyance. During 1986 a total of 53 non-crash FT fires occurred on British railways[1], providing a rate of 1 fire every 1 million km travelled. It is not known how many non-crash FT fires occur in BUAs. Assuming average FT speeds of 25 mph in BUAs and 45 mph in non-BUAs it is estimated here that 17% of non-crash FT fires occur whilst FTs pass through BUAs. The author has found no data which can be used to identify mean FT speeds. However, from contacts within British Rail[6,7] it is known that FT speeds are generally less in BUAs than in non-BUAs, and that mean FT speeds range somewhere between 20 mph and 40 mph and 40 mph and 60 mph in BUAs and non-BUAS respectively. Assuming a range of mean FT speeds between 20 mph and 40 mph in BUAs and between 40 mph and 60 mph in non-BUAs the proportion of non-crash FT fires in BUAs ranges from between 10% and 25%.

Following discussions with British Rail[8] and from reference to various Railway Safety reports it is concluded here that the vast majority of non-crash FT fires do not by themselves present a major threat to the train, its load or occupants. This is because most fires are small, localised and quickly extinguished.

Of the 68 FT non-crash fires detailed in the FTA survey for the years 1986 and 1987, approximately 82% started in hauling locomotives, the remaining 18% occurred else-where. The main causes of these fires were

a. axle bearings overheating,
b. irregular sparking of brake blocks,
c. electrical faults,
d. engine/exhaust malfunction.

Excluding locomotive fires the FTA survey suggests that approximately 60% of all FT non-crash fires (excluding leaking tank wagons) are the result of brake block sparks and hot axle boxes/pipes.

The FTA survey conducted by the author, for the years 1967 through to 1984, details only one severe FT non-crash fire (see Section 4.2). The fire occurred on 1 January 1969 near Ambergate, Derbyshire. Brake block sparks ignited oil escaping from insecure tank hatches. Fortunately no casualties were sustained although the fire caused extensive train damage. In comparison, the FTA survey details six FT crash fires. Of these four involved FTs conveying flammable liquids. However, only one of these incurred fatalities. The accident occurred on 7 December 1984. A PT travelling at approximately 50 mph collided into the rear of an FT laden with gas oil. The rear FT rail car

was thrown across adjacent track causing extensive damage and subsequent fire. Unfortunately over 60 members of the public were injured and 3 individuals killed. In comparison, both crash fire accidents, not involving flammable liquids, incurred fatalities. The first accident occurred on 8 April 1969 near Wolverhampton when a four coach PT collided head-on with a stationary 32 wagon steel laden FT at 45 mph. Both drivers were killed and over 30 people injured, including 1 fireman attending the scene. The second accident occurred on 6 October 1971 when two FTs, both conveying steel, collided near Beattock in Scotland. The speed of one train was estimated to be in excess of 80 mph when it impacted the rear of the other FT which was travelling at approximately 35 mph. The guard of the struck FT was killed. These two accidents highlight the significance of speed in FT crash fires which do not involve the carriage of flammable liquids.

Of the six crash fires detailed in the FTA survey all those involving casualties were the result of FT collisions with rolling stock. These incidents suggest that casualties are much more likely from crash fires resulting from rolling stock collisions than other crash fire types.

4.1.4 "Severe" Freight Train Accidents and Fires

Accidents designated here as "severe" are those accidents which endanger life and/or the integrity of the load under conveyance. Such accidents are often associated with extensive train, track and/or signalling equipment damage. Freight train collisions which are considered severe have been previously identified as those involving rolling stock. During 1986 the rate of severe FT collisions

was 1 every 2.8 million km travelled.

The FTA survey suggests that between the years 1967 and 1984, only 6 FT derailments were serious enough to be classified as severe. Two of these involved subsequent collision with PTs. Of the remaining 4, 2 involved subsequent fire of the flammable liquids under conveyance, one high speed derailment at a junction and one extensive track, signalling equipment and station platform damage, together with the risk of explosion due to the loss of its cargo of military ammunition. Assuming FTs travel an average of 59.2×10^6 km per year (9 year average, 1978 - 1986), then from the number of severe FT derailments given above (FTA survey) this suggests that the rate of severe derailments is 1 every 178 million km travelled. However, this figure is based on the reports readily available. It is thought that during this period a number of severe incidents may not have been reported, correctly classified, or made readily available. Therefore, it is considered (and shown below) that the rate calculated from the FTA survey under-estimates the actual rate of severe FT derailments.

The number of severe FT derailments per year is not known. Its estimation would require the analysis of a much larger sample of FT derailments than those included in the FTA survey. However, between 1975 and 1986 the number of staff casualties resulting from FT derailments totalled 70 (see Section 4.6, Table H3). During this period there were approximately 1900 FT derailments[1]. As previously mentioned in Section 4.1.2 there are about 4 FT derailments per year which result in subsequent collision with other rolling stock. Therefore, between 1975 and 1986 it is estimated that FT derailments (excluding subsequent collision with other rolling stock) totalled 1850. From these figures it can be calculated that there are about 0.04 staff

can be calculated that there are about 0.04 staff casualties per FT derailment (excluding subsequent collision with other rolling stock). Assuming FT derailments are distributed evenly over the 12 year period, 1975 through to 1986 and that the average annual distance travelled by FTs is 59.2 x 10^6 km, then it can be calculated that there are approximately 6 severe FT derailments (excluding subsequent collision with other rolling stock) per year at a rate of 1 every 10 million km travelled. All FT derailments followed by subsequent collision with other rolling stock are judged to be severe FT derailments. The rate of such derailments is given in Section 4.1.2 as 1 every 13.4 million km travelled. From the postulated rates given here it is estimated that the rate of severe FT derailments is approximately 1 every 5.7 million km travelled.

A similar treatment to that given above can be used to calculate the number and rate of severe FT fires. Between 1975 and 1986 only 3 minor and 1 serious injury were recorded out of a total of 644 FT non-crash fires. Thus, over the 12 year period there were approximately 0.006 casualties per FT non-crash fire. Assuming all non-crash fires resulting in casualties are severe fires and that FTs travel an average of 59.2 x 10^6 km annually, then it can be inferred from the figures given here that there are 0.33 severe non-crash fires per year at a rate of 1 severe non-crash fire every 178 million km travelled. However, it is thought that there are a significant number of severe FT non-crash fires which do not incur casualties. This statement is supported by the severe FT non-crash fire detailed in the FTA survey and the contrasting severe non-crash fire rate derived below.

A better estimate of the rate of severe FT non-crash fires can be gained by examining severe FT crash fires. From the FTA survey 4 collisions and 2 derailments were accompanied by fire. All 6 crash fires are classed as severe. Therefore, from the 34 crashes detailed in the FTA survey 6 involved fire. From this it can be calculated that there are about 0.18 severe FT fires per crash. The FTA survey is based on RI reports which concentrate on serious accidents and therefore the FTA survey is biased towards severe accidents. As a consequence of this the severe crash fire rate derived here can be considered as an upper bound. Freight train crashes total between 250 and 300 per year[2]. Judging from published data and data obtained through personal contacts[2,5] 1986 was a typical year for FT accidents and fires on British railways. During this year 271 FT crashes were recorded. Using this figure and the severe FT crash fire rate derived above (0.18) it can be estimated that there are about 50 severe FT crash fires per year. This provides a rate of 1 severe FT crash fire every 1.1 million km based on the number of miles travelled by FTs during 1986 (54×10^6 km). It can be inferred from the FTA survey that severe crash fires outnumber severe non-crash fires by a ratio of 6:1. Applying this ratio to the figures given here we could expect about 8 severe non-crash fires per year. This compares with 0.33 severe non-crash fires per year derived from non-crash fire casualty rates. It is acknowledged that severe non-crash fires are also likely to occur in the absence of casualties. Therefore, the true rate of severe FT non-crash fires lies somewhere between the two rates calculated here (i.e. between 1 every 178 million km (0.33 per year) and 1 every 1.1 million km (8 per year)). In the absence of further data it is not known to which end the actual rate lies. Assuming 1 severe FT non-crash fire every 15 million km travelled provides a mid-range value of about 4 severe non-crash fires per year.

The annual rate of severe FT accidents is the simple addition of severe collisions, derailments and non-crash fires (severe FT crash fires are included in severe FT collisions and derailments). Hence, annually, it is estimated that there is 1 severe FT accident every 1.7 million km, providing about 30 severe FT accidents per year.

4.2 Freight Train Accident Survey

Over 180 accident reports published by the Railway Inspectorate between the years 1967 and 1984 have been analysed by the author. Only 38 of the reports refer to freight train accidents. Accidents involving FTs are categorised as follows.

a. collisions,
b. derailments,
c. level crossing accidents,
d. fires.

The vast majority of the reports reflect the main preoccupation of the Railway Inspectorate, that is, to investigate rail accidents so as to identify their cause. This is undertaken in the hope that the consequences of future accidents can be minimised by preventive action/measures (especially with regards to casualties) and lead to the reduction or eventual elimination of such accidents.

Unfortunately some reports are not as concise as others. However, a brief review of the accidents analysed is given in this section.

4.2.1 Collisions

The survey includes 26 FT collisions, 16 of which involve passenger trains (PT), 6 other FTs and one each with a parcels train, engineers repair train, empty wagon and a newspaper train. A total of 16 collisions involve derailment of one or more vehicles. Overturning of one or more derailed vehicles occurs in 10 of the 16 derailments. Of the 26 collisions 21 involve death or injury. The 21 injury accidents account for 17 deaths and over 230 injuries. Approximately 70% of the collisions involve frontal impact of the train (locomotive), 20% rear impact and 10% side or glancing impact. Head-on collisions account for 23% of all collisions. The survey reveals that almost a third (30%) of all FT collisions occur when the FT itself is stationary.

It was found that in general the greater the closing speed the greater the likelihood of death or injury as Table 1 illustrates. However, the data given in Table 1 should be interpreted with caution. The data include collisions between FTs and PTs and, therefore, it can be argued that a disproportionate view of the effect of impact speed is portrayed by Table 1. This is because although it is accepted that impact speed increases the severity of accidents and consequently increases the chances of death of exposed individuals, the number of exposed individuals is greatly increased in FT accidents involving PTs regardless of speed and therefore a greater number of

casualties can be expected.

4.2.2 Derailments

Only 8 FT derailments were found amongst the 38 FT accidents. Speed of derailment ranged between 35 mph and 75 mph. Of the 8 derailments 2 resulted in subsequent collision with PTs. Excluding derailments involving subsequent collision only 1 derailment resulted in casualties. All three casualties were minor injuries to railway personnel. Three derailments involved overturning of vehicles, which by and large resulted in extensive train, track and property damage. Only 2 derailments were accompanied by fire, both of these involving tank wagons loaded with flammable liquids. The survey highlighted the fact that wagons may run derailed for many miles before rectification or overturning.

4.2.3 Level Crossing Accidents

The survey reveals only 3 level crossing accidents. These accidents tend to indicate that for collisions where FTs hit road vehicles obstructing the track, very little FT damage is caused. Additionally, road vehicles are likely to be driven/pushed by the train well past the crossing point. One incident also highlights the fact that such accidents can be the result of reckless and irresponsible driving by those in charge of road vehicles. It was impossible to derive any further useful information from the few reports available.

4.2.4 Fires

Only 1 report of an FT fire from the 187 reports studied was found. However, further data was made available through the Railway Inspectorate[5]. From these data 68 FT fires between the years 1986 and 1987 were analysed as to the cause of fire.

Not one of the 68 FT fires resulted in railway staff or members of the public being injured or killed. Approximately 82% of the fires occurred in hauling locomotives, the remaining 18% occurred elsewhere. Table 4 illustrates the causes of FT fires. By far the largest cause of fire is "sparking" from brake blocks igniting oil/dirt deposits and/or flammable liquids escaping from pipes and insecure tank hatches. Excluding locomotive fires, the causes of fires are spread fairly evenly between

a. brake block sparks igniting oil/dirt deposits.
b. overheating of axle boxes causing ignition of oil/dirt deposits and/or surrounding materials,
c. hot stove pipes in brake vans igniting surrounding materials.

It should be noted that a large proportion of the FT fires analysed were the result of insecure tank hatches facilitating the ignition of flammable liquids. Obviously this cause of fire is eliminated if tank wagons are not used or flammable liquids are not conveyed. Therefore, for FTs not exposed to this potential cause of fire, the survey suggests that fires, excluding locomotive fires, are largely the result of brake block sparks, hot stove pipes (brake vans) and overheating axle boxes.

Table 1: Freight train casualties with respect to closing speed: Freight train collisions: Freight train survey 1967 - 1984

Closing speed (mph)	Deaths (%)	Injuries (%)	Deaths/accident (mean)
1 - 20	18	17	0.4
20 - 25	0	19	-
25+	82	74	1.2

Table 2: Freight train collisions with other rolling stock with respect to impact speed: Freight train survey 1967 - 1984

Freight train impact speed (mph)	Proportion of impacts (%)
1 - 10	29
11 - 20	33
21 - 30	14
31 - 40	5
40+	19

Table 3: Freight train collisions with passenger trains with respect to impact speed: Freight train survey 1967 - 1984

Passenger train impact speed (mph)	Proportion of impacts (%)
1 - 10	10
11 - 20	27
21 - 30	18
31 - 40	18
40+	27

Table 4: Freight train fires with respect to cause: Freight train survey 1986 - 1987

4A: Freight train fires

Cause of fire	Proportion of fires (%)
Brakes/sparks	47
Exhaust system	10
Engine	16
Mechanical failures[a]	7
Electrical	4
Other[b]	15

Table 4: continued

4B: Freight train fires (excluding fires started in hauling locomotives)

Cause of fire	Proportion of fires (%)
Brakes/sparks[c]	66
Hot stove pipes	17
Hot axle boxes	17

4C: Freight train fires (hauling locomotive fires only)

Cause of fire	Proportion of fires (%)
Brakes/sparks	52
Exhaust system	13
Engine	20
Mechanical failures[d]	5
Electrical	5
Other[e]	5

Note

a. Includes hot axle boxes.
b. Includes hot stove pipes and leaking cargo/fuel.
c. Insecure tank hatches on rail tankers account for 33% of fires, leaking fuel accounts for a further 8% of fires.
d. Includes hot axle boxes.
e. Includes hot stove pipes and leaking cargo/fuel.

4.2.5 Freight Train Accident Descriptions

Freight Train Collisions

Date: 11 July 1967
Time: 00.16
Location: Winwick Junction
Deaths:
Injuries: 20 (all minor - 19 passengers + PT driver)
Description: A stationary 37 wagon FT was hit in the rear by a PT at 20 mph. The FT brake van and 3 of the last 5 wagons derailed. Only minor damage occurred to the PT and no coaches were derailed. FT 50 BWU.

Date: 30 October 1968
Time: 00.16
Location: Selside near Horton-in-Ribblesdale
Deaths:
Injuries: 2 (minor, driver + guard)
Description: A 24 wagon FT hit the rear of a stationary 46 wagon FT (56 BWU) at 30 mph causing 14 of the 46 wagons to derail. The stationary FT was driven 30 yards. Extensive damage to track and rolling stock.

Date: 8 April 1969
Time: 14.26
Location: Monmore Green, Wolverhampton
Deaths: 2 (drivers of both trains)
Injuries: 33 (30 passengers, 2 staff, 1 fireman)
Description: A 4 coach electric PT collided head-on at 45 mph with a stationary 32 wagon FT loaded with

steel. **Fire** ensued and extensive damage was caused to track (locos. were beyond repair). PT 158 tons, FT 791 tons (class 7 special FT).

Date: 27 May 1970
Time: 17.22
Location: Near Albion Sidings, Oldbury
Deaths:
Injuries: 2 (driver and guard of PT)
Description: Glancing collision between FT and PT. Derailment of PT coaches and 2 empty oil tank wagons. Speed of impact, PT 20-25 mph, FT 4 mph. PT 152 tons, FT 435 tons.

Date: 12 November 1970
Time: 21.38
Location: Bexley Station
Deaths:
Injuries:
Description: FT hit rear of stationary 6 coach PT at 10-15 mph. PT was driven forward 40 feet. FT 696 tons, (44 wagons + brake van + diesel-elec. loco.), PT 208 tons.

Date: 6 October 1971
Time: 03.20
Location: Near Beattock, Scotland
Deaths: 1 (guard of struck FT)
Injuries:
Description: A 24 wagon FT loaded with 10-12 tons of steel collided with the rear of a 34 wagon FT conveying containers and 17 wagons of steel. The 24 wagon FT hit the 34 wagon FT at approximately 80 mph. The initial speed of the

34 wagon FT was 35 mph. The collision completely demolished brake van and colliding loco (which also overturned and caught **fire**). Extensive damage to both trains was caused. FT (24 wagon) 967 tons, FT (34 wagons) 814 tons>

Date: 27 November 1971
Time: 19.25
Location: Sharnbrook
Deaths:
Injuries:
Description: A 61 wagon FT hit a stationary engineers train at 20 mph causing the engineers train to shunt another FT.

Date: 16 December 1971
Time: 06.15
Location: Nottingham
Deaths: 3 (all staff)
Injuries:
Description: Head-on collision between a parcels train and a 32 wagon FT loaded with coal. Both locos. derailed causing extensive damage
Speed on impact, FT 5-10 mph, PAR 40-50 mph. PAR moved backwards 20 feet. FT 1190 tons (24.5 ton hopper wagons + brake van), PAR 278 tons (13 vans).

Date: 25 March 1972
Time: 22.28
Location: Drem, Scotland
Deaths:
Injuries:
Description: Head-on collision between a PT and a 19 wagon

FT. PT hit FT at 15 mph. PT derailed. PT 451 tons.

Date: 8 May 1972
Time: 20.51
Location: Chester General Station
Deaths:
Injuries: 5 (minor - all staff)
Description: A 38 vehicle FT consisting of wagons laden with petroleum products collided with a stationary PT (empty) causing extensive property and train damage. FT loco. caught **fire**. FT impact speed, 20 mph. FT 981 tons.

Date: 29 August 1972
Time: 18.30
Location: Near Nuneaton
Deaths:
Injuries:
Description: PT consisting of 13 coaches hit open door of 20 wagon FT. The door was strewn across the line and a second PT ran into it at 98 mph.

Date: 6 September 1972
Time: 20.58
Location:
Deaths: 1 (loco. driver)
Injuries: 1 (guard)
Description: Eighteen wagon FT collided at 30 mph with forty empty wagons causing derailment and overturning of wagons. Extensive damage.

Date: 12 October 1972
Time: 19.48
Location: Wimbledon Station
Deaths:
Injuries:
Description: FT consisting of 22 wagons loaded with coal + brake van + diesel-elec. loco. collided with a stationary 6 coach PT at 25 mph. The PT was driven 35 yards. FT loco. derailed and extensive damage was caused. FT 544 tons, PT 135 tons.

Date: 27 April 1973
Time:
Location: Kidsgrove Station
Deaths: 1 (FT driver)
Injuries: 7 (FT guard, 4 staff + 2 NT staff)
Description: FT hit rear of stationary newspaper train (NT) at 12 mph. FT consisted of 9 empty mineral wagons, 3-empty hopper wagons and a brake van. Extensive damage to FT loco.. FT 529 tons, NT 499 tons.

Date: 5 November 1973
Time: 18.20
Location: Dingwall, Scotland
Deaths:
Injuries: 8 (6 passengers + 2 staff)
Description: Head-on collision between a 14 wagon FT loaded with whisky and a 4 coach stationary PT. Extensive damage to both locos., 3 leading wagons of FT derailed, minor damage to PT coaches. FT 467 tons.

Date: 27 November 1973
Time: 08.11
Location: Near Whitehaven
Deaths:
Injuries: 2 (PT driver + FT guard)
Description: PT hit rear of slow moving FT (1 mph) at 25 mph. Derailment of PT leading bogie and FT brake van. Extensive damage to PT loco..

Date: 23 October 1974
Time: 05.04
Location: Bridgewater
Deaths: 1
Injuries: 1
Description: Stationary 42 wagon FT (767 tons) hit in the rear by a 13 wagon FT (1082 tons) at 45 mph. Derailment and extensive damage.

Date: 31 May 1975
Time: 09.15
Location: Near Rutherglen Station, Scotland
Deaths:
Injuries: 37 (34 passengers + 3 staff)
Description: A stationary FT loaded with cement was hit by a 6 coach PT at 30-40 mph. Derailment of FT loco. and leading 4 coaches of PT. FT 1107 te, PT 256 te.

Date: 6 August 1975
Time: 22.12
Location: Weaver Junction
Deaths:
Injuries: Minor (FT crew + driver of FL)
Description: FT conveying 20 tank wagons hit side of 15

wagon FL. Both trains derailed and were extensively damaged. FT tank wagons were each loaded with 30 tons of caustic soda. FL wagons suffered extensive damage and piercing, the last 10 wagons derailed. Speed on impact, FT 60 mph, FL 70-75 mph. FT 1033 tons, FL 670 tons.

Date: 11 November 1976
Time: 10.10
Location: Melton Lane, near Ferriby
Deaths:
Injuries: 7 (all minor)
Description: A stationary FT consisting of 29 wagons, 13 of which were loaded to 21 tons was hit by a PT at 35 mph. The PT consisted of a two car-diesel and a trailer. PT loco. and last two wagons of FT derailed.

Date: 14 February 1979
Time: 20.15
Location: Chinley North Junction
Deaths:
Injuries: 7 (5 passengers + 2 staff of PT)
Description: A stationary FT was hit head-on by a PT at 10-15 mph. The FT was loaded with limestone in 22 46 te hopper wagons. FT 1146 te, PT 58 te.

Date: 30 July 1982
Time: 08.30
Location: Near Lindsey Oil Terminal
Deaths:
Injuries: Minor
Description: Head-on collision between two FTs (coal train

v 26 tank wagon train loaded with petroleum). Closing speed approximately 16 mph. Extensive damage to locomotives. 1556 te coal train, 1736 te petroleum train.

Date: 9 December 1983
Time: 18.18
Location: Wrawby Junction
Deaths: 1 (passenger)
Injuries: 3 (passengers)
Description: FT consisting of 9 empty oil tank wagons struck the side of a PT. First coach of PT derailed, PT loco. derailed and overturned. PT speed on impact 5-10 mph.

Date: 3 February 1984
Time: 02.14
Location: North Western Street, Wigan
Deaths: 2 (driver + guard)
Injuries:
Description: FT (658 te) consisting of 21 wagons 14 of which were loaded hit the rear of a stationary 10 wagon FT (630 te) at 5-8 mph. The struck FT was driven over 16 m by the impact.

Date: 11 October 1984
Time: 16.04
Location: Wembley Central Station
Deaths: 3 passengers
Injuries: 18 (17 passengers + driver of PT)
Description: Eight coach PT hit the 11 th wagon of a 20 wagon FL causing all but the rear PT coach to derail. The 1st two PT coaches overturned. PT speed on impact was estimated as 57 mph and

the FL as 15 mph. Damage was caused to track(extensive), signalling and overhead line equipment. FL wagons were undamaged. FL 1302 te, PT 316 te.

Date: 7 December 1984
Time: 10.37
Location:
Deaths: 3 (2 passengers + driver)
Injuries: 68
Description: A PT collided with the rear of an FT. The 6 coach PT hit the FT at approximately 50 mph throwing the rear FT wagon (100 ton) laden with gas oil over adjacent track. Oil tank wagons ruptured and contents ignited. PT loco. caught **fire**. Extensive damage to both trains was caused. FT consisted of ten 45 te wagons and five 100 ton wagons laden with gas oil. FT speed on impact was between 10 and 15 mph. FT 1062 te, PT 390 te.

Freight Train Derailments

Date: 12 June 1968
Time: 12.40
Location: Berkhamstead
Deaths:
Injuries:
Description: Five wagons of a 15 wagon FL derailed at 75 mph due to track misalignment. Only wagons 1 and 13 were loaded. FL 410 tons.

Date: 8 March 1969
Time: 11.46
Location: Near Ashchurch Station
Deaths: 2 passengers
Injuries: 45 (41 passengers + 4 staff)
Description: Forty one wagons of a 57 wagon FT loaded with coal derailed at 35 mph. An 11 coach PT hit the derailed wagons at 30 mph causing extensive damage.

Date: 22 October 1969
Time: 22.18
Location: Chelmsford Station
Deaths:
Injuries:
Description: The 8th wagon of a class 6 special FT conveying military explosives derailed at 45 mph. The FT consisted of 27 covered wagons hauled by a diesel-electric loco. The first 5 wagons and the last wagon were empty, the other 21 were loaded with just over 117 tons of ammunition and pyrotechnics. No wagon contained more than 7 tons. Extensive track, signalling and platform damage was caused. A hot axle box overheated and caught fire after derailment. Explosives were removed by the Army.

Date: 31 December 1969
Time: 11.35
Location: Near Roade Junction
Deaths: 1 (PT driver)
Injuries: 9 passengers
Description: Wagon of FT derailed at approximately 45 mph and ran derailed for over 2 miles before

overturning and causing other wagons to derail. A glancing blow by a PT with two of the derailed wagons caused extensive damage. The PT driver was killed when the PT loco. hit a mast supporting overhead electricity lines. FT 716 tons, PT 158 tons.

Date: 6 June 1973
Time: 16.48
Location: Berkhamstead
Deaths:
Injuries:
Description: The 14th wagon of a 15 wagon FL ran derailed for 3.5 miles at speeds of up to 60 mph before being rectified.

Date: 9 December 1975
Time: 08.58
Location: Ferryhill
Deaths:
Injuries: 3 (all staff)
Description: Rear-most wagon of 5 ran derailed for over 3 miles before overturning at a junction and derailing adjoining wagons. Derailment occurred at approximately 50 mph. The FT was conveying a small amount of acid and the public were evacuated. FT 713 te.

Date: 3 March 1983
Time: 07.10
Location: Near Warrington
Deaths:
Injuries:
Description: A 14.5 ton van behind the leading loco.

derailed and uncoupled from the loco. at 35-40 mph. The van subsequently derailed other wagons. The FT was conveying 14 tank wagons loaded with gas oil. One of the wagons hit a post carrying overhead wires and a **fire** ensued. Slight damage to loco.. Some wagons overturned and punctured.

Date: 20 December 1984
Time: 05.50
Location: Summit Tunnel
Deaths:
Injuries:
Description: FT consisting of 13 wagons loaded with 835 te of petroleum spirit derailed at 40 mph behind the third wagon upon entering Summit Tunnel. Wagons 6 and 10 overturned, wagon 13 remained on the track. Petroleum vapour was released due to the piercing of some wagons, **fire** ensued. Local residents evacuated. The fire was not considered under control until the evening of 24 December. Tunnel re-opened 19 August 1985.

Freight Train Level Crossing Accidents

Date: 8 March 1972
Time: 10.18
Location: Near Whittlesea
Deaths:
Injuries: Minor
Description: FT conveying 30 loaded 21 ton hopper wagons collided with a 23.5 ton HGV at 30 mph. Minor

damage to line, no derailment. FT 798 tons.

Date: 15 November 1980
Time:
Location:
Deaths: 2 (car occupants)
Injuries:
Description: Driver of car attempted to cross rail track by swerving around automatic half barrier. Car was hit by a 20 wagon FT at 70 mph and was driven 700 yards. FT 1100 tons

Date: 21 January 1983
Time:
Location: Reddish Lane
Deaths: 1 (car driver)
Injuries:
Description: FT hit side of car at 35 mph. Car was driven 80 m. Minor damage to loco..

Freight Train Fires (Non-Crash Fires)

Date: 1 January 1969
Time: 08.15
Location: Near Ambergate
Deaths:
Injuries:
Description: Brake block sparks ignited spillage of oil from unsecured tank hatch. FT consisted of ten 100 ton tank wagons and two barrier wagons.

4.3 Freight Train Accident Speeds

Information contained within this section refers to the closing speed of freight train collisions and the speed at which freight trains derail. Due to lack of data and/or insufficient detail where data are available, the author has been unable to relate speed to accident location. Therefore, a comparison between the speed of FT collisions and the speed of FT derailments in built-up and non-built-up areas is not made.

Data from various Railway Inspectorate (RI) accident reports have been used here to estimate the closing speed of FT collisions. It is considered that the closing speed estimates form a biased sample. This is because RI accident reports tend to detail those accidents associated with casualties and/or extensive damage. Although the sample is biased it is difficult to quantify a degree of error, and since no other information is available on which judgements can be made, the values in Table 5 are given without refinement. It is acknowledged that risk assessments using these data may produce conservative results.

The author has also been unable to obtain data on closing speeds with respect to collision types. The data listed in Table 5 refer to head-on, front-rear and rear-front FT collisions. Consequently the data do not refer to any one collision type but provide a generalised set of closing speed data.

From Figure 1 (and chi-square test) it can be seen that the closing speed data approximate to a normal distribution. Hence

sample size $n = 35$

best estimate of the mean $\bar{x} = \frac{x_1 + x_2 + \ldots\ldots\ldots\ldots x_n}{n}$

$\bar{x} = 26.95$

$= 27$ mph

best estimate of the variance $\sigma_{n-1}^2 = \frac{\sum(x_i - x)^2}{n - 1}$

$\sigma_{n-1}^2 = 173.63$

best estimate of the standard deviation is σ_{n-1}

i.e. $\sigma_{n-1} = \sqrt{\sigma_{n-1}^2}$

$\sigma_{n-1} = 13.18$

From the above, and using the usual formula, the closing speed data can be represented as a normal distribution (see Figure 2).

Very little data exist on the speed of FT derailments. The author has been unable to collect sufficient data on FT derailments. Therefore, a similar treatment to that given above for collisions cannot be performed for FT derailments. However, Taig[4] has analysed 300 FT derailments. The vast majority of FT derailments which result in casualties and/or extensive damage are those that

occur at high speed. This study is primarily concerned with high speed derailments and these are mainly the misfortune of plain track (Taig distinguishes between plain track and non-plain track but does not say what is meant by this. It is thought that plain track refers to track free from points and "cross-overs"). Plain track derailments are detailed in Table 6.

Table 5: Freight train closing speeds: Collisions

5A: Sample of freight train closing speeds

Closing Speed (mph)				
7	16	20	30	45
12	17	24	35	45
12	20	25	35	45
12	20	30	37	52

5B: Closing speed of freight train collisions

Closing speed (mph)	Proportion of collisions (%)
1 - 10	5
11 - 20	40
21 - 30	20
31 - 40	15
41 - 50	15
51 - 60	5

Table 6: Speed of freight train derailments

Derailment speed (mph)	Proportion of derailments (%)
1 - 10	15
11 - 20	20
21 - 30	6
31 - 40	18
41 - 50	26
51 - 60	9
61 - 70	3
71 - 80	2
81 - 90	1

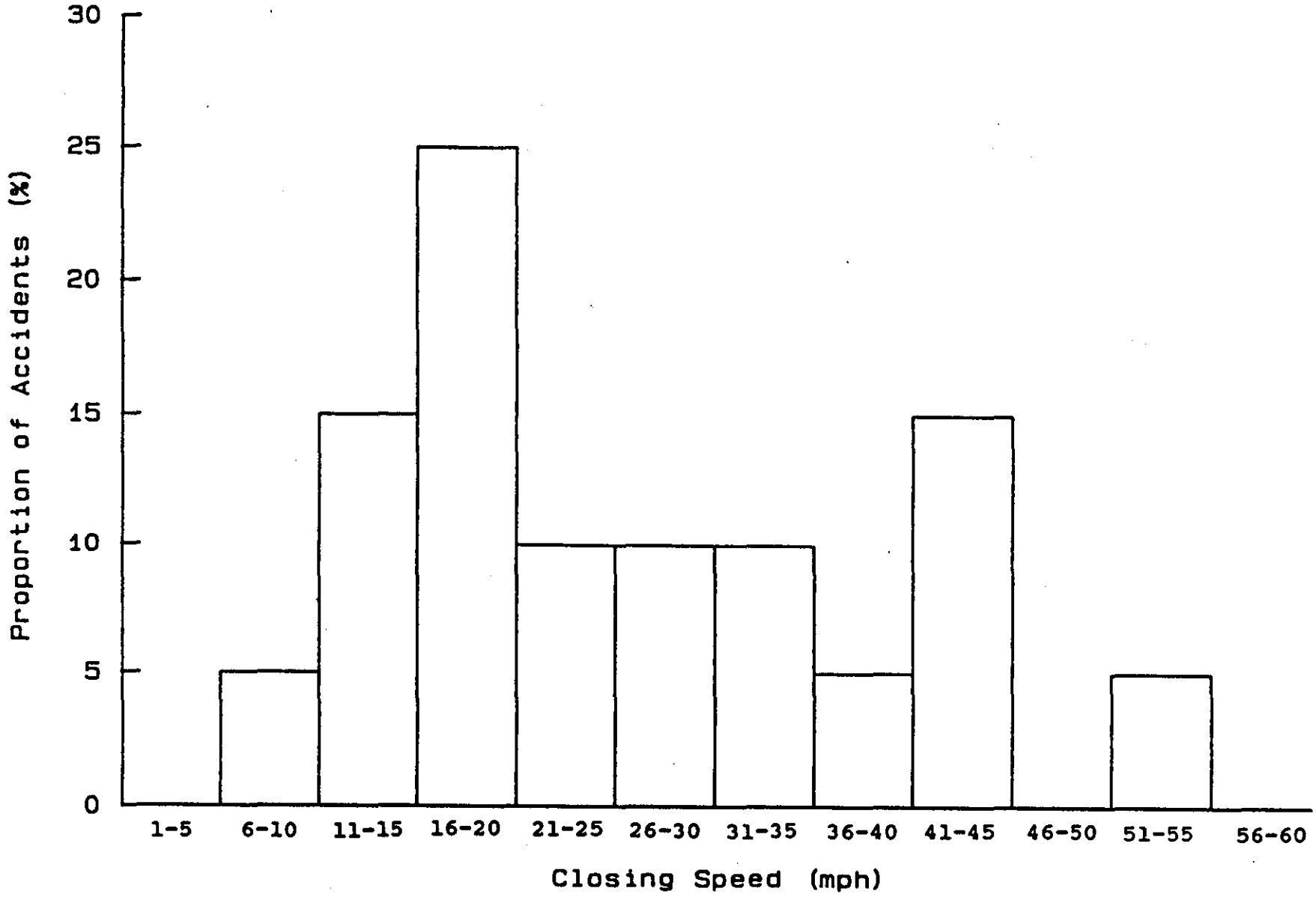

Figure 1: Freight train closing speeds

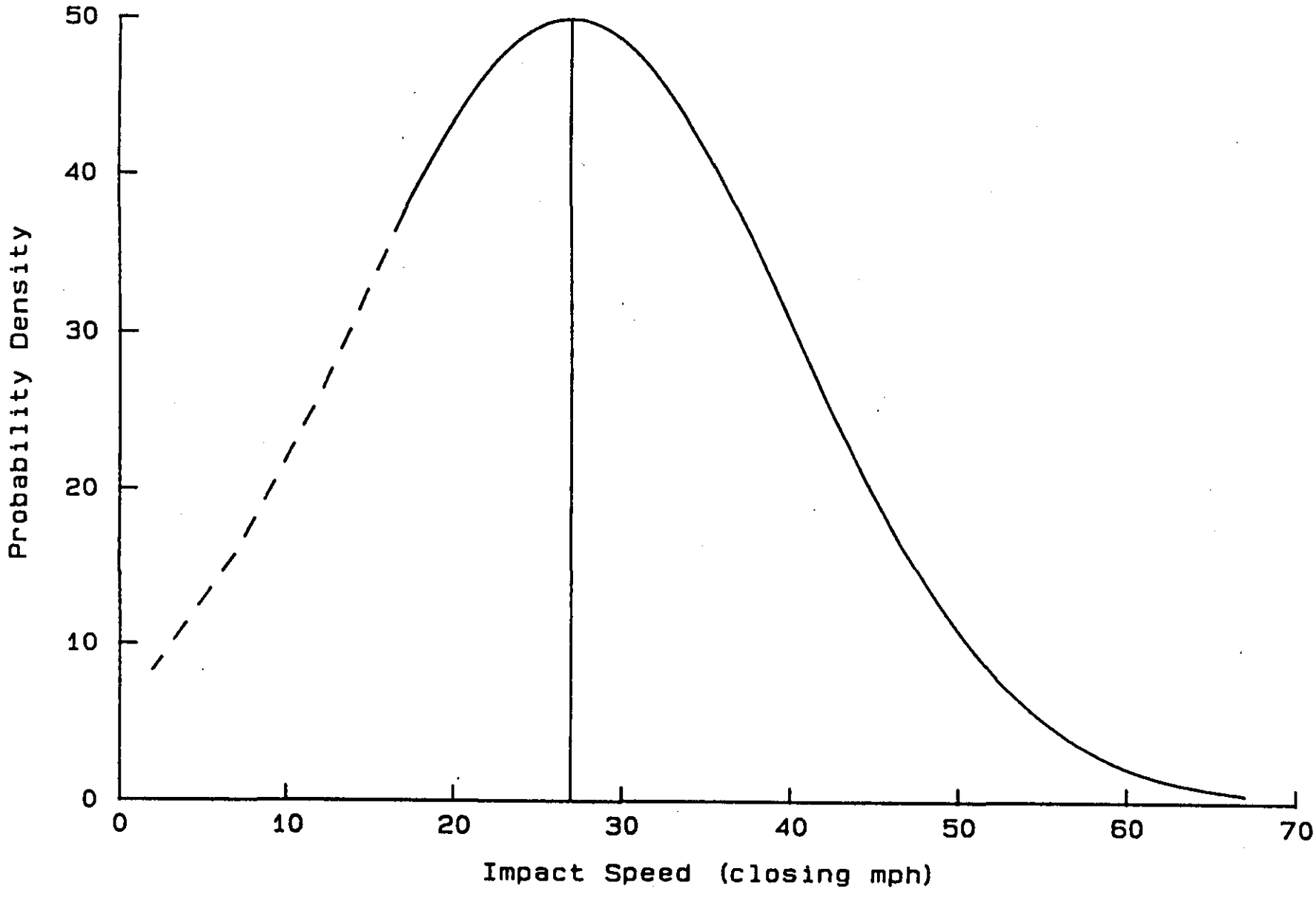

Figure 2: Distribution of freight train closing speeds

4.4 Accident Severity Index: Collision Accidents

It is shown here that an index can be formulated to help quantify/categorise (or predict) the severity of FT accidents. Much data are recorded by the Railway Inspectorate and detailed in various accident reports. However, as yet these data have not been used to quantify/categorise train accidents.

Assuming that accident severity is measured in terms of deaths, injuries and property damage, then the results of the FTA survey indicate that closing speed is the most important factor in accident severity. Generally, the greater the closing speed, the greater the number of casualties and the greater the magnitude of damage. As a consequence of this, closing speed is considered the primary component of accident severity. However, the FTA survey indicates that speed is not the only factor governing accident severity. Two second order effects, termed secondary components, are shown to influence accident severity. These secondary components are known as closing train momentum and closing train tonnage. Unlike train speed, greater closing momentum (CM) does not necessarily mean an increase in casualties and damage. For example, in one accident (from the FTA survey) the closing momentum was 14.72 MNm and 4 injuries resulted. In another accident the closing momentum was 1.6 MNm with a total of 3 deaths and 68 injuries. The closing speed for each accident was 20 mph and 35 mph respectively, illustrating the effect of closing train speed (CS). Closing train tonnage (CT) can be illustrated in a similar fashion. However, it does not follow that an accident involving large closing momentum will necessarily have a large closing tonnage. This is because momentum is a product of mass and speed. As a

consequence of this, a train may have a relatively low tonnage but a high speed giving it a relatively high momentum, and vice-versa.

The FTA survey indicates that deaths, injuries and damage are related to accidents which have a large primary component and at least one large secondary component (i.e. a large closing speed together with either a large closing momentum or a large closing tonnage). Thus, it appears that only two of the three criterion are needed for a potentially severe accident. However, one of the criterion must be high closing train speed.

In order to illustrate the concept of a numerical index to quantify/categorise FT accidents, a simple index is detailed here for FT collisions. Due to lack of data the index is based on only 10 of the 26 collisions detailed in the FTA survey.

The three criteria, speed, momentum and tonnage are each attributed a "score" until a means of satisfying the ten accidents is achieved. The three individual scores relate the three criterion and the sum of these provides an overall value of severity, known as the accident severity index (ASI).

Consider a freight train "X" colliding head-on with another freight train "Y". Freight train "X" is travelling at 25 mph (11.2 m/s) and freight train "Y" at 10 mph (4.5 m/s) before collision. The gross weight of each vehicle is 1000 te and 600 te respectively.

$CS = 25 + 10 = 35$ mph

$CM = (1000 \times 10^3 \times 11.2) + (600 \times 10^3 \times 4.5)$
$= 13.9$ MNm

$CT = 1000 + 600 = 1600$ te

From the accident severity chart (page 134)

$ASI = 8 + 3 + 5 = 16$

i.e. Derailment and over-turning is almost certain accompanied by deaths and injuries.

This simple accident severity index (ASI) has been cross-checked by applying it to a number of FT collisions. The remaining 16 FT collisions detailed in the FTA survey together with other similar accident reports have been used for this purpose. Although the data included in these reports are insufficient to assist ASI construction they are sufficient to provide a rough cross-check. The check tends to support the validity of the index in quantifying/categorising collision severity.

It should be noted that expressing accident severity in terms of closing speed, momentum and tonnage provides a rough estimate of accident severity. From the FTA survey it is apparent that an accident resulting in multiple deaths may be less severe (in terms of damage and expected deaths) than one having only a few deaths or none at all. Deaths, injuries and damage are not only dependent on the three criteria speed, momentum and tonnage, but individual exposure, vehicle orientation and the properties of the load under conveyance. Unfortunately, due to lack of data, such considerations have not been included in this index.

ACCIDENT SEVERITY CHART

Closing speed - CS

CS (mph)	Score
45+	10
35 - 44	8
25 - 34	5
20 - 24	3
Below 20	1

Closing momentum - CM

$(CM)^{1/3}$	Score
2.5+	5
1.19 - 2.49	3
1.00 - 1.90	1
Below 1.00	0

Closing tonnage - CT

$(CT)^{1/4}$	Score
5.0+	5
3.5 - 4.9	3
3.0 - 3.4	1
Below 3.0	0

SCORE

ASI	Possible consequences
15+	deaths
12 - 14	wagons over-turning and deaths
9 - 11	derailment and injuries
4 - 8	minor injuries

Sample used in formulating freight train accident severity index: Freight train collisions

1. FT (10 mph, 1556 te) v FT (10 mph, 1736 te)
   Head-on collision, 4 minor injuries.
   CS = 20 mph CM = 14.72 MNm CT = 3292 te
   ASI = 11

2. FT (15 mph, 696 tons) v FT (stationary, 208 tons)
   Front-rear collision.
   CS = 15 mph CM = 4.74 MNm CT = 904 te
   ASI = 7

3. FT (stationary, 1107 te) v PT (40 mph, 256 te)
   Front-rear collision, 40 minor injuries, OT.
   CS = 40 mph CM = 4.6 MNm CT = 1363 te
   ASI = 14

4. FT (10 mph, 1190 tons) v PAR (50 mph, 278 tons)
   Head-on collision, 3 deaths, OT.
   CS = 60 mph CM = 11.72 MNm CT = 1492 te
   ASI = 18

5. FT (35 mph, 814 tons) v FT (80 mph, 967 tons)
   Front-rear collision, 3 injuries, 1 death, OT.
   CS = 45 mph CM = 22.2 MNm CT = 153 te
   ASI = 18

6. FT (stationary, 791 tons) v PT (45 mph, 158 tons)
   Front-rear collision, 33 injuries, 2 deaths, OT.
   CS = 45 mph CM = 3.23 MNm CT = 964 te
   ASI = 16

7. FT (12 mph, 529 tons) v NT (stationary, 342 tons)
   Front-rear collision, 7 minor injuries, 1 death.
   CS = 12 mph CM = 2.88 MNm CT = 871 te
   ASI = 7

8. FT (stationary, 767 tons) v FT (45 mph, 1082 tons)
   Front-rear collision, 2 injuries, 1 death, OT.
   CS = 45 mph CM = 15.68 MNm CT = 1879 te
   ASI = 20

9. FT (15 mph, 1062 te) v PT (50 mph, 390 te)
   Front-rear collision, 68 injuries, 3 deaths, OT.
   CS = 35 mph CM = 1.6 MNm CT = 672 te
   ASI = 14

10. FT (stationary, 1146 te) v PT (15 mph, 58 te)
    Front-rear collision, 7 injuries.
    CS = 15 mph CM = 0.4 MNm CT = 1204 te
    ASI = 6

4.5 Movements of Explosives

It is thought that less than 10% of all commercial explosives are transported by rail, compared with about 60% of all military explosives. As a result of commercial confidentiality and the need for military secrecy very little data are available on explosives movements. No specific data are available on commercial movements, except general data, as given in Section 6.1. However, a substantial amount of data have been collected by the author on rail movements of military explosives during the currency of this study. Data have been made available through Movements 1(Army)[9], the Logistics Executive[10] and the assistance of staff at both the Central Ammunition Depot (CAD) Longtown[11] and Kineton[12]. Kind permission has been granted to illustrate the movements data.

The majority of the data refer to rail movements from CAD Longtown and CAD Kineton. A summary of these data are given below.

CAD Longtown: Rail Movements November 1987 - October 1988

During the twelve months November 1987 through to October 1988 234 wagons, classed as being laden with hazard division (HD) 1.1 munitions, were issued from CAD Longtown. It is not known how many of the wagons contained mixed loads, but between November 1987 and April 1988 26 out of a total of 84 HD 1.1 wagons contained mixed loads. It can be estimated from this that approximately 30% of HD 1.1 wagons issued between November 1987 and October 1988 contained military explosives of other hazard divisions.

Based on 17 mixed wagon loads, issued between November 1987 and April 1988, the ratio of HD 1.1 munitions to munitions of other classes is estimated here as 1:0.61 (in terms of gross munition weight).

Rail movements from CAD Longtown totalled 144 for the 234 wagon issues providing an average of almost 2 wagons per movement (1.63). A little under 170 te of explosive were moved between November 1987 and October 1988 (168.8 te), the mean net explosives quantity (NEQ -i.e. net weight of explosives excluding casings and packaging, etc.) per wagon approximating to 0.53 te.

From the years survey it has been possible to detail an average ratio of HD 1.1 NEQ with respect to gross munition weight, this being 0.26:1. Similarly, from the six months survey NEQ to gross munition weight for HD 1.2, HD 1.3 and HD 1.4 munitions approximates to 0.13, 0.16, and 0.06 respectively. The NEQ ratios given for HD 1.2 and HD 1.3 munitions have been based on very small samples, and as such, could be considered poor estimates. However, based on CAD Kineton data similar ratios have been derived from much larger samples.

CAD Kineton: Rail Movements November 1988 - February 1989

A detailed survey for the month of November 1988 of munitions wagons issued from CAD Kineton reveals that a total of 38 wagons were used to move approximately 28 te (NEQ) of explosive (excluding two very large and untypical wagon loads of HD 1.2 munitions). The number of movements totalled 35 providing an average of 1 wagon per movement.

Over the next three months, December 1988 and January and February 1989 similar amounts of explosive were moved, these being 22 te, 34 te, and 34 te respectively. During this four month period approximately 40% of the total NEQ moved was classed as HD 1.1, 22% as HD 1.2, 27% as HD 1.3 and 12% as HD 1.4.

Eighteen of the 38 wagons issued during November were classed as being laden with HD 1.1 munitions. However, 50% of the wagons also contained munitions of other hazard divisions. The mean NEQ of the 18 wagons approximates to 1.37 te. This compares with a maximum mean NEQ per wagon, from the CAD Longtown survey, of 1.30 te. Between November 1988 and February 1989 a total of 67 wagons classed as being laden with HD 1.1 munitions were issued from Kineton. Mixed wagon loads accounted for 40% of these. This compares with approximately 30% for similar issues from CAD Longtown between November 1987 and February 1988.

The data collected from CAD Kineton have been used to estimate the ratio of NEQ to gross munition weight for each hazard division. With the exception of HD 1.1 munitions the ratios compare favourably with those obtained using data from CAD Longtown. The HD 1.1 munition ratio based on CAD Kineton data is 0.14:1, compared with 0.26:1 based on CAD Longtown data. The CAD Kineton derived ratio for HD 1.2, HD 1.3 and HD 1.4 are 0.11, 0.16 and 0.07 respectively.

Table 7: Rail movements of munitions classed as HD 1.1: CAD Longtown November 1987 - October 1988

Month	Number of movements	Number of Wagons	NEQ/wagon (te)	Total NEQ (te)
Nov	15	21	0.96	20.15
Dec	10	11	0.34	3.71
Jan	8	11	0.32	3.50
Feb	8	10	0.41	4.10
Mar	14	21	0.60	12.64
Apr	8	10	0.22	2.16
May	15	24	0.70	16.87
Jun	21	35	0.50	17.34
Jul	15	20	0.53	10.63
Aug	9	10	0.41	4.12
Sep	7	35	1.17	40.92
Oct	14	26	1.26	32.63
Total	144	234	0.53	168.88

Table 8: Distribution of wagon loads: HD 1.1 munitions

Size of range (NEQ)	Mid-Range value (NEQ)	No. of Loads	Proportion of all loads
te	te	wagons	%
0 - 0.10	0.05	76	32.5
0.10 - 0.25	0.18	23	9.8
0.25 - 0.50	0.38	11	4.7
0.50 - 1.00	0.75	26	11.1
1.00 - 2.00	1.50	83	35.5
2.00 - 3.00	2.50	15	6.4

Note:

a. Data obtained through the survey of rail movements of munitions from CAD Longtown between November 1987 and October 1988.

4.6 Freight Train Accident and Transport Data

Table A: Freight train kilometres travelled by locomotive type: 1986

Locomotive type	kilometres x 10^6
Diesel	47.4
Electric	6.6
All locomotives	54.0

Source: Department of Transport[1]

Table B: Number of freight train accidents by accident type: 1986

Accident type	Number of accidents	Proportion of accidents
Collision*	113	35
Derailment	158	49
Fire	53	16
All accidents	324	100%

Source: Department of Transport[1]
* Sawer, D.A.[3]

Table C: Frequency of freight train accidents by accident type: 1986

Accident type	Frequency of accident (10^{-6} accidents/km)
Collision	2.09
Derailment	2.93
Fire	0.98
All accidents	6.00

Note:

a. Accident frequencies are derived from data given in Tables A and B.

Table D: Number of freight train collisions by collision type: 1986

Collision type	Number of collisions	Proportion of collisions
FT v FT	8	7
FT v PT	1	1
FT v ECS	10	9
Buffer stops	55	49
Animals	9	8
Misc. obstacles[a]	22	19
Level crossings[b]	6	5
Other	2	2
All collisions	113	100%

Note:

a. Obstacles include trees, railway debris and miscellaneous items falling or maliciously placed on the track.
b. Includes 4 collisions at protected and 2 at unprotected level crossings.

Source: Sawer, D.A.[3]

Table E: Frequency of freight train collisions by collision type: 1986

Collision type	Frequency of collisions (10^{-6} accidents/km)
FT v FT	0.15
FT v PT	0.02
FT v ECS	0.19
Buffer stops	1.02
Animals	0.17
Misc. obstacles	0.41
Level crossings	0.11
other	0.04
All collisions	2.09[a]

Note:

a. Discrepancy of value due to rounding.
b. Collision frequencies are derived from data given in Tables A and D.

Table F: Train* collisions at protected level crossings with road vehicles: 1986

Collision type	Number of Collisions
Train vs. Car	13
Train vs. Van	5
Car vs. Train	5
Van vs. Train	-
Total	23

Note:

a. * no data are available to distinguish between FT and PT accidents.
b. Total number of crossings at the end of 1986 totalled 8732 of which 7017 were unprotected.

Source: Department of Transport[1]

Table G: Number of train* accidents by principal cause and accident type: 1986

Principal cause	Number of accidents				
	Collisions	Derailments	Fire	Other	Total
Staff error	178(139)	114	4	22	318
Technical defects +	34(8)	69	146	11	260
Other causes ++	506(119)	9	24	55	594
All causes	718(266)	192	174	88	1172

Note:

a. * no data are available to distinguish FT accidents.
b. + includes vehicles, track and signalling.
c. ++ includes accidents due to the weather, animals on the line and irresponsible acts by the public.
d. Figures in brackets denote collisions between rolling stock, buffer stops and projections from rolling stock.

Source: Department of Transport[1]

Table H: Rail accident casualties: 1986

H1: All casualties

Accident type	Numbers of people		
	Killed	Injured	
		Major	Minor
Collisions	27	72	383
Derailments	-	5	26
Fires	-	-	6
Other	-	-	18
Total	27	77	433

Source: Department of Transport[1]

Table H: continued

H2: Railway staff casualties only

Accident type	Numbers of people Killed	Injured Major	Injured Minor
Collisions	5	-	-
Derailments	-	1*	3
Fires	-	-	1
Other	-	-	12
Total	5	1	16

Note:

a. * freight train derailment.
b. Railway staff include contractor staff.

Source: Department of Transport[1]

Table H: continued

H3: Railway staff casualties resulting from freight train derailment

Year	Deaths	Serious injury	Minor injury	All casualties
1986	-	1	-	1
1985	-	-	3	3
1984	-	1	2	3
1983	-	-	8	8
1982	-	-	6	6
1981	-	-	4	4
1980	1	1	5	7
1979	-	-	2	2
1978	-	-	5	5
1977	-	1	12[a]	13
1976	-	2	9	11
1975	-	-	7[b]	7
Total	1	6	63	70

Note:

a. Includes 2 passengers and 2 unclassified persons.
b. Includes 1 unclassified person.

Source: Department of Transport[1]

4.7 References

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PART B

5.0 EXPLOSIVES SENSITIVITY: ACCIDENTAL INITIATION IN ROAD AND RAIL ENVIRONMENTS

The need to quantify explosives sensitivity has led to numerous tests and a wealth of published literature. A comprehensive reference of data and tests pertinent to commercial explosives is given by Macek[1], whereas, the Sensitiveness Collaboration Committee[2] have compiled a full list and description of tests relative to military explosives. In addition, the United Nations (UN) Committee of Experts on the Transport of Dangerous Goods recommend a number of tests and criteria suitable for classifying both commercial and military explosives[3]. The tests are published as a handbook companion to the UN recommendations on the Transport of Dangerous Goods[4].

Explosives sensitivity testing is primarily performed so as to classify explosives into various hazard divisions and compatibility groups (see Section 6.1.1). More importantly here, explosives sensitivity test data enables judgements to be made on the vulnerability of explosives to stimuli which may be encountered during manufacture, storage and transport. In addition, the data are used by the Research and Laboratory Services Division (RLSD) of the Health and Safety Executive to highlight possible areas of concern and identify those explosives and tests requiring further research and development[5]. Testing by RLSD is undertaken on behalf of HM Explosives Inspectorate. Sensitivity tests are also carried out by a number of commercial manufacturers/users of explosives and by the Ministry of Defence at various centres throughout the UK (e.g. Royal Armament Research and Development Establishments (RARDE), Royal Ordnance, Nobels Explosives and IMI).

The problem of sensitivity in the context of this study, is one of identifying and quantifying stimuli which can cause explosives to initiate during road and rail transport. Fire and impact are considered here to be the most likely sources of initiation.

It is generally accepted that under normal transport conditions, explosives can be conveyed with little risk of initiation[6]. Normal conditions refer to usual transport environments where extremes of heat, shock and vibration, etc. are not encountered. However, vehicular accidents often have the potential to cause initiation of explosives, either by introducing stimuli or amplifying normally passive environments. Typical initiation stimuli, being either accident induced or passively present, have been identified here and are discussed below.

Note

It is considered here that all initiated explosives ultimately cause explosion (i.e. those explosives undergoing chemical decomposition or more precisely self sustaining exothermic reaction, as a result of contacting suitable initiation stimuli, explode). The term explosion is rather ambiguous. A popular definition is given by Uvarov and Isaacs[7]

> "[an explosion is] a violent and rapid increase of pressure in a confined space".

A more precise definition is given by Strehlow and Baker[8]

> ".... an explosion is said to have occurred..... if energy is released over a sufficiently small time and in a sufficiently small volume so as to generate a pressure wave of finite amplitude travelling away from the source".

The author has been unable to find a concise "scientific" definition of the term explosion. However, its use in this study refers to a sudden release of energy causing a pressure discontinuity, termed a blast wave. Furthermore, the term explosion refers to both deflagrative and detonative explosions. Deflagrative and detonative explosions are described fully by Cook[9], Baker[10] and Kinney[11]. For the purposes of this study it is sufficient to note that detonative explosions, unlike deflagrative explosions, produce a reaction front travelling at greater than sonic velocity through unreacted explosive. Both explosions can cause extensive damage. However, the blast wave produced by a detonative explosion is much more destructive than that produced by a deflagrative explosion.

5.1 Shock and Vibration

Shock is defined as a sudden and severe non-periodic excitation of an object. Most available data quantify shock in terms of acceleration in an identical manner to that found in vibration measurement. Unlike shock, vibration is a periodic oscillating motion. However, in normal transport environments vibrations are usually characterised by non-periodic oscillations accompanied by changing amplitude. Therefore, it is difficult to distinguish between shock and vibration, since high amplitude short term vibration, as experienced in vehicular accidents, can also be classed as shock.

During transit, and under normal transport environments, heavy goods vehicles (HGVs) are subjected to maximum shocks[12] of approximately 100 m/s^2. It should be noted here that such measurements are often expressed in terms of "g" where g refers to acceleration due to gravity (e.g. in this case 100 m/s^2 equates to approximately 10g). Provided packages are secure, such shock levels can be effectively neglected as a means of initiating explosives. However, it has been known for structures attached to road and rail vehicles to experience excitations above those of the transporting vehicle[12]. Excitations of the order of 200 m/s^2 have been recorded for loads carried by HGVs, whilst the HGV itself has experienced much lower shock levels. There is no evidence to suggest that shock amplification is a new phenomenon. Although large excitations are not commonplace, shock amplification is considered part of the normal transport environment. As a consequence of this, it is assumed here that shock amplification has little or no significant effect on transport incidents involving explosives.

Sensitivity of explosives to shock has been analysed since the early 1930's when Muraour[13] devised a rudimentary test known as the "Gap Test". From its infancy it has grown to become one of the main internationally recognised sensitivity tests. As shown in Figure 1, a shaped charge known as the "acceptor" is separated from a "donor" charge by an inert barrier of thin metal or plastic strips, typically 0.25 mm thick. Both the donor and acceptor geometries are fixed, the only geometric variable being gap thickness. Consequently, shock sensitivity is measured in terms of gap thickness; the smaller the gap the less sensitive is an explosive, and vice-versa. The thickness of the gap is determined when the acceptor has a 50% chance of detonating. Detonation is deemed to have occurred when a "witness plate" located on the acceptor suffers mechanical damage. This effectively indicates that sufficient propagation velocity has been attained and, hence, the charge has detonated.

The shock wave emanating from the donor charge consists of two distinct waves, namely pressure and thermal waves. Due to the gap thermal waves are isolated ensuring that only pressure waves reach the acceptor. The mechanism of initiation is essentially thermal. As the pure shock waves travel through the acceptor chemical reaction/molecular disruption is induced as a result of intense compression and consequent adiabatic heating. If the heat produced is of a sufficient temperature, whereby the reaction becomes self sustaining, shock waves are reinforced with reaction energy and after a transient delay steady state detonation results.

The results obtained from Gap Tests are relative to each particular test (i.e. gap material, charge composition and dimensions, etc.). Ordering of explosives sensitivity usually remains consistent regardless of material and parameter changes. Further information on the concepts of shock sensitivity, current testing procedures and equipment can be found through Kaye and Herman[14].

Results gained from shock sensitivity tests are of little use for the provision of "real life" sensitivity quantification. This is because the stimuli used are idealised and their rates of input far too large compared with those experienced in vehicular accidents[15]. As a consequence of this, shock sensitivity test results are of little value to this study except as a means of comparing the relative shock sensitivity of explosives. Typical Gap Test results for various explosive materials are listed in Table 1.

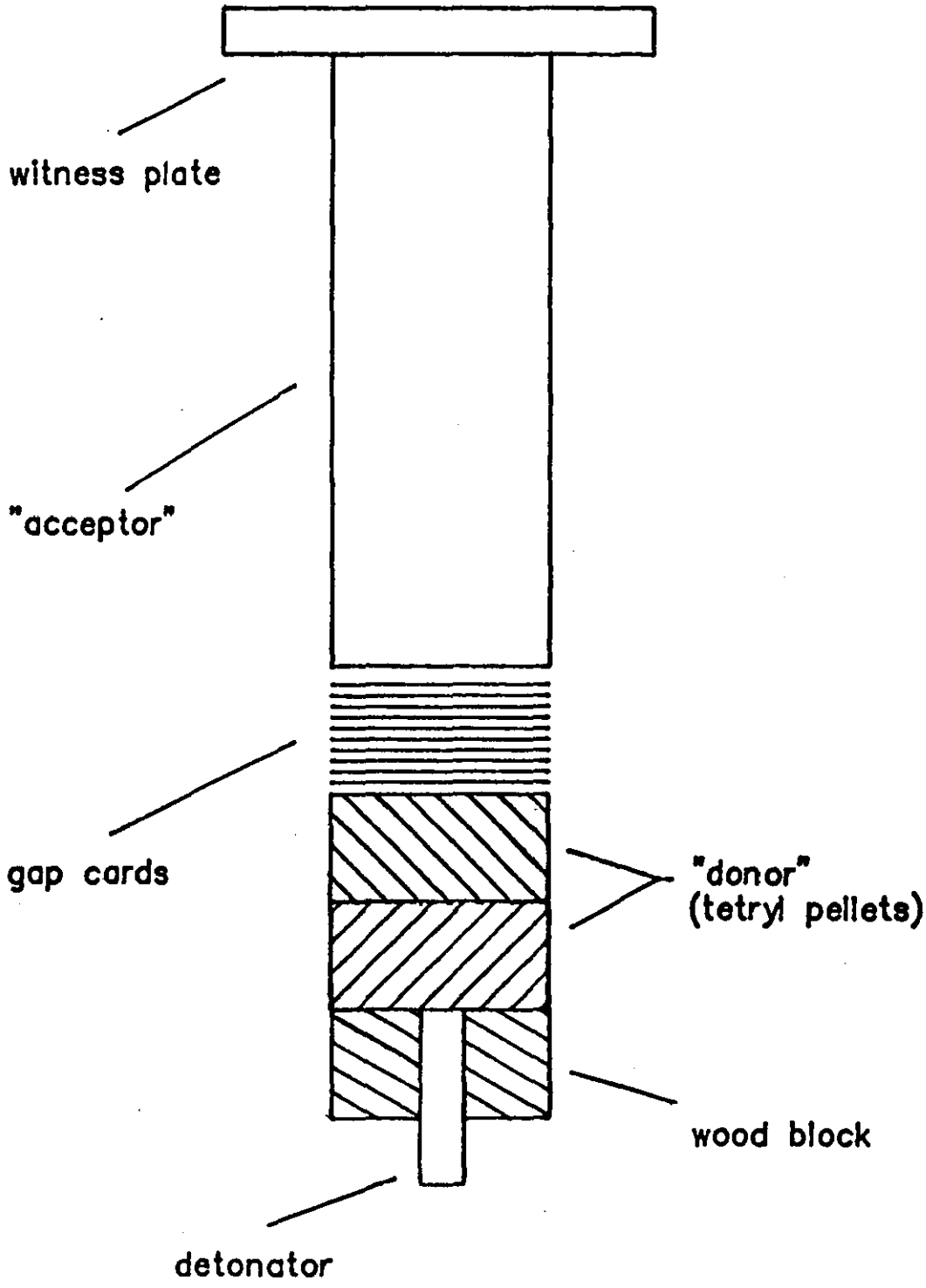
Although it is difficult to determine precise shock levels for explosives during conveyance, it is generally agreed that those shocks and vibrations experienced under normal transport environments are insufficient to cause explosive initiation[6,12]. However, it is thought that shock and vibration resulting from vehicular impacts have a finite likelihood of attaining suitable magnitudes to cause initiation. It is suggested here, that in vehicular accidents shock/vibration stimuli, sufficient to cause initiation, are accompanied by impact stimuli of magnitudes so great that initiation is much more likely as a result of impact. In addition to this, shock/vibration stimuli are difficult to distinguish and measure separately and therefore, initiation is often assumed to occur as a result of impact.

Table 1: US Naval laboratory gap test

Material	Cast or pressed	Density (g/cm^3)	Gap thickness (cm)
RDX	pressed	1.640	8.20
Pentolite	cast	1.684	6.70
Tetryl	pressed	1.615	6.63
Comp. B	pressed	1.663	6.05
Comp. A	pressed	1.590	5.34
Comp. B	cast	1.704	5.24
TNT	pressed	1.569	4.90
Amatol	cast	--	4.12
TNT	cast	1.600	3.50
Tritonal	cast	1.750	2.90

Source: Macek[1]

Figure 1: Typical gap test configuration: US Naval Ordnance gap test for solid explosives



Source: Macek[1]

5.2 Impact

Impact can be defined as the collision of a single moving object with another moving or stationary object. Such impacts are absent in the normal transport environment. However, impact usually occurs in vehicular accidents. Collisions with other moving vehicles may cause direct and/or indirect collision of the explosives under conveyance. Direct collision refers to actual contact between explosives and the offending vehicle(s), whereas, indirect collision refers to contact between separately packaged explosives and/or ancillary equipment and/or interior parts of the transporting vehicle. A similar analogy can be expressed for single vehicle accidents involving impact, such as, collisions with unyielding objects and structures.

Although it is thought that impact initiation is thermal in origin, why explosives ignite (sometimes) as a result of impact is not fully understood. On the basis of thermal initiation caused by the creation of localised thermal energy, known generally as "hot-spot" generation, energy transferred during impact must be greater than or equal to the Arrhenius energy of activation[12]. In this instance Arrhenius energy is the energy required to cause a small amount of explosive to decompose. It is believed that impact causes this decomposition by creating "hot-spots" above the explosives initiation temperature. This is thought to occur as a result of

a. friction between grains of explosive and/or grit particles,
b. adiabatic compression of small air cavities,
c. viscous heating caused by rapid extrusion,
d. localised adiabatic deformation of thin layers of explosive as a result of mechanical failure.

A full account of these initiation mechanisms is given by Heavens and Field[16] and Field et al[17].

Upon decomposition by one or more of the above heat generation mechanisms, additional energy is liberated which activates neighbouring material and so propagates a sustained reaction. There is a tendency for such exothermic reactions to become faster and rapidly increase the rate of heat production which ultimately leads to deflagration or detonation. For solid explosives the area over which energy is delivered appears to be an important criteria[12]. If the area is too small, neighbouring material will not receive sufficient energy to cause further decomposition and therefore explosion will not occur. In comparison, liquid explosives, including slurries and pastes, tend not to be critically dependent on the area over which energy is delivered. The reasons for this are not explained. For liquid explosives there is a tendency for energy to be recorded and measured in terms of energy per unit time (J/s) rather than energy per unit area (J/m^2) as with solid explosives.

Impact testing is well established as a standard explosives sensitivity test, although it is often acknowledged as a crude art rather than an exact science. This statement can be inferred from typical hammer impact tests, as described by Macek[1] and Bowden et al[18], and from "Susan" impact tests described by Parzel and Ward[19]. Unlike

the determination of shock sensitivity, where event initiation can be related back to a pure shock wave, impact initiation can be attributed to many factors. Such factors are in the main attributable to impact velocity, pressure, friction, viscous heating and explosive fluidity. Many more problems accompany impact testing. However, those mentioned above serve to demonstrate the complexity surrounding impact sensitivity testing and measurement. An in-depth discussion of the problems associated with impact testing is given by Macek[1] and Marshal et al[20].

The most common impact sensitivity test consists of a hammer of known weight being dropped from a pre-determined height onto an anvil layered with powdered explosive (see Figure 3). The distance between the hammer and explosive (height) is recorded as that distance which results in a 50% chance of detonation. The weight of the hammer is recorded and together with the height, which is found by trial and error, both are used as a measure of impact sensitivity. Since detonation is extremely rare during testing, an event is deemed to occur when an appreciable amount of noise, gas, odour, smoke or other suitable by-product is observed. Unfortunately, the results obtained from impact tests are of little value in real terms, except as a means of ordering explosives sensitivity to impact and highlighting the risk of impact initiation. Typical impact test results for various explosive materials are listed in Tables 2, 3 and 4.

It is suggested here that vehicular impacts associated with vehicular collisions are capable of initiating explosives. Evidence to support this stems from data collected on HGV and freight train (FT) speeds, upon and prior to collision, and data made available on the results of "Susan" impact tests[19]. Susan impact tests consist of

steel projectiles loaded with 0.45 kg of explosive which are propelled at various speeds (within and exceeding the range of vehicular impact speeds) into unyielding surfaces. The results of such tests indicate that explosives have a range of probable impact initiation speeds and that some explosives are much more sensitive than others. More importantly, the results indicate that a number of explosives can be initiated by impact at speeds which can be experienced in severe vehicular collisions. For example, an impact initiation speed of 52 m/s equates to approximately 115 mph, which as shown in Chapter 6.0, Section 6.5.1, is an attainable impact speed in head-on collisions between certain HGVs. A similar example is also shown in Section 6.5.1 for FT collisions with rolling stock. In addition to the above it is important to note that the report[19] from which the Susan test data are taken (and detailed here in Table 4) states that

> "a blanket assumption cannot be made that all warheads have survived a 15 m/s impact"

Vehicular collisions at such an impact speed (34 mph) or greater are not uncommon, as shown by the data presented in Chapters 3.0 and 4.0, Sections 3.2 and 4.3 respectively. Consequently, it is thought here that regardless of energy absorption by vehicles during collision and protection offered by packaging, etc., certain vehicular impacts are capable of initiating a number of military and commercial explosives.

Table 2: US Naval laboratory impact test

Material	Height (cm)
PETN	13
RDX	24
HMX	26
Pentolite	38
Tetryl	38
Comp. A3	60
Comp. B	60
Tritonal	107
Amatol	116
TNT	200
Ammonium nitrate	>320

Note:

a. 2.5 kg hammer, 35 mg sample.
b. Height - 50% chance of detonation/event.

Source: Macek[1]

Table 3: Fall hammer impact sensitivity

Explosive	Height (cm)
Gelignite	5 - 10
Nitroglycerine[c]	20 - 30
RDX	25 - 30
Ammon gelignite	30 - 40
PETN	60 - 80
RDX/TNT	80 - 100
TNT[c]	160 - 200
TNT	>200

Note:

a. 0.5 kg hammer
b. Height - 50% chance of detonation/event.
c. powder

Source: Bowden and Gurton[18]

Table 4: Impact initiation of explosives: Susan tests

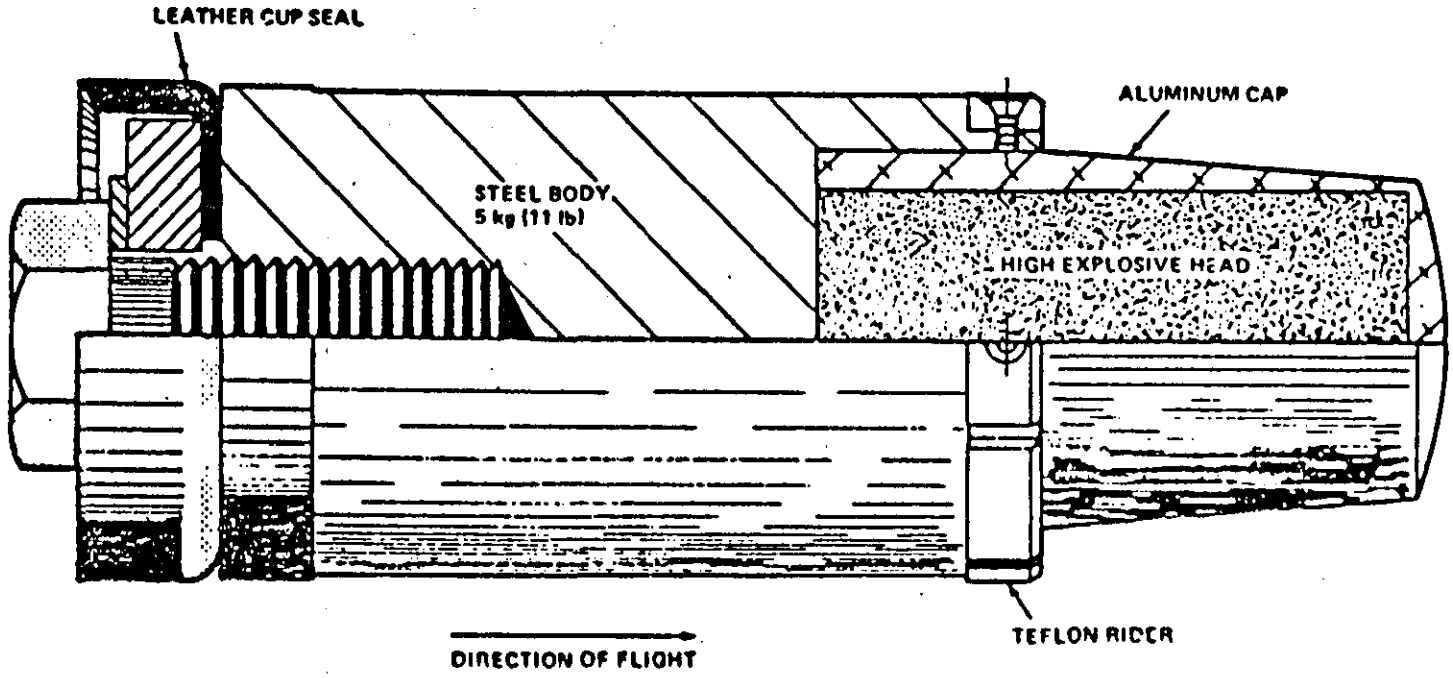
Explosive	Impact speed Initiation (m/s)	Impact speed Survived (m/s)	Mean p^o at 3.05 m (kN/m^2)
PBXN-105	52	32	1.1
EDC 38	65	78	8.1
OCTOLITE 70/30	66	62	51.8
CTX-1	67	51	19.6
EDC 29	77	66	12.6
EDC 37	79	80	4.1
EX 62	80	51	11.9
EDC 24	84	64	2.0
HMX/TNT 85/15	86	98	50.3
CW3	89	50	3.2
EDC 15	90	53	15.7
TORPEX 2A	98	87	0.7
HMX/POLY 85/15	120	89	3.6
RGPA TYPE 2	140	82	2.4
RDX/TNT 60/40 A	143	87	7.0
RGP	154	82	2.0
BX4	156	118	5.5
TORPEX 4D/TF	185	135	9.3
RDX/WAX/A1 2B	203	114	9.0
PE4	228	125	8.7
EDC 35	246	157	3.0
CPX 200/M5	285	108	26.6

Note:

a. p^o - peak overpressure

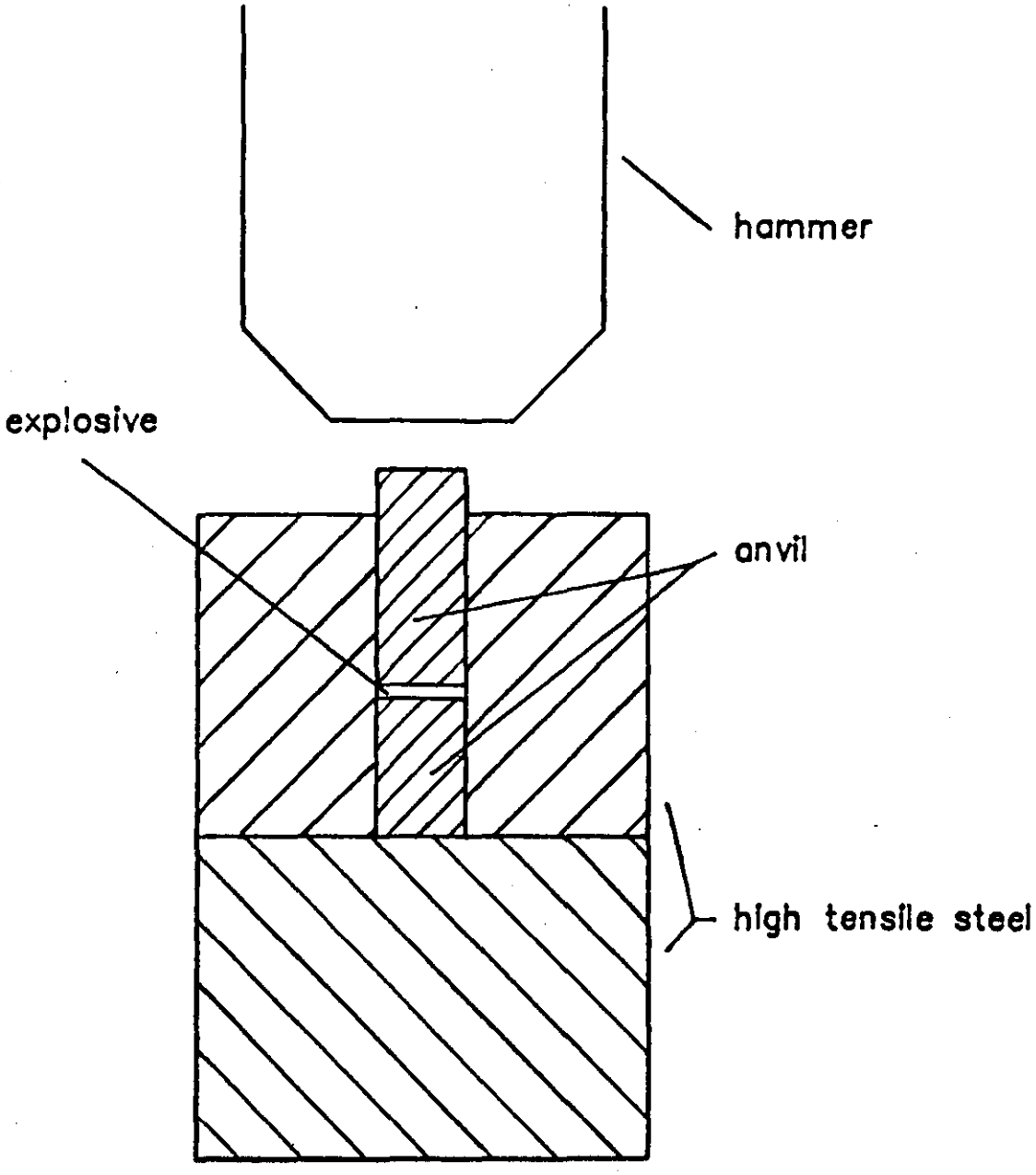
Source: Parzel and Ward[19]

Figure 2: Susan impact test projectile



Source: Parzel and Ward[19]

Figure 3: Hammer impact sensitivity test



Source: RARDE[2] and Fordham[22]

5.3 Friction

Friction sensitivity of explosives has been investigated by many researchers since the late 1930's[18,21]. Many tests have been devised, the most common ones being the Torpedo Test, Friction Wheel and Sliding Friction Test (see Figure 4). Sensitivity testing by the aid of a friction wheel has been established for many years[22]. Simply, a small amount of explosive is smeared on the surface of a rotating disc on which rests a rod which can be varied in weight. The higher the speed of rotation and the greater the load before initiation the less sensitive is an explosive. In comparison, the sliding friction test essentially consists of a pendulum, anvil and plate. The plate is layered with explosive and the pendulum designed so as to slide the anvil over the plate perpendicular to the force vector and at a pre-set constant velocity. Initiation is detected by observation or with the aid of an infra-red analyser which can detect small amounts of decomposition gases. Typical friction test results are listed in Table 5.

Results gained from friction tests provide a measure of friction sensitivity which can be loosely extrapolated to frictional forces experienced in transport environments. For example, Hercules Inc. USA[23] through the Allegancy Ballistics Laboratory (ABL) have employed a sliding friction machine to determine whether explosives can be initiated by friction under normal transport environments. The results, which are detailed in terms of combined pressure and velocity, confirm that normal transport environments do not provide sufficient frictional stimuli to initiate explosives. Hercules found that the most sensitive explosive tested, Gel-Power A-2 slurry, when subjected to a rubbing velocity of 3 m/s, required a pressure of 3.7×10^8 N/m^2 to commence initiation. During

transit Hercules suggest that loads experience velocities far below 3 m/s and pressures above 2.8×10^8 N/m^2 are unlikely to be encountered.

Frictional stimuli are inherent in impact initiation. It is considered that in transport environments frictional stimuli are largely a result of severe vehicular collisions, and are therefore often masked by impact stimuli. One initiation mechanism associated with friction and impact is that of "stab-initiation". However, it can be argued that stab-initiation is basically a frictional stimulus[24]. For example, a metal rod piercing and passing through an explosive may cause a thin layer of explosive to adhere to the rod surface. This can cause frictional rubbing between the adhered layer and surrounding explosive resulting in localised heat generation. It is considered here that such an initiation mechanism in an accident environment would require large impact forces sufficient to breach vehicle bodies, packaging and casing, etc. As a consequence of this, it is generally thought that stab-initiation is as much (if not more) an impact stimulus as it is a frictional stimulus.

In the absence of impact stimuli capable of initiating explosives, frictional stimuli may attain sufficient magnitude to cause initiation. Such frictional initiation, under certain conditions is possible from the stimulus of sliding frictional force. This is measured as the force required to overcome resistance to horizontal motion and is recorded in terms of normal force per unit area (N/m^2). For explosives to be initiated by sliding frictional force during transit, a spillage of explosive requires a "rubbing" velocity[12] of approximately 3 m/s between package/equipment and explosive. Such action can produce "hot-spots" of sufficient temperature to cause thermal

decomposition and hence, initiation. Incidents resulting from such action are extremely unlikely (though not incredible). This is because in addition to insufficient pressure packaged explosives rarely lose their integrity and cause spillage when exposed to normal transport environments. Furthermore, unless acted upon by large external forces, load movements are subjected to velocities far below 3 m/s. Large forces resulting in load velocities above 3 m/s are possible from vehicular accidents. However, it is unlikely that vehicular accidents other than collisions involving severe impacts will cause packages to lose their integrity, thereby subjecting explosives (possibly) to sliding frictional forces above 3 m/s. In conclusion, it is thought here that severe collisions are more likely to cause initiation through impact than friction.

Table 5: Friction sensitivity

Explosive	Torpedo friction[b] (cm)	Friction wheel[c] (kg)
RDX	10 - 20	--
Gelignite	40 - 60	4
PETN	35 - 40	10
RDX/TNT	40 - 45	--
Ammon gelignite	40 - 60	30
TNT	80 - 120	>50
TNT[a]	100 - 120	>50
Nitroglycerine[a]	>150	>50

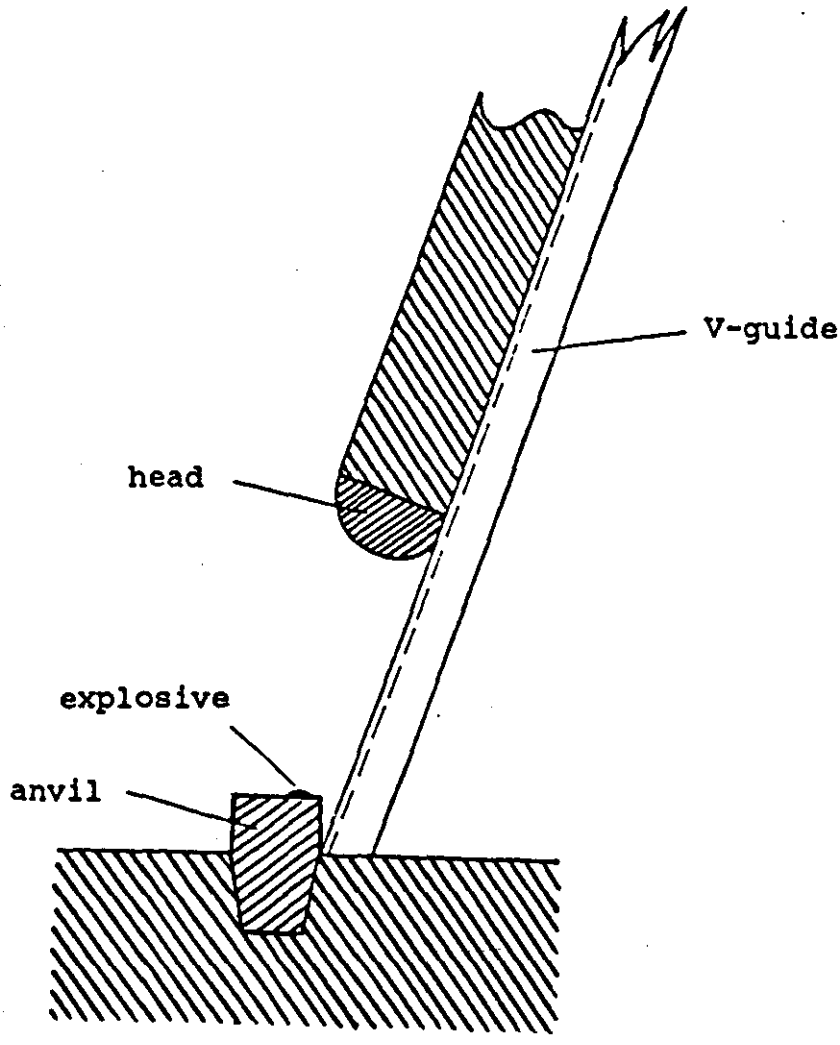
Note:

a. powder
b. 1 kg at 80°
c. 0.5 m/s
d. Values given are those which may cause an event. The chance of an event is not given.

Source: Fordham[22]

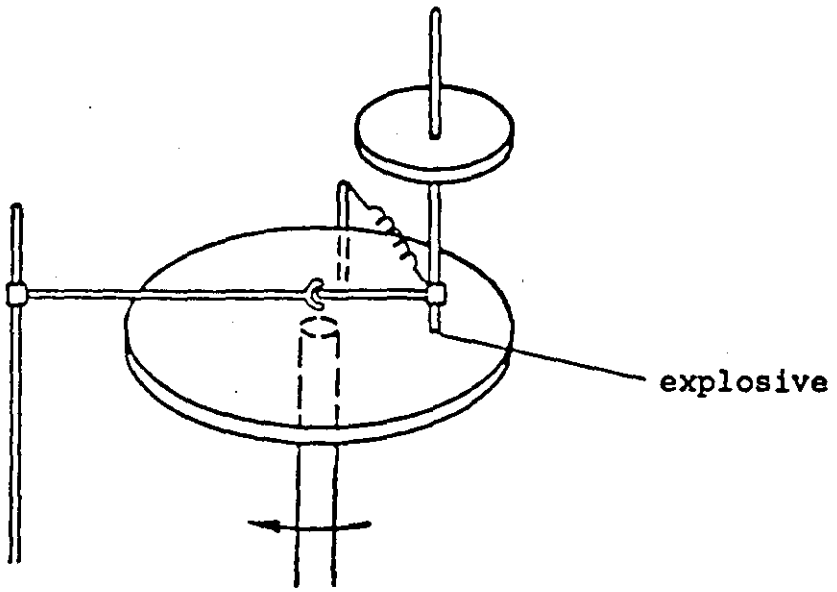
Figure 4: Friction sensitivity tests

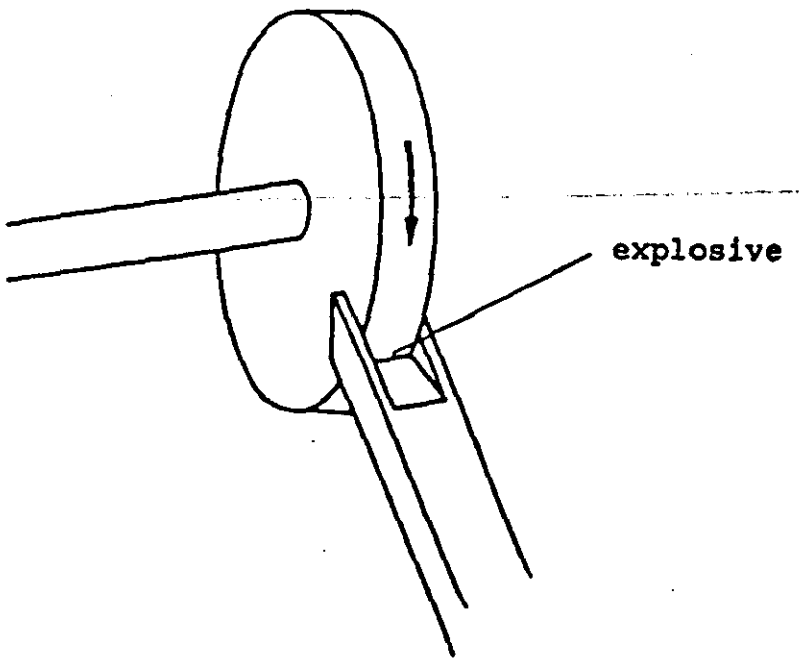
a. Torpedo friction test



Source: Fordham[22]

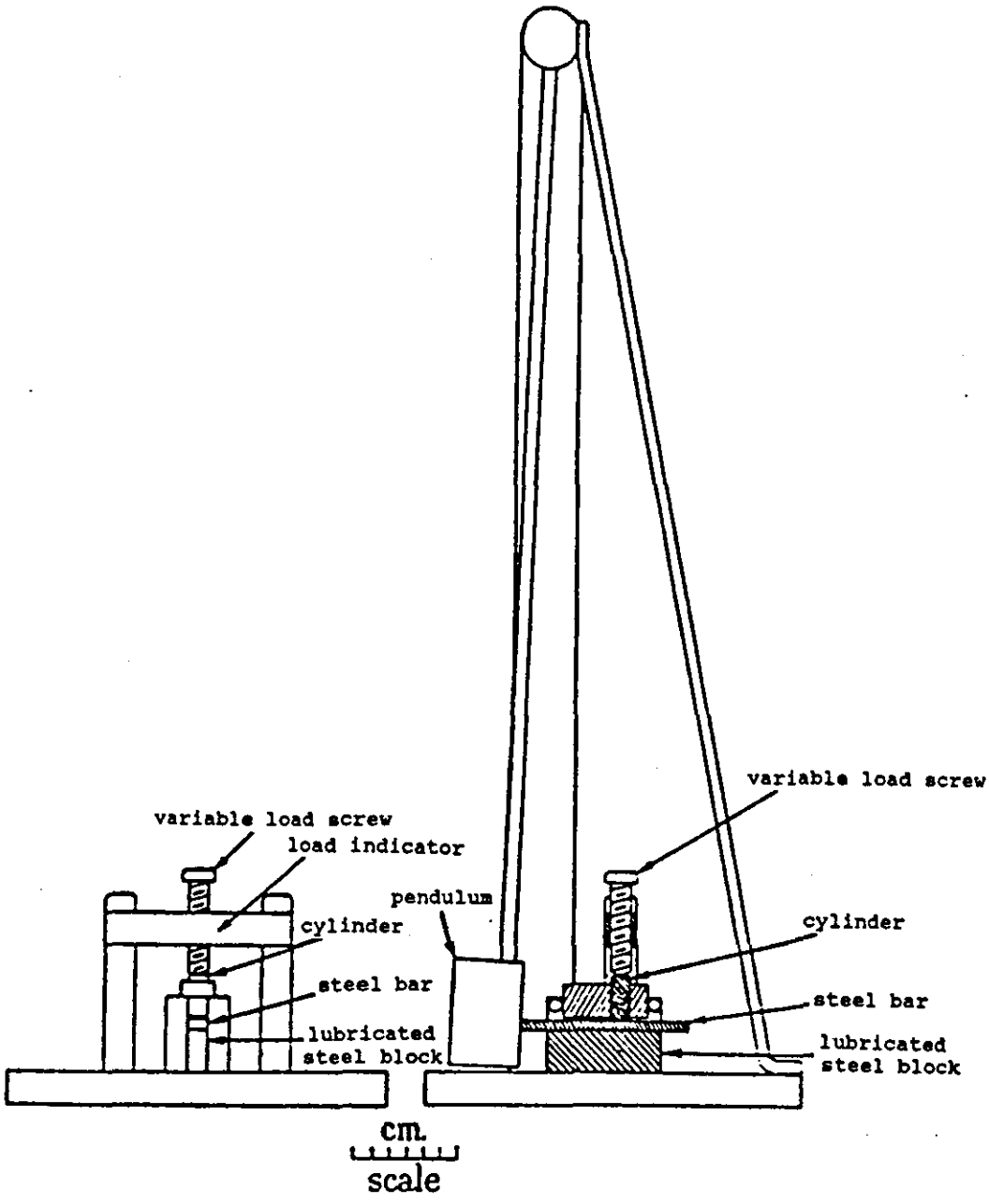
b. Friction wheels





Source: Fordham[22]

c. Sliding friction test



Source: Bowden and Gurton[18]

5.4 Thermal Energy

All explosives can be initiated by thermal stimuli. Initiation occurs when an exothermic reaction is realised or the rate of heat generation is much greater than the rate of heat loss. The critical temperature above which explosion occurs is dependent not only on explosive composition but also explosive geometry and length of exposure to thermal stimuli. In addition, Arrhenius activation energy, thermal conductivity and heat capacity, to name just a few, are contributing factors which affect thermal sensitivity of explosives. A thorough analysis of these factors and the techniques required to determine sensitivity are given by Longwell[25] and Anderson[26].

Determination of critical explosion temperature is mainly performed using thermal "cook-off" techniques. These usually involve the immersion of small amounts of explosive in molten solutions[27], the employment of differential scanning calorimetric equipment, where exothermic onset temperature is evaluated, or by the adoption of differential thermal analysis[28,29].

Results gained from thermal sensitivity tests are dependent on factors particular to each individual test. However, the results are useful in providing a guide to thermal stimuli which are capable of initiating explosives. It is apparent from the results given by the US Army Materiel Command[27] that explosives are extremely unlikely to be initiated by thermal stimuli when exposed to normal transport environments. This point is tentatively supported by the high temperatures required to initiate explosives. For example, TNT requires a temperature of 465°C sustained for a minimum of 10 seconds or 520°C for 1 second to

undergo initiation[12]. In comparison, a typical Hercules manufactured dynamite when subjected to a temperature increase of 10°C/min yields an onset exothermic temperature not much greater than 145°C. Unfortunately, Kloeber et al[12] have not expanded upon these results. The quantity and geometry of explosives used and the source of heat are not detailed. Therefore, the applicability of these results, with respect to the quantification of thermal sensitivity, is not clear.

Ignition temperature for a number of explosive materials under various conditions is given in Table 6.

It is concluded by Kloeber et al and the US Department of Transport[12] that the temperatures cited above, and especially the rate of temperature increase, are extremely unlikely to be encountered under normal transport environments. Military explosives have in fact been subjected to temperatures as high as 46 °C, whilst undergoing truck shipment through Death Valley, California, and in excess of 65°C during air travel[12]. However, explosives are characterised by poor heat dissipation. This can lead to thermal decomposition when exposed to prolonged high temperatures and may ultimately cause explosives to ignite.

In transport environments the main threat of explosives initiation from thermal stimuli is that of fire. This statement is supported by historical incidents (see Appendix B), data collected by the US Materiel Command[27] and work carried out in the early 1980's at the Royal Armament Research and Development Establishment (RARDE). The results of this work illustrate that many explosives will initiate and burn to deflagration, and in some cases

detonation, when subjected to engulfing or torch fires similar to those experienced in store and transport accidents. It has been shown by Dyer et al[30] that the time required for the initiation of munitions in pallet fire tests and torch flame tests varies with respect to the type of fire and explosive used. For standard 155 mm shells filled with 11.5 kg of explosive (RDX/TNT or CW3) typical initiation times for pallet fire tests range from 0.6 minutes to approximately 18 minutes. Dyer et al note that shell case temperatures vary from between 370°C (or less) to over 590°C, and that there appears to be no correlation between case temperature and detonation. However, only a minority of the tests actually result in shell detonation. It is thought that case failure, causing loss of confinement, inhibits transition from deflagration to detonation. From this it can be surmised that explosives subjected to vehicular fires are more likely to deflagrate than detonate (especially commercial explosives which are unlikely to be confined). The short duration times from fire inception to initiation recorded by Dyer et al are thought to be a consequence of ignition at metal/explosive interfaces rather than any internal self-heating effect. This suggests that vehicular fires, which are usually of a short duration and similar intensity to that of pallet fire tests, have the potential to cause initiation of explosives. In fact vehicular fires, especially HGV fires, may be fuelled by petroleum or diesel thereby increasing heat intensity and the likelihood of initiation. Physical orientation to heat and flame also has a notable effect on the length of exposure before initiation. For example, the average time for 155 mm shells to initiate when subjected to pallet fires increases substantially from 3.5 minutes when laid horizontally to over 11 minutes when positioned vertically[30]. The reasons for this are thought to result from the greater uniformity and intensity of heat endured by explosives when shells are laid horizontally.

The fundamental causes of vehicle and load fires and their likelihood of occurrence are discussed in Chapters 3.0 and 4.0. Probability of initiation given engulfing vehicle fire is discussed in Chapter 6.0, Section 6.5.2.

Table 6: Ignition temperatures of explosives

Explosive	Ign. temp.[a] (°C)	Min. hot-spot temp. for initiation by Friction (°C)	Impact[b] (°C)
Tetrazene	160		400-430
Mercury fulminate	170		500-550
Tetryl	180		
Nitroguanidine	185		
Nitrocellulose	187		
Nitroglycerine	188	450-480	
PETN	205	400-430	400-430
RDX	213		
TNT	240		
Lead Styphnate	250	430-500	500-550
HMX	300		
Lead azide	350	430-500	500-550

Note:

a. The Royal Military College of Science
b. Impact initiation in the presence of grit.

Source: Bowden and Gurton[18]

5.5 Chemical Instability/Reactivity

Both commercial and military explosives can under certain conditions or over long periods of time decompose to provide a risk of unintended initiation. For example, dynamites containing nitro-glycerine decompose during long storage periods and ultimately become liable to accidental initiation. Also, if such explosives are contaminated with other chemicals, such as, nitric acid, they decompose violently and become unstable.

However, the initiation of explosives by chemical reactivity during transport, either autogenously or by the introduction of external agents, is an extremely unlikely event. All commercial and military explosives are designed and manufactured so that they can be transported and handled without loss of integrity, thus avoiding possible decomposition. In addition, explosives are packaged with compatible materials which protect against internal and external stimuli. It is suggested here, that due to the factors outlined above the possibility of explosive initiation by chemical reactivity in transport environments is highly unlikely.

5.6 Electrical Energy

Explosives can be initiated by electricity if sufficient energy is discharged. All explosives have a specific ignition energy level, above which initiation will occur. Most explosives have ignition energy levels below, for example, the energy released from arcing of electrical equipment. However, initiation is not only dependent upon

the specific electrical properties of the explosive, but also environmental generation, storage and discharge mechanisms.

Electrical energy can take one of three forms,

a. current electricity,
b. electromagnetic radiation,
c. static electricity.

Current electricity is a common means of initiating explosives, especially explosives linked to electric detonators and ignition systems. However, in transport environments current electricity is unlikely to be encountered except in extreme cases where electricity sub-stations are encountered and breached or contact is made with "live" overhead power lines. Similarly, electromagnetic radiation poses a threat of accidental initiation only to those explosives forming electro-explosive devices. Stray radiation waves from transmitters may emit energy levels capable of initiating such devices. Sources of radiation waves stem from radio transmitters to citizen band (CB) frequency amplifiers. However, electro-explosive devices are packaged in anti-induction configurations and materials, thereby effectively eliminating initiation unless (intentionally or unintentionally) package integrity is breached.

The main electrical hazard is that of static electricity. Under certain conditions up to 0.02 J of electro-static energy can accumulate on the human body (although this is extremely uncommon). Such energy is sufficient to initiate certain sensitive explosives. For example, some ether/oxygen and lead styphanate mixtures

have ignition energy levels below 0.05 mJ and even common explosives such as PETN, nitro-cellulose and various cordites have ignition energy levels between 0.015 J and 0.1 J. For transport purposes, with respect to static electricity, explosives can be chiefly divided into those explosives which are liable to initiate below 0.02 J and those which require greater energy input.

Electro-static sensitivity testing of explosives essentially consists of a series of charged capacitors, which can be controlled to discharge electrical energy between 5×10^{-4} J and 5 J. Initiation is either physically observed or verified with the aid of an infra-red analyser to detect decomposition gases, as previously mentioned. Tests performed by Hercules Inc. USA[23], with capacitors charged to 5000 volts, found that TNT and Gel Power A-2 slurry initiate at energy levels of 0.075 J and 1.26 J respectively. However, the Allegancy Ballistics Laboratory[23] (ABL) indicate that possible electro-static discharge paths in normal transport environments are unlikely to discharge sufficient energy levels to cause explosives to initiate. For example, from an isolated conductor, having a surface area of approximately 400 cm^2, ABL found the discharge energy to be less than 0.02 J. Similarly, other tests conducted at the same time could find no sources of energy approaching a level required to cause TNT to initiate.

It should be noted that all the tests performed by ABL were on unpackaged explosives. Packaging would, it is suggested here, often isolate explosives from electro-static discharge, reducing further the small possibility of initiation from such stimuli. In conclusion, under normal transport environments or even in the event of vehicular accidents, the possibility of explosives being initiated by

electro-static discharge is extremely unlikely.

5.7 Conclusions

Accidental initiation of commercial/military explosives is possible in principle from a number of stimuli, namely

a. shock and vibration,
b. impact,
c. friction,
d. fire (thermal energy),
e. chemical instability/reactivity,
f. static electricity (electrical energy).

However, as this chapter illustrates by far the most likely stimuli to cause initiation in transport environments are impact and fire. Initiation by shock/vibration is thought to be unlikely except when accompanied by large impact forces, where it becomes difficult to distinguish between shock/vibration initiation and impact initiation. Similarly, initiation by friction is thought to be unlikely without the presence of large impact forces capable of breaching packages and instigating sliding frictional forces; or large impact forces capable of piercing packages and explosives thereby instigating friction/impact stimuli associated with stab-initiation. The data and arguments presented in this chapter assume that all explosives are transported in a serviceable/perfect condition, or as termed by the Armed Forces in an "A1" condition. Similarly, vehicles are assumed to be in good condition and explosives packaged and designed so as to prevent contact with substances liable to cause decomposition. Thus, initiation as a result of chemical instability/reactivity is considered here to be extremely

unlikely. Explosives are also packaged and designed so as to prevent initiation by electrical stimuli. In transport environments electrical stimuli likely to cause initiation are characterised by energy levels below that necessary to cause initiation. Therefore, initiation as a result of electrical energy is also considered to be extremely unlikely.

Finally, from the discussion given in this chapter it can be concluded that at present explosives sensitivity cannot be quantified in exact units of measure. In-fact collated data only provide a comparative means of assessing explosives sensitivity. More importantly, however, initiation of explosives is not so much dependent on the amount of energy delivered, but rather on its rate of delivery (i.e. energy density, expressed in watts/kg). This latter point has recently been acknowledged and work begun to relate explosives sensitivity to energy density[31]. It is hoped that such an approach will provide an absolute measure of explosives sensitivity regardless of the way in which energy is delivered.

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PART C

6.0 RISK ASSESSMENT METHODOLOGY

Risk assessment provides a means of quantitatively assessing hazards so that objective judgements can be made on their acceptability. The discipline is not only useful in the assessment of incidents which have occurred and therefore have accumulated historical data, but also for incidents which have not occurred but have a certain likelihood, however small, of realisation.

The majority of risk assessment methodologies have been developed for fixed installations whose surrounding and on-site populations are clearly identified[1,2]. Such methodologies are only useful as a guide to the development of methods suitable for the assessment of transport risks. This is because transport environments add a degree of complexity to the risk assessment process. For example, unlike fixed installations, transport incidents have a certain likelihood of occurring at any point along a transport route. This provides an uncertainty of incident location and therefore variability in the numbers of exposed individuals. Similarly, geographical and meteorological conditions change along the route presenting additional assessment considerations with respect to consequences and exposure.

The methodology developed here encompasses a number of features from previous analyses on the transport of hazardous goods[3,4,5] together with the basic methodologies of quantitative risk assessments. The incidents considered are vehicular accidents and/or vehicular fires. Incidents have been quantified by their frequency of occurrence and consequence, and both are used to determine the level of

risk. The list below outlines the basic approach which has been employed as the means of assessing the risks and hazards associated with the transport of explosives by road and rail in Great Britain[6,7].

a. Description of the problem, data collection, requirements and classification.

b. Identification and assessment of accident scenarios.

c. Evaluation of the frequency and consequences of explosion.

d. Sensitivity assessment.

6.1 Problem Description

It is important from the outset to clearly define the transport problem. The problem in the context of this study is the transport by road and/or rail of explosives. A clear and concise definition helps to formulate a coherent strategy when assessing the risks of those exposed to hazards.

Essentially the problem arises from the need to transport explosives from location "A" to location "B". The problem itself results from the requirement to transport these explosives in

a. a safe manner minimising the likelihood of hazard realisation,
b. a manner which conforms to regulations enforceable by law,

c. an economical, viable and profitable manner.

In order to formulate a "problem description" a simple series of questions need to be answered.

1. What is being transported ?
2. How much is being transported ?
3. How often is it being transported ?
4. How is it being transported ?
5. From where and to whom ?
6. What is the hazard ?
7. Who is exposed to the hazard ?

Full and concise answers to these questions ensures that

a. accident rate and explosion rate estimates reflect the transport and accident environments associated with the movement of explosives,

b. the hazard of accidental initiation is known,

c. those exposed to the hazard are identified.

The series of questions (1 to 7 listed above) are addressed below. Each question is in some respects specific to the type of movement or explosives conveyed. As a consequence of this the transport of commercial and military explosives are discussed here in general terms.

6.1.1 What is being transported ?

Commercial and military explosives are essentially substances or articles which can cause harm or damage or both as a result of explosive and/or pyrotechnic effects. The United Nations Committee of Experts[8] on the Transport of Dangerous Goods (UN Committee) define an explosive substance as

> ".... a solid or liquid substance (or a mixture of substances)... capable by chemical reaction of producing gas at such a temperature and pressure and at such a speed as to cause damage to the surroundings".

A pyrotechnic substance is defined as

> ".... a substance or mixture of substances designed to produce an effect by heat, light, sound, gas or smoke or a combination of these as the result of non-detonative self-sustaining exothermic chemical reactions",

and an explosive article is defined as

> ".... an article containing one or more explosive substances".

Such goods are classed by the UN Committee as class 1 dangerous goods and depending on individual substance/article characteristics are assigned an additional "divisional" category. These hazard divisions are detailed in Table 1.

In addition to the adoption of a divisional category class 1 dangerous goods are assigned to one of twelve compatibility groups. (Designated by a letter A through to S, excluding I and M through to R). The purpose of the groups is to ensure that mixing of explosives does not significantly increase either the probability of explosion, or for a given quantity, the magnitude of explosion effects. (Unfortunately the UN Committee do not explain what is meant by a significant increase). As a general rule explosive substances and/or articles can be transported together provided they bear the same compatibility group letter. Where hazard division categories differ the load must be treated as belonging to the division having the smallest number.

Compatibility groups and classification procedures are detailed more fully in two publications issued by the UN Committee[8,9]. For completeness here the compatibility groups are illustrated in Table 2. It should be noted that packaging can greatly affect the hazard associated with explosive substances/articles, and therefore the assignment of a particular division and/or compatibility group. As a consequence of this explosive substances and articles are not always characterised by the same hazard division and compatibility group.

The most commonly conveyed commercial explosives are those based on ammonium nitrate and nitroglycerine. Ammonium nitrate is used in conjunction with fuel oils (to give the common explosive ANFO) or water to produce typical blasting explosives used extensively by the mining and quarrying industries. Solid mixtures are manufactured by the crystallisation of ammonium nitrate and the addition of sensitisers, such as, nitroglycerine (NG) and trinitrotoluene (TNT). Nitroglycerine is so sensitive that

it is used mainly as an additive in solid or semi-solid (gelatines) explosives. However, one explosive whose only active ingredient is NG is commonly known as dynamite. This explosive is basically a solid stick of siliceous earth impregnated with NG by the process of adsorption. Other popular NG explosives are those containing nitrocellulose, such as plastic gelatines. These explosives are popular because they can be easily shaped, they provide high bulk strength and are resistant to the effects of water. Resistance to water is an important characteristic for explosives based on NG. Water contamination of NG explosives can give rise to hydrolysis, and hence the precipitation of nitrates and nitric acid causing spontaneous decomposition. Other commercial explosives are those based on TNT and pentaerythritol tetranitrate (PETN). Although more sensitive than ammonium nitrate based explosives they are not as sensitive as NG based explosives. In terms of manufactured quantity, TNT and PETN based explosives account for only a small proportion of all commercial explosives.

Military explosives mainly consist of mixtures of TNT and cyclotrimethylenetrinitramine (RDX), and TNT and cyclotetramethylenetetranitramine (HMX), together with additional binders and sensitisers. Such mixtures tend to form the bulk of shell and warhead fillings.

TNT is manufactured by the nitration of pure toluene and is surprisingly of low toxicity. Once produced it is relatively safe to handle and can be readily mixed with other explosives. However, TNT is oxygen deficient and for complete combustion requires mixing with oxygen rich substances, such as ammonium nitrate. These explosive compounds are commonly known as "amatols". RDX and HMX are produced by the nitration of hexamine solutions and are

considered to be very stable both chemically and thermally[10]. However, they are extremely sensitive to impact and friction and are usually desensitised by mixing with wax. RDX is also mixed with mineral jellies or similar materials to form plastic explosives. Other common military explosives include PETN and tetryl. PETN is very sensitive to both impact and friction and like RDX and HMX is considered chemically and thermally stable[10]. Its use is mainly in the form of pentolite, which is a mixture of PETN and TNT. Mixed with plasticised nitrocellulose or synthetic rubbers PETN is also used as a plastic explosive. Tetryl is considered to be moderately sensitive to friction and shock. As a consequence of this it is commonly used in priming devices initiated by friction or percussion.

Explosives used in priming devices, which find not only military but also commercial application, include mercury fulminate, lead azide, lead styphnate and tetrazene. For reasons of storage and initiating power lead azide is a popular initiating explosive. However, it has two drawbacks, firstly, in moist conditions it tends to be chemically unstable and secondly it is relatively insensitive to flame initiation[10]. The addition of gelatine and/or lead styphnate improves the sensitivity of lead azide to flame impingement and therefore its application in electric and delay initiating devices which are ignited by "spark". Mercury fulminate and tetrazene are fast losing popularity as a result of chemical instability and poor initiating power respectively.

Rapid and controllable combustion producing large volumes of hot gas as a means of propulsion is the necessary function of propellants. Such controlled deflagration is the means by which cartridges and rockets are propelled through space. Although propellants are based

on explosive compounds they are not intended to cause detonative explosion or damage to surroundings. Propellants are classed as either single-base, double-base or triple-base and can be powder, solid block or liquid. Single-based propellants only contain one explosive ingredient, this being nitrocellulose. Double-based propellants contain two explosive ingredients, nitroglycerine and nitrocellulose, whereas triple-based propellants also contain nitroguanidine. In addition to these ingredients propellants contain various plasticisers, burning rate moderators, lubricants and flash inhibitors, the compositions of which vary depending on application. As a result of the need for long storage periods propellants have good chemical stability. Storage life is commonly between eight and ten years. The greatest thrust is provided by triple-based propellants and as a consequence of this they find application in rockets and large guns. Triple-based propellants are difficult to ignite compared with single-based and double-based propellants, hence they tend not to be used in small arms ammunition. A disadvantage of double-based propellants is their incompatibility with certain plastics[10]. As a consequence of this and the apparent geometric characteristics and needs of weapon systems both double-based and single-based propellants are used extensively in small and medium sized munitions/weapons.

In conclusion typical loads conveyed by road or rail may simply consist of single explosive substances or a combination of "compatible" explosives. Loads such as these form the bulk of commercial movements. In comparison, military movements consist mainly of loads containing explosive articles. Additional hazards may be presented by explosive articles which contain priming devices (i.e. fuses and detonators, etc.) and "boosters" (i.e. explosive charges with or without means of initiation used to

increase the initiating power of detonators). As a consequence of this a significant hazard may be presented by the priming device or booster in addition to, or instead of the main explosive charge (where the main explosive is unlikely to initiate). In addition, the likelihood of accidental main charge initiation may increase due to the greater likelihood of priming device and/or booster initiation. However, it should be noted that most explosive articles have independent protective features designed to prevent main charge initiation in the event of accidental operation and/or initiation of priming devices and boosters.

Table 1: Class 1 explosives: Hazard divisions

Division	Consequence description
1.1	Substances and articles which have a mass explosion hazard (a mass explosion hazard is one which affects the entire load virtually instantaneously).
1.2	Substances and articles which have a projection hazard but not a mass explosion hazard.
1.3	Substances and articles which have a fire hazard and either a minor blast hazard or a minor projection hazard or both but not a mass explosion hazard. This division comprises substances and articles which a. give rise to considerable radiant heat, b. burn one after another, producing minor blast or projection effects or both.
1.4	Substances and articles that present no significant hazard. This division comprises substances and articles which present only a small hazard in the event of ignition or initiation during transport. The effects are largely confined to the package and no projection of fragments of appreciable size or range is to be expected.

Table 1: continued

Division	Consequence description
1.5	Very insensitive substances which have a mass explosion hazard. This division comprises a. substances which have a mass explosion hazard but are so insensitive that there is very little probability of initiation or of transition from burning to detonation under normal conditions of transport, b. articles which contain only extremely insensitive detonating substances and which demonstrate a negligible probability of accidental initiation or propagation.

Source: UN Committee[8]

Table 2: Classification codes (Compatibility groups)

Description of substance or article to be classified	Comp. group	Class. code
Primary explosive substance	A	1.1A
Article containing a primary explosive substance and not containing two or more protective features	B	1.1B 1.2B 1.4B
Propellant explosive substance or other deflagrating explosive substance or article containing such explosive substance	C	1.1C 1.2C 1.3C 1.4C
Secondary detonating explosive substance or black powder or article containing a secondary detonating explosive substance, in each case without means of initiation and without a propelling charge, or article containing a primary explosive substance and containing two or more effective protective features	D	1.1D 1.2D 1.4D 1.5D
Article containing a secondary detonating explosive substance, without means of initiation, with a propelling charge ((other than one containing a flammable or hypergolic liquid)	E	1.1E 1.2E 1.4E

Table 2: continued

Description of substance or article to be classified	Comp. group	Class. code
Article containing a secondary detonating explosive substance with its own means of initiation, with a propelling charge (other than one containing a flammable or hypergolic liquid) or without a propelling charge	F	1.1F 1.2F 1.3F 1.4F
Pyrotechnic substance, or article containing a pyrotechnic substance, or article containing both an explosive substance and an illuminating, incendiary, lachrymatory or smoke-producing substance (other than a water-activated article or one containing white phosphorus, phosphide or a flammable liquid or gel)	G	1.1G 1.2G 1.3G 1.4G
Article containing both an explosive substance and white phosphorus	H	1.2H 1.3H
Article containing both an explosive substance and a flammable liquid or gel	J	1.1J 1.2J 1.3J
Article containing both an explosive substance and a toxic chemical agent	K	1.2K 1.3K
Explosive substance or article containing an explosive substance and presenting a special risk needing isolation of each type	L	1.1L 1.2L 1.3L

Table 2: continued

Description of substance or article to be classified	Comp. group	Class. code
Substance or article so packed or designed that any hazardous effects arising from accidental functioning are confined within the package unless the package has been degraded by fire, in which case all blast or projection effects are limited to the extent that they do not significantly hinder or prohibit fire fighting or other emergency response efforts in the immediate vicinity of the package	S	1.4S

Note:

a. Comp. - compatibility.
b. Class. - classification.
c. The term primary explosive refers here to initiating explosives (i.e. those explosives which readily ignite or detonate as a result of small mechanical or electrical stimulus - those explosives commonly found in priming devices).
d. The term secondary explosive refers to those explosives which can be made to detonate and are used to produce work on their surroundings (i.e. those explosives which are used as blasting agents and/or used as the main explosive in articles - sometimes termed high explosives).

Source: UN Committee[8]

6.1.2 How much is being transported ?

It is not known with any certainty the total quantity of commercial and military explosives transported annually either by road or rail. Such details are confidential and not for public knowledge. However, from personal contacts[11] it is thought that between 33,000 te and 37,000 te (NEQ - i.e. net weight of explosives excluding casings and packaging, etc.) of commercial explosives are transported annually in the UK. Most commercial explosives movements[11,12] are known to be by road, it is estimated that the proportion conveyed by rail is probably less than 10%. In comparison, it is thought that about 60% of military explosives (NEQ) go by rail and 40% by road[13].

6.1.3 How often is it being transported ?

From discussions[11,12] with those involved in the manufacture and distribution of explosives, it is estimated that commercial explosives, which are mainly transported by road, are conveyed over three to four million kilometres per year. Explosives movements by road are chiefly divided into primary and secondary movements. Primary refers to movements from manufacturing plants to depots and secondary refers to movements between depots and depots, and depots and customers. It is known that secondary movements account for over 60% of annual travel distance and that about 35% of the total distance covered involves empty journeys[11,12]. In comparison, it is estimated that military explosives are annually conveyed over one to two million kilometres and that between 60% and 75% of this distance is covered by road.

6.1.4 How is it being transported ?

Subject to quantity limits explosives can be conveyed by road in four different ways (termed modes).

a. In a vehicle being used to carry passengers for hire or reward.
b. In a private motor car and any other method of conveyance which does not fall under any other mode.
c. In a goods vehicle with basic safety precautions.
d. In a goods vehicle with additional safety precautions.

The majority of explosives moved by road are conveyed in dedicated heavy goods vehicles (HGVs) which comply with the Conveyance of Explosives by Road Regulations 1989 (i.e. modes "c" and "d" listed above). The net explosives quantity (NEQ) for dedicated HGVs is 5 te or 16 te for special vehicles. Special vehicles are those vehicles which have additional fire protection and convey explosives in freight containers. Although the limit for special vehicles is set at 16 te (NEQ) in reality this is never achieved. This is due to the requirement for gross vehicle weight not to exceed 90% of a vehicles "plated weight". All HGVs conform to the following requirements.

a. Engine fuels do not give off flammable vapours at temperatures less than 150°F.
b. Fuel feed pipes are fitted with quick acting "cut-off" valves.
c. A clear gap of at least six inches exists between HGV cab and the body of the vehicle.

d. Fire resistant screen (carried to within twelve inches of the ground) protects HGV body from exhaust system.
e. HGV body (including cargo floor area) is completely covered externally with sheet steel.
f. Cargo floor is lined with asbestos or wood treated to render it flame retardant.
g. Load area does not open except at the rear or as approved by HM Inspectorate of Explosives.

It has been found in the course of this study that often additional safety measures are taken by road hauliers. Pennine Transport[11] who convey explosives for Explosives and Chemical Products Limited (ECP) insist on the following additional requirements.

a. An electrical isolation switch.
b. Vehicle body constructed of high strength aluminium mounted on the chassis in a slightly forward position (so that in the event of a rear collision the majority of impact energy is absorbed by the chassis).
c. Anti-lock braking systems to prevent "jack-knifing" of articulated vehicles.

Although military movements of explosives by road are exempt from the Conveyance of Explosives by Road Regulations 1989, it is understood that wherever practicable military movements are to abide by the regulations.

Typical HGVs used for the conveyance of commercial and military explosives are illustrated in Appendix C.

Explosives are conveyed by rail in dedicated single-destination rail wagons. Single-destination implies that explosives are not off-loaded en route. Commercial movements are limited to 36.25 te total weight (NEQ, plus casings and packaging) per train, whereas military movements, specified as British Rail (BR) class 1.1 goods (equivalent to UN hazard division 1.1) are limited to 40 te (NEQ) per train. There are no limits imposed on military explosives specified by BR as class 1.2, 1.3 or 1.4 (equivalent to UN hazard divisions 1.2, 1.3 and 1.4). Mixed consignments of commercial and military explosives must not exceed 36.25 te total weight (NEQ, plus casings and packaging).

Rail wagons used for the conveyance of explosives are dedicated wagons constructed mainly of wood and steel, although in recent years aluminium has been used. The most popular wagon for conveying commercial explosives is a 2-axle air-braked wagon having a carrying capacity of 29.5 te and unladen weight of 16.6 te. Military explosives are also conveyed in these wagons. Other common wagons used for military movements include

a. 2-axle, air-braked, 29 te capacity wagons constructed of aluminium and steel (wooden floor - unladen weight 17 te),
b. short wheel base, 2-axle, air-braked, 12 te capacity wagons constructed mainly of wood (unladen weight 7.7 te).

The short wheel based wagons are only used on long-established sidings and depots having sharp track curvatures.

All rail wagons used for the conveyance of explosives conform to the following basic requirements[14,15].

a. Wagon body and floor free from dents (greater than 19 mm), distortion and excessive deterioration (holes, etc.) caused by oxidation or other deleterious effects.
b. Interior is free from protrusions (except those forming part of the wagon).
c. Roof is secure (water-tight) and free from cracks.
d. Floor is free from cracks and protrusions.
e. Where necessary spark-guards are fitted to braking systems.
f. Electrical wiring is securely fixed and protected against moisture and mechanical damage.
g. Lighting is only by means of incandescent electric bulbs protected from moisture and mechanical damage.

Typical rail wagons used for the conveyance of commercial and military explosives are illustrated in Appendix C.

Explosives themselves (including articles) are packaged or palletised depending on their geometry, use and storage requirements. Above all other considerations, however, explosives which are transported on public roads and railways must be packaged and stowed in such a manner as not to increase risks to health and safety[16]. Typical packages for commercial explosives consist of simple fibre-board and secure metal boxes. Military explosives are packaged in a similar fashion, although palletisation is much more common. Typical palletised loads consist of shells, missiles and bar mines. Once loaded into either road vehicles or rail wagons packages and pallets (commercial and military) are secured by tie ropes and/or "packing" (wooden posts/strips, etc.) to prevent movement

under normal transport environments.

6.1.5 From where and to whom ?

Explosives are conveyed throughout the year supplying mining and related industries, firework manufactures, royal ordnance factories (ROF) and the Armed Forces. The majority of commercial movements are between storage depots and customers. As mentioned in Section 6.1.3, such movements are known as secondary movements by commercial road hauliers. The vehicles used for secondary road movements are usually 5 te (NEQ) capacity dedicated rigid 2-axle HGVs. Primary movements essentially consist of movements between explosive manufactures and storage depots. These movements are most commonly performed by special vehicles using freight containers of 16 te (NEQ) capacity (see Section 6.1.4). In comparison, military movements are not classed as either primary or secondary. Movements include travel between army depots, ammunition storage facilities, naval ports, airfields, ROF, armed units, manufacturers, testing ranges, refurbishment establishments and disposal sites. The vehicles used for these movements include dedicated rail wagons, dedicated rigid 2-axle HGVs and special HGVs. Vehicle characteristics for both commercial and military movements are discussed in Section 6.1.4 and illustrated in Appendix C.

6.1.6 What is the hazard ?

By virtue of motion and/or physical presence both road and rail transport are hazardous activities. This is because both road and rail transport have the capacity to cause harm and damage. Explosives by their very nature are hazardous. Explosives are designed and manufactured to perform work on their surroundings either by exerting pressure, causing fragmentation and missile generation and/or thermal radiation. Thus, the transport of explosives provides a physical situation which has the potential to cause human injury, property damage and environmental damage.

6.1.7 Who is exposed to the hazard ?

Regardless of whether explosives are transported by road or rail at various times throughout a journey it is almost certain that members of the public are exposed to the hazard. This is because it is impractical if not impossible to avoid certain built-up areas. Wherever practicable built-up areas are avoided. However, residences along roadsides, communities surrounding depots, factories, rail stations, rail terminals and marshalling yards all have either "static" or "mobile" populations (or both in varying quantities). Populations referred to as "static" are those in and around permanent places of residence and/or work and those referred to as "mobile" are those populations in and around rail stations and other places where population size can vary from a few to hundreds or even thousands. In addition to members of the public, transport crews are also highly likely to be exposed and in certain circumstances (such as fire) personnel from the emergency services

(police, fire and ambulance) are also vulnerable to exposure. Determination of those exposed and the number of exposed individuals is detailed in Section 7.4.

6.2 Data Collection - Data Sources

There is an abundance of information and statistics on road and rail transport. Data sources stem from government departments through to learned institutions. However, the methods of collecting and recording data tend to vary. As a consequence of this identical information is often interpreted differently. For example, the Department of Transport classify a goods vehicle as a heavy goods vehicle (HGV) if its unladen weight is greater than, or equal to, 1.5 te. In comparison, the Transport and Road Research Laboratory (TRRL) in certain reports have classed goods vehicles as HGVs if their unladen weights are in excess of 3 te. Such variation in data representation is important to note when using statistics, otherwise erroneous mixing of supposingly similar data may occur.

The data sources listed below have either been used or referred to in compiling the transport and accident data contained within this study. It is suggested that where possible all data should be cross-checked for integrity by consulting and comparing with independent/other sources. The list given below consists of data sources most likely to provide information suitable for use in the assessment of road and rail transient hazards.

1. Governmental Departments and Related Organisations

a. Central Statistical Office, (Directorate of Statistics), 2 Marsham Street, London.
b. Department of Transport (Railway Inspectorate), 2 Marsham Street, London.
c. Explosives Storage and Transport Committee (ESTC), St. Mary Cray, Orpington, Kent.
d. Explosives Inspectorate, Health and Safety Executive, Magdalen House, Bootle, Liverpool.
e. United Kingdom Atomic Energy Authority (Safety and Reliability Directorate), Culcheth, Warrington.

2. Learned Institutions and Similar Organisations

a. Accident Research Unit (Department of Transportation and Environmental Planning, University of Birmingham)
b. Institution of Chemical Engineers, Railway Terrace, Rugby.
c. Institution of Explosive Engineers, Epic House, Charles Street, Leicester.
d. Institution of Mechanical Engineers, Birdcage Walk, London.
e. Plant Engineering Group, University of Technology, Loughborough, Leicestershire.
f. Motor Industry Research Association (MIRA), Watling Street, Nuneaton, Warwickshire.
g. National Transportation Research Board, Washington DC, USA.
h. Transport and Road Research Laboratory (TRRL), Crowthorne, Berkshire.

3. Miscellaneous

a. British Rail, Director of Operations, Paddington Station, London.
b. Explosives and Chemical Products Limited, Commonwealth House, New Oxford Street, London.
c. Freight Transport Association, Hermes House, St. Johns Road, Tunbridge Wells, Kent.
d. Imperial Chemical Industries (ICI), Nobel's Explosives Co. Limited, Nobel House, Stevenston, Aryshire.
e. London Fire and Civil Defence Authority, Albert Embankment, London.
f. Pennine Transport, Alfreton, Derbyshire.
g. Road Haulage Association, New Kings Road, London.
h. United Kingdom Petroleum Industries Association, Kingsway, London.

6.3 Basic Data Requirements

The first requirement in the assessment of transient hazards is the determination of the number of historical accidents/incidents which have occurred during transit over a measurable period. This can then be compared with the total distance travelled during this period, thereby providing the rate of historical accidents/incidents per measured period, and the rate of accidents/incidents per unit distance during this period. Determination of the number of movements/journeys per period, the number of vehicles used and identification of vehicle types is required so as to ensure that accident/incident rates are fleet related. It should be noted that the number of journeys and overall distance travelled is required in a form by which the final risk is to be measured. Commonly

such data are expressed as a total per year or per month. However, it may be required to express the risk as a function of, for example, the number of vehicles. In such cases data are needed in the form of miles travelled per "N" vehicles (where "N" is a pre-set number used as the standard of measure). Depending upon consequence model complexity, required assessment accuracy and more often than not availability of data, the average number of journeys and average distance travelled per measured period or per vehicle may be sufficient.

So as to calculate the individual risk of those involved in actual transport operations the number of journeys undertaken by crew members is required. However, unless a detailed account of individual risk for each crew member is needed it is suggested that a mean estimate for all crew members is sufficient. In order to determine incident consequences data are required on the number of vehicles per movement (i.e. road convoys, rail cars), vehicle weights (laden/unladen), load types and load distributions. In most instances it may well be impractical to assess each vehicle/journey individually and mean values are best employed. Explosives packaging and means of securement (in load area) may affect the hazard or its likelihood of realisation. As a consequence of this packaging and securement details need to be considered. Finally, details are required on the physical and chemical properties of the explosives conveyed. The data are used as input into consequence models and also as a means of assessing the likelihood of explosive initiation resulting from stimuli encountered during normal transport and accident environments.

Table 3: Summary of basic data requirements

Number of historical accidents/incidents
Distance travelled
Number of movements/journeys
Number of vehicles used
Vehicle description/specification (type)
Number of journeys undertaken by crew
Number of vehicles per movement
Vehicle weights (unladen/laden)
Type of load conveyed
Distribution of load(s)
Packaging and securement of load(s)
Physical and chemical properties of load

6.4 Classification of Data

6.4.1 Vehicle Classification

Initially vehicles under analysis need to be classified so as to provide a starting point for the determination of vehicle accident rates. Heavy goods vehicles (HGVs) can be classified by both body type and axle configuration, as shown in Table 4. If required, these classes can be further sub-divided into "makes" of vehicle. However, for all intents and purposes this is unnecessary, regardless of manufactured origin most HGVs having the same body type and axle configuration are similar in all respects.

If it is intended to assess a fleet of HGVs whose body and axle configurations differ greatly then the best accident rate estimation will be gained from assessing HGVs individually. However, if the fleet is large individual assessment may prove time consuming and impractical. In such cases it may suffice to classify HGVs in grouped sets. For example, ignoring axle configuration HGVs may be classed as simply "rigid" or "articulated". Classification of HGVs can also be based solely on axle configuration or load capacity. However, in order to obtain good estimates of HGV accident rates it is best to classify HGVs on two or more criteria. If this is not possible generalisation of the whole fleet (or part of) may have to be adopted. This suggests that the accident rate used is the same for all HGVs in the fleet (or part of). It should be noted that accident rates vary considerably between HGV types (see Section 3.6, Table F). For example, it has been found in the course of this study that on non built-up class A roads 3-axle HGVs have an accident rate twice that of 2-axle HGVs. Thus, careful judgement is needed when classifying vehicles, since poor "grouping" and/or approximations at

this stage may culminate in unrepresentative accident rates and ultimately unmeaningful risk assessment results.

For rail transport, classification of accident rates can take either of two forms, namely, classification by locomotive type (e.g. diesel multiple unit (DMU) or electric multiple unit (EMU)) or by rail wagon. As with HGVs, locomotives and rail wagons can be sub-divided further by weight, load capacity and bogie type, etc.. Locomotives are best classed as either diesel or electric. This is because there are insufficient data for further categorisation. However, further distinction may prove useful where data suggest that certain locomotive types are more susceptible to particular accidents/fires than other locomotives. For example, before rectification in the early 1980's, class 47 diesel multiple units were prone to oil leaks causing these locomotives to form a large proportion of all locomotive fires on British railways[17]. Obviously, if it is clear that certain locomotives are more accident prone than others this fact should be catered for and reflected in the assigned freight train (FT) accident rate. It should be noted, however, that the author has found few identifiable trends linking specific locomotives with certain accident types. Rail wagon classification may take many forms, from differing load size through to the type of bogie employed. However, it is suggested here that due to limited accident and transport data on individual rail wagons, classification for accident rate purposes is best left with locomotive type. Further distinction with respect to rail wagons can be included when addressing the consequences of rail accidents (i.e. the likelihood of puncture, weight of wagon, load capacity, geometry and buffer protection, etc.).

Table 4: Classification of heavy goods vehicles

Rigid	Articulated
2-axle	3-axle
3-axle	4-axle
4-axle+	5-axle+

Note:

a. axle+ - number of axles or more.

6.4.2 Route Classification

Identifying and categorising the routes taken by vehicles is an important step towards refining accident rates. Accident rates vary widely with respect to rural and urban areas. For HGVs rural and urban areas can be sub-divided further into categories based on road class, as shown in Table 5.

Simply, the routes taken by HGVs are divided into the parts shown in Table 5 together with specific distances attributed to each part. Current data sources class roads as either built-up or non built-up. Built-up roads have speed limits of 40 mph or less whereas non built-up roads have speed limits in excess of 40 mph. Built-up and non built-up road notation has replaced built-up and non built-up area notation used previously by the Department of Transport. The main reason for the change in classification results from the difficulty in correctly identifying built-up and non built-up areas. However, built-up and non built-up roads chiefly correspond to built-up and non built-up areas (i.e. urban and rural areas respectively).

Similarly, FT accident rates can be sub-divided further into urban and rural classes. Accident rates not only vary with population alongside railway track, but also with population distribution. Freight train accident rates can be determined for single sided track (i.e. population only on one side of track) and double sided track (i.e. population on both sides of track). However, it is suggested here that such distinction is best dealt with when considering incident consequences. This is because most consequence models can readily adapt to varying population density and the distance of exposed populations

from hazard sources.

For completeness the meteorological and geographical conditions alongside transport routes should be considered. Meteorological data requirements usually pertain to conditions which may affect explosion consequences or accident frequencies. For example, a greater number of accidents may occur at locations where rainfall is particularly heavy or where visibility is poor due to frequent bouts of persistent fog. Similarly, it is known that atmospheric conditions can affect blast overpressure. In the far field Lees[18] describes the increase in overpressure resulting from surface temperature inversion conditions. However, in most explosives consequence models meteorological data are not required. This is because common weather conditions have little or no influence on explosion consequences (especially in the near field).

The collection of geographical data is primarily concerned with the strength and type of rock/material upon which vehicles travel and/or may contact accidentally. Such data are used to assess the initiation vulnerability of explosives upon impact with naturally occurring and/or man-made materials. Data may also be required on the physical characteristics of vehicle routes with respect to gradients, embankments, rivers and bridges, etc. together with meteorological conditions, in order to identify

a. areas where accidents are most likely to occur and/or are most likely to cause incidents,
b. conditions which may affect explosion consequences.

It should be noted that in the main both meteorological and geographical data are used at the consequence analysis stage and need not always be reflected in accident rates.

Important note

Provided there is sufficient data detailed vehicle and route classifications should be used. However, care should be taken to avoid over-classification so as to eliminate obviously ludicrous and unrepresentative categories.

Unfortunately, data are often scarce and it may prove impractical to follow detailed vehicle and route classifications. If only generalised data are available then data are best combined to form a single classification. For example, where data do not discriminate between vehicle types, or data on certain vehicle types are limited, then an all engrossing or combined classification is best used. This will ensure that a risk assessment is representative of a complete fleet of vehicles (collective representation) even though it will not represent any specific class of vehicle. This point is illustrated by reference to HGV accident rates. The accident rate of a rigid 3-axle HGV on a class A road designated as being non built-up is over twice that of an articulated 4-axle HGV over identical road, the rates being 0.74×10^{-6} and 0.33×10^{-6} accidents per km respectively. This compares with the "all HGVs" accident rate of 0.66×10^{-6} accidents per km. A similar example could also be portrayed for FT accidents.

Table 5: Route classification of highways

Urban	Rural
A roads	A roads
B roads	B roads
motorways	motorways
other roads	other roads

Note:

a. Unless data are specific motorways are best classed as rural. This is because most available data tend to class motorways as rural regardless of individual accident locations.
b. Roads designated as "other" refer to minor roads and roads which are unclassified.

6.5 Incident Sequence Identification and Quantification

Regardless of the quality and mass of collated accident data it cannot by itself provide a means of identifying incidents. The series of events leading to an incident and hence explosion require detailed analysis of accident types, accident consequences and the stimuli liable to cause explosives to initiate. With respect to incident analysis, accident types have been well documented in Chapters 3.0 and 4.0 and provide a strong base for accident categorisation. Similarly, stimuli liable to cause initiation of explosives have been chiefly identified as impact and fire, and therefore aid the direction of consequence analysis. As a result of the two main initiation stimuli, impact and fire, it is suggested that analysis is best divided into those incidents associated with fire and those incidents where fire is absent (i.e. fire incidents and non-fire incidents).

6.5.1 Non-Fire Incidents

Explosives vary considerably in their vulnerability to impact initiation. As Chapter 5.0, Section 5.2 outlines, quantifying explosives impact sensitivity is far from an exact science. Not only is it difficult to provide a measure of sensitivity which is meaningful, but explosives suffer from initiation variability. This variability may manifest itself in one of two ways. Relative ranking of explosives may differ depending on the conditions of the test (environmental and physical) or more commonly on the type of test used. Such cause of initiation variability may produce results which contradict previously recorded results. Secondly, an identical explosive tested under

identical conditions may provide very different results from that expected. This type of variability is hard to measure and explain satisfactorily. On occasion it has been known for impact speed test results[19] to differ by as much as 60% (recorded impact initiation speed).

One impact sensitivity test which appears to have some relevance regarding the assessment of vehicular impacts is the "Susan" test[19]. The test was initially developed to ascertain whether impact from aircraft crashes could cause conventional explosives, within nuclear devices, to explode. Basically, the test consists of a projectile loaded with explosive which is propelled at high speed into an unyielding surface. Results from the test are recorded in terms of impact speed (m/s) and therefore can be related to vehicular impacts. However, as with all sensitivity tests it suffers from initiation variability of explosives and its results contradict many established relative ranking lists. For example, some military explosives composed of ammonium perchlorate, aluminium and active binders are classed as very sensitive when compared on the Susan scale (relative ranking list) but insensitive when compared on certain gap test scales[19]. The least sensitive explosives measured by the Susan test tend to be those based on TNT, these have impact initiation speeds well in excess of 100 m/s. Those explosives of moderate sensitivity are in the main mixtures of RDX and TNT, which have impact initiation speeds between approximately 80 m/s and 150 m/s. The most sensitive explosives are those composed of, or containing, HMX/nitrocellulose, RDX/nitrocellulose and HMX/RDX. Some of these explosives have impact initiation speeds as low as 15 m/s.

To cause initiation of munitions and/or commercial explosives it can be argued that a greater impact speed is required in vehicular collisions than that required in Susan tests. This is because during transit many munitions and commercial explosives are encased and/or packaged providing some protection from impact. Furthermore, in many vehicular collisions the vehicle itself will offer protection (i.e. absorption of impact as a result of construction and vehicular materials etc.). These features provide mitigation against impact initiation. However, the degree of protection is difficult to assess. Its estimation would require Susan tests to be performed on packaged/cased explosives together with tests on the behaviour of loads in road vehicles/rail wagons during collisions. As a consequence of this it is acknowledged here that the use of Susan test data to assess the impact initiation vulnerability of explosives in vehicular collisions will tend to over-estimate explosives sensitivity to vehicular collisions.

Impact initiation of explosives as a result of vehicular collisions is largely dependent on speed and weight. Accidents which have the potential to cause impact initiation can be estimated through the application of momentum theory. Although momentum theory is rather simplistic and can only consider idealised impacts it provides a means of quantifying incidents in terms of impact speed which can be compared with Susan impact test data. A number of simplifying assumptions are necessary in order that vehicular collisions can be treated as idealised collisions, these assumptions are listed below.

1. Vehicles act as idealised masses (i.e. mass is evenly distributed).

2. Explosives form part of the conveying vehicle's idealised mass and therefore the change in velocity of the explosives is the same as the change in velocity of the conveying vehicle.

3. Vehicles do not overturn during or after collision (for road vehicles 95% of overturning occurs in single vehicle accidents[20]).

4. Collisions are inelastic (see note).

5. Vehicle rotation has negligible effect on impact velocity and therefore can be ignored[20].

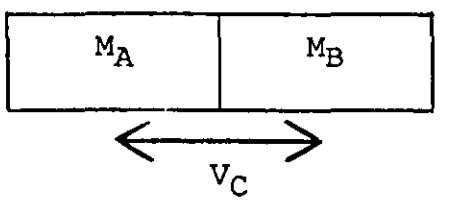
6. Vehicles remain in contact upon impact (full surface contact is assumed).

Note:

As regards assumption 4; in practice all collisions experience "rebound" (i.e. masses collide and part with a certain rebound velocity). However, the mild steels of which vehicles are made are such good energy absorbers (about 95% absorption[20]) that rebound is minimised and therefore collisions between vehicles are almost inelastic.

Consider an idealised head-on collision between a rigid 2-axle HGV (M_A) loaded with explosives and an articulated 5-axle HGV (M_B). The impact speed and laden weight of M_A and M_B are 50 mph and 75 mph, and 13 te and 32 te respectively. The explosives carried by M_A are vulnerable to impact initiation at speeds of 35 m/s or more.

Pre-Impact



Impact

Applying momentum theory

$$V_C = \frac{M_A V_A + M_B V_B}{(M_A + M_B)} \quad \ldots\ldots\ldots\ldots 1$$

where

M_A = mass of A (13 te)
M_B = mass of B (32 te)
V_A = velocity of A (22.35 m/s)
V_B = velocity of B (33.52 m/s)
V_C = velocity of both A and B after impact

Substituting for M_A, V_A and M_B, V_B in (1)

V_C = (-) 17.4 m/s

Assuming part of the explosives load breaks from its restraint during initial collision then the idealised impact speed, U, on the part is given by

$U = V_A - V_C$ 2

Substituting for V_A and V_C in (2)

U = 39.8 m/s

Thus, it is conceivable that a part of the explosives load may be subjected to an impact speed above the minimum required to cause initiation (i.e. 35 m/s). Therefore, it is suggested that such a collision has the potential to cause impact initiation of explosives.

Using the momentum balance above it is possible to determine the minimum closing speed required to cause impact initiation.

Substituting for M_A and M_B in (1)

$V_c = 0.29V_A + 0.71V_B$

Substituting for V_c in (2)

$U = 0.71(V_A - V_B)$ 3

minimum impact initiation speed = 35 m/s
substituting 35 m/s for U in (3)

$V_A - V_B = 49.3$ m/s = 110 mph

Thus, in this instance a closing speed of 110 mph is estimated as the minimum closing speed required to cause possible impact initiation of the explosives.

The probability that collisions occur at certain closing speeds can be estimated through data collected on vehicular impacts. For example, impact speed distributions can be modelled from impact data, such as that given in Section 3.2. Combining impact speed distributions provides a means of estimating closing speeds for vehicular accidents. The combination of two separate impact speed distributions provides a combined impact speed distribution for specific collisions between those vehicles represented by the data.

i.e.

$$f(x_3) = f(x_1) + f(x_2)$$

where

$f(x_1)$ = impact speed distribution (vehicle 1)
$f(x_2)$ = impact speed distribution (vehicle 2)
$f(x_3)$ = combined impact speed distribution (closing speed) for impacts between vehicle 1 and vehicle 2

From the combined distribution, the probability, P, that a certain proportion of impacts, X, occur at closing speeds between x_a and x_b (for normally distributed data) is given by

$$P[(x_1) < X < (x_2)]$$

$$= P\left[\frac{(x_1 - \bar{x})}{\sigma} < Z < \frac{(x_2 - \bar{x})}{\sigma}\right]$$

$$= P[(a) < Z < (b)]$$
$$= I(a) - I(b)$$
$$= P$$

Values I(a) and I(b) are obtained from standard normal mathematical tables[21].

For the example given here, the probability that a head-on collision between a rigid 2-axle HGV and an articulated 5-axle HGV, occurs at a closing speed of 110 mph or more can be estimated from the impact speed data given in Section 3.2. Assuming that the collision occurs on a built-up road and that the data given in Section 3.2, Table 5 is applicable for all collision types and all HGVs then

$$f(x_c) = f(x) + f(x)$$

where

$f(x_c)$ = combined impact speed distribution for all impacts between HGVs

$f(x)$ = impact speed distribution for all HGVs

Thus

$$\bar{x}_c = \bar{x} + \bar{x}$$
$$= 2\bar{x}$$

$$\sigma_c^2 = \sigma^2 + \sigma^2$$
$$= 2\sigma^2$$

$$\sigma_c = \sqrt{2}\,\sigma$$

From the above, and using the data given in Section 3.2

$$\bar{x}_c = 2(30.6)$$
$$= 61.2 \text{ mph}$$

$$\sigma_c = 2(12.2)$$
$$= 17.3 \text{ mph}$$

Using the usual formula the combined impact speed data can be represented by a normal distribution (see Chapter 3, Figure 1). For the HGV collision considered here the probability that it occurs at 110 mph or more is calculated below as 2.3×10^{-3} (assuming a maximum obtainable combined impact speed of no more than 130 mph).

i.e.

$$P[(110) < X < (130)]$$

$$= P\left[\frac{(110 - 61.2)}{17.3} < Z < \frac{(130 - 61.2)}{17.3}\right]$$

$$= P[(2.82) < Z < (3.98)]$$
$$= I(3.98) - I(2.82)$$
$$= 0.9999 - 0.9976$$
$$= 2.3 \times 10^{-3}$$

A similar approach to that given above can be used to quantify train collisions, and hence relate impact speeds to Susan test data. However, unlike road vehicle collisions where the load is contained within the impacted vehicle (enabling load impact speed estimates to be easily derived), freight wagons are often isolated from the initial collision. Freight wagon damage and subsequently load damage is most commonly the result of secondary collisions between adjacent wagons or objects alongside the track. Train collisions can be modelled identifying impact speeds of individual wagons. Unfortunately a relationship between wagon impact speed and damage is difficult to correlate due to a number of uncontrollable variables. For example, in head-on collisions regardless of individual wagon loads, wagon impact speeds tend to decrease towards the rear of the train. This suggests that damage is related to distance, and therefore, in head-on collisions wagons located towards the rear of the train suffer less damage than those located towards the front of the train. This damage pattern has been shown to exist by Westbrook[22] and the author[7] in two different but equally simple train damage and train impact analysis models. However, such models do not account for wagon derailment. Derailment is related not only to speed but also to wheel base, wheel type and track type. As far as impact speed analysis is concerned wagon derailment is difficult to model and predict with any confidence. Derailment can cause wagons having relatively low impact speeds (compared with other wagons in the train) to incur extensive damage. In addition to these problems train impact analysis suffers from the unpredictability of wagon numbers per train and their respective loads.

Although the simulation approach discussed above could be explored further a much more simple means of identifying and quantifying train accidents, liable to cause initiation of explosives, can be obtained through the study of train accidents, together with data collected on train impact speeds. The author has examined almost 200 Railway Inspectorate accident reports and it is concluded that the majority of train accidents which are likely to incur sufficient impact stimuli (to cause explosives to initiate) are those accidents which result in casualties and/or extensive train damage, such as

a. high speed collisions between rolling stock,
b. high speed collisions between trains and road vehicles at level crossings,
c. high speed collisions of trains with massive objects,
d. high speed collisions/derailments causing wagons to fall from bridges/viaducts onto hard surfaces.

The accident speed data given in Chapter 4.0, Section 4.3, can be used to estimate the probability of freight train collisions which occur at specific impact speeds. With respect to collision types and the impact sensitivity of explosives, expected train damage and hence impact initiation (of explosives) are assumed to be functions of collision speed. For example, the probability that if a freight train collides with another train it does so at a closing speed of 70 mph or more is calculated below to be 5.6×10^{-4} (based on a mean freight train closing speed of 27 mph). Whether such a train impact has the potential to cause initiation of explosives (which are sensitive to impacts below 70 mph) is open to argument and is obviously collision type and impact location dependent.

i.e.

$$P[(x) < X]$$

$$= P[\frac{(70 - 27)}{13.18} < Z]$$

$$= P[(3.26) < Z]$$
$$= I(3.26)$$
$$= 5.6 \times 10^{-4}$$

The sequence of events for explosion from non-fire initiated incidents can be illustrated by the use of fault trees. Consider a rigid 2-axle HGV laden with 1 te of military explosives sensitive to impacts of 35 m/s or more. The munitions vehicle has a gross weight of 13 te and is travelling along a non built-up road designated as class A. On approaching a bend in the road at 50 mph it collides head-on with a 32 te articulated 5-axle HGV travelling at 75 mph. As shown previously by the application of simple momentum theory such an accident has the potential to cause explosives to initiate. Similarly, consider a 7 wagon FT conveying 3 wagons of explosives which are sensitive to impacts of 30 m/s or more. As the FT negotiates an intersection one of the wagons laden with 5 te of commercial explosives is hit by a leading locomotive of an express train at 80 mph causing the explosives to initiate.

The incidents described above are represented in Figures 1 and 2 by simple fault trees. Both fault trees can be further developed (as the fault trees imply). For example, the type of HGV collision will greatly affect closing impact speed and therefore accident severity. Exposure of explosives is dependent on packaging, loading and vehicle

construction as well as crash orientation. Similarly, the type of FT collision will greatly affect impact speed and accident severity. Furthermore, wagon exposure will depend largely upon crash orientation and the energy absorbing characteristics of the trains/structures involved.

Figure 1: Fault tree for crash initiated explosion: Road

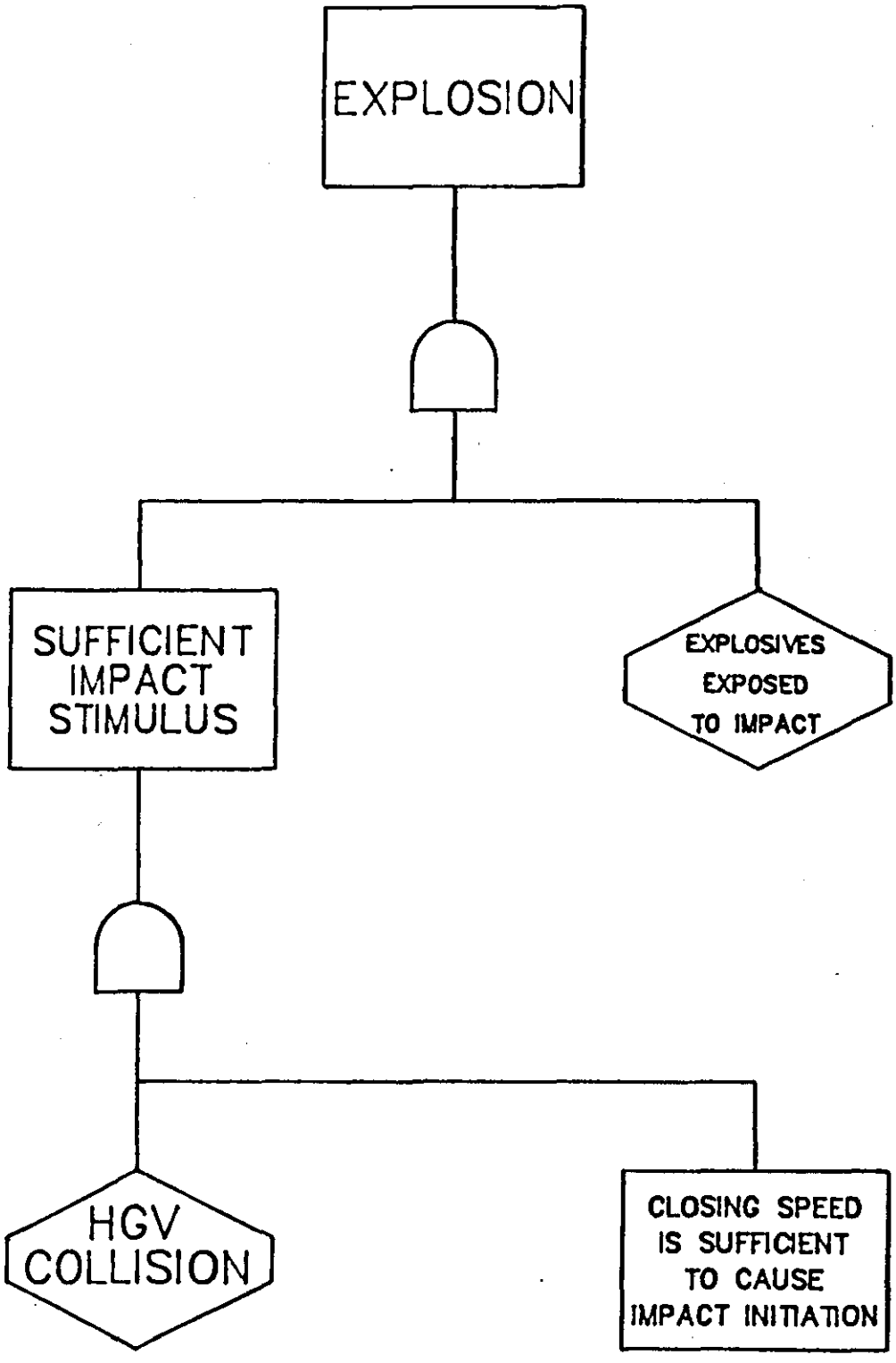
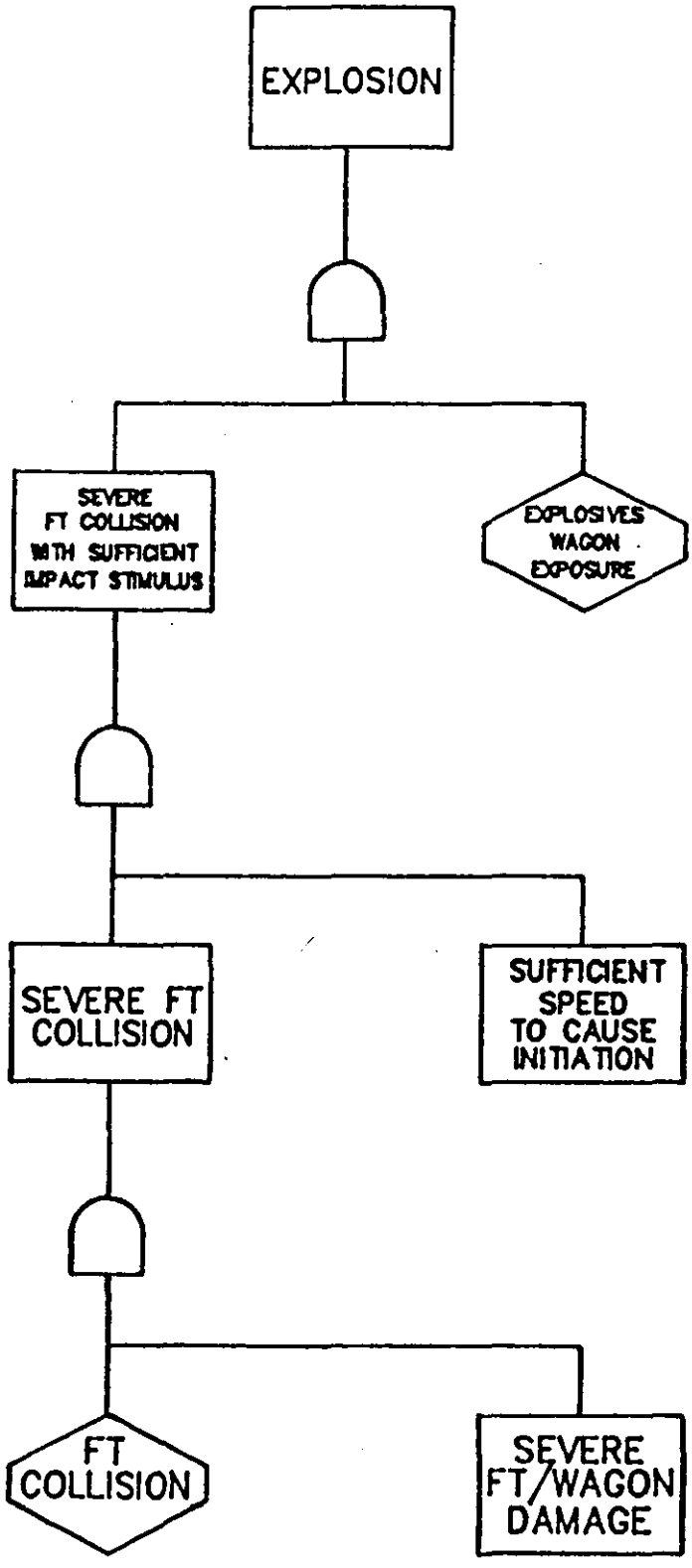


Figure 2: Fault tree for crash initiated explosion: Rail



6.5.2 Fire Incidents

Almost all explosives are sensitive to thermal initiation and therefore it is prudent to assume that all explosives have a likelihood, however small, of initiating as a result of fire. The incidence of fires can be quantified through the application of data given in Chapters 3.0 and 4.0. Fire incidents can be divided into those fires resulting from vehicular accidents, known here as crash fires, and those fires caused by other means, known as non-crash fires.

Regardless of whether fire is a result of crash or not, for explosion to occur it is generally agreed that explosives must be exposed to an engulfing fire for a reasonable duration[11,12,13,23,24]. For military explosives the mean delay from fire inception to explosion has been estimated to be as low as 3 minutes[25]. Stone[26] suggests that in transport incidents this delay is too short and that between 10 and 15 minutes is a better estimate. From a series of pallet fire tests performed by the Royal Armament Research and Development Establishment[24] (RARDE), it is estimated here that once munitions are engulfed between 5 and 10 minutes is a typical time for munitions to burn to explosion. The time for commercial explosives to burn to explosion is generally thought to be longer than that for military explosives, although not excessively[27]. However, it should be noted that the common practice of conveying detonators, separated from, but alongside commercial explosives, is likely to reduce burn-to-explosion time in engulfing fires[27].

In addition to explosives burn-to-explosion time, the time taken for vehicles/wagons to become engulfed affects the delay from fire inception of vehicles/wagons to explosion. One estimate given by the London Fire and Civil Defence Authority[28] is that typical HGVs take between 3 and 4 minutes to become engulfed. It is thought that the time for typical rail wagons (authorised to convey explosives) to become engulfed is no less than that for HGVs, and as a result of the absence of fuel pipes and vehicular furniture etc. is possibly greater. However, it should not be forgotten that many rail wagons are constructed mainly of wood and if not treated for fire retardency may hasten engulfment.

It should be noted here that not all fires lead to engulfment. Engulfment depends on a multitude of factors (detailed in Chapters 3 and 4, Sections 3.3 and 4.2.4 respectively). For both HGVs and rail wagons the probability of engulfing fire given a non-crash fire is estimated here to be between 5% and 40%. This range has been derived from data made available through the Home Office[29], personal contacts[28,30] and the FTA survey conducted by the author(see Section 4.2). Based on similar sources this probability range compares with a probability of engulfment given a crash fire of between 40% and 60%. These estimates were originally derived from data collected by the author during the assessment of the hazard of the transport of explosives[6,7] (conducted for the Ministry of Defence). The data are detailed in Chapter 3.0, Section 3.3 and Chapter 4, Section 4.2.4.

The time taken for the fire services to attend vehicular fires is obviously location dependent. Fire brigades, through the guidance of the Home Office, divide areas into categories of risk. Each category is designated a minimum number of pumps (i.e. fire-engines) which are required to attend the scene. In addition, recommended maximum times for the arrival of pumps are stipulated. For vehicular fires a reduced attendance is common practice. Unless there are additional reasons for concern (e.g. a large number of calls regarding a particular fire, additional hazards or public/ministry advice) only 1 pump is dispatched to a vehicular fire. From discussion with the London Fire Brigade[28] and information on military and commercial movements the areas through which explosives are likely to be moved by road chiefly correspond to areas requiring a minimum attendance time of 20 minutes. The mean time for the fire services to attend vehicular fires in such areas is between 10 and 15 minutes. Taking into consideration

a. the time for an HGV/MV to be entirely engulfed in flames (3 to 4 minutes),
b. the time for explosives to burn-to-explosion (discussed previously),
c. the fact that the fire services withdraw and attempt localised evacuation of the public when explosive loads are engulfed,

then it is clear that the fire services are unlikely to arrive in time to prevent engulfment and hence explosion. Compared with road incidents, the fire services have additional problems when dealing with rail incidents, namely the problem of access. As a consequence of this, it is also unlikely that the fire services would arrive in time to prevent engulfment and hence explosion of rail wagons.

The numbers of individuals exposed to the hazard considered here may be reduced by evacuation of the surrounding area. Unfortunately evacuation is a time consuming exercise. The London Fire Brigade[28] estimate that it takes in the region of 20 minutes to evacuate a typical urban area within 25 m of a fire. It is thought that if evacuation is implemented only a very small proportion of those exposed would be evacuated to a safe distance. Due to uncertainties in

a. burn-to-explosion time,
b. delay in the notification of the fire services,
c. speed of fire service response,
d. problems of co-ordination and execution,

it is considered that the effect of evacuation on reducing the numbers of exposed individuals (if possible to implement in such a short time) is very small.

The probability of explosion given engulfing fire is dependent on the type of explosive engulfed. Rather than explode it has been remarked that thin cased or lightly clad munitions, as they are often termed, suffer only violent pressure bursts and that the chances of actual explosion are remote[31]. In comparison, heavily clad munitions are thought to have a greater probability of explosion[31], possibly in the region of 20% - 30%. It has also been suggested[13,31] that munitions classed by United Nations classification, as being HD 1.2, (hazard division) are less likely to explode as a result of fire than those munitions classed as HD 1.1. Commercial explosives based on nitroglycerine are known to be extremely sensitive to thermal stimuli. A view which has been expressed on a number of occasions[11,12] is that nitroglycerine based explosives will almost certainly explode if engulfed in flames. This compares with ammonium nitrate based

explosives, such as commercial slurries and emulsions, whose chances of explosion when engulfed in flames are estimated to range between 1% and 10%.

Identification and quantification of the sequence of events which lead to explosion can be best illustrated by a series of examples. Consider a rigid 2-axle HGV travelling along a built-up road designated as class A. The vehicle is loaded with 1 te of commercial explosives which are sensitive to thermal initiation. If engulfed in flames it is thought that the explosives packaging will not retard the onset of initiation. Towards the end of the journey a fuel leak develops which is subsequently ignited by hot engine parts. The crew of the vehicle are unable to extinguish the fire and before the fire services arrive at the scene the load area is engulfed in flames. The fire services attempt to extinguish the fire but are unable to prevent the explosives being engulfed for a period exceeding that which the explosives can withstand, and hence explosion occurs. Similarly, consider a 10 wagon FT conveying 4 wagons of military explosives (HD 1.1) which are sensitive to thermal initiation and whose packages offer no thermal protection. As the train reduces speed sparks from worn brake blocks ignite oil/dirt deposits on the bogie of a munitions wagon. The train crew are unable to extinguish the fire, the fire services arrive too late to prevent a prolonged engulfing fire, and hence explosion occurs.

A diagrammatic representation of the sequence of events for both of these incidents can be illustrated by a simple fault tree, shown here in Figure 3. The fault tree can be further developed for both HGV and FT non-crash fires (as the "diamond" events shown in the fault tree imply). For example, fuel leaks may result from fuel line blockages,

development of pipe cracking as a result of stress corrosion or ageing, and the deterioration of seals etc.. Whereas, ignition sources may arise from bearings overheating through to faults in electrical circuitry. Failure of the crew to extinguish the fire or at least prevent engulfment of the load may result from lack of suitable fire-fighting equipment through to inappropriate use of equipment or just simple failure to discover the fire before it becomes well established. In comparison, failure of the fire services to extinguish the fire may result from a delay in their notification, their response time and/or the fact that not all means of extinguishing the fire can be employed as a result of load engulfment and imminent explosion.

The sequence of events which lead to explosion as a result of crash fire incidents can be illustrated in a similar fashion to that given above for non-crash fire incidents. Consider the two examples given previously for non-crash fire incidents except in this case assume that

a. the HGV collides with a motor car rupturing its fuel tank and subsequently spilt fuel ignites engulfing the HGV,
b. the FT is hit by a motor car whilst passing over a level crossing causing extensive damage to one of the munitions wagons which subsequently becomes engulfed in flames.

These two incident scenarios are illustrated in Figure 4 as a simple fault tree.

As with the fault tree developed for the non-crash fire examples, shown in Figure 3, the fault tree given in Figure 4 for the two crash fire scenarios can be developed further. The reasons for the fire services not successfully extinguishing fires are the same as those given for non-crash fire scenarios. However, it is more probable that crew members might suffer disabling injuries during crash incidents reducing their ability to perform first aid fire-fighting. In addition, fires may not only result from the ignition of spilt fuel but also as a result of localised heat generation caused by shearing of vehicle parts etc.. Furthermore, fires may be dependent on crash orientation (i.e. frontal, side or rear impact) as well as the speed of impact and the type of colliding vehicle.

Very little data are available which can help quantify the causes of HGV and FT fires, especially the root causes of fires. The data which are available are detailed in Chapters 3.0 and 4.0 and have been collated mainly through a number of personal communications and material published by the Department of Transport.

Figure 3: Fault tree for non-crash fire initiated explosion: Road or rail

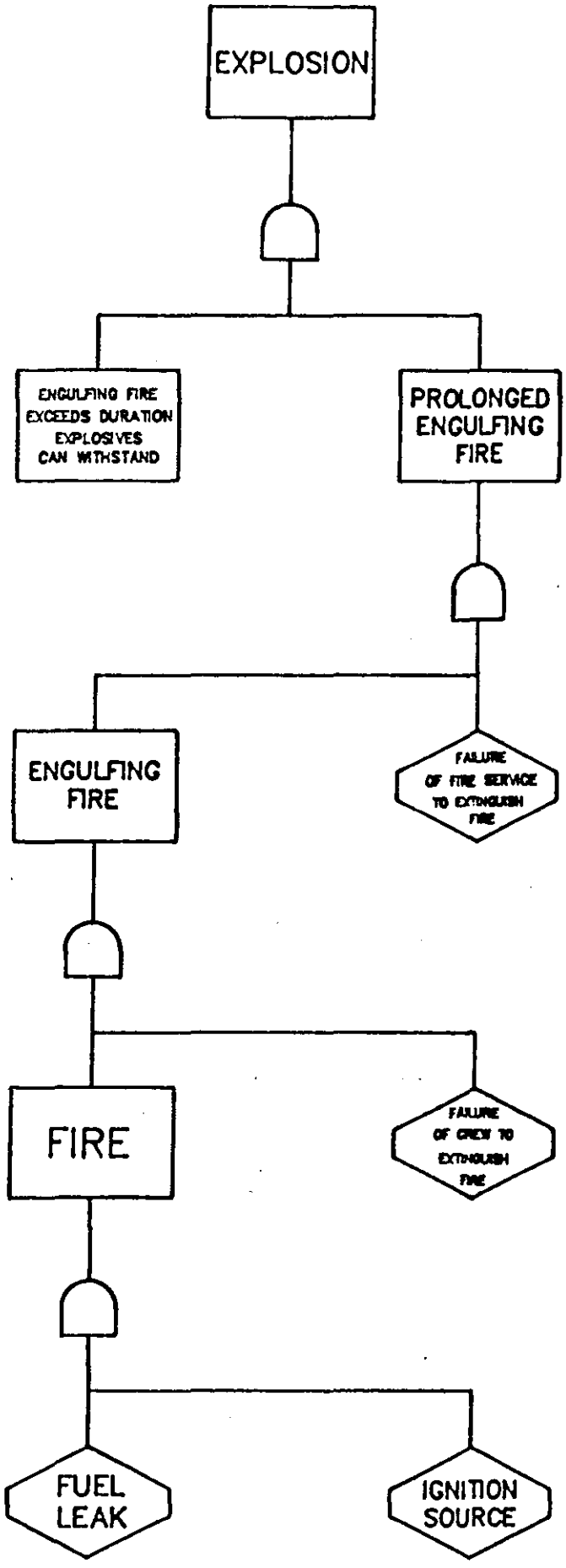
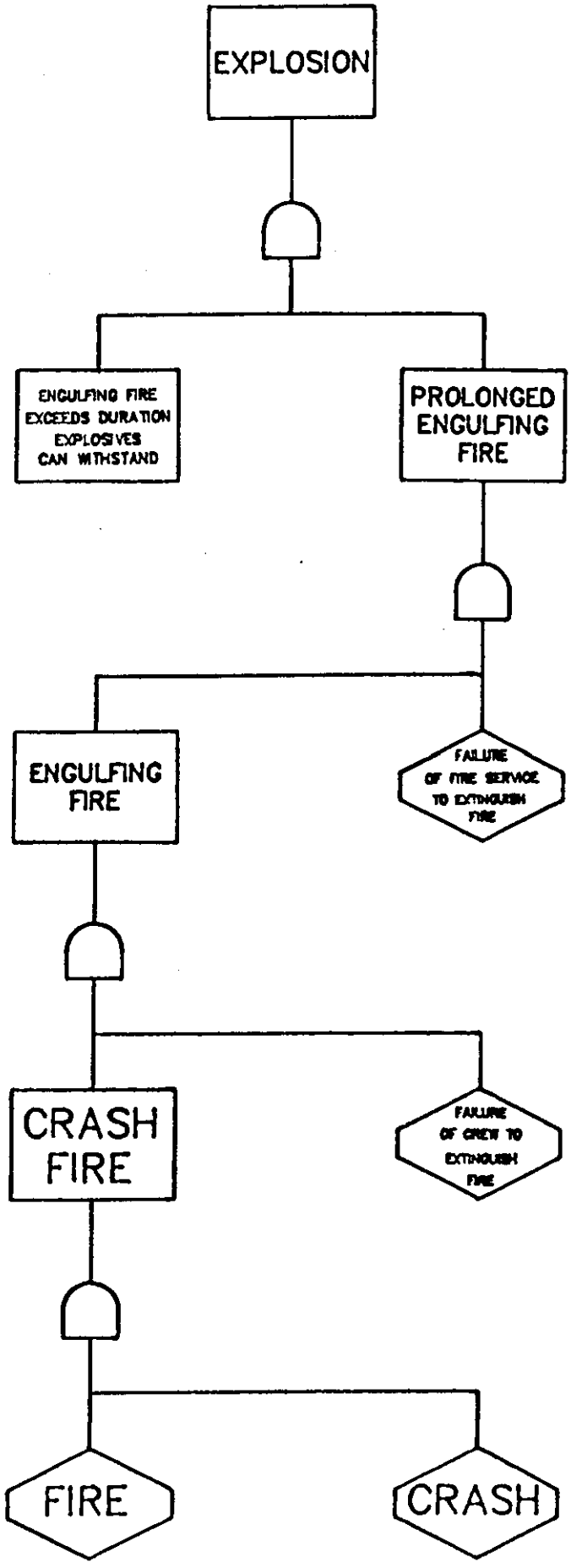


Figure 4: Fault tree for crash fire initiated explosion: Road or rail



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7.0 EXPLOSION CONSEQUENCES: EVALUATION

Damage caused to both property and people, as a result of explosion, requires detailed analysis so that credible risk assessments may be performed. Most data on explosion effects refer to outdoor environments although to a large extent the problem is one of assessing indoor environments (i.e. individuals spend most of their time indoors). The following sections describe explosion consequences and illustrate how certain effects can be quantified. Where data are available reference is made to indoor environments.

Since the beginning of the 1950's the vast majority of work in explosion theory and effects has concentrated on nuclear explosions. However, the damage caused by nuclear explosions is not easily extrapolated to the damage associated with chemical explosions. This is because explosions are essentially yield related. Consequently, thermal and pressure impulses differ between nuclear and chemical explosions, and hence each type of explosion produces different degrees of damage. As a consequence of this it is difficult to compare nuclear explosions, having typical yields of 100,000 tonnes or more, with the low yield chemical explosions of interest here (i.e. no more than approximately 40 te). In addition, data from nuclear explosions include the effects of ionising radiation together with other nuclear peculiarities, such as, thermo-nuclear pulse. As an example of their differences consider the case of nuclear and conventional fireballs. The black body temperatures of nuclear initiated fireballs are orders of magnitude greater than their chemical counterparts. Radiation temperatures for nuclear explosions approximate to 10^7 K, which is over 2000 times that of many high

explosive and propellant explosions[1]. Similarly, nuclear weapons emit energy in the range 0.01 nm to 10 nm compared with 200 nm to 500 nm for conventional explosives.

Unfortunately, there are no simple scaling laws which can be used to relate chemical and nuclear explosions, or simple means of isolating ionising effects etc., so that data can be readily extrapolated. Consequently, the following sections, where possible, only refer to chemical explosions. This is because the inclusion of nuclear data may lead to erroneous assumptions and conclusions being made on the effects of relatively low yield chemical explosions.

7.1 Blast Damage and Injury

The term blast wave is used here to mean the shock wave caused by an explosion and should not be confused with the detonation wave. Upon detonation a detonation shock front travels away from the charge causing the temperature of the surrounding air to rise[1]. This initial shock front is known as the detonation wave (or confusingly, the initial shock wave). After a short distance of travel the detonation wave is overtaken by a new shock front which leaves a zone of rarefied air immediately behind it. This new shock front is known as the blast wave and although its peak pressure and initial velocity is lower than that of the detonation wave it decays much more gradually and therefore exerts its force over a greater distance[1]. The blast wave from all chemical explosions has a definite and measurable pattern. Upon detonation a sudden and violent release of energy causes the surrounding air pressure to rise rapidly creating a region of positive pressure known as

"overpressure". As the blast wave moves away from its source at high velocity (supersonic) the overpressure increases sharply to a peak value, known as the peak overpressure, and then gradually recedes. The overpressure phase is followed by a region of negative pressure or "underpressure". This pressure is generally insignificant compared with the overpressure phase, although such negative pressure can cause moderate damage especially at close distances from the charge.

The characteristics of blast waves are discussed by Lees[2] and detailed accounts are given by Kinney[3] and Baker et al[1]. It is sufficient here to simply identify a means by which blast wave characteristics, in particular overpressure, can be estimated so that their effects on buildings and people can be quantified.

Damage and injury as a result of explosion is largely a consequence of two loading effects, known as diffraction and drag. Diffraction loading is related to the peak overpressure of a blast wave as it passes over and around an object or structure. Peak overpressure refers to the pressure above ambient at a given location (often termed side-on overpressure). In this instance overpressure refers to the pressure above ambient upon blast wave interaction with an object or structure. Diffraction loading refers to the force exerted on an object or structure during blast wave envelopment. The loading consists of two components; firstly, that resulting from the pressure differential that exists between the front and back of an object/structure prior to envelopment and secondly, static loading ("crushing" forces) due to the pressure differential between internal and external environments. The process of envelopment is described in detail by Glasstone and Dolan[4]. Essentially, upon striking an object or structure

blast wave reflection occurs. This not only changes blast wave direction but also its momentum as it collides with the "winds" following its passage. Such collision results in a rapid rise in pressure termed the reflected overpressure. As the pressure drops the blast wave bends or "diffracts" over and around the structure loading other faces (peak overpressure). In comparison, drag loading is related to dynamic pressure. This is the air pressure behind a shock front and unlike overpressure has no reference to ambient pressure. Forces exerted by drag loading are the result of transient winds which accompany the passage of a blast wave.

For very large explosions (peak overpressure greater than about 4.8 bar) dynamic pressure is greater than peak overpressure. As a consequence of this drag loading tends to be the main cause of damage in large explosions. This can also be the case where objects and structures present little resistance to blast waves. For example, buildings whose walls, windows and doors rapidly fail during blast wave interaction cause prompt equalisation of interior and exterior environments. This in turn can reduce the duration and magnitude of diffraction loading to a negligible level[4]. (This is one means by which the effects of diffraction loading can be minimised). For the types of explosions considered here peak overpressure is greater than dynamic pressure and therefore damage is largely the result of diffraction loading. However, this is not always true. It should be noted that all objects and structures simultaneously suffer both diffraction and drag loading. This is because overpressure and dynamic pressure both exist during blast and cannot be separated. The relative importance of each load type is largely dependent on size, shape, weight and resistance of objects and structures. Closed or semi-closed structures, such as buildings with small openings or large tanks, etc. are vulnerable to

diffraction loading, whereas, tall thin objects and buildings with large openings are vulnerable to drag loading. The discussion given here, together with Table 1, provides a rough guide in judging the type of load most important to particular objects and structures. A detailed appraisal of the behaviour of objects and structures to diffraction and drag loading is given by Glasstone and Dolan[4].

Blast wave damage is most commonly related to overpressure. This is probably due to its ease of measurement and estimation compared with other damage-relation criteria. However, blast wave damage is also a function of rate of pressure rise and wave duration. As a consequence of this, impulse is also used as a measure of blast damage. Impulse is a function of both overpressure and wave duration and therefore is often considered a better measure of blast wave damage. However, using impulse as a damage-relation criterion can cause confusion. For example, based solely on impulse blast waves may be assumed to posses certain damage potential but in fact be unable to deliver this due to insufficient overpressure[1,5]. Overpressure itself is not an entirely satisfactory measure of blast damage. This fact has been acknowledged and has led to the development of pressure-impulse correlations commonly known as P-I diagrams or curves. Similarly, distance-charge relationships have been derived (R-W correlations) relating distance and yield to structural response. Unfortunately, both of these techniques suffer from lack of usable data. This is not to say that the techniques are ineffective or unusable, current opinion suggests that P-I and R-W correlations provide improved means of assessing blast damage compared with the traditional overpressure-damage relation[1,5].

It is apparent that blast damage is not adequately defined by a single parameter, but P-I and R-W correlations, have as yet, limited use due to lack of data (as previously mentioned). Attempting to relate a number of criteria to the assessment of blast damage is not new. Limits of damage with respect to peak overpressure were suggested by Robinson[6] as long ago as 1944, and more recently by the Explosives Storage and Transport Committee[7] (ESTC). The empirical relationship devised by the ESTC and described by Jarrett[7] is the foundation of the British Safety Distances for military and commercial explosives[5]. Basically blast damage is split into various categories and each category related to yield, distance and housing damage. These relationships and damage categories are illustrated here in Table 2. Using the work described by Jarrett and that of Assheton[8], Scilly and High[5] illustrate not only damage with respect to overpressure and damage category (described by Jarrett[7]) but also with respect to the mass of explosive consumed. The data given by Scilly and High are reproduced here in Table 3. For further detail on damage categories reference should be made to the original work of Jarrett[7].

From the discussion given above, and the fact that much work relating overpressure and blast damage has been performed and recorded, for most practical purposes overpressure provides a good estimation of blast wave damage. An additional reason for the adoption of overpressure as the primary measure of blast damage is possibly due to the fact that in addition to diffraction loading, drag loading can also be related to peak overpressure. This is because the dynamic pressure associated with drag loading is a function of wind speed and air density (behind the shock front) and both of these can be related to peak overpressure[4].

As a consequence of all the factors discussed above overpressure is used henceforth to describe blast damage. For further details on the rate of pressure rise, wave duration, pressure-impulse and distance-charge correlations (in relation to blast damage) reference should be made to either Baker et al[1], Kinney[3], Scilly and High[5], Baker[9] or Glasstone and Dolan[4].

A multitude of scaling laws have been devised which relate blast overpressure, charge size and distance etc.. A number of these are discussed by Baker[9]. Far the most popular and widely used is based on the "principle of similarity" proposed by Hopkinson[10] in 1915. Provided the scales used to measure blast from any explosive are altered by the same factors as the dimensions of the relative charges then the properties will be similar. Rather than use the dimensions of the charge it is more practical to use charge weight and assume that explosive charges are compact and symmetrical. This method has been used to develop what is commonly known as the "cube root" law. Based on the fact that overpressure is related to distance, the scaled distance, Z, at which peak overpressure is known can be found.

$$Z = R / (W^{1/3})$$

Where

Z = scaled distance ($m/kg^{1/3}$)
R = distance from charge (m)
W = charge size (kg)

Strictly the scaling law is based on available energy. However, for simplicity it is assumed that the energy released is proportional to the mass of explosive.

Using the scaled distance in conjunction with Figure 1 the peak overpressure at distance, R, can be estimated. The graph of peak overpressure vs. scaled distance, shown in Figure 1, is taken from Lees[2] and is based on data given by Baker[9] for the explosion of TNT. Similar graphs are given by Kinney[3], Brasie and Simpson[11] and Stull[12] and more complex ones by Baker[9]. However, the graph presented here is considered to be a good approximation of peak overpressure with respect to scaled distance. This is because the values obtained from it tend to correspond well with other works[3,11,12].

Before further discussing the effects of blast it should be noted that the terms "primary", "secondary" and "tertiary" are not well defined in the literature. Workers appear to use the terms differently. So as to avoid confusion, in this section primary refers to all effects directly attributable to the blast wave (e.g. lung haemorrhage and eardrum rupture), secondary refers to all indirect effects such as bodily translation and tertiary refers to the damage associated with the secondary effect of translation.

Blast damage can effectively be divided into two discrete categories, namely, building damage and human damage. With respect to building damage large amounts of data exist describing and quantifying the effects of overpressure. Robinson[6] provides an extensive analysis of minor and serious damage resulting from blast and Eisenberg et al[13], using data supplied by Fugelso et al[14], derive probit equations relating structural damage to peak overpressure. A summary of blast damage with respect to peak overpressure is given by Clancey[15] and reproduced here in Table 4. Generally an overpressure of 0.07 bar (1 psi) is considered sufficient to cause partial demolition of

typical British brick and concrete constructions, whereas, 0.70 bar (10 psi) is taken as resulting in total demolition. However, these figures are not agreed upon by all. Turnbull and Walter[10] quote 1.5 bar as the onset of considerable building damage. This disagreement may well stem from the omission of certain blast criteria. Unlike human damage, the estimation of building damage tends to be sensitive to the response time of structures and blast reflection. Regardless of these additional criteria it is generally considered that overpressure is adequate in assessing building damage.

Human damage, or as it is more commonly termed injury, is either due to direct blast wave contact or secondary effects, such as, whole body translation and missile impact. The most susceptible parts of the body to blast damage are those organs possessing large density differences amongst neighbouring tissue[16]. As a consequence of this most deaths from blast overpressure (i.e. primary effects) are a result of lung haemorrhage and heart failure. In comparison, minor injury is often based on eardrum rupture, since the ear, although not a vital organ is exceptionally sensitive to pressure. An increase in pressure of only 2×10^{-5} N/m^2 (2.1×10^{-9} psi) will cause the eardrum to move less than the diameter of a single hydrogen molecule[17]. Eisenberg et al[13] have derived probit equations relating peak overpressure to the likelihood of death. The probit is based on lung haemorrhage and is given by

$$Pr = -77.1 + 6.91 \ln p^o$$

Where

Pr = probit (originally given as Y)
p^o = peak overpressure (N/m^2)

Similarly, they derive a probit equation for minor injury based on eardrum rupture.

$$Pr = -15.6 + 1.93 \ln p^{o}$$

A sample of the results gained using these equations is given in Tables 5 and 6. The equations were developed for early risk assessments and still remain popular although their accuracy has been questioned.

Predicting lung haemorrhage and eardrum rupture is an extremely difficult task and many researchers present differing results. In comparison to the results given by Eisenberg et al[13] shown in Tables 5 and 6, Turnbull and Walter[10] quote a figure of 3 bar rather than 1.4 bar as the pressure needed to cause 50% fatalities from lung haemorrhage. Similarly, Baker et al[1] using the results of Vadala[18], Henry[19] and Reider[20] have produced a plot of the percentage of eardrum ruptures vs. peak overpressure. From the plot they estimate that the probability of eardrum rupture at 1 bar (14.5 psi) is approximately 50% and not 90% as given by Eisenberg et al. The plot presented by Baker et al is reproduced here in Figure 2. More recently Pietersen[21] has described probit relations derived by TNO[22] for the estimation of injury based on lung haemorrhage and eardrum rupture. The probits are derived in part from the abundance of work performed on explosion effects at the Lovelace Foundation[23] in the US during the 1950's and 1960's, in particular the work performed by Bowen et al[24,25], White[16] and Hirsch[26]. The probits based on lung haemorrhage and eardrum rupture illustrated by Pietersen provide similar results (marginally lower) to those given by Eisenberg et al[13] and are therefore not detailed here.

Death and non-fatal injury from secondary effects, as previously stated, is generally the result of bodily translation or missile contact. The effects of missiles on the human body are dealt with in Section 7.2 and are not discussed here. Bodily translation or tertiary blast impact, as it is sometimes termed, consists of displacement and subsequent decelerative impact with the ground, building materials and/or other objects. Damage occurs as a result of the head or other vulnerable body parts colliding with hard surfaces causing fracture, concussion and/or haemorrhage. The degree of injury is related to impact velocity, duration, terrain, distance thrown, impacting surface and orientation. Baker and Oldham[27] have developed a method of quantifying damage caused by bodily translation based on specific impulse and incident overpressure. Using the method together with data gained through White[16] and Clemedson et al[28] tertiary damage (caused by translation - secondary effect) is expressed in terms of impact velocity. Abstracted results from Baker and Oldham[27] are given in Tables 7 and 8. Longinow et al[29] have also estimated tertiary damage. They derive a relationship between the probability of death and impact velocity. A graphical representation of the relationship is reproduced here in Figure 3. It can be seen that the values given by Baker and Oldham correspond well with the relationships given by Longinow et al for skull and whole body impact.

Other characteristics associated with blast waves, such as, toxic gases, ground shock and crater are considered here to be insignificant compared with those effects described above. This is because such phenomena only become a serious hazard in exceptionally large or confined (toxic gases) explosions. Additionally, the likelihood of death or injury from such effects is small compared with death or injury from direct and indirect blast effects. Therefore, the effects of toxic gases, ground shock and crater are not

discussed here. Further information, with respect to these phenomena can be gained through Lees[2], Robinson[6], Clancey[15] and Pietersen[21].

Table 1: Principal loading vulnerability of structures and objects

1A: Structures susceptible to diffraction loading

Multistory reinforced concrete buildings with concrete walls, small window areas, 3-8 stories.
Multistory wall-bearing buildings, brick apartment houses, up to 3 stories.
Multistory wall-bearing buildings, monumental types, up to 4 stories.
Wood frame buildings, house types, 1 or 2 stories.

1B: Structures and objects susceptible to drag loading

Light steel frame industrial buildings, low strength walls which quickly fail, single story.
Heavy steel frame industrial buildings, lightweight low strength walls which quickly fail, single story.
Multistory steel frame office-type building, lightweight low strength walls which quickly fail, both earthquake and non-earthquake resistant, 3-10 stories.
Multistory reinforced concrete frame office-type building, lightweight low strength walls which quickly fail, both earthquake and non-earthquake resistant, 3-10 stories.
Highway and railroad bridges.
Telegraph poles, electricity pylons
Transport equipment and vehicles
Trees and vegetation

Source: Glasstone and Dolan[4]

Table 2: Housing damage categories in relation to the distance from condensed phase explosions

Damage category (constant K)	Description
A (3.8)	Almost complete demolition.
B (5.6)	50-75% external brickwork destroyed or rendered unsafe, requiring demolition.
Cb (9.6)	Houses uninhabitable - partial or total collapse of roof, partial demolition of one or two external walls, severe damage to load-bearing partitions requiring replacement.
Ca (28)	Not exceeding minor structural damage, and partitions and joinery wrenched from fixings.
D (56)	Remaining inhabitable after repair - some damage to ceilings and tiling, more than 10% window glass broken.

$$R = \frac{KW^{1/3}}{(1 + (3175/W^2))^{1/6}}$$

Where

R = distance from condensed phase explosion (m)
W = mass of explosive (kg)
K = constant

Note:

a. "R", defines the average radii for idealised circles within which dwellings suffer the damage associated with a chosen category. Those dwellings that suffer damage for a given category outside the circle are balanced by those within the circle which do not suffer such damage.
b. The formula and constants given above are given in imperial units by Jarrett.

Source: Jarrett[7]

Table 3: Explosion damage with respect to overpressure, degree of damage and mass of explosive consumed

Structure or object	Damage	Approximate peak overpressure (bar)		
		1 te	10 te	100 te
Window panes	5% broken	0.010	0.007	0.007
	50% broken	0.025	0.017	0.014
	90% broken	0.062	0.041	0.037
Houses	Tiles displaced	0.044	0.029	0.026
	Doors and window frames may be blown in	0.090	0.059	0.053
	Category D damage	0.045	0.030	0.029
	Category Ca damage	0.124	0.079	0.076
	Category Cb damage	0.276	0.165	0.159
	Category B damage	0.793	0.359	0.345
	Category A damage	1.827	0.793	0.758
Telegraph poles	Snapped	3.585	1.793	1.655
Large trees	Destroyed	3.930	1.793	1.655

Table 3: continued

Structure or object	Damage	Approximate peak overpressure (bar)		
		1 te	10 te	100 te
Primary missiles	Limit of travel	0.014	0.010	0.008
Rail wagons	Limit of derailment	1.827	0.793	0.758
	Bodywork crushed	1.379	0.600	0.579
	Damaged but easily repair-able	0.793	0.393	0.379
	Superficial damage	0.317	0.179	0.172
Railway line	Limit of destruction	14.13	6.688	6.412

Note:

a. All distances (overpressures) from the explosion source are measured to the furthest point of the structure or object.
b. Overpressures originally estimated in imperial units (psi).

Source: Scilly and High[5]

Table 4: Damage produced by blast

Pressure (bar)	Damage
0.0014	Annoying noise (137 dB), if of low frequency (10 - 15 Hz).
0.0021	Occasional breaking of large glass windows already under strain.
0.0028	Loud noise (143 dB). Sonic boom glass failure.
0.0069	Breakage of windows, small, under strain.
0.010	Typical pressure for glass failure.
0.020	"safe distance" (probability 0.95 no serious damage beyond this value). Missile limit (some damage to house ceilings; 10% window glass broken).
0.028	Limited minor structural damage.
0.034 - 0.069	Large and small windows usually shattered; occasional damage to window frames.
0.048	Minor damage to house structures.
0.069	Partial demolition of houses, made uninhabitable.
0.069 - 0.138	Corrugated asbestos shattered. Corrugated steel or aluminium panels, fastenings fail, followed by buckling. Wood panels (std. housing) fastenings fail, panels blown in.
0.090	Steel frame of clad building slightly distorted.
0.138	Partial collapse of walls and roofs of houses.
0.138 - 0.207	Concrete or cinder block walls, not reinforced, shattered.

Table 4: continued

Pressure (bar)	Damage
0.159	Lower limit of serious structural damage.
0.172	50% destruction of brick work of house.
0.207	Heavy machines (3000 lb) in industrial building suffered little damage. Steel frame building distorted and pulled away from foundations.
0.207 - 0.276	Frameless, self-framing steel panel building demolished. Rupture of oil storage tanks.
0.276	Cladding of light industrial buildings ruptured.
0.345	Wooden utilities poles snapped (telegraph poles, etc.). Tall hydraulic press (40000 lb) in building slightly damaged.
0.345 - 0.483	Nearly complete destruction of houses.
0.483	Loaded train wagons overturned.
0.483 - 0.552	Brick panels, 8-12 in. thick, not reinforced, fail by shearing or flexure.
0.621	Loaded train box-cars completely demolished.
0.689	Probable total destruction of buildings. Heavy machine tools (7000 lb) moved and badly damaged. Very heavy machine tools (12000 lb) survived.
20.68	Limit of crater lip.

Source: Clancey[15]

Table 5: Probability of fatality from lung haemorrhage for a given overpressure

Probability of fatality (%)	Peak overpressure (Bar)	(psi)
1	1.00	14.5
10	1.20	17.5
50	1.40	20.5
90	1.75	25.5
99	2.00	29.0

Source: Eisenberg et al[13]

Table 6: Probability of eardrum rupture for a given overpressure

Probability of eardrum rupture (%)	Peak overpressure (Bar)	(psi)
1	0.17	2.4
10	0.19	2.8
50	0.44	6.3
90	0.84	12.2

Source: Eisenberg et al[13]

Table 7: Criteria for tertiary damage (decelerative impact) to the head

Skull fracture tolerance	Related impact velocity (m/s)
mostly "safe"	3.05
threshold	3.96
50 percent	5.49
near 100 percent	7.01

Source: Baker et al[1,27]

Table 8: Criteria for tertiary damage involving total body impact.

Total body impact tolerance	Related impact velocity (m/s)
mostly "safe"	3.05
lethality threshold	6.40
lethality 50 percent	16.46
lethality near 100 percent	42.06

Source: Baker et al[1,27]

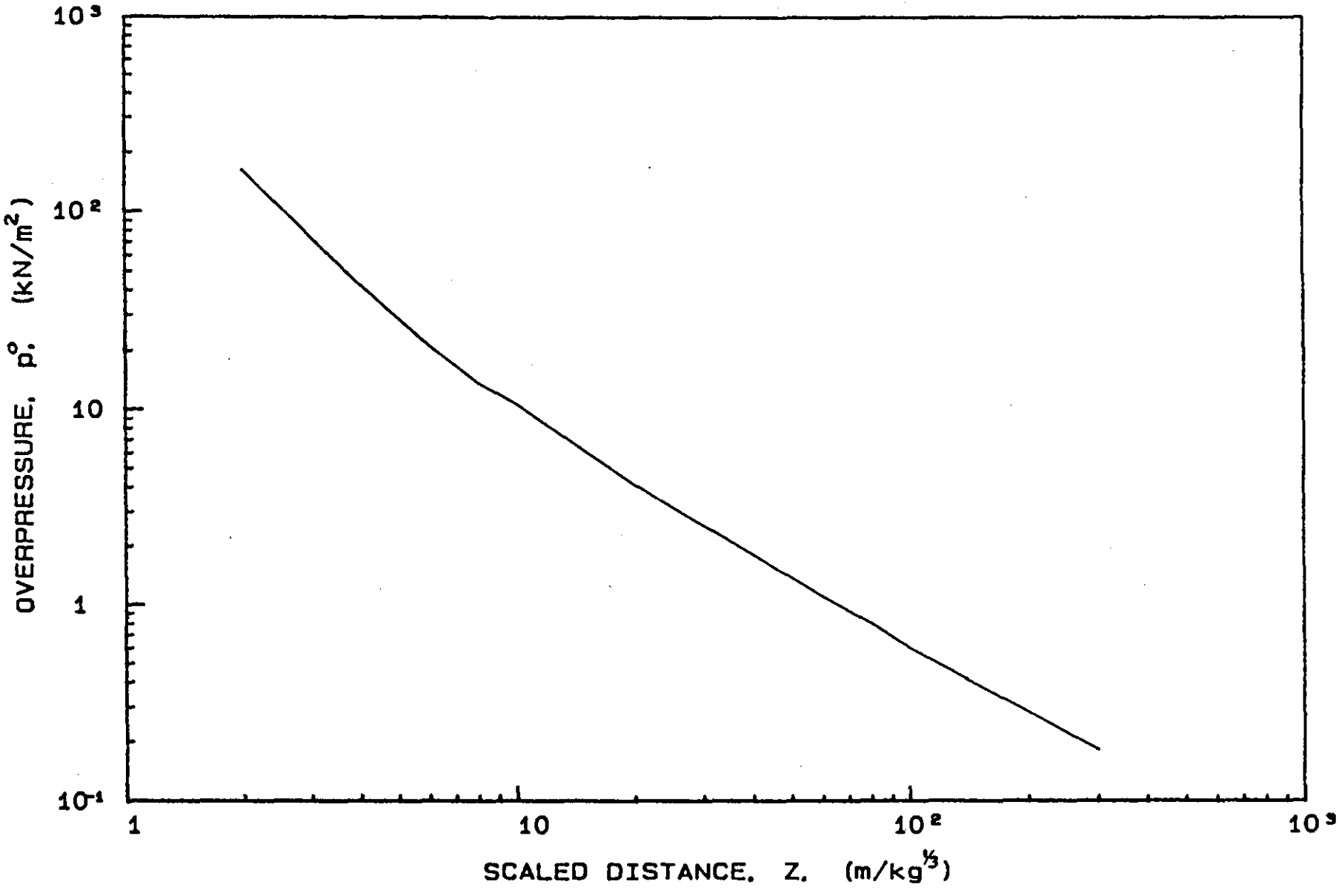
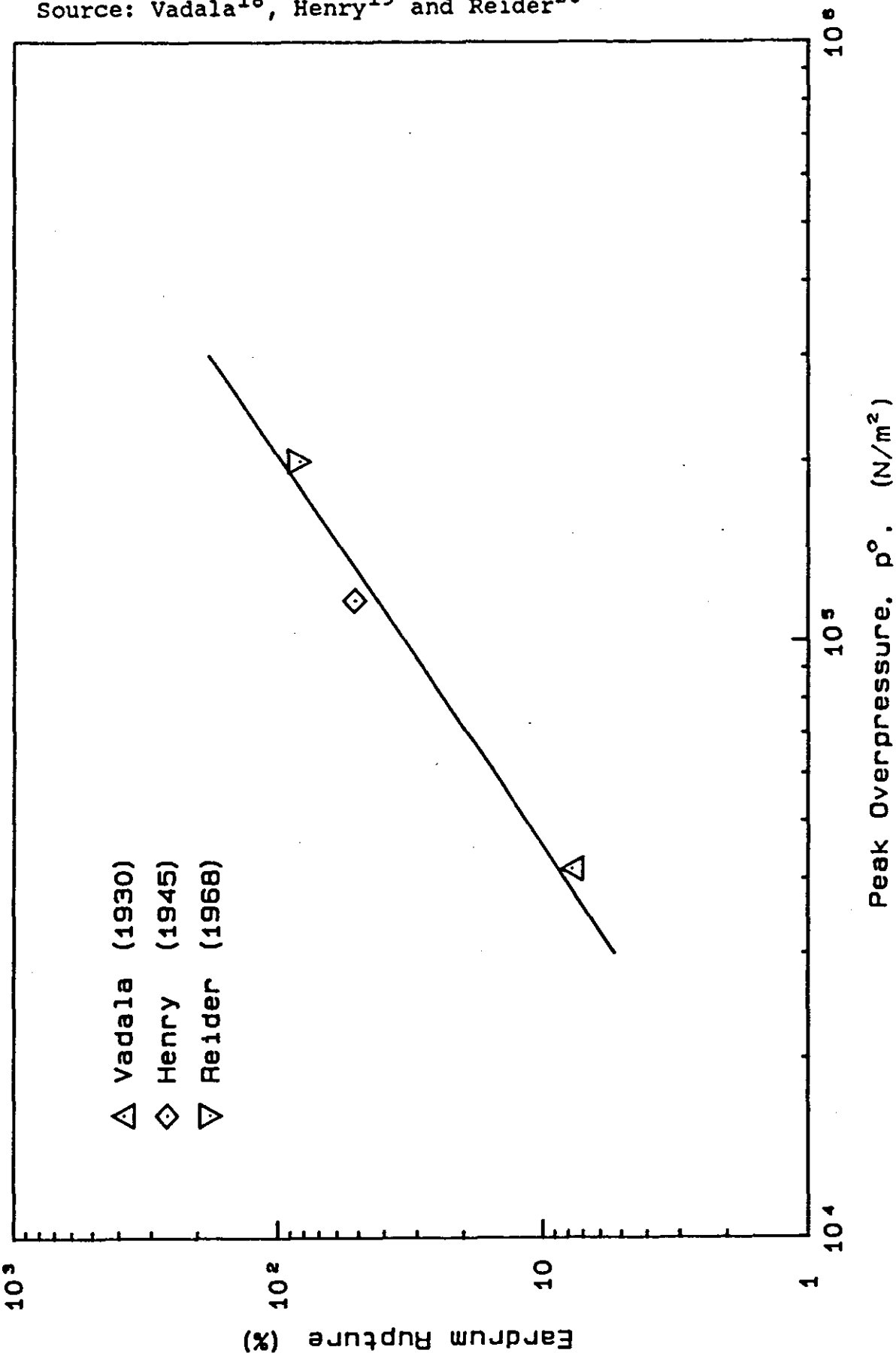
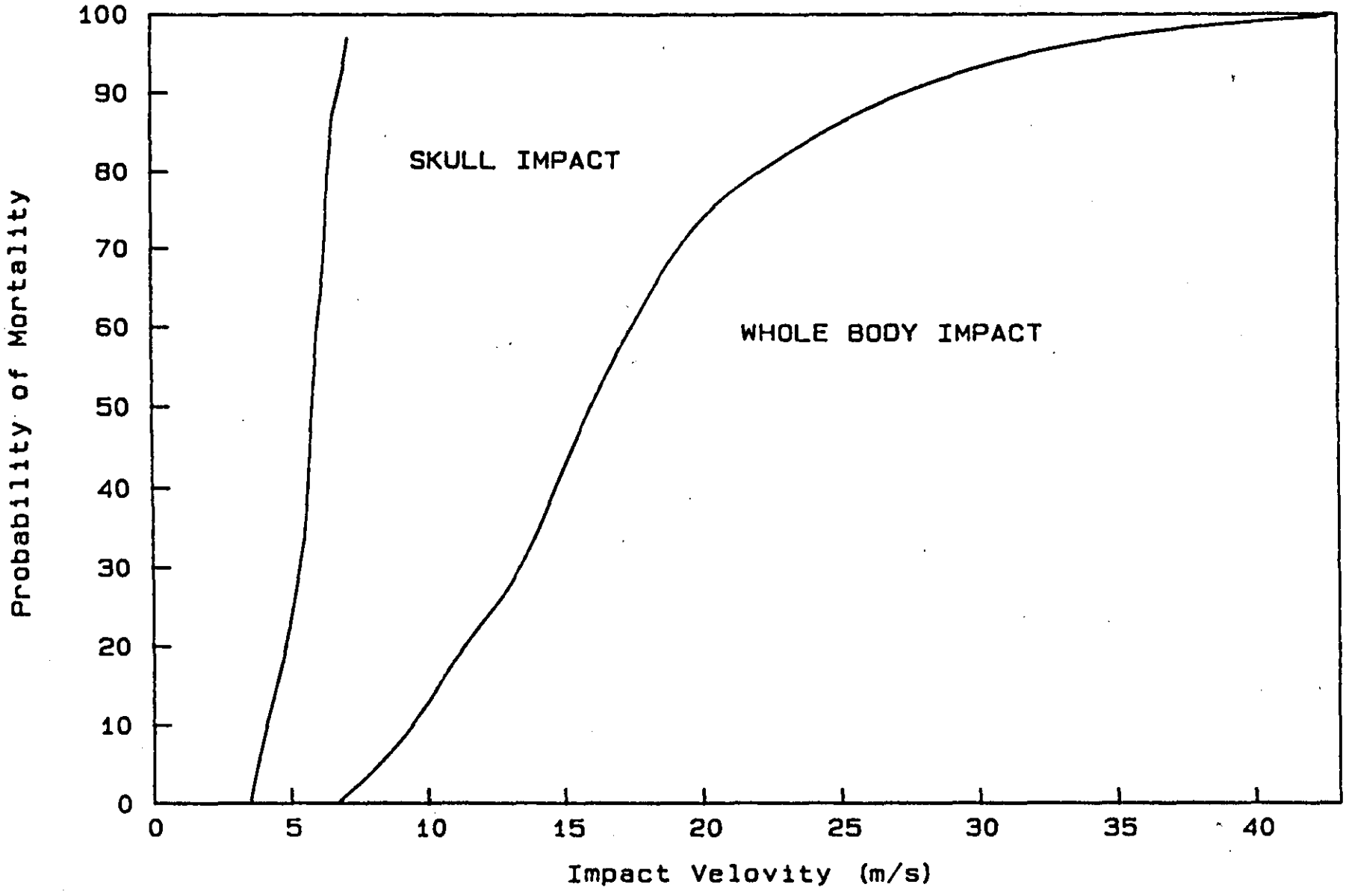


Figure 1: Peak overpressure vs. scaled distance

Figure 2: Eardrum ruptures (%) vs. overpressure

Source: Vadala[18], Henry[19] and Reider[20]





Source: Longinow et al[29]

Figure 3: Fatality criterion: Bodily translation

7.2 Missile Damage and Injury

Fragment generation, as a result of explosion, can produce significant damage to the receiving medium. Energy delivered to fragments from blast waves causes fragments to become airborne and act as missiles characterised by velocity, range and penetration. Such missiles are often classed as being either primary or secondary[1]. Primary missiles consist of casing and/or container fragments from the explosive item, whereas, secondary missiles consist of fragments from objects located close to the explosion source which have interacted with the blast wave.

Unlike the one or two large fragments which result from typical storage vessel "bursts"[1,30], the casings and packages of high explosives rupture into large numbers of small primary fragments. Although the fragments are small and irregular, they are generally of a "chunky" appearance (in as much that all linear dimensions are of a similar magnitude) and for typical shell casings weigh in the region of one gram[31,32]. In addition, high explosive primary missiles have velocities over ten times that of typical pressure burst fragments; velocities approaching several thousand metres per second are not uncommon[31].

Secondary missiles, as mentioned above, are the result of blast wave interaction with objects located near to the source of explosion. Such fragments are often termed as being either "constrained" or "unconstrained". The terminology depends upon whether the blast wave tears them from their fixings[1] or simply "up-roots" them from their position. The fragments may take a multitude of forms from building materials through to vegetation. Velocity, range and penetration of secondary missiles are, in the main,

much less than those of primary types. However, it is not unknown for blast waves to accelerate secondary fragments to velocities where they become capable of inflicting serve impact damage[1,32].

It is not the intention of this study to explain in depth the means of calculating, from accidental explosions, missile projectory, penetration, range or velocity. Much work has already been done on these subjects. A brief description is given by Lees[2] and detailed accounts by Baker et al[1], Clancey[15] and High[33]; all of these contain references to other works. However, for completeness a brief description of the methods used to calculate missile range, velocity and penetration are included here.

Missile range (horizontal) can be estimated through the consideration of initial kinetic energy and initial fragment velocity. For typical fragments from cased charges the range varies from between 20% and 60% of the initial kinetic energy[2].

$$E = 0.5 * M * V^2$$

Where

E = initial kinetic energy (J)
M = mass of fragment (kg)
V = initial velocity of fragment (m/s)

Initial fragment velocity is difficult to calculate. Clancey[15] estimates that for the majority of fragments, resulting from TNT explosions, fragment velocities are as follows.

Thin case	8000 ft/s	(2438 m/s)
Medium case	6000 ft/s	(1829 m/s)
Thick case	4000 ft/s	(1219 m/s)

The velocities have been estimated from empirical data on the assumption that any size charge will propel fragments the same distance. Although this assumption is untrue, since large explosions propel fragments further than small explosions, the estimates do assist in preliminary analysis. Clancey[15] also details an empirical calculation of missile range. Modifying the formula so as to incorporate SI units, the range is given by

$$X = (W^{1/3} / k * a) * (\ln U/V)$$

Where

X = range (m)
W = mass of fragment (kg)
U = initial fragment velocity (m/s)
V = fragment velocity (m/s)
k = constant (0.002 velocity supersonic, 0.0014 velocity subsonic)
a = drag coefficient

Drag coefficients are a function of fragment shape and orientation during flight. Typical drag coefficients range between about 0.8 and 2.0, with regular symmetric type shapes tending towards the lower values. A number of drag coefficients for various shapes and flight orientations are given by Hoerner[34].

Missile penetration is examined in-depth by Clancey[15] and Baker et al[1]. However, the equations given below are from neither of these sources, but are considered here suitable for approximating penetration through building materials by fragments of less than 1 kg (this is useful here since casing fragments are generally much less than 1 kg, as indicated previously). The equations are taken from the High Pressure Safety Code[35] which suggests that a safety factor of between 1.5 and 2 should be applied to the results. It should be noted that irregular fragments may have a penetration capability only half of that calculated, whereas, pointed fragments may penetrate even further.

$$t = k * M^a * V^b$$

Where

t = penetration (m)
M = mass of fragment (kg)
V = velocity of fragment (m/s)

The constant "k" and indices "a" and "b" vary depending on target material, as shown below.

	k	a	b
Concrete (crushing strength 35 MN/m^2)	18×10^{-6}	0.40	1.5
Brickwork	23×10^{-6}	0.40	1.5
Mild steel	6×10^{-5}	0.33	1.0

Damage caused by missiles, needless to say, can vary from superficial to extensive. As a guide the Explosives Storage and Transport Committee[36] (ESTC) estimate that lethal missiles, with regards to humans, are missiles having approximately 80 J of kinetic energy. The ESTC also suggest that 1 fragment per 56 square metres provides individuals who are out in the open with a 1% chance of being hit. Buildings and other relatively large objects can be crushed or penetrated by missiles leading to minor hazards, such as, falling debris and glass breakage. However, impulsive loading during impact, especially from large heavy missiles, presents the greatest indirect hazard. This is because impulsive loads may instigate or encourage collapse of structures and/or escalate the amount and rate of falling debris and glass breakage. All of these missile effects may also lead to the initiation of secondary fires adding further injury. Secondary fires are discussed in Section 7.3.

The term "indirect hazard" as used above refers to all damage caused to solid media, such as, building materials and vehicles which may then present a hazard to man. It follows that "direct hazard" refers to direct injury of the human body as a result of actual physical missile contact.

The majority of injuries from direct hazards relate to skin laceration and open wounds. If the velocity of the missile is sufficient and contact is made with vital organs then death may result. Experiments on skin penetration have been performed by Sperrazza and Kokinakis[37]. They have found that a relationship exists between missile mass and exposed cross-sectional area (CSA). This relationship is based on a limiting velocity (V_{50}) which corresponds to a 50% probability of skin penetration. The tests, performed with steel cubes, spheres and cylinders impacting 3 mm thick human/goat skin, assume that all missile penetration causes severe damage. Sperrazza and Kokinakis conclude that limiting velocity depends linearly on the ratio of fragment area and fragment mass, as shown below.

$$V_{50} = k * (A/M) + b$$

for $A/M > 0.09\ m^2/kg$ and $M > 0.015$ kg

Where

V_{50}= limiting velocity (m/s)
A = CSA of missile along trajectory (m^2)
M = mass of fragment (kg)
k = constant (1247.1)
b = constant (22.03)

Other work has been performed on skin penetration. Unfortunately, direct comparisons with the findings of Sperrazza and Kokinakis are difficult to make as a result of the many differing approaches to the problem. However, Baker et al[1] using a number of simplifying assumptions, have compared results compiled by other researchers, as shown in Figure 4. It can be seen from Figure 4 that the

relationship estimated by Sperrazza and Kokinakis compares well with the findings of Glasstone[4], White et al[38], Custard et al[39] and Kokinakis[40]. More recently Pietersen[21] has described a relationship derived by TNO[22] relating the probability of skin penetration with fragment velocity and mass. The relationship is in the form of a probit equation, as shown below, and is applicable to fragments of less than 0.1 kg.

$$Pr = -29.15 + 2.10 \ln S$$

Where

$S = MV^{5.115}$
M = mass of fragment (kg)
V = velocity of fragment (m/s)

Not all fragments are penetrating. Non-penetrating fragments may cause injury or death by virtue of their mass and velocity being so great that they inflict bodily translation and/or crushing effects. Such action usually results in cerebral concussion, fracture, haemorrhage and/or serve bruising of the victim. Ahlers[41] has studied the effect of non-penetrating missiles on individuals, the results of which are presented here in Figure 5. Pietersen[21] illustrates two probit relations derived by TNO[22] for the probability of death from such missiles. For fragments between 0.1 kg and 4.5 kg the probit is related to kinetic energy (i.e. $S = \frac{1}{2}MV^2$)

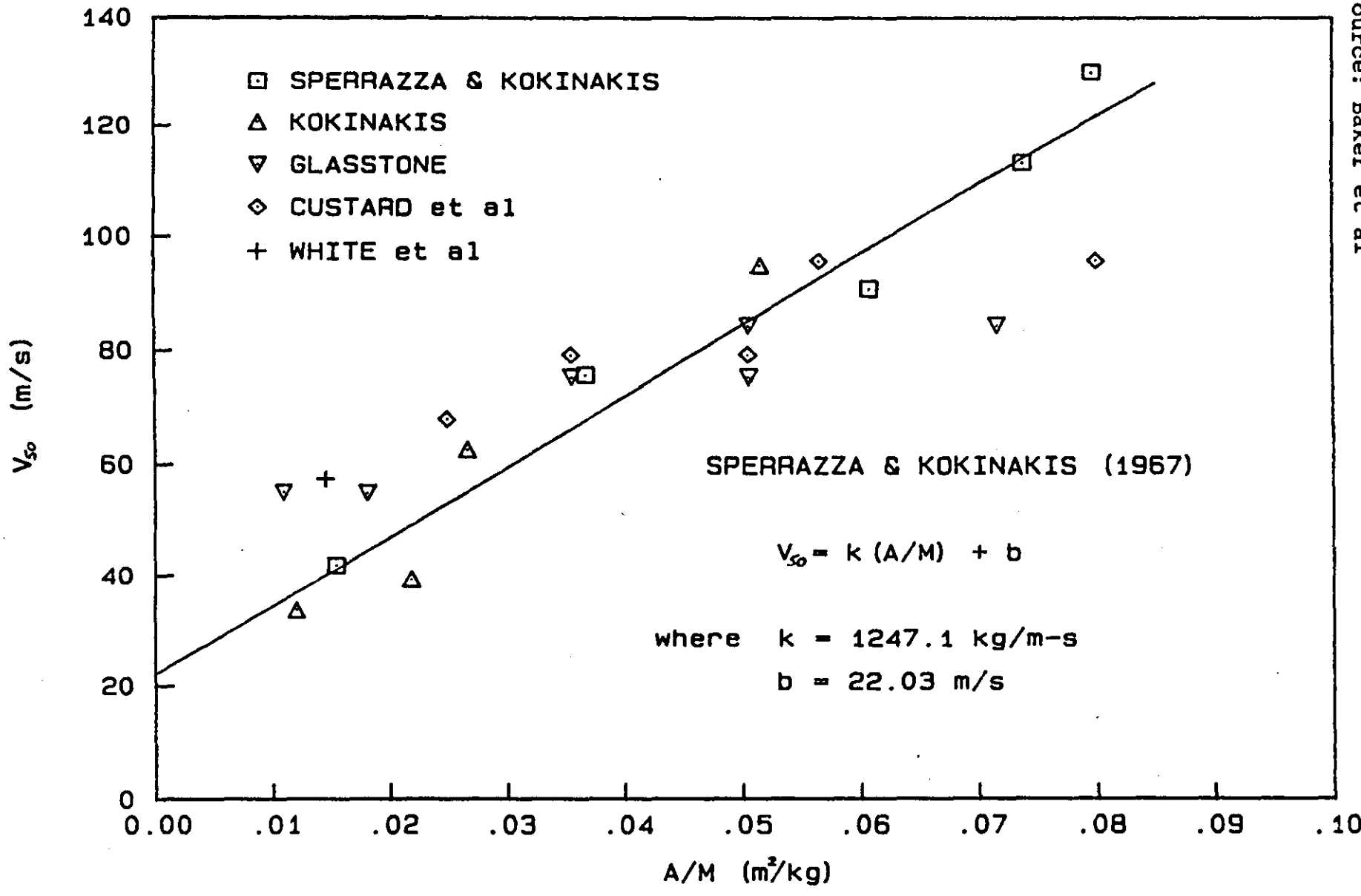
$$Pr = -17.56 + 5.30 \ln S$$

where M and V are as given above for skin penetration. For fragments greater than 4.5 kg the probit is related to skull fracture and given by

$$Pr = -13.19 + 10.54 \ln V$$

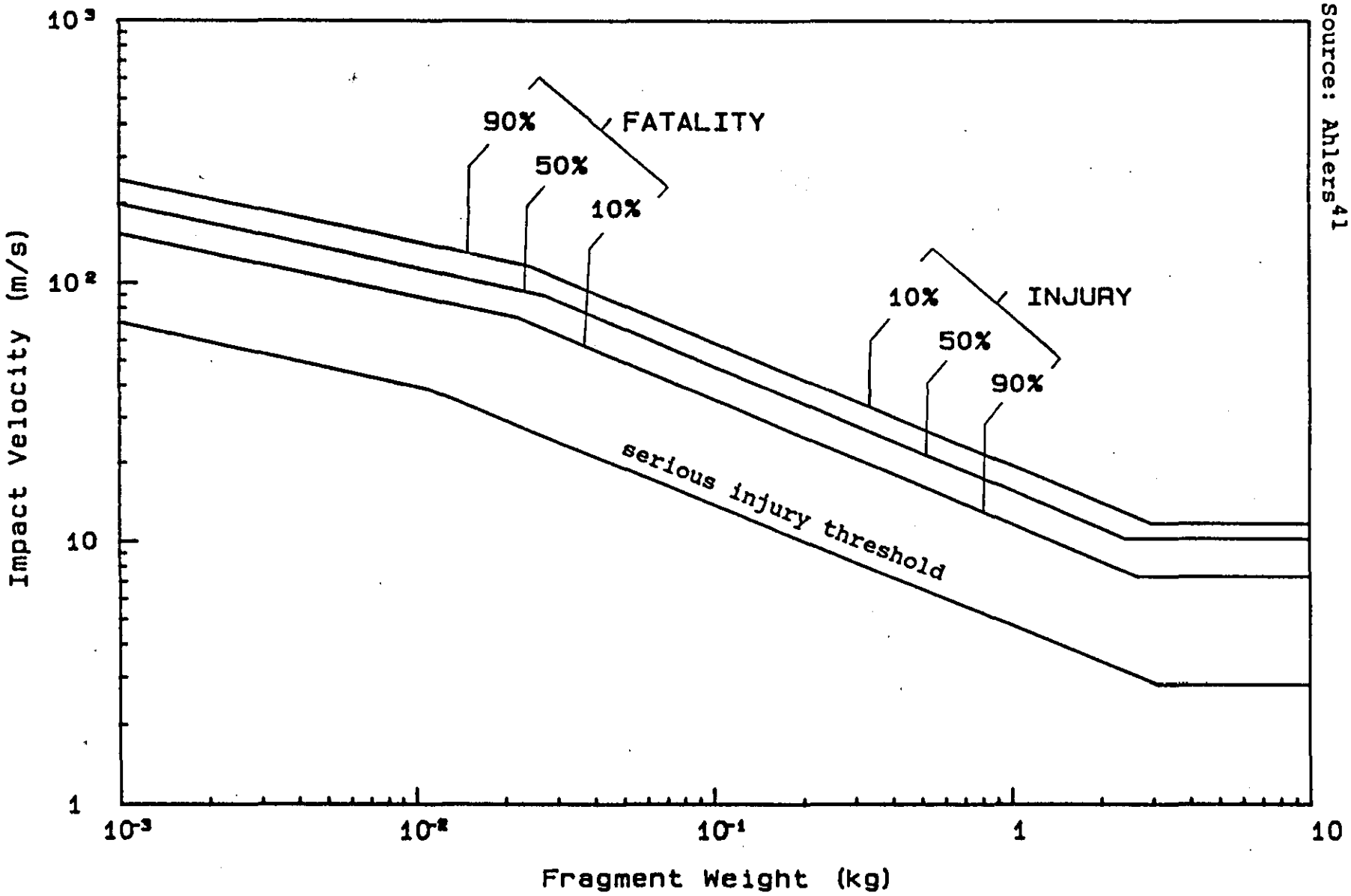
where V is the fragment velocity.

Further information on the effects of missile impact, with respect to humans can be gained through White[16], TNO[22], Clemsdon et al[28], Sperrazza and Kokinakis[37], and Kokinakis[40].



Source: Baker et al[1]

Figure 4: Ballistic limit (V_{50}) vs. fragment area/mass for isolated human and goat skin



Source: Ahlers[41]

Figure 5: Fragment impact: Human response to non-penetrating missiles

7.3 Thermal Damage and Injury

Extensive thermal damage from explosions is usually caused by the phenomenon of fireball growth. Fireballs cause damage as a result of igniting combustible materials and injuring humans by direct immersion and intense radiation. Thermal damage may also occur as a result of secondary fires. These fires are initiated either by instantaneous combustion of materials due to radiation exposure above material threshold levels or by missile and blast interaction with ignition sources. The number of secondary fires caused by explosion is extremely hard to quantify. For propane explosions Geffen et al[42] have estimated the number of secondary fires as a factor of heat radiation threshold and building density. It is suggested here that a similar analogy could be employed for commercial and military explosives. Compared with fireballs, secondary fires present only a minor thermal hazard and, as such, their specific characteristics are not expanded upon here. Detailed information on secondary fires can be gained through Lees[2], Geffen et al[42] and Rausch et al[43].

As previously mentioned, the major hazard from fireballs is the effect of thermal radiation damage. As a result of this most investigations into fireball characteristics have concentrated on radiant rather than conductive and convective heat transfer. However, it has been suggested by Baker et al[1] that for small fireballs, in which less than 10 kg of substance are consumed, heat transfer by conduction and convection may play a substantial part in the heat transfer process. Regardless of this omission, for the purposes of hazard assessment, the current catalogue of research tends to support historical data collected on fireball incidents. The most authoritative work in this

field is given by Rakaczky[44], with regards to munitions explosions, Gayle and Bransford[45], High[46], Bader et al[47] and Hasegawa and Sato[48] with regards to liquid propellants and fuel explosions, and Roberts[49] with regards to releases of liquefied petroleum gas (LPG). It should be noted that much work in this field relates specifically to nuclear explosions[4]. Unfortunately the results gained on fireballs from nuclear explosions do not correspond well with data collected on fireballs resulting from chemical explosions. This disparity should be borne in mind when attempting fireball analysis. This study is chiefly concerned with commercial and conventional military explosives, and therefore the following discussion on fireball growth and damage omits any reference to nuclear explosions.

Evaluation of fireball consequences for hazard assessment requires the quantification of fireball temperature, fireball duration and fireball size. Temperature is dependent on the heat capacity of the fuel consumed and varies from approximately 1350 K for flammable gases to about 5000 K for chemical explosives. It is important to note this fact when using fireball models so as to avoid erroneous conclusions. For example, High's[46] predictions for fireball size and duration are based on liquid propellants having fireball temperatures of 3600 K, whereas, Rakaczky's[44] estimates are for fuels, such as, propane, pentane and octane which have substantially lower fireball temperatures (i.e. approximately 2500 K). Similarly, Roberts[49] equations relate to propane fireballs. However, variations between fireball models are largely dependent upon the mass of substance consumed, and as such size and duration estimates may vary by as much as 50%.

As stated above, estimation of fireball size and duration varies from model to model. It is suggested by Baker et al[1] that the results from the various models, used to estimate size and duration, are asymptotic or limiting cases of a more general solution. This claim is supported by the mathematical similarities between the models and the fact that some methods are suitable for use on fireballs consuming small quantities (i.e. less than 10 kg - Hasegawa and Sato[48]), whereas, others are best used on fireballs consuming relatively modest quantities of material (i.e. more than 20 kg - High[46] and Rakaczky[44]). However, from a review of fireball models Roberts[49] suggests that for a large range of releases (1 kg to over 100,000 kg) the following equation provides a reasonable approximation of fireball size.

$$D = 5.8 * M^{1/3}$$

where

D = fireball diameter (m)
M = mass consumed (kg)

Similarly, Roberts suggests that for fireballs consuming less than 5 kg fireball duration is best estimated by

$$T = 1.1 * M^{0.097}$$

and for quantities greater than 5 kg

$$T = 0.83 * M^{0.316}$$

where

T = fireball duration (s)
M = mass consumed (kg)

Duration time, T, is referred to here as the period during which fireballs radiate heat. Further time-scales (of minor importance here) are those associated with duration of combustion with regards to momentum, buoyancy and deflagration and time for fireball "lift-off". These time-scales are discussed in detail by Roberts[49] together with three distinct stages of fireball development, namely

a. rapid growth (rapid combustion, dominated by initial momentum of release, very bright flame),
b. little change in size (dominated by buoyancy and combustion effects, flame cooling from bright yellow to dull orange),
c. fireball lift (rapid cooling, dominated by buoyancy effects).

The main difficulty in estimating duration is essentially the absence of discrete fireball termination. A general consensus has not been reached on the estimation of duration and therefore large deviation is often found between fireball models. In comparison, the estimation of fireball size tends to be more consistent. This is because most hazardous materials generate fireballs which expand rapidly reaching a maximum size which is maintained for a measurable time until collapse. Rakaczky[44], in a literature review of explosions, observed that fireball size and duration can be expressed by

$$D = 3.76 * M^{0.325}$$

and

$$T = 0.258 * M^{0.349}$$

Unfortunately, no limits of applicability are given for the equations above and therefore they should be used with caution. Baker et al[1], however, contend that Rakaczky's equations are for fireballs with temperatures approximating 2500 K. Other researchers, namely High[46] and Hasegawa and Sato[48], have evaluated similar equations, abstracted results of which are shown in Tables 9 and 10. It is suggested by Baker et al that High's equations should be used for liquid propellants having fireball temperatures of approximately 3600 K and where more than 20 kg of hazardous material is consumed, and that Hasegawa and Sato's equations be employed on fireballs consuming less than 10 kg.

High[46]	Hasegawa and Sato[48]
$D = 3.86 * M^{0.32}$	$D = 5.25 * M^{0.314}$
$T = 0.299 * M^{0.32}$	$T = 1.07 * M^{0.181}$

The models discussed above have yet to be refined so as to incorporate conductive and convective heat transfer mechanisms, which may greatly affect heat loss in small fireballs, as previously mentioned. In addition, the emissivity of fireballs has not been fully addressed. Most models assume emissivity values of between 0.7 and 1.0. However, some fireballs have extremely low "black-body"

capabilities rendering the above equations inappropriate (e.g. hydrogen fireballs).

Fireball size and duration is summarised in Table 11.

Further analysis is required if fireball consequences are to be evaluated. Such analysis takes the form of estimating thermal radiant heat flux and, subsequently, radiated thermal energy. The treatment and derivation of these parameters are complex and too detailed to expand upon here. A suitable explanation is given by High[33] and Baker et al[1]. It is sufficient here to note that the analysis is based on fireball size, temperature and duration. On the assumption that fireball size and temperature remain constant High derives the following equations for radiant heat flux, q, and radiated energy per unit area, Q.

$$(q/o^4) = (G * D^2/R^2) / (F + D^2/R^2)$$

$$Q / (bG * M^{1/3} * o^{2/3}) = (D^2/R^2) / (F + D^2/R^2)$$

where

q = heat flux (J/m^2s - i.e. W/m^2)
Q = radiated energy (J/m^2)
D = diameter of fire ball (m)
o = temperature of fireball (K)
R = distance to fireball (stand-off distance) (m)
M = consumed mass (kg)
F = transmission coefficient (161.7)
G = transmission coefficient (5.26×10^{-5})
bG = transmission product (2.04×10^4)

Both equations above are based on static fireball diameters. High[33] (employing a time variant analogy) has shown that equations can be derived to allow for fireball growth. However, these are not expanded upon here since they add little to the assessment of fireball damage.

Total radiated heat, E, is given by Roberts[49] as

$$E = \frac{F * M * Q}{T}$$

where

E = total radiated heat (kW)
F = fraction of total heat released (0.2 - 0.4)
M = mass consumed (kg)
Q = heat of combustion (kJ/kg)
T = fireball duration (s)

From the above the intensity of heat radiation on a target perpendicular to the direction of radiation (i.e. heat flux) is given by

$$I = \frac{E}{4 * \# * L^2}$$

where

I = intensity of heat radiation (kW/m^2) (note; "I" is referred to as "q" in the equations given by High[33])
E = total radiated heat (kW)
L = distance from centre of fireball to target (m)

The effect of fire on buildings can be related directly to the intensity of radiated heat (i.e. heat flux). Most research has concentrated on the ignition of wood[1,50]. Lawson and Simms[50] estimate spontaneous ignition of wood from the following equation.

$$(q - q_s) * t^{4/5} = k$$

where

q = heat flux (W/m^2)
q_s = critical heat flux for spontaneous ignition (W/m^2) (25400)
t = duration of heat flux (s)
k = constant (6730)

The equation given above is based on empirical data and is a general relationship for all types of wood. The critical radiation intensity (i.e. heat flux) to cause spontaneous ignition of wood is given as 25.4 kW/m^2. Other relationships for differing materials exist. However, the vast majority refer to nuclear explosions which are not strictly comparable with chemical explosions, as previously explained. For further information reference should be made to Glasstone and Dolan[4] and Baker et al[1].

Damage to the human body from thermal radiation may result in death or injury from severe burns. Injury caused by radiation can be quantified by temporary or permanent loss of sight. Miller and White[51] have derived relationships linking heat flux and choriorentinal burns with respect to time. However, thermal radiation injury is more commonly based on the burning of bare skin[1,13,52]. Buettner[52] estimates human pain with respect to heat flux.

Figure 6 illustrates the relationship derived by Buettner with respect to heat flux for non-nuclear fires. The two lines shown provide a split between bearable and unbearable pain (second degree burns). Unbearable pain is said to occur[52] when a temperature of 44.8 °C is exceeded at a skin depth of 0.1 mm. Exceeding such a temperature rapidly increases the victims pain. The pain then gradually fades indicating that total skin irradiation has occurred. It is stated by Hymes[53] that for each increase of 1 °C above the threshold the rate of injury is trebled. For example, compared with the threshold the damage rate is roughly 100 times greater at 50 °C.

The probability of death from second degree burns has been estimated by the US Department of the Army[54]. They derive a plot of the probability of fatality vs. the percentage of second degree burns, as shown in Figure 7. Exposed skin varies from season to season but is estimated to average[42] about 27%. This estimate of skin exposure approximates to the exposure of the head and both arms. Thus, from Figure 7 it can be seen that the probability of fatality from second degree burns for average skin exposure is about 10%.

A detailed review of the physiological and pathological effects of thermal radiation is given by Hymes[53] together with new information. It is broadly concluded that those exposed to heat fluxes capable of inflicting third degree burns within 10 seconds are unlikely to survive. Precise probabilities of injury and survival are difficult to gauge. The effects of radiation burns are related to burnt surface area, depth of burn, age of recipient and clothing characteristics, etc.. All of these factors are discussed by Hymes[53].

Probability of death with respect to the proportion of body surface area burnt is given by Pietersen[21] and reproduced here in Table 12. As a "rule of thumb" it is suggested by Hymes[53] that for 15% burnt surface area (adult, head and hands) and injury no worse than second degree-plus all healthy adults under 50 can be expected to survive, whereas, 50% of those over 60 can be expected to die. Compared with adults the proportion of infants surviving is somewhat lower. This is due to the greater surface area exposed (i.e. head and hands approximate 30% of infant surface area) and the greater medical attention required. The approximate distribution of adult surface area (skin) is given in Table 13.

From a number of empirical relations[13,55], and based on an average population, Pietersen[21] derives probits relating burns and death (an average population is not defined). The probits assume approximately 20% exposed surface area. Severity of injury is categorised by the depth of skin to which a temperature difference of 9 K occurs, such that

1st degree burns < 0.12 mm skin penetration
2nd degree burns < 2 mm skin penetration
3rd degree burns > 2 mm skin penetration

The probits given by Pietersen are as follows.

$$Pr = -39.83 + 3.0186 \ln(t * q^{4/3}) \quad \text{1st degree burns}$$

$$Pr = -43.14 + 3.0188 \ln(t * q^{4/3}) \quad \text{2nd degree burns}$$

$$Pr = -36.38 + 2.56 \ln(t * q^{4/3}) \quad \text{lethality (death)}$$

where

Pr = probit
t = exposure time (s)
q = heat radiation (kW/m^2)

For completeness, certain radiation threshold levels and effects are detailed here in Tables 14, 15, and 16.

Finally, it should be noted that transient and steady state fires (for both materials and humans) require differing magnitudes of heat flux for specific levels of damage. For example, first degree burns from secondary fires (steady state fires) are likely from heat fluxes approaching 4.5 kW/m^2, whereas, similar damage from fireballs (transient fires) require over 25 times as much radiant heat. Tables 14 and 15, which are reproduced in-part from the Rijnmond Public Authority Study[56] into the hazards from a number of chemical installations, serve to illustrate this point.

Table 9: Comparison of methods estimating fireball duration

Mass (kg)	Time (s) Rakaczky	High	Hasegawa and Sato	Roberts
1	0.26	0.30	1.07	1.10
10	0.58	0.63	1.62	1.72
10^2	1.29	1.31	2.46	3.56
10^3	2.87	2.74	3.74	7.36
10^4	6.42	5.72	5.67	15
10^5	14	12	8.60	32
10^6	32	25	13	65
10^7	79	52	20	135

Source: Baker et al[1]

Table 10: Comparison of methods estimating fireball diameter

Mass (kg)	Diameter (m) Rakaczky	High	Hasegawa and Sato	Roberts
1	3.76	3.86	5.25	5.80
10	7.95	8.06	11	13
10^2	17	17	22	27
10^3	36	35	46	58
10^4	75	74	95	125
10^5	159	154	195	269
10^6	335	321	402	580
10^7	708	671	828	1250

Source: Baker et al[1]

Table 11: Fireball diameter and duration

$$D = A * M^B \qquad T = A * M^B$$

	Diameter (m) A	Diameter (m) B	Duration (s) A	Duration (s) B
High	3.86	0.320	0.299	0.320
Hasegawa & Sato	5.25	0.314	1.070	0.258
Rakaczky	3.76	0.325	0.258	0.349
Roberts	5.8	0.333	0.830	0.316
Roberts*	--	--	1.100	0.097

Note:

a. High[46] - liquid propellants and fuel explosions, fireball temperatures approx. 3600 K, greater than 20 kg.
b. Hasegawa and Sato[48] - liquid propellants and fuel explosions, less than 10 kg.
c. Rakaczky[44] - munition explosions, fireball temperatures approx. 2500 K.
d. Roberts[49] - propane, 1 kg to over 100,000 kg, * - less than 5 kg.

Table 12: Relation between age, proportion of body surface area burnt and mortality rate

Body area burnt (%)	Age (years) 0-4	5-9	10-14	15-19	20-24	25-29
93+	1	1	1	1	1	1
88-92	0.9	0.9	0.9	0.9	1	1
83-87	0.9	0.9	0.9	0.9	0.9	0.9
78-82	0.8	0.8	0.8	0.8	0.9	0.9
73-77	0.7	0.7	0.8	0.8	0.8	0.8
68-72	0.6	0.6	0.7	0.7	0.7	0.8
63-67	0.5	0.5	0.6	0.6	0.6	0.7
58-62	0.4	0.4	0.4	0.5	0.5	0.6
53-57	0.3	0.3	0.3	0.4	0.4	0.5
48-52	0.2	0.2	0.3	0.3	0.3	0.3
43-47	0.2	0.2	0.2	0.2	0.2	0.3
38-42	0.1	0.1	0.1	0.1	0.2	0.2
33-37	0.1	0.1	0.1	0.1	0.1	0.1
28-32	0	0	0	0	0.1	0.1
23-37	0	0	0	0	0	0
18-22	0	0	0	0	0	0
13-17	0	0	0	0	0	0
8-12	0	0	0	0	0	0
3-7	0	0	0	0	0	0
0-2	0	0	0	0	0	0

Table 12: continued

Body area burnt (%)	Age (years) 30-34	35-39	40-44	45-49	50-54	55-59
93+	1	1	1	1	1	1
88-92	1	1	1	1	1	1
83-87	1	1	1	1	1	1
78-82	0.9	1	1	1	1	1
73-77	0.9	0.9	0.9	1	1	1
68-72	0.8	0.8	0.9	0.9	0.9	1
63-67	0.7	0.8	0.8	0.9	0.9	1
58-62	0.6	0.7	0.7	0.8	0.8	0.9
53-57	0.5	0.6	0.7	0.7	0.8	0.9
48-52	0.4	0.5	0.6	0.6	0.7	0.8
43-47	0.3	0.4	0.4	0.5	0.6	0.7
38-42	0.2	0.3	0.3	0.4	0.5	0.6
33-37	0.2	0.2	0.3	0.3	0.4	0.5
28-32	0.1	0.1	0.2	0.2	0.3	0.4
23-37	0.1	0.1	0.1	0.2	0.2	0.3
18-22	0	0.1	0.1	0.1	0.1	0.2
13-17	0	0	0	0.1	0.1	0.1
8-12	0	0	0	0	0.1	0.1
3-7	0	0	0	0	0	0
0-2	0	0	0	0	0	0

Table 12: continued

Body area burnt (%)	Age (years) 60-64	65-66	70-74	75-79	80+
93+	1	1	1	1	1
88-92	1	1	1	1	1
83-87	1	1	1	1	1
78-82	1	1	1	1	1
73-77	1	1	1	1	1
68-72	1	1	1	1	1
63-67	1	1	1	1	1
58-62	1	1	1	1	1
53-57	1	1	1	1	1
48-52	0.9	1	1	1	1
43-47	0.8	1	1	1	1
38-42	0.8	0.9	1	1	1
33-37	0.7	0.8	0.9	1	1
28-32	0.6	0.7	0.9	1	1
23-37	0.4	0.6	0.7	0.9	1
18-22	0.3	0.4	0.6	0.8	0.9
13-17	0.2	0.3	0.5	0.6	0.7
8-12	0.1	0.2	0.3	0.5	0.5
3-7	0.1	0.1	0.2	0.3	0.4
0-2	0	0.1	0.1	0.2	0.2

Source: Pietersen[21]

Table 13: Distribution of skin surface area (adult)

Body part	proportion (%)
Head	7
Trunk	35
Arms	14
Hands	5
Thighs	19
Legs	13
Feet	7

Table 14: Radiation intensity damage: Steady state fires

Heat flux (kW/m^2)	Effect
37.5	damage to industrial equipment
25.0	minimum energy required to ignite wood at infinitely long exposure
4.5	sufficient to cause pain to personnel if unable to reach cover within 20 s 1st degree burns likely
1.6	no discomfort to long exposure

Source: Rijnmond Public Authority[56]

Table 15: Radiation intensity damage: Transient fires

Heat flux (kW/m^2)	Effect
375	3rd degree burns
250	2nd degree burns
125	1st degree burns
65	threshold of pain, no reddening or blistering of skin

Source: Rijnmond Public Authority[56]

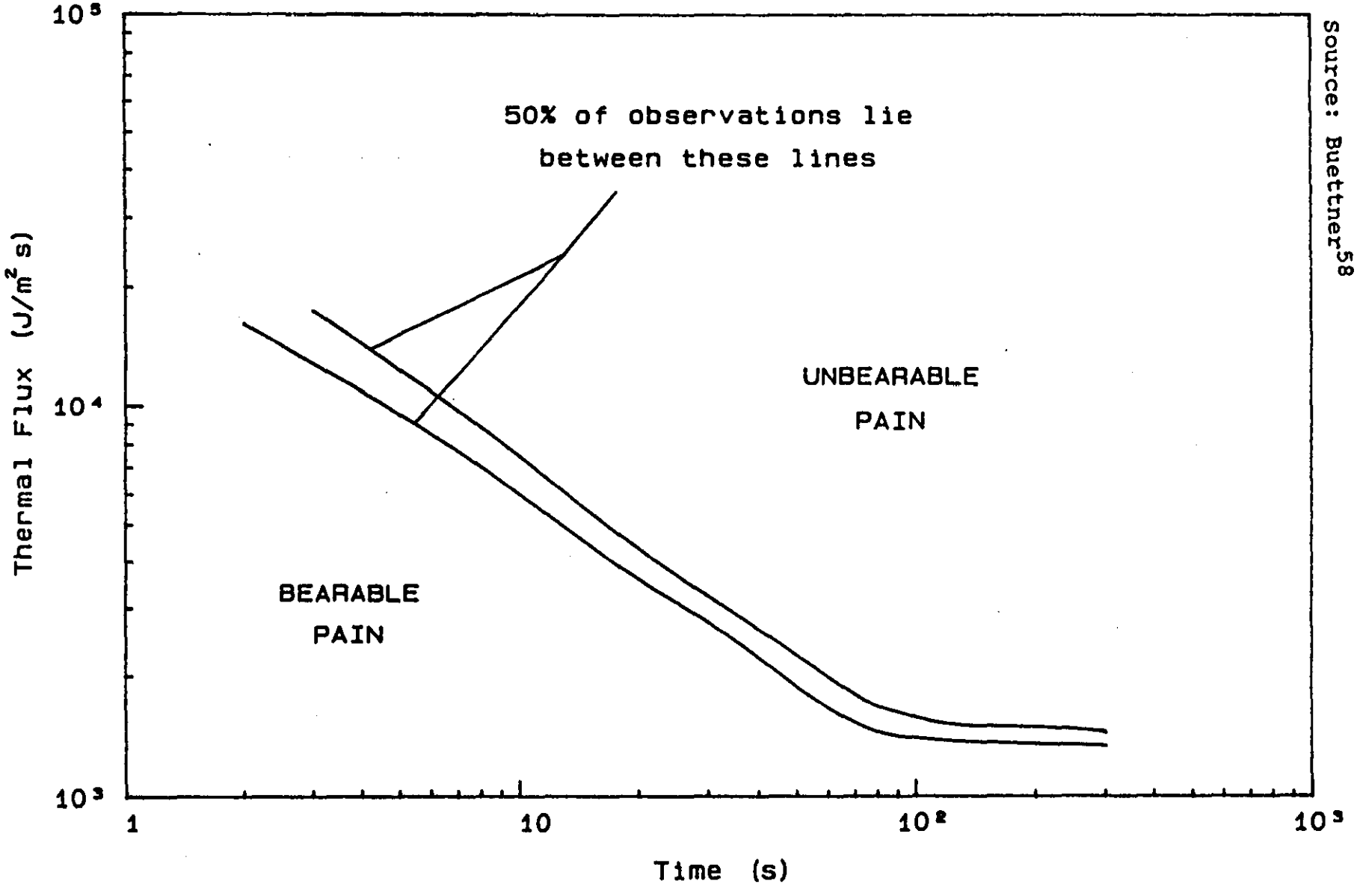
Table 16: Pain and blister thresholds with respect to heat radiation intensity and time

Heat flux (kW/m^2)	Time (s) Pain	Blister
3.7*	20.0	---
4.2	13.5	33.8
5.2	10.1	---
6.2*	10.0	---
6.3	7.8	20.8
8.4	5.5	13.4
9.7*	5.0	---
12.6	2.9	7.8
16.8	2.2	5.6
18.0*	2.0	---

Note:

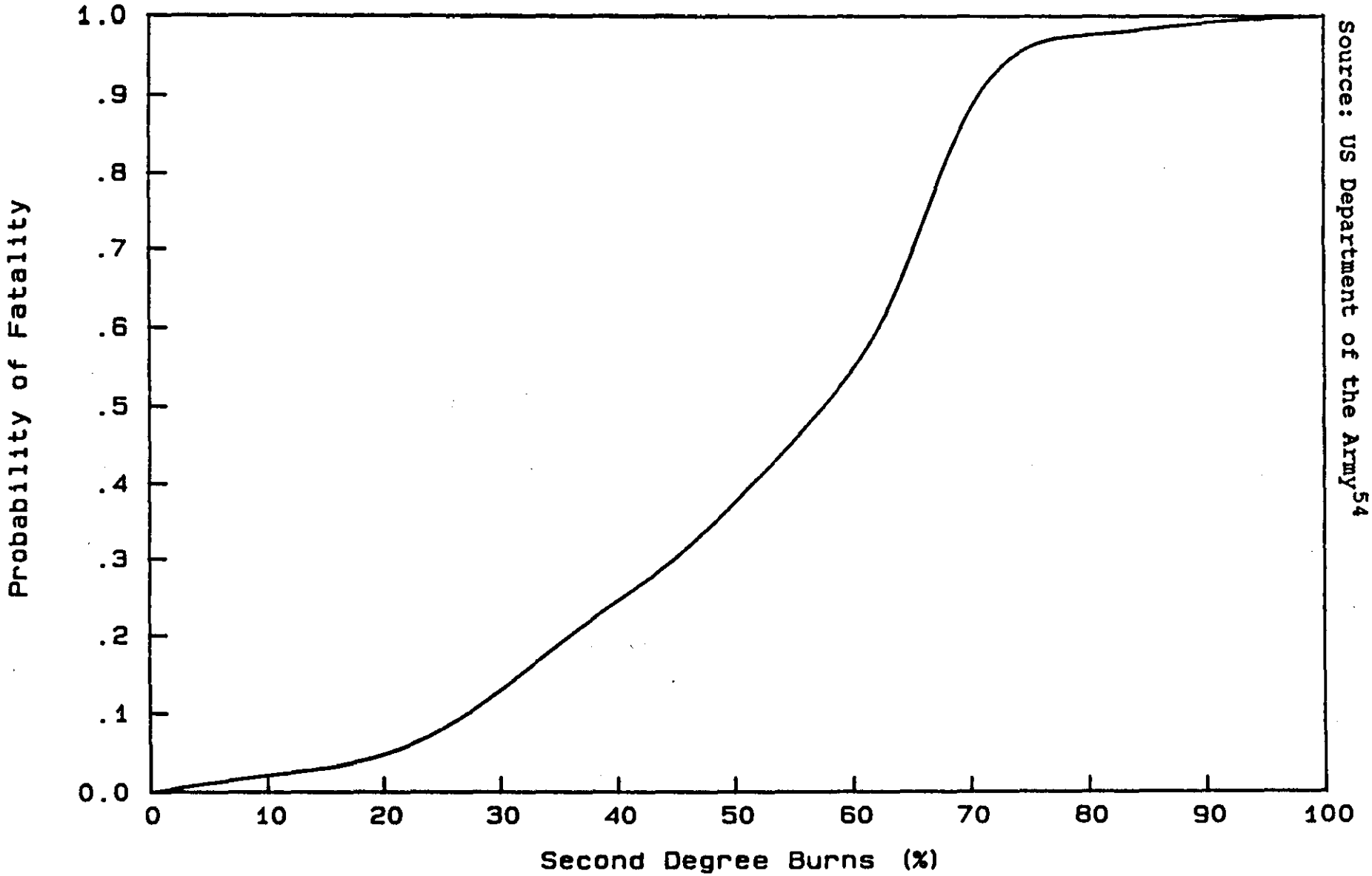
a. Time to threshold of pain, data from Stoll and Greene, except time to unbearable pain (*) data from Buettner.

Source: Stoll and Greene[57], Buettner[58]



Source: Buettner[58]

Figure 6: Threshold of pain from thermal radiation on bare skin



Source: US Department of the Army[54]

Figure 7: Fatality criterion: Second degree burns

7.4 Estimating the Numbers of Individuals Exposed to Transport Hazards: Road and Rail Incidents

Factors which need to be considered when attempting to assess and quantify

a. the number of exposed individuals,
b. the type of individuals exposed (i.e. crew members, the public, emergency personnel, etc.).

specific to transport hazards are discussed below. Most of the factors are applicable to all transport hazards, although emphasis is given to the hazard presented by the transport of explosives.

Transport hazards add a degree of complexity to the estimation of numbers exposed. Unlike fixed hazards, where exposed populations tend to follow familiar and predictable patterns, populations exposed to transport hazards continually change and can vary from one extreme to another. As a consequence of this, estimating the numbers of individuals exposed to transport hazards compared with fixed hazards is more complex and prone to miscalculation. Estimation essentially consists of estimating the density of surrounding populations together with

a. the proportion of the population indoors and out in the open,
b. the numbers of individuals entering/attending the scene,
c. the numbers of individuals exposed in traffic (i.e. in cars and lorries, etc.).

For incidents involving commercial and military explosives it is necessary to determine the numbers exposed to blast, fragments and fire so that the numbers of casualties can be estimated. The number of people exposed is dependent on a multitude of factors which can be summarised as follows.

a. Scale and severity of accident.
b. Accident location.
c. Action taken by individual members of the public.
d. Response and actions of the emergency services.

The most obvious individuals exposed to the hazard of explosion are those involved in the accident. These will involve the crew of the vehicle used to convey the explosives and often other road and/or rail users who may be involved in the initial/subsequent collision or fire. The numbers involved in the initial accident may vary from two or three in a road accident to well over one hundred in a multiple rail collision involving passenger trains. Average occupancy for private motor vehicles is given by the Department of Transport[59] as 1.75. The author has been unable to obtain data on the average occupancy of heavy goods vehicles but it is thought to be less than that for private motor vehicles (possibly between 1 and 1.1). From the accident survey detailed in Chapter 4 together with other Railway Inspectorate reports, occupancy for freight trains is typically two or three. Passenger trains have the greatest variability in occupancy. Such traffic is greatly affected by routes and time of day. Therefore, average occupancy of passenger trains may well vary from tens to hundreds of individuals.

It should not be forgotten that a number of initially exposed individuals may subsequently relocate to an area at a distance too great to be affected by explosion or an area having other means of protection effectively eliminating or limiting the effects of blast, missiles and fire. Such relocation may be instigated by exposed individuals themselves or by the actions of crew members and emergency service personnel.

Once the numbers of people involved in the vehicular accident have been determined then the numbers of individuals in the vicinity of the accident and individuals who subsequently attend the scene needs to be quantified.

Members of the public may be exposed to the hazard as a result of

a. living or working close to the accident site and within the blast/missile/thermal (BMT) range potential of the explosives,
b. travelling past or near the accident site on foot or by other forms of transport and therefore being exposed whilst travelling through the BMT range, or being exposed for longer periods due to a build-up of traffic causing congestion as a result of blockages and diversions,
c. attempting to help those injured by the initial accident or simply by viewing the scene and proceedings,
d. reporting and recording the events unfolding at the accident site (i.e. media personnel).

Excluding those involved in the vehicular accident, it is suggested here that in built-up areas the majority of those exposed to the hazard are members of the public. Population densities vary with the type of housing exposed. Petts et al[60] have investigated and reviewed population densities around major hazards and estimate that for dense terrace housing population densities approximate 15,000 persons per km^2. This compares with 10,000 persons per km^2 and 1000 persons per km^2 for semi-detached housing and sparse detached housing respectively. The average UK population in built-up areas (urban) is about 4000 persons per km^2 and in non-built-up areas (rural) 200 persons per km^2. It is important to note that population densities may well exceed 15,000 persons per km^2 where high density targets, such as high-rise flats, offices, and hospitals are exposed. In addition to these difficulties population densities vary during the day. Petts et al[60] address this problem and detail those at home during different parts of the day. From this work the author estimates that during the school day (0800h-1600h) average house occupancy is 1.26, during the working day (0800h-1830h) 1.72 and at night (1830h-0800h) 2.71 (based on 5% unemployment).

The numbers of individuals exposed is difficult to limit by evacuation of the public to safe areas. Evacuation may be impractical to implement or ineffective due to the little time available. In particular, if explosive initiation is instantaneous obviously no evacuation is possible (i.e. impact initiated crash incidents). Even if evacuation is instigated it will be fraught with difficulties. These difficulties are chiefly

a. the time taken to identify the need for evacuation,
b. co-ordination of the police force in implementing evacuation,
c. the resources needed to evacuate people from buildings and traffic,
d. the time required to relocate individuals to safe areas,
e. the obvious complications that exist in evacuating hospitals, residential homes and schools, etc..

Much work has been done on the effectiveness, time-scales and problems of evacuation, especially for nuclear installations. Of particular interest is the work performed by Urbanik[61] and Technica[62,63].

In certain incidents (typically sparsely populated areas) the majority of those exposed (excluding those involved in the vehicular accident) may in fact be those requested to attend the accident scene. These will include personnel from the three emergency services (police, fire and ambulance), possibly specialist medical staff, explosives experts and in the case of accidents involving military explosives personnel from the Joint Service Ordnance Disposal Operations Centre.

The speed of attendance and the number of individuals dispatched by the emergency services will depend to a large extent on the quality of information received and inter-service liaison. The quality and depth of information with regard to the scale and severity of an accident will fashion the size and speed of initial police, fire and ambulance response. Other important points affecting the quality of information on which the emergency services formulate their response can be summarised as follows.

a. Accident location.
b. Number and type of vehicles involved.
c. Estimate of the number of casualties.
d. Indication of the severity of injuries.
e. Possibility and likelihood of future or imminent casualties.
f. Danger to the emergency services.

On arrival at the accident scene each emergency service has its own priorities which shape the size of individual service attendance. The first priority for all three services is to save life. However, the numbers of personnel from each service will depend on the help that they can provide, their resources and the need for their assistance[64,65,66]. For example, the numbers of police are determined by the need to

a. maintain public order,
b. enforce the law,
c. co-ordinate communication and assistance between the emergency services,
d. regulate traffic,
e. collect information for any subsequent enquiries and/or court proceedings,
f. possible evacuation of the local vicinity within the hazard (BMT) range,
g. protect property,
h. restore normality.

The above is by no means a complete list of the demands on the police force at an accident site, however, it does illustrate the main pre-occupation of the police force. In comparison, the numbers of fire service personnel are determined by the need to

a. control, extinguish and prevent fires,
b. rescue individuals (i.e. remove people from crumpled and distorted vehicles),
c. clear and remove potentially hazardous materials,
d. determine the necessity for evacuation (often in conjunction with expert advice),
e. ensure rescue work is conducted in a safe environment and manner.

Similarly, the numbers of ambulance personnel are determined by the need to

a. provide initial first-aid and subsequent first-aid cover,
b. care for injured individuals,
c. transfer casualties to hospital.

A typical road accident involving injury and fire would probably be attended by 1 police patrol car (2 individuals), 1 fire tender (4-5 individuals) and 1 ambulance (2-3 individuals) providing about 10 additional individuals at the scene[67,68]. Obviously where hazardous goods are involved, time permitting, the response is likely to be greater. Those most likely to be first at the scene are the fire service (2-3 fire tenders) exposing up to 15 additional individuals. Emergency service attendance is similar for rail accidents[67,68]. However, speed of attendance at rail accidents is often hampered by poor track access. It should be noted here that in many cases most emergency service personnel are likely to arrive after explosion (see Chapter 6.0, Sections 6.5.1 and 6.5.2).

As noted previously, specialist medical staff may also be present at the accident site. Usually such staff only attend major disaster accidents where there are many severely injured people. In addition, a number of explosives experts may be called upon to assess

a. the hazard to and from the explosives,
b. the means of eliminating the chances of explosion,
c. safe removal and/or disposal of explosives.

Where military explosives are concerned such advice is given by the Joint Service Ordnance Disposal Operations Centre (JSODOC) and one or more representatives may attend the scene. However, attendance is extremely unlikely from JSODOC staff or medical specialists prior to explosion or if imminent explosion is likely.

In addition to the individuals already detailed above, the numbers around an accident site may increase as a result of

a. the arrival of vehicle recovery personnel,
b. accidents occurring in tunnels, at railway stations and ports.

For example, at a road accident members of the public or the police force may request the assistance of a private vehicle recovery firm. Depending on arrival time recovery personnel may be exposed to the explosion hazard, although this is unlikely. Similarly, accidents occurring in tunnels or stations/ports may not only expose large numbers of the general public but tunnel/station/port staff.

Finally, it is important to note that the numbers of exposed individuals at accident sites may not only be high but extremely concentrated (e.g. high-rise flats, offices, hospitals, rail stations, etc). In addition, the concentration of people at such sites, especially where individuals are distributed unevenly, may greatly affect the number of expected casualties. This is because fatality models often adopt a fixed population density which is assumed to be evenly distributed. In addition, it is not uncommon for the effects of accidental explosions to be directional as a result of protection offered by the surrounding environment and other coincidental factors.

7.5 Consequence Models

As can be inferred from the information and data presented in this chapter, the evaluation of explosion effects is often detailed and prone to inaccuracy. Estimating the number of casualties and extent of building damage is hindered by a multitude of factors, namely

a. mass of explosive consumed,
b. distance from source to target,
c. blast duration,
d. terrain,
e. exposure,
f. fragment generation, velocity, range and projectory,
g. heat intensity,
h. structural and material building characteristics.

Furthermore, it is difficult to distinguish between fatalities simply caused by overpressure effects, bodily translation and missile impact. Other causes of death which are hard to distinguish include asphyxia following burial, carbon monoxide poisoning and chronic illness aggravated by shock. In addition to these problems the majority of urban populations will be indoors during an explosion. Only a limited amount of research has been conducted on the effects of explosion with regards to "indoor" populations. The US Department of Transportation[43] have attempted to produce credible methodologies in order to quantify indoor population damage. However, "indoor" and "outdoor" environments are not easily related and no simple scaling laws or means of extrapolating external blast damage to internal blast damage are available. Consequently, the assessment of damage to indoor populations is limited and the accuracy of results poor.

As a consequence of the differences between indoor and outdoor environments, and as a result of the problems outlined above, there are very few simple consequence models which are useful in estimating damage and casualties from explosion. A number of models have been developed for vapour cloud explosions but very few for those explosions of interest here (i.e. condensed phase explosions from the accidental initiation of commercial/military explosives). It is apparent from those concerned with explosives safety, that a simple and accurate means of estimating damage and casualties from condensed phase explosions would be very useful. It is thought here that the best means of achieving this is by the analysis of historical events to produce empirical methods of evaluation. Work at the University of Technology, Loughborough[69], has adopted this approach and produced a model suitable for the assessment of condensed phase explosions, occurring without warning in built-up areas.

The consequence model developed at Loughborough by Withers and Lees[69] is applicable only to those explosives which have a mass explosion hazard (i.e. UN hazard division 1.1 explosives). Fatalities are estimated from data collected on historical events and empirical data collected on the effects of blast overpressure. Historical events include World War II bombings, chemical explosions, domestic gas explosions and a number of natural disasters such as earthquakes and tornadoes. Empirical data consist primarily of relationships linking injury and blast overpressure. Due to the difficulties encountered in estimating fatalities cause of death is split into primary and secondary types. Primary deaths are classed as those which occur in the near field and are entirely due to overpressure. The likelihood of death from overpressure is related to impulse and duration. In comparison, secondary deaths are related to housing damage, specifically the number of dwellings made uninhabitable. For every 10 dwellings made uninhabitable 1 secondary death is assumed. Both primary and secondary deaths are related to distance and mass of explosive consumed and hence are categorised by primary and secondary radii. Individuals who survive within the radii are balanced by those who survive outside the radii. The explosion consequence model is detailed here in Figures 8 and 9. An example of model use is given in Chapter 9.0.

It should be noted that the terms "primary" and "secondary" are used by the workers at Loughborough in relation to deaths; they are used by the present author in Sections 7.1 and 7.2 to refer to damage/injury and missiles respectively.

The explosion effects model developed at Loughborough[69] suffers from one or two omissions, namely the absence of deaths resulting from casing/packaging fragments and deaths from primary and secondary fires. However, the model estimates well the number of fatalities from a number of historical incidents. Of particular interest is the estimate of fatalities from low yield explosions. The model approximates favourably fatalities from V-2 rocket/bombing raids. The net explosives quantity (NEQ) of such rockets is estimated to be 0.64 te and this value is in the range of typical NEQs encountered during the road and rail transport of commercial and military explosives.

Figure 8: Primary and secondary causes of death for man: Mass of explosive and distance for 50% mortality

Source: Withers and Lees[69]

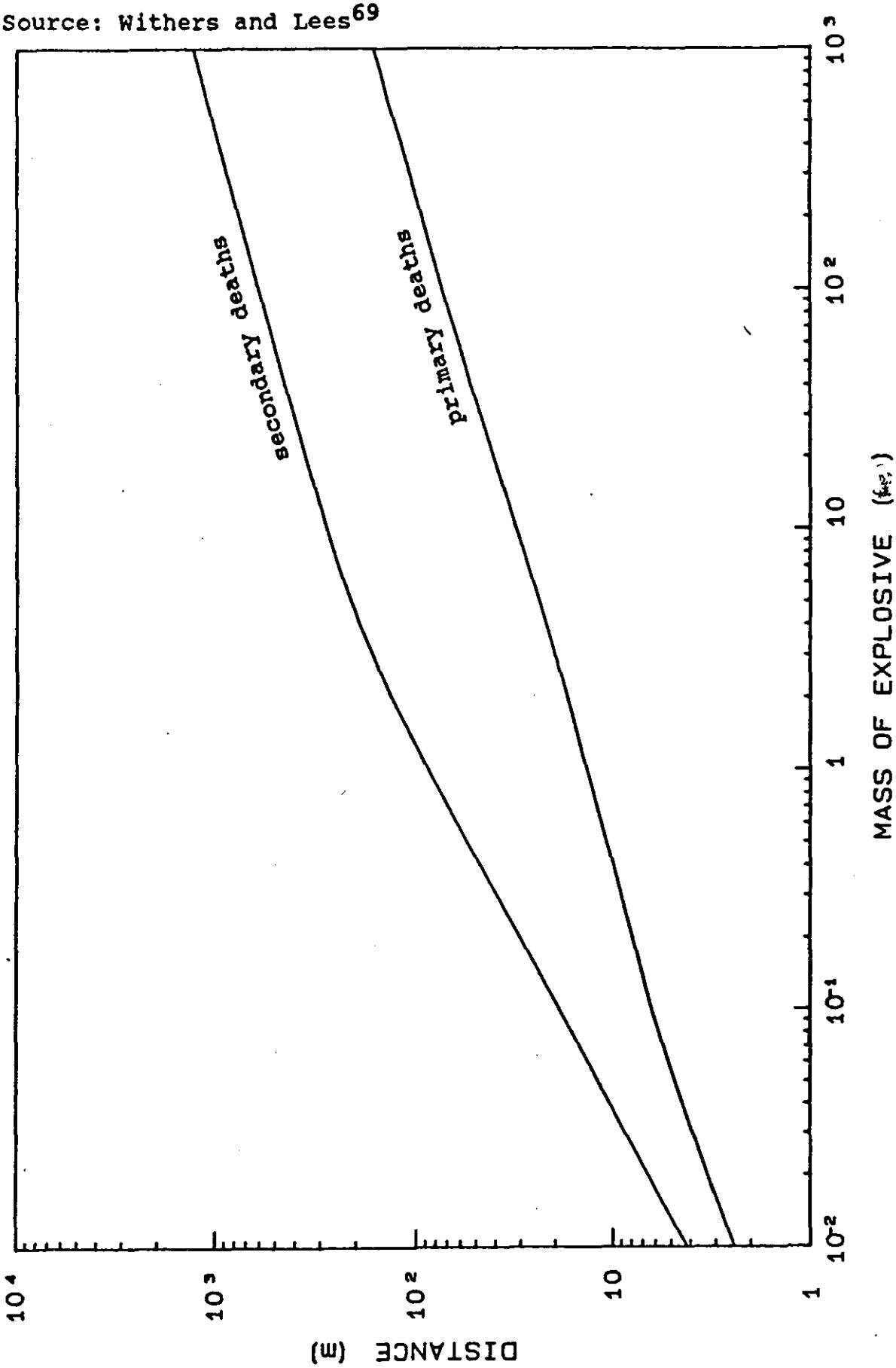
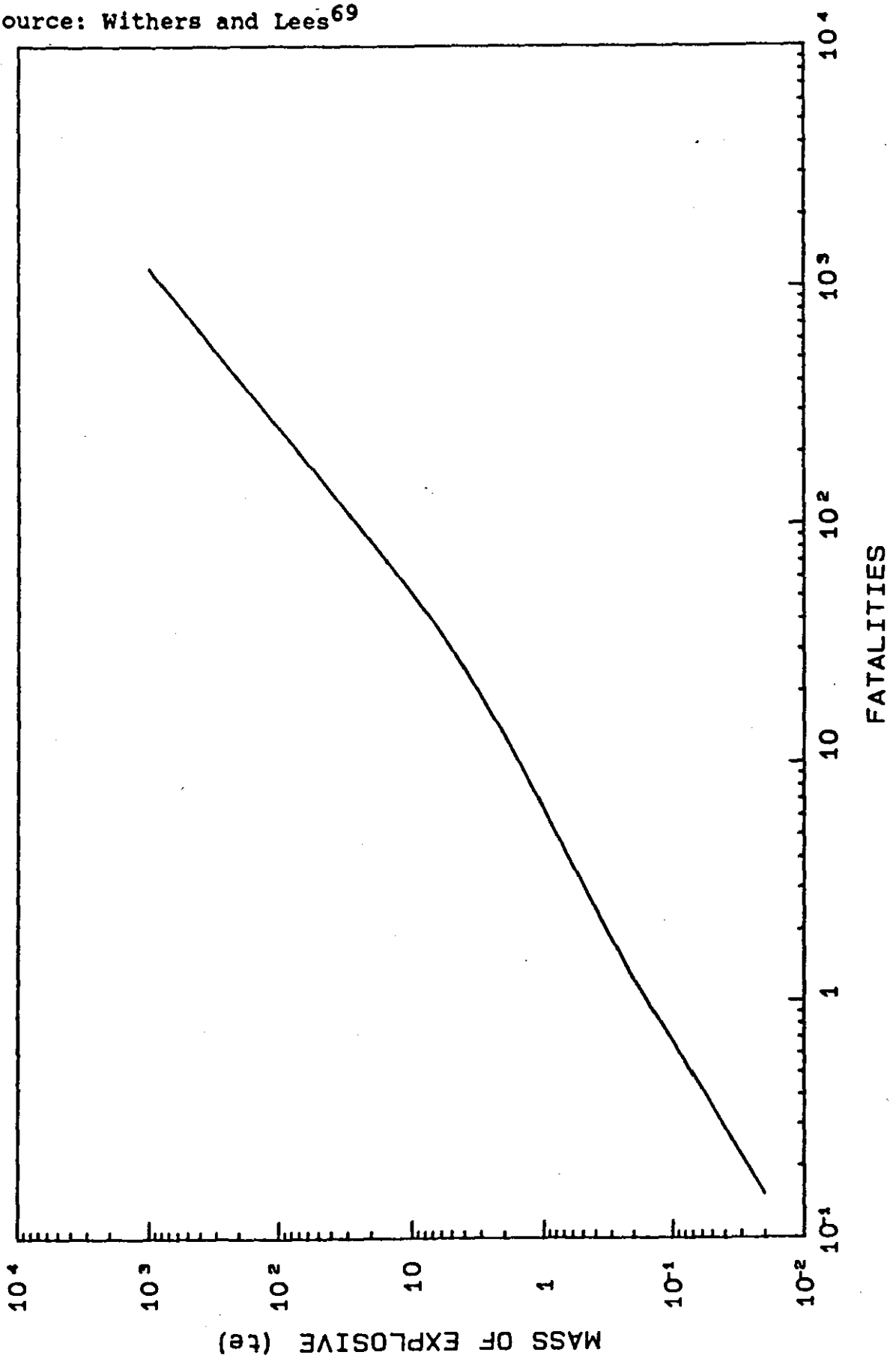


Figure 9: Model for fatalities resulting from an explosion of a condensed phase explosive in a built-up area (Basis 4000 persons/km^2, 2.5 persons/house)

Source: Withers and Lees[69]



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PART D

8.0 AN OVERVIEW OF RISK ASSESSMENT

8.1 Historical Background and Review

It is suggested that risk assessment is an extension of both reliability engineering and operational research[1] (OR). Reliability engineering has its roots in the aircraft industry of the 1920's and 1930's, where the development of multi-engined propulsion necessitated the need to estimate engine failures[2]. In comparison OR[3,4] was developed primarily for the Armed Forces during the late 1930's. The technique was used to determine economical allocation of resources and efficient use of equipment. Two early uses of OR[4] are found in the development of radar to detect enemy aircraft (1937-38) and in the development of effective air campaign procedures against German U-boats (1941). During the 1960's the nuclear industry, followed in part, and extensively a decade latter, by the chemical industry, adopted these techniques and developed methodologies capable of assessing risks from major hazard installations, such as nuclear power stations and chemical plants[5]. Initially, the techniques developed concentrated on producing methodologies to estimate the frequency of undesired events in process and safety equipment. Once these techniques had been refined (and confidence gained) techniques progressed to assess the consequences of undesired events, in particular the risks posed to the public.

It is accepted that the first major risk assessment study which encompassed, refined and advanced risk assessment techniques was instigated by the United States Atomic Energy Commission. Known commonly as the WASH 1400 report[6] and published in 1975 the methodology utilised event trees, fault trees and consequence modelling

techniques. Although heavily criticised[7] (which is not uncommon for "pioneering" work) WASH 1400 is acknowledged as the first study to successfully highlight the techniques and benefits of risk assessments[8]. In fact it is claimed with good cause that WASH 1400 directly influenced future risk assessment techniques not only in the USA but also in the UK[9].

The first major risk assessment study in the UK was performed by the Safety and Reliability Directorate (SRD) of the UK Atomic Energy Authority, who between 1976 and 1978 estimated the risks from existing and proposed petrochemical plants at Canvey Island, Essex. Publication of the (first) Canvey Report[10] in June 1978 led to both praise and criticism being levelled at the methodology and assumptions used[11,12]. The criticism led to a further investigation culminating in the publication of a second Canvey Report[12] in 1981. Regardless of criticism (both reports are thought to over-estimate risks and imply that high levels of calculated risks are acceptable[12]), the reports were, and still are, of unquestionable value in the understanding of risk and its assessment.

Probably as a result of the concern and attention given to hazards from fixed installations detailed assessment of transport hazards is not much more than a decade old. Early studies were essentially simple hazard analyses assessing risks in qualitative terms. In 1971 the MOND Division of Imperial Chemical Industries (ICI) instigated a study into the carriage of liquid chlorine by road and rail[13]. The methodology used, although simple by today's standards, encompassed the estimation of accidents which could cause spillage, probability of spillage and consequence analysis. Furthermore, the sensitivity of the study to a number of fundamental calculations was considered. The major

criticism of the study is its limited scope. For example, fires and spillage not resulting from collision are ignored* and comparison between road and rail is based on the assumption that all traffic goes either by road or by rail. Despite these drawbacks, in a similar fashion to WASH 1400 and Canvey the study provided a basis for discussion and development of risk assessment methodologies, in this instance directly applicable to transport operations. (It is perhaps worth noting that the study preceded both WASH 1400 and Canvey and therefore could not draw upon the advances made in risk assessment during the late 1970's). Similar work to that initiated by ICI[13] was mirrored at the same time in the United States (US), albeit on a much larger scale, the work being initiated by the US Department of Transport and the US National Transportation Research Board. Perhaps the one study of greatest acclaim (more for consequence analysis rather than methodology development) is that attributed to Eisenberg et al[14]. Known as the "Vulnerability Model" the study concerns itself with the consequences of maritime spills of hazardous materials. Much of the work, however, is applicable to other transport modes particularly with regards to the quantification of fatalities from fire and explosion. Of particular interest is the attempt to relate external environments to the damage suffered by "indoor" populations. Other early studies of note include those performed by Simmons et al[15,16] on the risk of material spills. A number of other risk assessment studies are listed in the bibliography.

From these early beginnings a large number of extensive risk assessment studies on the transport of hazardous goods have been published. At present the most noteworthy of these are from the USA, although over the last few years

* From this study and other work[17,18] it is known that the frequency of road and rail non-crash fires can be much greater than crash fires and therefore non-crash fires can present a much greater hazard than crash fires.

the Health and Safety Executive (HSE) together with SRD have initiated detailed studies into the risks associated with the transport of hazardous goods by road, rail and barge in the UK. These studies have yet to be made publicly available and therefore are not detailed here. In addition to the HSE and SRD, the Ministry of Defence (MOD) through the Explosives Storage and Transport Committee (ESTC) have initiated studies into the risks associated with the transport of military explosives by road and rail. These studies have been conducted by the Plant Engineering Group of the University of Technology, Loughborough, headed by Professor F.P. Lees. As yet the reports are not publicly available. However, much of the work undertaken at Loughborough has provided the momentum for this study.

The following pages review some of the more important and useful risk assessment studies which are publicly available. Each review provides a brief description of the study and highlights useful data, results and points of interest. A number of studies are also listed in the bibliography. It is envisaged that much useful data and techniques are detailed in internal HSE, SRD, MOD and ESTC risk assessment studies.

Risk Assessment of Air versus other Transportation Modes for Explosives and Flammable Cryogenic Liquids
Kloeber, G. et al. (December 1979). ORI, Inc., Silver Spring, Maryland, USA. NTIS, PB80-138480.

Risks associated with the conveyance of class A explosives and cryogenic liquids by aircraft, truck, rail car and barge are estimated and compared for six different routes. Class A explosives chiefly correspond to United Nations class 1 dangerous goods. All cryogenic liquids are assumed to be characterised by liquid hydrogen. The routes are compared by the derivation of an expected risk value based on the likelihood of

a. accidents,
b. incidents as a result of accidents,
c. fatalities, injuries and property damage.

The expected risk value is defined as "the likelihood of a loss-generating event times the amount of loss resulting from that event" and is characterised by the likelihood of certain severity levels resulting from specific accidents and events.

Although the report contains a multitude of detailed transport and accident data together with various simple consequence models, confidence is lost in the risk assessment results and conclusions due to a number of simplifying assumptions. Firstly, accident rates for vehicles conveying hazardous goods are assumed to be the same as vehicles conveying non-hazardous goods. It is shown in this thesis that such an assumption can lead to results of questionable accuracy (i.e. risk assessments employing common accident rates disregarding vehicle type and use are inherently misleading, even though they may loosely

approximate overall risks). Secondly, populations are assumed to be evenly distributed along journey routes (varying only by county). Such an assumption magnifies risks in areas of low population, such as rural areas, and provides an aggregated risk estimate which in reality does not represent the route analysed. Finally, casualties are calculated in relation to overpressure and fire intensity in a similar way to the consequence evaluation methods detailed in Chapter 7.0 of this study. However, all individuals are assumed to be affected by an incident as if they are situated out in the open. At any time of day the vast majority of individuals are indoors and therefore, for any given population, only a small minority of individuals are exposed to the direct effects of explosion and fire.

The culmination of the assumptions described above, together with the policy of conservatism where data are scarce, leads to little confidence in the risk assessment. It may be argued that a relative risk comparison can be made between the four transport modes. However, as a result of the assumptions on population distribution and accident rates and the difficulty in attributing equal "conservatism" to assumptions (as claimed), it is doubtful whether such an argument can be substantiated.

An Assessment of the Risks of Transporting Propane by Truck and Train

Geffen, C.A., et al. (1980). Pacific Northwest Laboratory, Richland, Washington, DC, USA. NTIS, PNL-2133.

Individual and societal risks are estimated using the probabilistic risk assessment methodology developed by Pacific Northwest Laboratory[19]. The methodology is discussed in "An Assessment of the Risks of Transporting Gasoline by Truck" reviewed later in this section. Assessment of risks resulting from propane transport is essentially the same as that for gasoline transport. Data and discussion are given on material characteristics, truck and rail car characteristics, origin and destination details and the transport and accident environments. It is estimated that two thirds of all propane consumed in the United States is moved by road and only about 3% by rail, the remainder being transported by pipeline. Significant propane releases resulting from road accidents are estimated to total 14 per year compared with only 1 significant release every 2 years caused by accidents on the rail network. Expected number of annual fatalities from road and rail incidents total no more than about 17 and 2.5 respectively. As the expected number of annual fatalities suggests the risks from rail transport are much less than those from road transport. The report concludes that the risks to the public from the road and rail transport of propane are comparable with many common risks and are less than those from the transport of gasoline by road.

Consequences of propane releases are quantified in terms of fatalities from the assessment of

a. direct flame exposure,
b. radiant heat,
c. secondary fires,
d. explosion effects.

As a result of shielding offered by buildings and vehicles etc. and possible reduction in the numbers of exposed individuals by evacuation efforts only 10% of the available population are assumed to be exposed. Deaths from direct flame exposure and radiant heat are related to fireball exposure, size and duration. It is assumed that all persons in direct contact with flames are killed. Deaths from radiation are related to distance and severity of burns. Second degree burns are used as the fatality criterion. It is estimated that the threshold for second degree burns is 5 cal/cm^2 and for average skin exposure (27% of body surface area), which equates to both arms and the head, the probability of death is given as 10%. The number of deaths from secondary fires is estimated from the number of subsequent building fires. All buildings are assumed to be constructed of whitewood so that a simple correlation between spontaneous ignition and radiant heat intensity can be used. The definition of whitewood and the reason for its choice is not given, but it is assumed that its choice is a direct result of the wide-spread use of wood in American buildings. Fatalities caused by explosion are based on the effects of overpressure and missiles. Consumed propane is equated in terms of TNT from which overpressure and missile generation can be estimated. All persons within the limit of total building destruction (0.69 bar) are assumed to be killed, whereas only 10% and 0.1% are assumed killed within the limits of serious structural damage (0.17 bar) and missile generation (0.02

bar) respectively.

As with gasoline assessment (reviewed later), it is thought here that the risk assessment methodology is applied conservatively (i.e. over-estimates the risks) and many assumptions are pessimistic. For example, all truck and rail car fires are assumed not only to be engulfing but to be immediately engulfing. However, sensitivity assessments have been performed and indicate that fires account for only a small proportion of the risks and that impact and puncture incidents account for over 80% of the estimated risks.

Risk Assessment Processes for Hazardous Materials Transportation

Transportation Research Board, Washington, DC, USA. (November 1983). NTIS, PB84-143635.

Risk assessment techniques which may be of interest to local authorities in their attempts to identify

a. risks to communities from the transport of hazardous goods,
b. mitigation strategies to reduce community vulnerability,

are reviewed. It is concluded that enumerative index models provide the simplest and most cost-effective risk assessment techniques for local authorities. Regression models, such as the one developed by Urbanek et al[20,21] are disregarded for two reasons; firstly, the magnitude of accident consequences are inadequately assessed and secondly, the models are more adapt at comparing transport

routes than assessing overall risks. Network and distribution models[22,23,24] are disregarded for similar reasons, whereas, probabilistic risk assessment models[19,25,26,27] are considered to be too time consuming and detailed for application by local authorities. The enumerative index model chosen is a simplified version of the model developed by Russell et al[28]. A risk index formulated from a simple scoring system based on traffic flow, route distance and accident consequences, etc., provides a means of assessing risks in relation to a pre-determined scale. Unlike the model developed by Russell et al[28] the simplified model is intended for use only on three hazardous goods, namely, gasoline, chlorine and anhydrous ammonia. The reasons for this simplification are based on the assumption that if these materials posses a low community risk then other hazardous materials will also posses a low community risk. This line of thought stems from the fact that for hazardous goods transport in the United States over 50% of all multiple fatality incidents involve these materials.

In addition to the development of the simplified model the report also provides a short review of the hazardous goods accident environment in the United States and details briefly the role of authorities, governments and academia in risk and community vulnerability assessment. It is interesting to note that the report states that fewer than 400 hazardous goods shipments from an annually estimated total of over 250,000 actually result in casualties. Between 1971 and 1980 more than 111,000 accidents involved hazardous goods causing a total of 248 fatalities and 6873 injuries. The average number of fatalities per year is estimated to be 25, of which 80% are attributable to highway shipments and 18% to railroad shipments.

The major criticism of this model is that it only provides a relative measure of risk, classifying risks as either low, medium or high. In addition, although the report criticises other models on account of being route specific and inadequate with regards to consequence assessment, these charges can be directed at this model. However, the risk assessment technique is simple to apply requiring little risk assessment knowledge and the data required as input to the model is readily accessible.

An Assessment of the Risks of Transporting Gasoline by Truck

Rhoads, R.E., et al. (November 1987). Pacific Northwest Laboratory, Richland, Washington, DC, USA. NTIS, PNL-2133.

Accident occurrence together with accident consequences are investigated and related providing a measure of individual and societal risk. The probabilistic risk assessment methodology used is based on a model previously employed at Pacific Northwest Laboratory (PNL) for the risk assessment of the transport of radioactive materials[29,30]. Risk is characterised by the simple addition of the individual products of risk (frequency) and consequence from all accidental releases. All risk values and consequences are tempered according to the amount and loss of material, prevailing weather conditions and population exposure.

The methodology is split into five discrete areas,

a. system description,
b. release sequence identification,
c. release sequence evaluation,
d. environmental consequence evaluation,
e. risk calculation and assessment.

System description essentially sets the scene identifying material characteristics, truck characteristics and origin and destination details. It is estimated that gasoline represents about a third of all hazardous material shipments in the United States and that for 1980 1.14×10^{11} gallons of gasoline are transported providing a total of 1.36×10^{7} shipments. An average shipment is thought to consist of a truck conveying 8400 gallons of gasoline over 50 miles.

Following system description the accident environment is investigated so as to identify and evaluate release sequences and thereby provide a basis for fault tree formulation. Special emphasis is given to fire, impact, puncture and abrasion. These four accident environments are considered the most likely causes of tank failure. Fires are estimated to occur in 1.6% of all truck accidents and have durations from as little as a few minutes to several hours. A typical vehicle fire having a mean temperature of 1010°C is considered to be sufficient to cause tank failure. However, it is thought that large quantities of gasoline may vaporise and escape through pressure relief valves before tank failure diminishing the consequences of such events. Impact is assessed in terms of velocity and kinetic energy. It is estimated that side impacts of the tank into flat barriers at speeds as low as 18.7 mph can cause tank failure. Tank failure by puncture is considered to result whenever a probe having a length of six inches or

more contacts the tank wall. This estimate is based on stress analysis of aluminium tank walls together with the energy available in truck accidents and assumes that probes exceed 0.4 inches in diameter. Abrasion is discussed in terms of skid velocity with respect to various road surfaces. Depending on road surface tank failure is considered likely at skid velocities as low as 20 mph.

Consequences of gasoline releases are assessed in terms of pool fires and vapour clouds. Of particular interest is the estimation of building damage and casualties. It is considered that total destruction of buildings, serious structural damage and missile damage can be expected at up to 30 ft, 75 ft and 300 ft respectively from the centre of an explosion. All occupants of destroyed buildings are assumed to be killed, whereas 10% of occupants in buildings suffering serious damage and only 0.1% of occupants within the missile range are assumed to receive fatal injuries. In addition, all vehicle occupants involved in initiating road accidents are considered to die. Unfortunately "road-side" and "street" populations are disregarded and therefore fatality estimates may be under-estimated.

The report concludes that individual risk (deaths/year) to a member of the public is comparable with that expected from natural disasters, such as tornadoes and lightning strikes. Societal risks are presented in the form of a frequency-consequence curve and are reproduced here in Figure 1. Two sensitivity assessments have been performed. The first identifies that over 90% of all spills result from punctures, impact and abrasion. It is postulated that increasing tank resistance to such failure stimuli by an order of magnitude reduces the expected annual number of deaths by as much as 70%. Secondly, the installation of accident activated fire suppression systems is assessed and

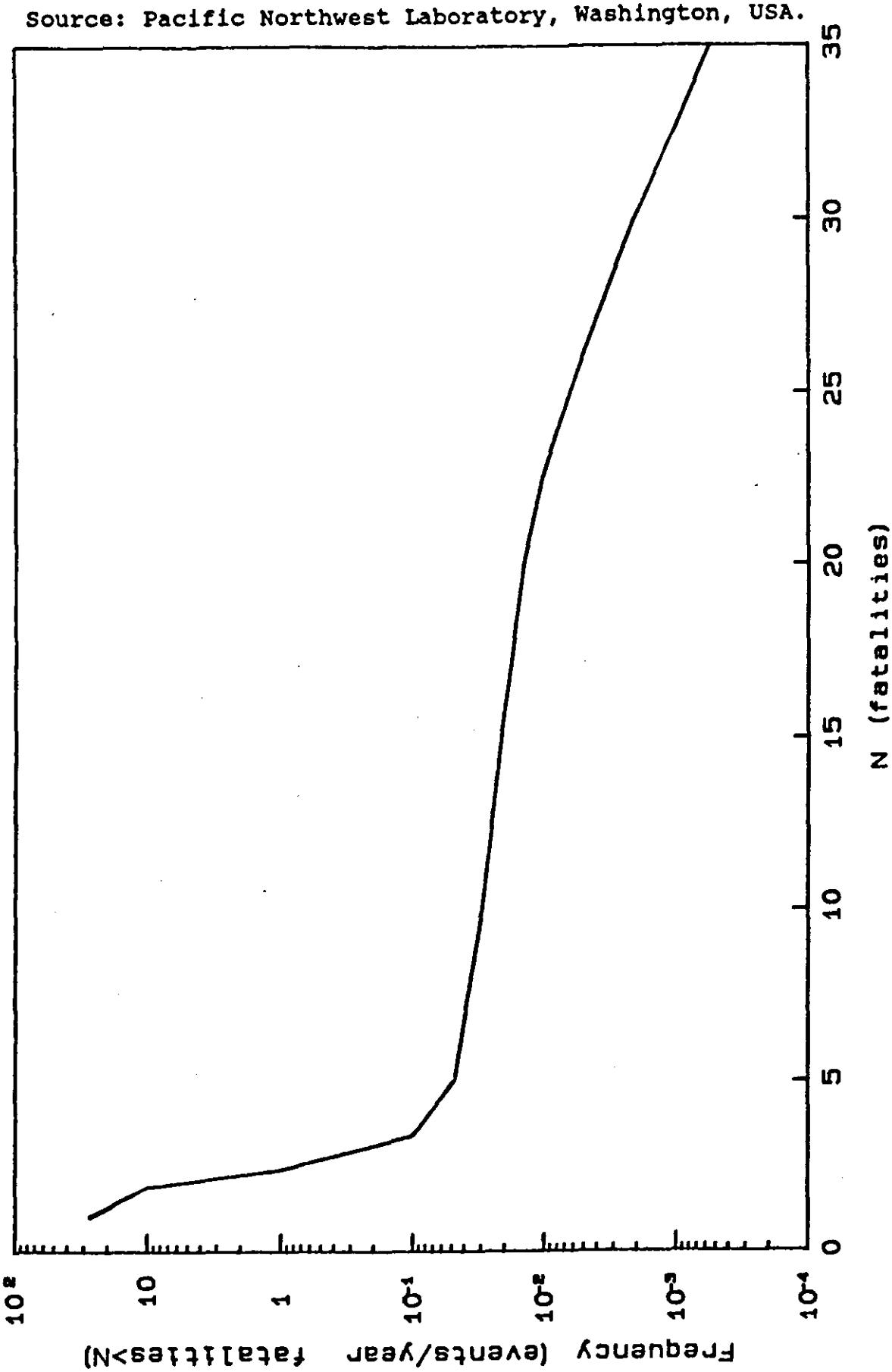
it is concluded that such systems have the potential to reduce expected fatalities to less than one per year. However, it is acknowledged that neither the results nor the sensitivity assessments provide a definitive basis for establishing socio-political acceptability levels of risk. It is suggested that the risk assessment provides a base for cost-benefit analysis and hence judgement on acceptability.

In addition to the methodology and risk analysis much information is provided on tank truck construction, operating procedures, the physical properties and characteristics of gasoline and general truck accident data. Of particular interest is the distribution of truck accidents with respect to pre-accident speed. From an analysis of 10,838 truck accidents in the state of Texas it is estimated that almost 54% of all accidents occur at 20 mph or less, about 27% between 20 mph and 40 mph, a little over 19% between 40 mph and 70 mph and only about 0.5% at speeds greater than 70 mph.

Finally, it is thought here that the risk assessment methodology is applied conservatively (i.e. over-estimates the risks) and therefore does not instil confidence in the accuracy of the derived risk values. However, the methodology is a well developed and proven approach to risk estimation and has been used extensively in the United States for assessing the transport of hazardous materials.

Figure 1: Societal risks for release of gasoline from tank truck accidents: 1980

Source: Pacific Northwest Laboratory, Washington, USA.



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8.2 Benefits, Limitations and Problems

Risk assessment studies involve systematic examination of intended operation and unintended operation of one or more systems. Such examination helps to

a. identify, illustrate and quantify the environment to which a system is exposed,
b. identify, illustrate and quantify the harmful effects from a system.

In addition to the above, risk assessment studies

a. lead to the improved understanding of risks and their component parts,
b. identify actions which can be taken to reduce or eliminate risks.

Thus, risk assessments provide a foundation from which judgements can be made on the acceptability of system risks. The Canvey investigation is a good example of a risk assessment study identifying and quantifying risks and suggesting ways in which risks can be reduced[31]. For example, the individual risk from Canvey (for those most at risk[32]) was estimated as 2.57×10^{-3} deaths per year. Safety measures were recommended and once implemented estimated individual risk was assessed as 7.0×10^{-5} deaths per year (both estimates are considered conservative - i.e. over-estimates). This reduction in risk highlights the benefits of risk assessment studies. Not only does it provide a means of determining risk reduction, it also provides a logical way of judging the benefits of implementing safety measures.

Although the benefits of risk assessment outweigh any criticism there are a number of limitations and problems. Perhaps the most criticised is the quality of data used. Assessments are only as good as the data they are based on. Therefore, the relevance and reliability of data are paramount to the validity of assessments in their prediction of system behaviour. Unfortunately, data are often scarce, incomplete or not directly applicable to the system under consideration. Consequently, assumptions have to be made which may necessitate the need to simplify the assessment. As a result of this a degree of uncertainty is introduced and confidence may be lost in assessment results. Such loss of confidence can also arise as a result of uncertainties in consequence modelling and vulnerability assessment.

It is important to note that risk assessments have been shown to omit a number of undesired events and that risk assessments of major hazards are thought to be at best 80% complete[33]. So as to minimise these problems it is essential that analysts have a thorough understanding of risk assessment techniques together with an appreciation and knowledge of the system being assessed. Poor appreciation of all possible factors which may affect events can produce results which are at best questionable. One study conducted in the USA estimated a figure for an LPG spillage of 10^{-53} per year. This figure is believed to be the lowest estimated in any risk assessment study[34]. It is suggested by Van de Putte[35] and Farmer[36] that values below about 10^{-6} should be treated with caution as often a sub-event has been omitted. Farmer also suggests that estimates below about 10^{-6} are meaningless if the parts forming them are not rigorously assessed and validated. However, there are many instances of estimated values in the range 10^{-6} to 10^{-9}. For example, the probability of being struck by lightning in the UK[37,38] is estimated as

10^{-7} per year, and the probability of death in the USA[39] from a major railroad crash is estimated as 8.4×10^{-9} per year.

The benefits, limitations and problems of risk assessment studies are summarised in Table 1.

Table 1: Benefits, limitations and problems associated with risk assessment studies

Benefits

1. Identify, illustrate and quantify,
   a. system environment,
   b. harmful system effects.

2. Improve understanding of risks.

3. Identify measures to improve safety and hence, reduce risk.

4. Quantify risk reduction measures.

5. Provide a basis from which the acceptability of risks can be judged.

Limitations and Problems

Assessment accuracy, applicability, validity and confidence can be lost as a result of the following.

1. The need for "quality" data, which is
   a. relevant,
   b. reliable.

2. The need to use assumptions as a result of
   a. scarce data,
   b. incomplete or limited applicability of data.

3. Risk assessment studies may fail to identify all possible events as a result of
   a. poor understanding of techniques by analysts,
   b. poor appreciation and knowledge of systems under investigation.

8.3 Presentation of Results (specific to this thesis)

The two most widely used expressions of risk are "individual" and "societal" and it is these expressions which are used in Chapter 9.0 of this study. Individual risk is defined by The Institution of Chemical Engineers[40] as

> "the frequency at which an individual may be expected to sustain a given level of harm from the realisation of specified hazards"

and societal risk is defined as

> " the relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realisation of specified hazards".

The difference between individual risk and societal risk is implicit in the definitions given above, namely, that individual risk takes no account of the numbers exposed. Individual risks and societal risks are commonly expressed in terms of deaths per unit time and both provide a basis for the comparison of risks from activities which can cause harm. Death is usually chosen as the measure of harm since it is easily identifiable and definite. However, there is a problem of delayed deaths from the realisation of a hazard. Most risk assessments avoid delayed deaths by the consideration of "instant" deaths or deaths within a measurable period. A method of accounting for delayed deaths from radiation exposure has been proposed by Bishop[41]. As yet no detailed proposals have been suggested for the assessment of delayed deaths from chemical explosions.

Individual risk is characterised by a single value indicating the chance of harm per unit time for a specified individual at a specified location. The fundamental expression of risk can be given by the following equation.

$$R = f \times p$$

where

R = individual risk (e.g. deaths/year)
f = frequency of an event with the potential to cause a specified level of harm
p = probability that an event causes a specified level of harm

As mentioned above individual risk takes no account of the numbers of people affected by a single event. It is widely accepted that the public have greater repugnance/aversion to single events which kill large numbers of people than multiple events which kill the same numbers but only one or two at a time. As a consequence of this, methods have been developed to measure risk in terms of frequency of occurrence and magnitude of consequence. This measure of risk is known as societal risk and requires information on the distribution of people around a hazard in time and space. Societal risk can be presented in tabular form but is commonly illustrated graphically as shown in Figures 2 and 3. Such graphical representation of societal risk is known simply as a frequency-number curve (FN curve) or "FN" line. The FN curve is most commonly made up of discrete data points; each point represents the frequency (F) at which a certain number (N) of people or more are killed. Thus, FN curves illustrate the cumulative frequency of killing N or more people. Societal risks can also be represented by non-cumulative means so that each discrete point represents the frequency of an event which

kills an exact number of people. This type of societal risk representation was first suggested by Farmer[5]. However, it is more usual to adopt the cumulative approach (proposed by Kinchin[42]) so as to "smooth" out data thereby allowing for instances where events may kill say 50 people but not 49, 51 or 52 people, etc.

In a similar fashion to individual risks, societal risks are useful for risk comparisons. In addition, judgements can be made on socio-political considerations. However, the FN curve approach has a number of other advantages. Historical data can be expressed and compared and prediction by means of extrapolation is possible.

Table 2 and Figure 3 illustrate various estimated individual and societal risks from a number of activities.

Note

For a complete understanding of the terms defined above reference should be made to the Institute of Chemical Engineers study on hazard and risk assessment nomenclature[40]. The study provides definitions for most terms encountered in risk assessment work. The terms used in this thesis reflect those given by the Institute of Chemical Engineers. Other definitions of risk assessment terminology are available[34,39,41] the most notably of which are those given by the Royal Society[43] in their study of risk assessment.

Table 2: Individual risks

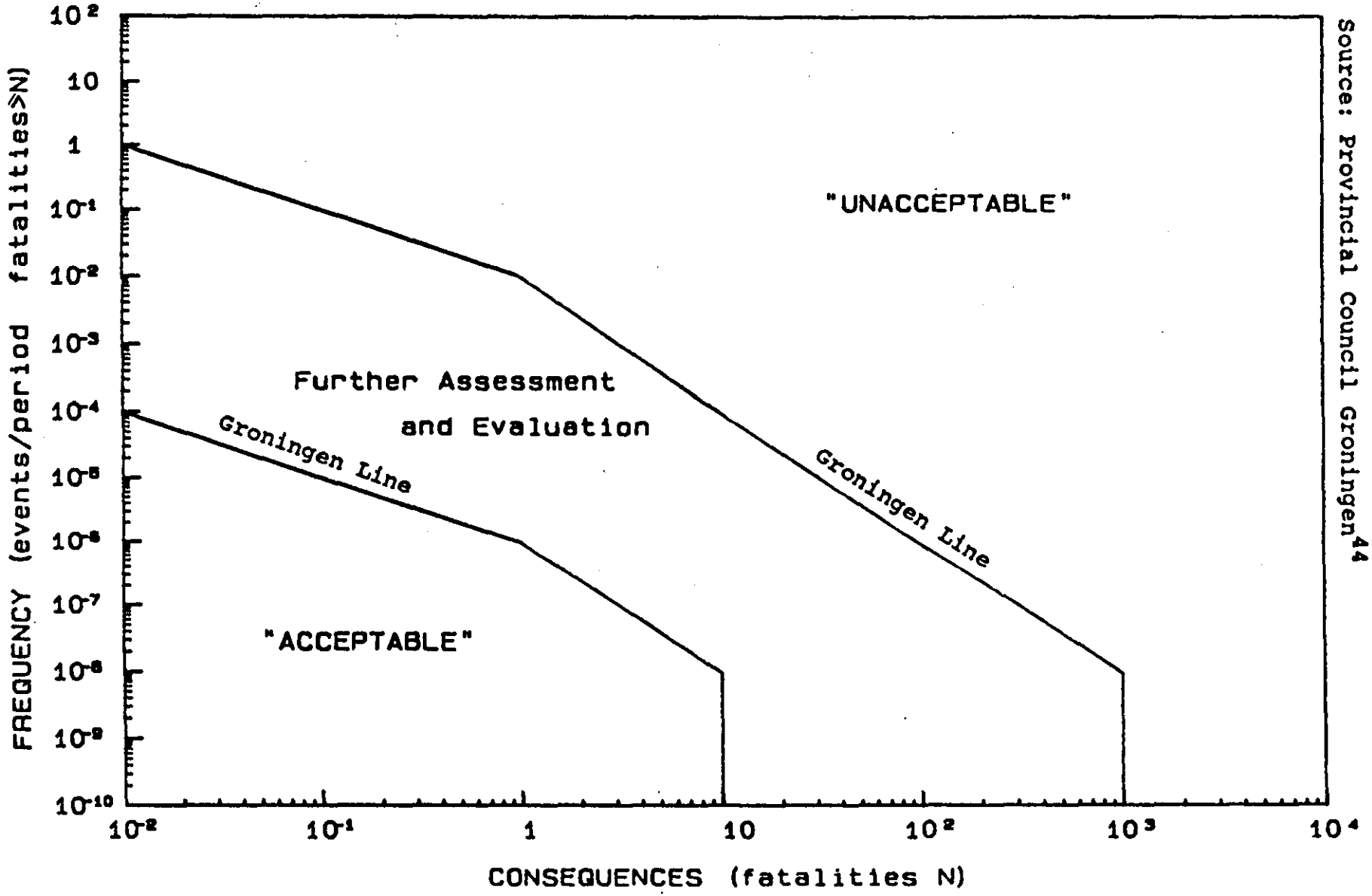
Cause of death	Individual risk (10^{-6}/year)
All causes	11900
Cancer	2800
All accidents(a)	343
Road accidents(a)	138
Motor vehicle accidents(b)	122
Road accidents	100
Railway accidents(a)	3.3
Gas incidents(c)	1.8
Lightning	0.1
Bites and stings(d)	0.085
Industrial accidents to employees	
Deep sea fishing(e)	880
Quarries	390
Coal extraction(f)	106
Construction(f)	92
Agriculture(f)	87
Offices, shops and warehouses	4.5
Risk of death as a consequence of travel	
Driving by car(g)	0.005 per million km
Flying(h)	0.0003 per million km
Rail travel(i)	0.00014 per million km

Note:

All values are mean values over the entire population of GB for the year 1985, unless otherwise stated.

a. 1971-5.
b. Excludes pedestrians 1975.
c. 1981-5.
d. 1958-78.
e. 1984.
f. 1986-7.
g. Drivers and passengers.
h. UK scheduled airlines, passengers 1975-9.
i. Passengers 1981-5.

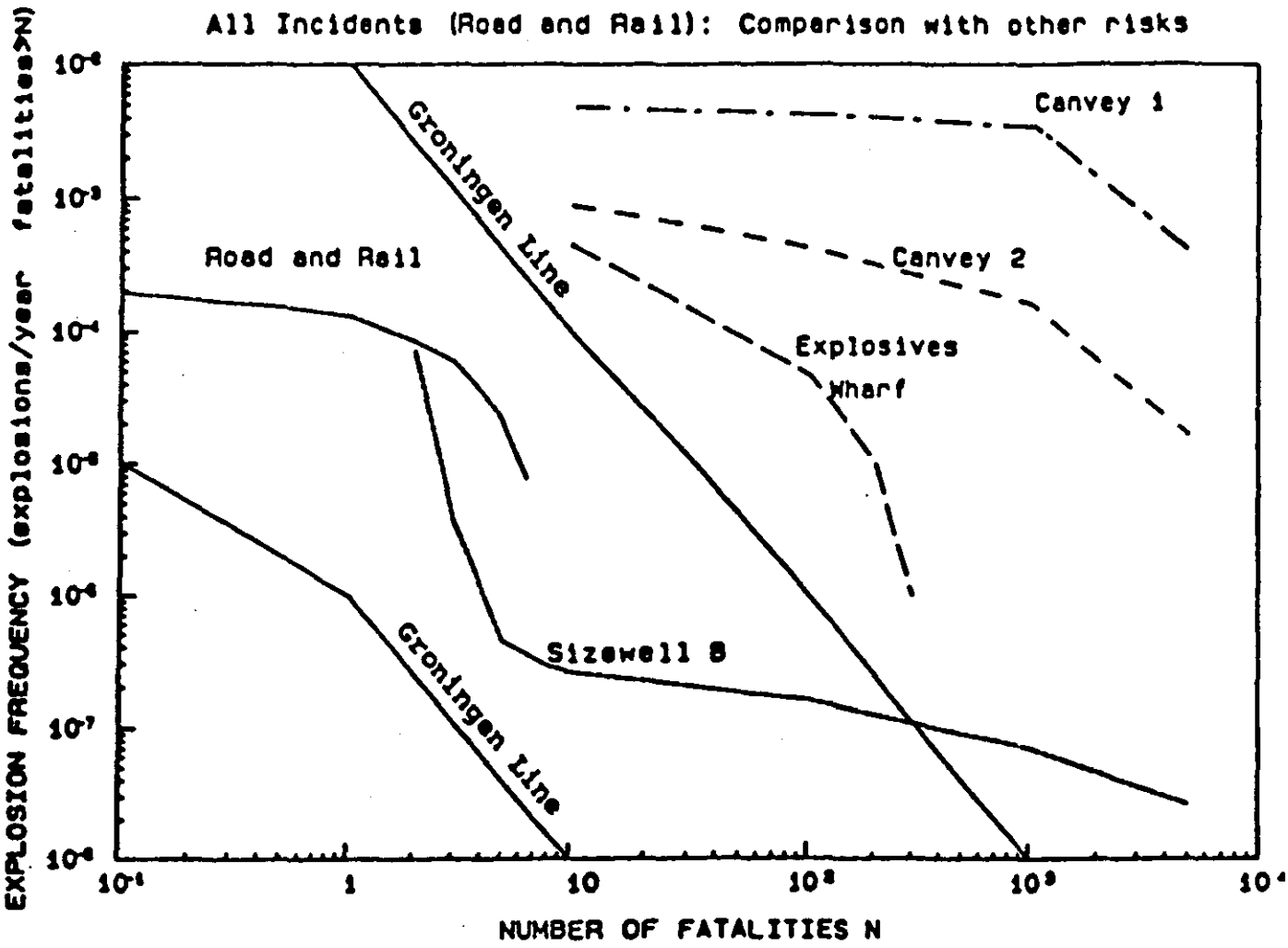
Source: Health and Safety Executive (see ref. 38 and 39)



Source: Provincial Council Groningen[44]

Figure 2: Provincial Waterstaat Groningen societal risk criterion

Figure 3: Some typical societal risk estimates



Source:

Canvey 1 - first Canvey report[10,32] (with proposed development)
Canvey 2 - second Canvey report[12,32]
Explosives wharf - HSE[32]
Sizewell B - one installation, implied design requirement[32]

8.4 Acceptability of Risks

Risk is inherent in almost all human activity, from driving a motor car to having one of the many rudimentary vaccinations as a child. In general the public have little perception of the risks incurred in daily activities. The chance of death per vaccination is one in a million (England and Wales 1967-76[43]), whereas, five people die annually for every 1000 km travelled by motor car (GB 1985)[45]. Risk, as discussed in Section 8.3 is expressed as a probability or frequency of the occurrence of a particular harm (assumed here to be death). However, there is little evidence to support the claim that the public understand such probabilistic risk expressions and therefore the significance and acceptability of risks. Essentially governments balance risks against benefits. This suggests that there is a level of risk which is acceptable provided the activity causing risk produces suitable benefits.

The question remains, "what is acceptable ?" Unfortunately for governments the public's perception of risk, especially if channelled and nurtured by opposing political factions and pressure groups, is critical to "acceptability". However, the public's perception is not a constant measurable factor as the 1982 attitude survey conducted by the HSE confirms[46]. The report states that only about two thirds of the UK population believe they are at risk from nuclear and chemical installations. Of these the majority feel that a substantial distance between themselves and such installations is needed for them to be free from worry (possibly 50 miles or more). Those living near major industrial installations consider the risks to be less than other members of the public and those on relatively high incomes tend to be the most worried that a

serious incident could occur.

As can be inferred from the above, public perception of risk is variable, often inconsistent and therefore difficult to measure. In addition the public are vulnerable to the "dread factor". It appears there is no advantage to be gained from suggesting that a two week holiday amongst the granite rocks of Cornwall will provide a greater dose of radiation than radiation leakage from the entire UK nuclear industry (normal activities over a ten year period), as suggested by Wrixon[47]. This is because, regardless of whether the public trust and believe scientific predictions, calculations and reassurances, and no matter how low the likelihood of occurrence they fear a catastrophic event, such as that which occurred at Chernobyl in March 1986 (the worlds worst civil nuclear disaster). This analogy applies to many activities and is tempered only by tangible benefits.

A number of proposals suggesting acceptable levels of risk have been put forward. Chicken[48] and Ashby[49] both suggest a value for individual risk of 10^{-6} per annum (i.e. a one in a million chance of death). It is often suggested[34] that a risk of 10^{-6} is acceptable for average members of the public and that for workers acceptable risk is about 10^{-5} per annum. However, as a result of

a. direct and indirect benefits to those exposed to risk activities,
b. direct and indirect benefits to the general public,
c. economic considerations,
d. political considerations,

levels of acceptable individual risk vary. Based on the above considerations (a-d) both the HSE[38] and the Royal

Society[43] state that the maximum tolerable risk to workers in any industry should be no more than 10^{-3}, and that the maximum tolerable risk to members of the public from large scale industrial hazards should be no more than 10^{-4}. A risk of 10^{-4} equates to the average annual risk of death from a traffic accident in GB[32]. However, these levels of risk are only tolerable where there is little choice but to accept such risks. The HSE estimate that the risk to the average worker in the nuclear industry (termed radiation worker) is between 10^{-4} and 10^{-5}. In comparison, the risk to members of the public living near to nuclear installations is estimated to be between 10^{-5} and 10^{-6} (during normal operations). It is acknowledged that there may be a small minority of workers and members of the public exposed to risks greater than 10^{-4} and 10^{-5} respectively. The (first) Canvey Report[10,32] estimates that the risk to individual members of the public was 2.57×10^{-3} and this was deemed to be intolerable, even allowing for the economic importance of Canvey. After improvements[12,32] the risk to individual members of the public was estimated as 7.0×10^{-5} and deemed tolerable. It should be noted that the term "acceptable" tends to be used by the HSE when risks are considered trivial. In comparison the term tolerable tends to be used when risks are endured in return for substantial benefits. At present the HSE propose a tolerable individual risk level of 10^{-5} for all new housing developments near existing major industrial hazards[32]. This value of individual risk is not, however, a fixed unyielding limit. This is because there are many other considerations which need to be taken into account when determining acceptability/tolerability. These other considerations are discussed in detail later in this section.

As with individual risk there is no uniformly applicable limit of acceptable societal risk. In their assessment of risk[32] and its tolerability[38] the HSE concluded that

> "where we have little choice but to accept a major societal risk, [not defined but clearly non-nuclear and capable of killing 500-1000 people or more] we require the risk to be less than 1 in 1000 [10^{-3}] and if possible less than 1 in 5000 [0.2×10^{-3}] per annum, that is, something like these are the maximum levels we would tolerate, and we would want to do better. But we might very reasonably demand a lower order of risk than this where we had some choice whether to accept it or not".

From HSE literature[32,38] it appears that an upper bound for societal risk tolerability from major industrial hazards is in-fact between 10^{-3} and 10^{-5} depending on specific circumstances.

In order to help classify societal risks, areas or bands have been proposed categorising societal risks into "acceptable/tolerable", "further assessment required/as low as reasonably practicable" and "unacceptable/intolerable" risks. The criterion suggested by the Provincial Waterstaat Groningen[44] is illustrated in Figures 2 and 3. From these bands acceptable and unacceptable societal risks are estimated to be about 1.5×10^{-6} and 1.5×10^{-2} per annum respectively. It has been remarked[50] that the differing totals of expected fatalities inferred by the criterion illustrate the measure of doubt in categorising risk in simple terms. It can be seen from Figure 3 that the estimated societal risks from Canvey[10,12,32] exceed the limit enclosing the area of "unacceptability". The societal risks estimated at Canvey (first report[10]) were initially deemed to be intolerable, but after improvements and a less

conservative assessment (second report[12]) they were deemed to be tolerable[32]. However, as the HSE points out the societal risks are only tolerable for the specific circumstances relative to Canvey. Figure 3 also details the societal risks from a Wharf handling explosives. Although the societal risks, when expressed as an FN curve, are substantially below those from Canvey they were deemed to be intolerable. Thus, it is apparent that although societal risks are informative they cannot be easily classified by FN curve representation or simply compared one with another. Obviously, (in a similar fashion to, and in conjunction with individual risks) other factor need to be considered and are critical to the acceptability of societal risks.

Estimating individual and societal risks is an important part in the quantification of risks. However, such quantification does not by itself determine the acceptability of risks. There are a number of unquantifiable factors such as

a. public aversion to particular risks (e.g. nuclear hazards, explosions of plant, etc.),
b. economic benefits,
c. political implications (international, national and local).
d. limitations of risk assessments,
e. nature of hazards.

However, these factors (a-e) and many others require some means of assessment and judgement. It is apparent that these considerations have been assessed to varying degrees, otherwise there would be no basis or justification for accepting risks shown to be greater than other risks deemed unacceptable (when expressed in individual and/or societal

terms). The HSE have produced a list of factors[32] which are useful in determining the acceptability of risks and these are reproduced here in Table 3. It is acknowledged by the HSE that the list is by no means exhaustive. In addition, from their analysis of a number of risk assessment studies, it is suggested that numerical weighting of factors is futile. This is because the factors tend to vary in their relative importance, are of a political nature, depend on the decision maker and the specific circumstances of the decision.

From this section it can be concluded that their are no hard and fast rules in the judgement of acceptability. It is apparent however that quantified risk assessments are an important part of the decision process.

Table 3: Factors of importance in judging acceptability (tolerability) of individual and societal risks

A: The hazard, the consequential risks and the consequential benefits.
1. The nature of the hazard and the risk it presents to the public. a. Is it natural or man made ? b. Does the hazard arise from a fixed installation or a distributed or mobile installation ? Does it present different aspects in different situations (as with most mobile risks) ? c. Does the hazard present a continuous or catastrophic risk ? d. Can the hazard arise in normal peacetime situations or only in war time or other extreme situations ?
2. The nature of potential effects upon health of the public; and the particular qualities of the harm, as a factor additional to the numbers that might be affected. a. How are the victims affected - through injuries, or induced disease ? b. What is the particular agent of possible death - impact, blast, fire, drowning, gassing or radiation ? c. Timing of harm - immediate or delayed ? d. Is the harm likely to be confined to immediate locality/spread over a wide region/spread internationally ? e. Are sectors of the public (e.g. infirm, old, young, etc) particularly at risk ? f. Is there a possibility of harm to future generations (i.e. through genetic effects) ?
3. Other consequential effects upon the public. a. Is there a possibility of interdicting other developments, or areas (i.e. Seveso or Chernobyl) ? b. Effect upon amenity prior to any accident (including manifestation of this in property prices) ?

Table 3: continued

4. Offsetting economic benefits.

Those exposed:
a. What proportion get a livelihood from the plant or proposed plant ?
b. What other benefits does the plant provide to the exposed community (e.g. support for leisure or community facilities, rate income, improvements to local amenity, or special prices for local consumers etc) ?

Those not exposed:
c. Can any judgement be made on the societal or economic benefit in general terms of the development proposed ?

B: The nature of the assessment.

5. The nature, purposes and limitations of the risk assessment.

a. What was its purpose - justification or optimisation, conservative or best estimate ?
b. Uncertainties in predictions of;
   (i). probabilistic calculations,
   (ii). consequences.

C: Factors of importance to those generating the risk, to government, or to regulators.

6. Economic factors influencing the occupier/developer/ regulatory agency.

a. The new plant vs. existing plant dimension; is the issue in question one of development (extension or creation of risk) or control (reduction of existing risk) ?
b. Is what is being proposed an extension to a new plant (or housing estate); or a new development on a green field site ?

Table 3: continued

c. Questions of reasonable practicability; can relatively cheap modifications significantly reduce the risks ?
d. Does substantial investment run the risk of being written off by disaster ? Is this risk insurable ? If not who will bear the cost (company/taxpayers) ?

7. Matters affecting the interest of the nation as a whole; and of local authorities.

a. The importance to the nation of the project, including both economic benefits and other benefits.
b. What is the purpose of the installation presenting the hazard ? Is it production/distribution of essential goods, public utility or private manufacturing or service/leisure activity ?
c. What are the available alternatives and the implications ?
d. What are the constraints arising from past decisions ?
e. How well could the nation, its institutions and its services, actually absorb the consequences of any really serious event ?
f. Where national societal risk enters into the equation stricter controls upon an industrial development may be required than local decision makers might themselves wish. A similar factor will apply, though in reverse, where a risk which is principally local in character is undertaken for a national benefit.

8. Relevant wider political aims of government, local government and interest groups.

a. Political objectives at national and local level.
b. The influence of organised pressure groups at local, national and international level.

Table 3: continued

D: Public attitudes
9. Dimensions of public concern about the inherent aspects of the activity and the consequential risks. a. Is it familiar and long established risk or a new and/ or dread risk ? Does at least a proportion of the public regard the plant as well established and secure ? b. Is it a voluntary risk ? c. Perception of associated benefits. d. Irreversibility of possible detriment. e. Unpopular associations in the minds of particular groups (e.g. "police state" said to be associated with "development of the plutonium economy"), or more substantial members of the public (an association of civil nuclear power with "the bomb" may be inferred to be influential in attitudes to nuclear power stations). f. Can one be confident that if one has survived one is not still at risk as a consequence of the original accident ? (Contrast Flixborough and Mexico City with Chernobyl and Bhopal). g. Has a similar accident occurred ? In particular, has it occurred fairly recently ? It will be borne in mind that "public attitudes" are rarely if ever homogeneous, and can be influenced in regard to any particular risk by factors or consequences which lie well beyond it. **10. Public confidence in authorities; government, regulatory authority, plant operators, experts and emergency services.** a. Public decision making process (does the public believe that all views have been heard, all alternatives have been considered and that the government has fairly considered the necessity of the proposal) ? b. The regulatory process (does the public have confidence in the effectiveness and independence of regulatory authorities) ?

Table 3: continued

c. Expert advice (does the public have confidence in the independence and quality of expert advice) ? d. What is known about the quality of the project and plant management ? e. Ability of emergency and medical services to cope with any event, either in the short or long term.

Source: Quantified risk assessment: Its input to decision making[32]

8.5 Risk Assessment Sensitivity

Results gained from risk assessment techniques are often presented in such a way that they appear definitive and absolute. It is therefore not surprising that many people are unconvinced of the scientific merit and validity of risk assessments, even allowing for the persuasive and convincing nature of statistics and probabilistic analysis. This is because presenting results in absolute terms neglects the fact that all risk assessments are subject to some error and uncertainty. It is generally agreed that most data are subject to uncertainty and therefore very few absolute values exist[34]. In addition, doubts exist as to

a. the relevance of data,
b. the accuracy of assumptions,
c. limitations inherent in risk assessment techniques,

all of which can affect accuracy and assessment validity.

It is apparent that all risk assessments need to be realistic in approach (i.e. a best-estimate) rather than conservative (i.e. err on the side of caution - over-estimate). This is because a policy of conservatism throughout an assessment will culminate not only in a conservative assessment, but one which may provide unrealistic and meaningless results. Paramount to any risk assessment study, therefore, is the need to assess and acknowledge

a. sensitivity of results with respect to uncertainties in data and assumptions,
b. relative importance of specific data, assumptions and estimates,
c. limitations of risk assessment techniques.

Dunster and Vinck[51] indicate a degree of error which can be expected from a risk assessment, they state that

> "Uncertainties in estimates of probability .... by factors of less than two or three can hardly be expected, and uncertainties by a factor of ten or more may occur"

Assuming that uncertainties in estimated values are as pessimistic as those suggested by Dunster and Vinck[51], then the accumulation of such factors may well lead to results which are orders of magnitude above/below reality. It is shown here that for only small errors in values, results can vary significantly.

Consider the probability of explosion of an imaginary vehicle laden with explosives as a result of crash and subsequent fire. The probability of explosion, P_x, is given by

$$P_x = P_a \cdot P_f \cdot P_e \cdot P_t$$

Where

P_a = probability of accident (crash) (10^{-4})
P_f = probability of fire given crash (2×10^{-3})
P_e = probability that fire becomes engulfing (0.05)
P_t = probability that engulfing fire is sustained for a duration exceeding that which explosive can passively withstand (0.8)

Hence

$$P_x = 10^{-4} \times 2 \times 10^{-3} \times 0.05 \times 0.8$$
$$= 8 \times 10^{-9}$$

Assuming that the estimated probabilities are no more than 10% in error provides a range of P_x between 1.17×10^{-8} and 5.25×10^{-9}, a variation of +46% and -34%. In this instance it is unlikely that such a large error (i.e. +46% or -34%) would occur in practice, the estimated probability most likely falling somewhere between 1.17×10^{-8} and 5.25×10^{-9}. However, uncertainties in estimates by factors of 2 or more are not uncommon in risk assessment studies. A large uncertainty in one of the above probabilities could possibly affect the estimate of explosion by orders of magnitude. For example, assuming an error in the estimation of engulfment by a factor of 3 (from the data given in Chapter 3.0 this is not unreasonable, i.e. a value of P_e between 0.017 and 0.15), provides approximately one order of magnitude between the lowest and highest estimate of explosion (i.e. 3×10^{-8} and 2×10^{-9}).

One view, expressed by Dunster and Vinck[51], suggests that risk assessment uncertainties can be limited, but not eliminated, by careful analysis and sound professional judgement. More precisely, JC Consultancy[34] suggest that sensitivity assessment is best served by

> "An allowance for errors .... incorporated into each stage of the analysis [assessment]"

The approach suggested above is of some considerable merit, although for a number of reasons

a. lack of data,
b. relevance of data,
c. differences of opinion amongst experts/analysts,
d. time constraints,
e. cost constraints,

it is rarely practicable. In cases where such an approach is impracticable, for one or more of the above reasons, then the best means of assessing sensitivity is by discretionary analysis of a number of estimates/data known or thought to be important. This approach is the one most favoured by analysts and others involved in risk assessment studies.

The sensitivity of risk assessment techniques themselves is dealt with in terms of limitations, and has been discussed in Section 8.2. Finally, it should be noted that sensitivity is often considered to be a technical or mathematical problem. However, it is not uncommon for risk assessment sensitivity to be affected by economic and socio-political factors. These factors are discussed in Section 8.4.

8.6 Monitoring Risk: Hazard Warning Structure

Although risk assessments may suggest a frequency of major hazard realisation so low as to be negligible, it does not alter the fact that realisation could occur tomorrow. In addition to this, almost all risks are the result of a number of events and sub-events, all of which are subject to change. Consequently, for risks to remain acceptable/tolerable they require a system by which they can be continually monitored. Such a system has been devised by Lees[52]. The system is known as "Hazard Warning Structure" and is similar in concept to fault tree analysis, in as much that

a. logic gates are used ("AND" and "OR"),
b. the hazard is illustrated in such a way that events leading to its realisation are clearly shown by a formal structure.

However, unlike fault tree analysis, where it is simply shown that a number of lesser events are necessary for the occurrence of higher events, hazard warning structure incorporates a concept used in pyramid models[53]

> "that as the severity of an accident [event] increases its frequency decreases"[52]

This concept is commonly illustrated in the form of an accident pyramid, such as that given by Heinrich[53] and shown here in Figure 4.

While combining features of both fault tree analysis and pyramid models[53] hazard warning structure introduces the concept of "time relation" between lesser and higher events. Thus, as concluded by Lees[52] hazard warning structure is not only useful in showing that the frequency of a major event is low, but also that

a. the probability is very low that a major event will not be preceded by a number of lesser events,
b. these lesser events serve as warnings from which remedial action can be taken to avoid the realisation of a major event (higher event).

The construction of a hazard warning tree essentially consists of identifying event-mitigation pairs and arranging these pairs in the form of a "tree". Such construction is not an exact science and it is possible to derive a number of trees for a particular system. However, the exact form of the tree is of minor importance provided selected events are observable, and measurable protection from escalation is offered by mitigating features. A typical hazard warning tree is shown in Figure 5. The top event or major accident is shown at level 3 and will only occur if there is failure of mitigating features at levels 1 and 2 (i.e. failure of mitigating feature 1 escalates event 1 into event 2 and failure of mitigating feature 2 escalates event 2 into the top event).

Mitigating features are expressed in the form of attenuation factors (>1) or attenuation fractions (<1). The most common means of expression is the attenuation fraction which equates to the probability of mitigation failure. As the attenuation fraction increases so its escalation protection diminishes. Depending on the protection offered these fractions are considered as "strong" or "weak". For

example, an attenuation fraction less than 0.1 is usually considered a strong feature providing a good degree of protection from escalation. In comparison, an attenuation fraction above 0.1 tends to be considered as a weak feature.

A number of examples illustrating the application of hazard warning structure, with respect to major industrial hazards, is given by Lees[55,56]. However, only one example refers to a transit hazard, this being the transport of liquefied natural gas by pipeline. Two further examples of hazard warning structure application, specific to transit hazards, have been given by Davies and Lees[17,18], These hazard warning trees relate to the transport of military explosives by road and rail in the UK. In both the assessment of road transit and rail transit, hazard warning trees detail separately fire and non-fire incidents. The hazard warning trees for the transport of explosives by road are reproduced here in Figures 6 and 7.

It is apparent that strong mitigating features need to be consolidated and maintained, since they provide good protection against escalation. In comparison, weak mitigating features require strengthening, so as to increase the assurance that a major event will not occur. Both the hazard warning trees shown in Figures 6 and 7 contain examples of strong and weak mitigating features, some of which can be controlled by management policy. The principal mitigating features shown by the trees are as follows.

Mitigating feature	Attenuation fraction (failure probability)
Non-exposure of a major target	0.01
Collision with other HGVs	0.05
Insufficient impact stimulus	<0.01*
Engulfing non-crash fire	0.05
Fire given crash	0.02

* For confidential reasons actual value is not disclosed.

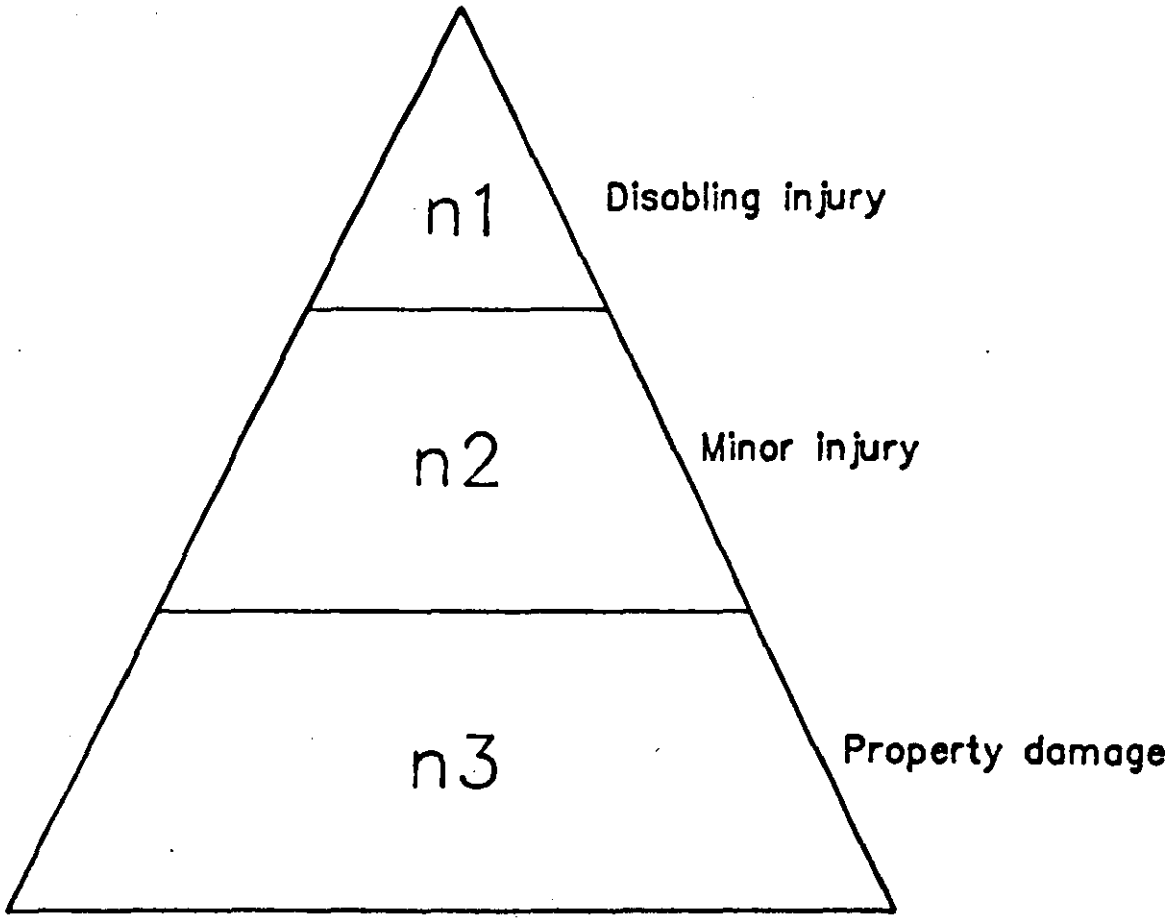
By far the strongest mitigating feature for non-fire incidents is "insufficient impact stimulus". It is suggested that this mitigating feature can be strengthened further by

a. stressing the importance of vehicle speeds to drivers and crew,
b. ensuring the enforcement of speed restrictions.

Limited control is also possible over target exposure, thereby strengthening the mitigating feature "non-exposure of a major target". This can be done, wherever practicable, by re-routing movements so as to avoid high density areas. In comparison, it is acknowledged that management have very little control over the strongest mitigating feature for fire incidents, that of "fire given crash". Similarly, only limited control is possible over vehicle engulfment given a non-crash fire. However, it is thought that both mitigating features, "fire given crash" and "engulfing non-crash fire" may benefit from

a. strict and thorough vehicle maintenance,
b. crew awareness and competence in first aid fire-fighting techniques.

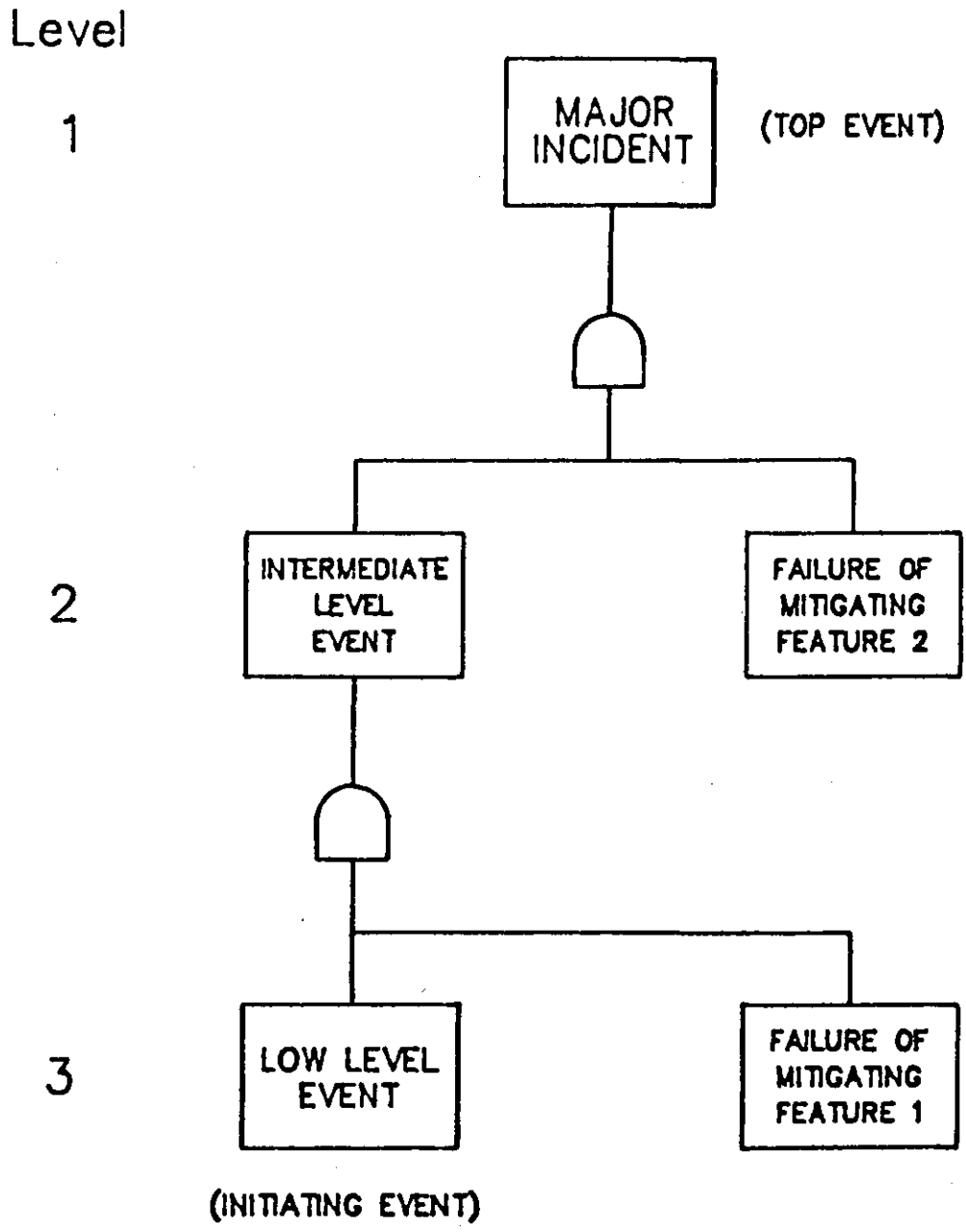
Figure 4: Accident pyramid



n1:n2:n3 is given as 1:29:300 (Heinrich[53])
and 1:100:500 (Bird and German[54])

Source: Lees[52]

Figure 5: A typical hazard warning tree



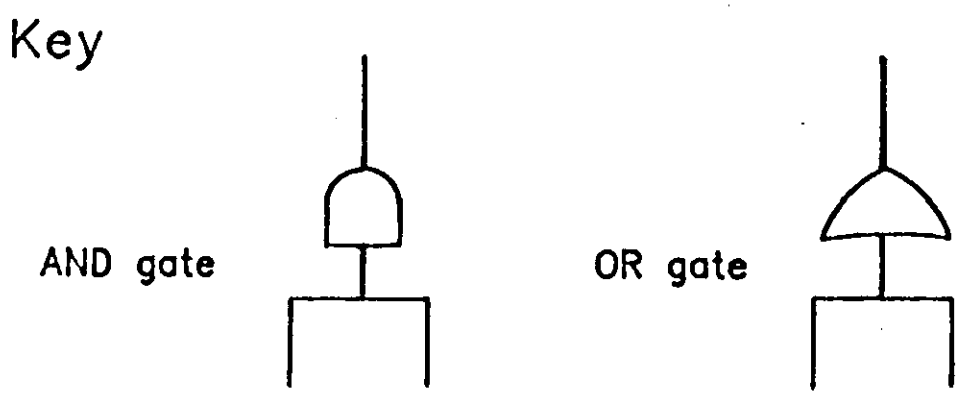
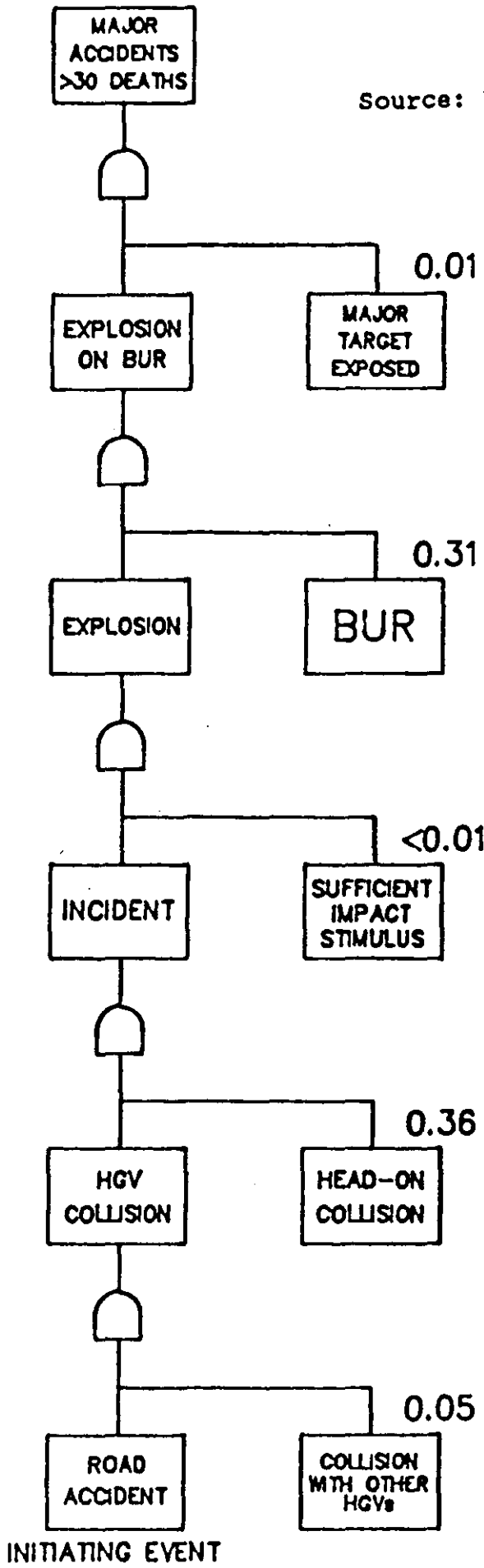


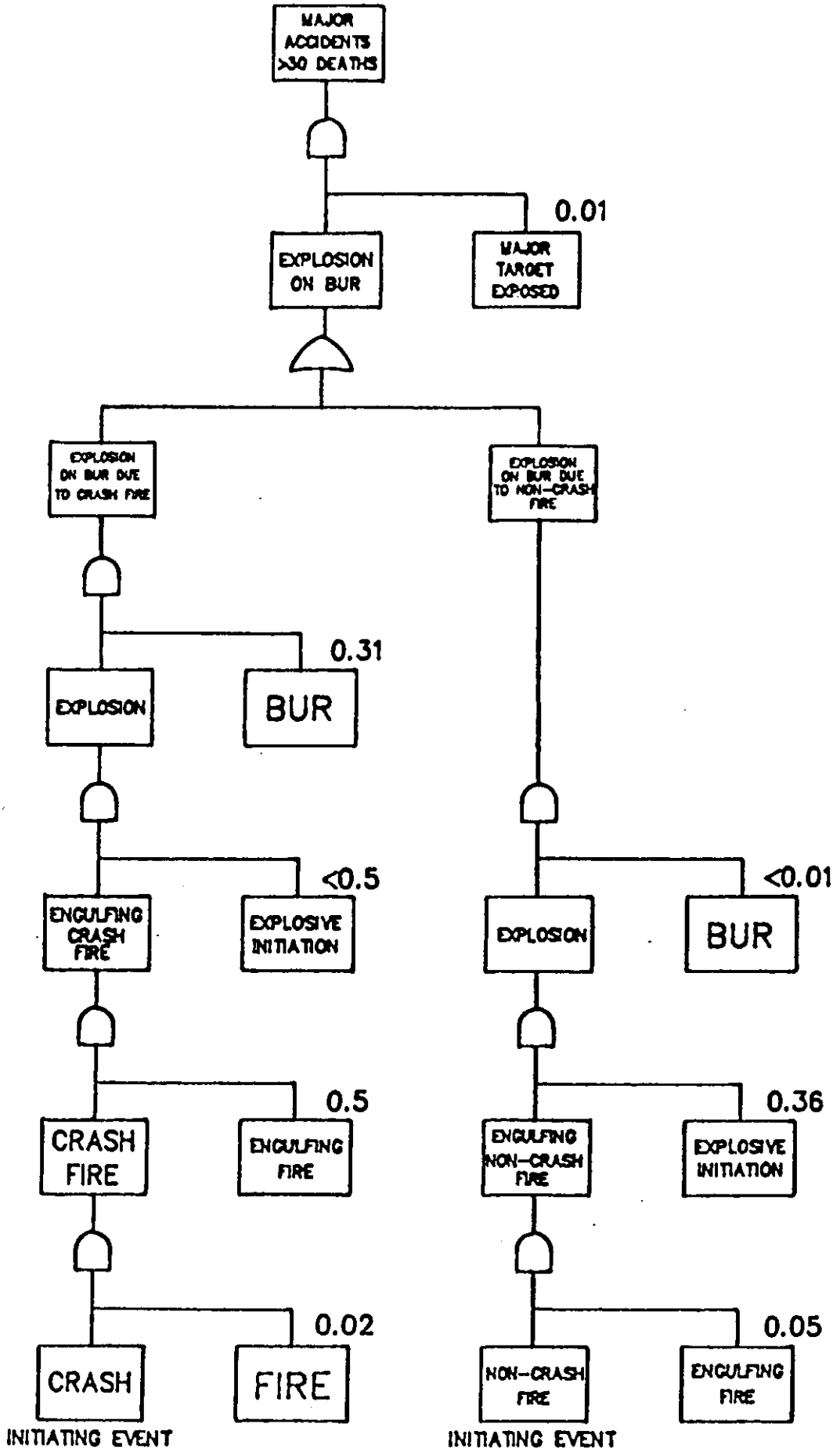
Figure 6: Hazard warning tree for a major accident resulting from the road transport of military explosives: Non-Fire incidents



Source: Davies and Lees[17]

Figure 7: Hazard warning tree for a major accident resulting from the road transport of military explosives: Fire incidents

Source: Davies and Lees[17]



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PART E

9.0 METHODOLOGY APPLICATION

Application of the risk assessment methodology developed in the preceding chapters is illustrated here for the rail transport of military explosives (i.e. munitions). Due to gaps in some of the data a number of simplifying assumptions are made. Rather than a series of definitive results the following should be considered as a demonstration of methodology application.

Consider the transport of mass initiating UN hazard division 1.1 (HD 1.1) munitions by rail through built-up areas (BUAs) in Great Britain. Munitions are conveyed in dedicated freight wagons by electric or diesel locomotives. Typical freight trains (FTs) conveying munitions consist of 20 wagons of which no more than 4 are laden with explosives[1]. Average net explosives quantity (NEQ) per wagon of HD 1.1 explosives approximates to 0.8 te. Distribution of wagon loads for HD 1.1 munitions is shown in Table 1. One half of all loaded movements involve HD 1.1 explosives. Loaded movements account for 0.5 million km; 10% of this distance is on track passing through built-up areas.

Table 1: Distribution of wagon loads: HD 1.1 munitions

Size of range (NEQ) te	Mid-Range value (NEQ) te	Proportion of all loads %
0 - 0.10	0.05	33
0.10 - 0.25	0.18	10
0.25 - 0.50	0.38	5
0.50 - 1.00	0.75	11
1.00 - 2.00	1.50	35
2.00 - 3.00	2.50	6

Note:

a. Data are based on a survey conducted by the author of rail movements from CAD Longtown between November 1987 and October 1988.

Source: Central Ammunition Depot[2]

9.1 Rail Transport: Non-Fire Incidents

9.1.1 Identification of accidents liable to cause explosion

The simulation approach adopted for the assessment of road vehicle collisions, and detailed in Chapter 6, Section 6.5.1, suffers from a number of impediments when applied to train collisions. The reasons for this are discussed in Chapter 6, Section 6.5.1. As a consequence of this, train accidents liable to cause initiation of explosives are identified and quantified here from data collated on train accidents, detailed in Chapters 4 and 6.

Only those accidents resulting in casualties and/or extensive damage are likely to incur stimuli having initiation potential. In addition, it is assumed that of those accidents only those possessing initial closing speeds above 35 m/s are likely to cause initiation. Accidents liable to incur sufficient impact stimuli have been previously identified in Chapter 6, Section 6.5.1 as

a. high speed collisions between rolling stock,
b. high speed collisions between trains and road vehicles at level crossings,
c. high speed collisions of trains with massive objects,
d. high speed collisions/derailments causing wagons to fall from bridges/viaducts onto hard surfaces.

9.1.2 Frequency of accidents

As mentioned in Chapter 4, Section 4.1, there is no evidence to suggest that FTs conveying hazardous goods are less likely to be involved in accidents than FTs conveying non-hazardous goods. As a consequence of this, regardless of load conveyed it is assumed that all FTs have identical accident rates.

The proportion of FT accidents that occur in BUAs is not known. Therefore, due to lack of suitable data it is assumed that the likelihood of FT accidents is independent of location. Thus, FT accidents per unit distance are the same in BUAs as in non-BUAs (i.e. 10% of travel distance occurs on track passing through BUAs, therefore, 10% of accidents occur in BUAs).

Freight trains travelled a total of 54×10^6 km on British railways during 1986 and were involved in 113 collisions. Of the 113 FT collisions 19 involved other rolling stock. It is assumed here that 1986 was a typical year for FT accidents between 1980 and 1989 (there is no evidence to suggest otherwise).

The frequency of accidents can be expressed per unit distance or per unit time. Hence

Frequency (accidents/km) of FT collisions with rolling stock in BUAs

$= 19 / 54 \times 10^6$

$= 3.52 \times 10^{-7}$ accidents/km

Loaded movements for FTs conveying military explosives (CME) equals 0.5×10^6 km.
10% of distance is covered on track passing through BUAs.

Frequency (accidents/year) of FT (CME) collisions with rolling stock in BUAs
$= 3.52 \times 10^{-7} \times 0.5 \times 10^6 \times 0.1$
$= 0.018$ accidents/year

Thus, it is estimated that there are 0.018 FT (CME) collisions with rolling stock per year in BUAs.

A total of 6 FT collisions occurred on level crossings[3] during 1986. The number of such collisions involving road vehicles is not known. However, it is argued in Chapter 4, Section 4.1.1, that approximately half of all level crossing collisions involve road vehicles. Similarly, it is not known how many of these collisions occur in BUAs. However, the vast majority of level crossings are protected in BUAs and therefore it is thought that no more than a third of BUA collisions involve road vehicles.

Frequency (accidents/km) of FT collisions with road vehicles on level crossings in BUAs
$= (6 \times 0.5 \times 0.33) / 54 \times 10^6$
$= 1.85 \times 10^{-8}$ accidents/km

Frequency (accidents/year) of FT (CME) collisions with road vehicles on level crossings in BUAs
$= 1.85 \times 10^{-8} \times 0.5 \times 10^6 \times 0.1$
$= 9.25 \times 10^{-4}$ accidents/year

Thus, it is estimated that there are 0.001 FT (CME) collisions with road vehicles on level crossings per year in BUAs.

Collisions with objects on the track are unlikely to cause extensive damage from impact. As noted in Chapter 4, Section 4.1.1, most objects lying on track include rail debris, animals and objects placed maliciously or otherwise. Such objects are of insufficient mass to endanger trains or their loads. As a consequence of this, initiation from collisions with objects on track is not considered further. However, such accidents can cause train derailment and subsequent collision with massive objects off the track and these collisions are considered here.

Derailments of FTs on British railways totalled 158 during 1986. It is not known how many of these resulted in subsequent collision with rolling stock or massive objects. However, from a study conducted by Taig[4], and detailed in Chapter 4, Section 4.1.2, approximately 2.6% and 4% of derailments lead to subsequent collision with rolling stock and objects off the track respectively.

Frequency (accidents/km) of FT derailments followed by subsequent collision with rolling stock in BUAs

$= (158 / 54 \times 10^6) \times 0.026$

$= 7.61 \times 10^{-8}$ accidents/km

Frequency (accidents/year) of FT (CME) derailments followed by subsequent collision with rolling stock in BUAs

$= 7.61 \times 10^{-8} \times 0.5 \times 10^6 \times 0.1$

$= 3.81 \times 10^{-3}$ accidents/year

Thus, it is estimated that there are 0.004 FT (CME) derailments followed by subsequent collision with rolling stock per year in BUAs.

Frequency (accidents/km) of FT derailments followed by subsequent collision with objects off the track in BUAs
$= (158 / 54 \times 10^6) \times 0.04$
$= 1.17 \times 10^{-7}$ accidents/km

Frequency (accidents/year) of FT (CME) derailments followed by subsequent collision with objects off the track in BUAs
$= 1.17 \times 10^{-7} \times 0.5 \times 10^6 \times 0.1$
$= 5.85 \times 10^{-3}$ accidents/year

Thus, it is estimated that there are 0.006 FT (CME) derailments followed by subsequent collision with objects off the track per year in BUAs.

Train derailment may occur whilst a train is passing over a bridge. Consequently, wagons have a likelihood of falling from bridges onto surfaces below. Railway Inspectorate accident reports detail damage and FT speeds. Using this information it is estimated here that derailment would need to occur at high speed, possibly 70 mph or more, for at least one wagon to leave the track with sufficient momentum to crash through bridge perimeters and fall onto surfaces below. From a study conducted by Taig[4], and noted in Chapter 4, Section 4.3, approximately 2% of FT derailments occur at 70 mph or more. Based on a survey of over 1500 km of rail track, Cook and Shears[5] indicate that 1 bridge is encountered every 1.64 km (average). Assuming

a. the survey is representative of British rail track,
b. incidence of bridges is the same in BUAs as in non-BUAs,
c. likelihood of derailment is the same at any point along the track,
d. average bridge length[5] equals 140 m which equates to an exposed bridge length of 70 m (from which wagons may fall),

then the frequency of FT derailments whilst passing over bridges followed by at least one wagon falling onto hard surfaces below can be calculated as shown.

Frequency (accidents/km) of FT derailments whilst passing over bridges in BUAs followed by at least one wagon falling onto surfaces below

$= (158 / 54 \times 10^{6}) \times 0.02 \times (70 \times 10^{-3} / 1.64)$

$= 2.50 \times 10^{-9}$ accidents/km

Frequency (accidents/year) of FT (CME) derailments whilst passing over bridges in BUAs followed by at least one wagon falling onto surfaces below

$= 2.50 \times 10^{-9} \times 0.5 \times 10^{6} \times 0.1$

$= 1.25 \times 10^{-4}$ accidents/year

Thus, it is estimated that there are 1×10^{-4} FT (CME) derailments leading to at least one wagon falling from a bridge/viaduct per year in BUAs.

9.1.3 Frequency of explosions

There is a possibility that one rail wagon explosion may propagate another rail wagon explosion (virtually instantaneously) (i.e. as a result of sympathetic explosion/detonation caused by overpressure and/or fragmentation). British Rail[6] maintain that wherever practicable rail wagons containing explosives are not marshalled "side-by-side", but are separated throughout the train. The Explosives Storage and Transport Committee[7] (ESTC) suggest a sympathetic explosion/detonation distance given by the equation

$$D = 0.8Q^{1/3}$$

where

D = distance beyond which sympathetic explosion/detonation is not expected to occur (m)
Q = mass of explosive (kg)

It should be noted that the equation given above is based on overpressure and is used chiefly on insensitive munitions, such as general purpose bombs and shells etc.. However, for the situation considered here it is thought to be a best estimate of sympathetic explosion/detonation.

Common rail wagons used for the conveyance of munitions, detailed in Appendix C, vary in length from 10.2 m to 12.8 m (over headstocks) (Railfreight wagon designations VAB, VBA, VBB and VGA). Assuming a distance of one typical rail wagon (similar to those used for the conveyance of explosives) between wagons containing explosives, together with an additional distance of no more than 2 m to account

for couplings and buffers, then just over 3.5 te (NEQ) of explosives have a chance of causing sympathetic explosion/detonation.

i.e.

$$10.2 + 2 = 0.8Q^{1/3}$$
$$\ln Q = 3(\ln 15.25)$$
$$Q = 3.55 \text{ te}$$

Military explosives are also conveyed by short wheelbase wagons (SWB) (5.3 m over headstocks). Based on the above sympathetic explosion for SWB wagons is possible from 0.73 te (NEQ) of explosives. However, SWB wagons are only used by BR on long-established private sidings and depots having sharp track curvatures. As a consequence of this, the use of such wagons is declining. It is considered that SWB wagons are much less likely to move along track in BUAs, compared with other common wagons used for explosives movements. In addition, SWB wagons have a carrying capacity of only 12 te compared with 29.5 te and 29 te for common 10.2m and 12.8m wagons respectively. The load movement survey detailed in Chapter 4.0, Section 4.5, indicates that the mean gross weight of typical munitions is between five and six times its NEQ. For a typical NEQ of 2 te this suggests that a gross weight of 12 te is not uncommon. Thus, it seems reasonable to assume that the greater NEQ loads are conveyed in the larger rail wagons. Therefore, the probability of 0.73 te (NEQ) or more of explosives loaded into SWB wagons is much less than that for the larger rail wagons. The load movement survey detailed in Chapter 4, Section 4.5, reveals that not one wagon issued from CAD Longtown between November 1987 and October 1988 and CAD Kineton between November 1988 and February 1989 was laden with 3.5 te (NEQ) or more of explosives. The largest recorded load (HD 1.1) in any one rail wagon was no more

than about 2.7 te (NEQ).

From the above, it is considered here that the vast majority of wagon loads capable of causing sympathetic explosion of other wagon loads are conveyed in 29.5 te and 29 te capacity rail wagons. Based on a train size of 20 wagons and at least one wagon (containing non-explosive goods) separating explosive laden wagons, and as a consequence of the fact that average wagon loads consist of 0.8 te (NEQ) of explosives and rarely exceed 2.5 te (NEQ), sympathetic explosion is not considered further. It should be noted that neglecting sympathetic explosion does not greatly affect calculated risk values. However, the affect of sympathetic explosion on individual and societal risks is detailed in Section 9.5.4.

Wagon exposure is dependent on a number of factors such as accident type and position in train. However, wagons are not marshalled together and therefore wagons are unlikely to experience identical accident environments. As a consequence of this, and in the absence of the risk of sympathetic explosion, it is assumed here that only one munitions wagon explodes per explosion incident.

Freight train accident speeds are detailed in Chapter 4, Section 4.3. Unfortunately, the data collected do not discriminate between collision types and are thought to be a biased sample. The reasons for this are discussed in Section 4.3. It is sensible to assume that the closing speed of head-on collisions will tend to be greater than for other collision types. However, the data do not convincingly support this. It is important to note that even with sufficient data to distinguish between collision types the probability value derived below would not alter

the explosion estimates significantly.

From the FT closing speed distribution given in Chapter 4, Section 4.3, the probability that an FT collides (with other rolling stock) at a combined impact speed of 78 mph or more (i.e. 35 m/s, minimum speed to cause impact initiation) is approximately 5×10^{-5} (based on a mean FT closing speed of 27 mph).

i.e. $P[(x) < X]$

$$= P\left[\frac{(78 - 27)}{13.18} < Z\right]$$

$$= P[(3.87) < Z]$$
$$= I(3.87)$$
$$\approx 5 \times 10^{-5}$$

Glancing collisions with rolling stock, in the main, cause only minor train damage (although they account for about 25% of all FT collisions[4]).

Frequency (accidents/km) of FT glancing collisions with rolling stock in BUAs

$= 3.52 \times 10^{-7} \times 0.25$

$= 8.80 \times 10^{-8}$ accidents/km

Frequency (accidents/year) of FT (CME) glancing collisions with rolling stock in BUAs

$= 8.80 \times 10^{-8} \times 0.5 \times 10^{6} \times 0.1$

$= 4.4 \times 10^{-3}$ accidents/year

The frequency of glancing collisions are given above for completeness only. Compared with other collision types they are extremely unlikely to introduce stimuli capable of initiating munitions. The minor nature of glancing collisions is supported by a number of FT reports studied by the author. Consequently, FT glancing collisions are excluded from the following explosion estimates.

One half of all loaded movements involve HD 1.1 munitions. Hence

Frequency (explosions/year) of FT explosions resulting from collisions with rolling stock in BUAs

$= (0.018 - 4.4 \times 10^{-3}) \times 5.0 \times 10^{-5} \times 0.5$

$= 3.40 \times 10^{-7}$ explosions/year

From the level crossing accidents recorded in the freight train accident (FTA) survey and detailed in Chapter 4, Section 4.2, it is apparent that a small proportion of level crossing accidents have the potential to cause extensive train damage. It follows that such accidents may introduce stimuli capable of initiating military explosives. No data are known to be available which would help quantify level crossing accidents by their severity and hence initiation potential. Therefore, it is assumed here that all level crossing accidents with road vehicles which occur at 35 m/s or more are capable of initiating munitions. In addition, it is assumed that the probability of such accidents occurring at 35 m/s or more is the same as that estimated for collisions between rolling stock.

A significant proportion of level crossing accidents involve road vehicles impacting trains rather than trains impacting road vehicles[8] (22%). From data obtained through the Metropolitan Police Forensic Science Laboratory[9],

regarding HGV impact speeds, together with information supplied by the Transport and Road Research Laboratory[10], it is concluded that the proportion of road vehicle impacts at 35 m/s or more in BUAs is no more than about 5×10^{-5} (by coincidence this value is the same as that estimated for train impacts at 35 m/s).

Frequency (explosions/year) of FT explosions resulting from collisions with road vehicles on level crossings in BUAs

$= 9.25 \times 10^{-4} \times 5.0 \times 10^{-5} \times 0.5$

$= 2.31 \times 10^{-8}$ explosions/year

As with rolling stock collisions it is assumed here that only FT derailments which result in subsequent collision with rolling stock or massive objects at 35 m/s or more are capable of initiating military explosives. For a rolling stock collision the probability that it occurs at 35 m/s or more has been estimated previously as 5×10^{-5}. It is considered here that this value is a good estimate for all train collisions at 35 m/s or more.

Frequency (explosions/year) of FT explosions resulting from derailment and subsequent collision with rolling stock in BUAs

$= 3.81 \times 10^{-3} \times 5.0 \times 10^{-5} \times 0.5$

$= 9.53 \times 10^{-8}$ explosions/year

The likelihood of FT collision following derailment whilst the derailed FT is still moving is considered here to be so small it can be neglected (accounting for such collisions would have negligible effect on the explosion estimates given below).

From a survey of FT derailments conducted by Taig[4] it is considered here that about 2% of FT derailments occur at 35 m/s or more. However, for impacts to occur with objects off the track, at 35 m/s or more, it is suggested that derailment would need to occur at speeds well over 40 m/s. Obtainable speeds of FTs are considered here to be no more than 100 mph (at the most extreme). It is estimated that about 0.1% of FT derailments occur at 40 m/s or more. The probability of hitting a massive object is thought to be very small. Assuming a typical journey of 350 km, no more than about 5 km over which there are objects off the track (presenting a potential collision accident), and of these only 20% massive, then the probability of hitting a massive object for the constraints given here is estimated as 3×10^{-3}.

Frequency (explosions/year) of FT explosions resulting from derailment and subsequent collision with massive objects off the track in BUAs

$= 5.85 \times 10^{-3} \times 0.001 \times 3.0 \times 10^{-3} \times 0.5$

$= 8.78 \times 10^{-9}$ explosions/year

For initiation to occur from FT derailment and subsequent wagon impact, as a result of falling from bridges, a bridge height in excess of 60 m is required (for a terminal wagon impact speed of 35 m/s or more). From a survey of over 1500 km of track[5] no bridge was recorded as exceeding 50 m (at its highest point). As a consequence of this, and in addition to the small proportion of exposed bridge length at maximum height, and the fact that not all impacted surfaces will be hard and "unyielding" (i.e. surfaces will include trees, other vegetation, lakes, and rivers etc.), explosion as a result of falling from bridges is thought to be considerably less than for other causes calculated above and therefore is not considered further.

Using the explosion frequencies calculated here the overall frequency of explosions resulting from non-fire incidents can be estimated.

Frequency (explosions/year) of FT explosions resulting from non-fire incidents in BUAs

$= 3.40 \times 10^{-7} + 2.31 \times 10^{-8} + 9.53 \times 10^{-8} + 8.78 \times 10^{-9}$

$= 4.67 \times 10^{-7}$ explosions/year

Thus, it is estimated that there are 5×10^{-7} explosions per year as a result of FT non-fire accidents in BUAs.

9.1.4 Explosion consequences

The "explosion effects" model developed at Loughborough by Withers and Lees[11] and described in Chapter 7, Section 7.5, is used here to determine individual and societal risks. A number of critical assumptions, many of which are detailed in preceding chapters, are required so as to calculate risk values.

a. Explosion is instantaneous, hence no evacuation is possible[a].
b. Average population density[b] equals 4000 persons/km^2.
c. Populations are situated on both sides of track (i.e. double-sided track).
d. Munitions may be transported at any time during the day or night, therefore average house occupancy equals 2.5 persons per dwelling[b].
e. No route incurs more than 1% of annual traffic[6].
f. Large loads are not disproportionally allocated among journey routes.

g. Average distance travelled through BUAs equals 35 km per movement[1].

h. Only 1 munitions wagon explodes per incident.

Note:

a. See Chapter 6, Section 6.5.2.

b. See Chapter 7, Section 7.4.

It is not known how many movements crew members undertake per year. Therefore, a judgement is made here that no individual is involved in more than 2% of all annual movements[1,6,12]. The probability of death resulting from an event is taken as unity.

Individual exposure = 0.02
Probability of death = 1.0
Frequency of explosion = 4.67×10^{-7} explosions/year

Hence

Individual risk (FT crew)
= $0.02 \times 4.67 \times 10^{-7}$
= 9.34×10^{-9} deaths/year

This is the risk to an individual member from a "pool" of train crew used in a single year. The number of deaths expected from the "pool" assuming that there are 2 crew members per movement is estimated as 9.34×10^{-7} deaths per year (i.e. 1 death every 1 million years). This estimate assumes that crew members have no possibility of escape prior to explosion. Thus, there are 2 crew deaths per explosion.

Based on an average wagon load of 0.8 te (NEQ), primary and secondary death circle radii are 12.8 m and 73 m respectively. These radii are derived from the "explosion effects" model detailed in Chapter 7, Section 7.5.2 (including Figure 8).

As outlined in Chapter 7, Section 7.5.2, "primary" refers to death by direct effects. The numbers who survive within the zone are assumed to be balanced by those who die outside. Similarly "secondary" refers to a zone within which dwellings are made uninhabitable, and only a fraction of people killed (1 death for every 10 uninhabitable dwellings).

From the "explosion effects" model an effective or equivalent death circle radius can be identified. In this case the effective death circle radius approximates to 14 m, as shown below.

Note:

a. Although FTs conveying explosives pass through BUAs it is thought that very few people actually reside within 20 to 30 metres of rail track. Accounting for the distance between track and inhabitable dwellings effectively eliminates deaths from primary causes and reduces the number of expected deaths within the secondary death circle.

Hence

Secondary area

$= \# \times 0.073^2$

$= 0.017 \text{ km}^2$

Secondary area (void of dwellings)
= # x 0.025^2
= 1.96×10^{-3} km^2

Number of dwellings in secondary area
= (population density/house occupancy) x area
= (4000/2.5) x ($0.017 - 1.96 \times 10^{-3}$)
= 24.1 dwellings

Number of secondary deaths
= number of dwellings x deaths per dwelling
= 24.1 x 0.1
= 2.41 deaths

Total number of deaths
= 2.41 deaths

From the total number of deaths an effective death circle radius can be estimated.

R^2 = (2.41) / (4000 x #)
R = 13.8 m

Using the effective death circle radius calculated above, together with the traffic incurred per route per year and the BUR distance per movement, public exposure along a typical route can be estimated.

Proportion of annual traffic = 0.01
Death circle diameter = 27.6 m
BUR distance per movement = 35 km

Hence

Exposure probability

$= (27.6 / 35 \times 10^3) \times 0.01$

$= 8.0 \times 10^{-6}$

From this estimate individual risk to members of the public can be calculated.

Exposure probability $= 8.0 \times 10^{-6}$

Frequency of explosion $= 4.67 \times 10^{-7}$ explosions/year

Hence

Individual risk (members of the public)

$= 4.67 \times 10^{-7} \times 8.0 \times 10^{-6}$

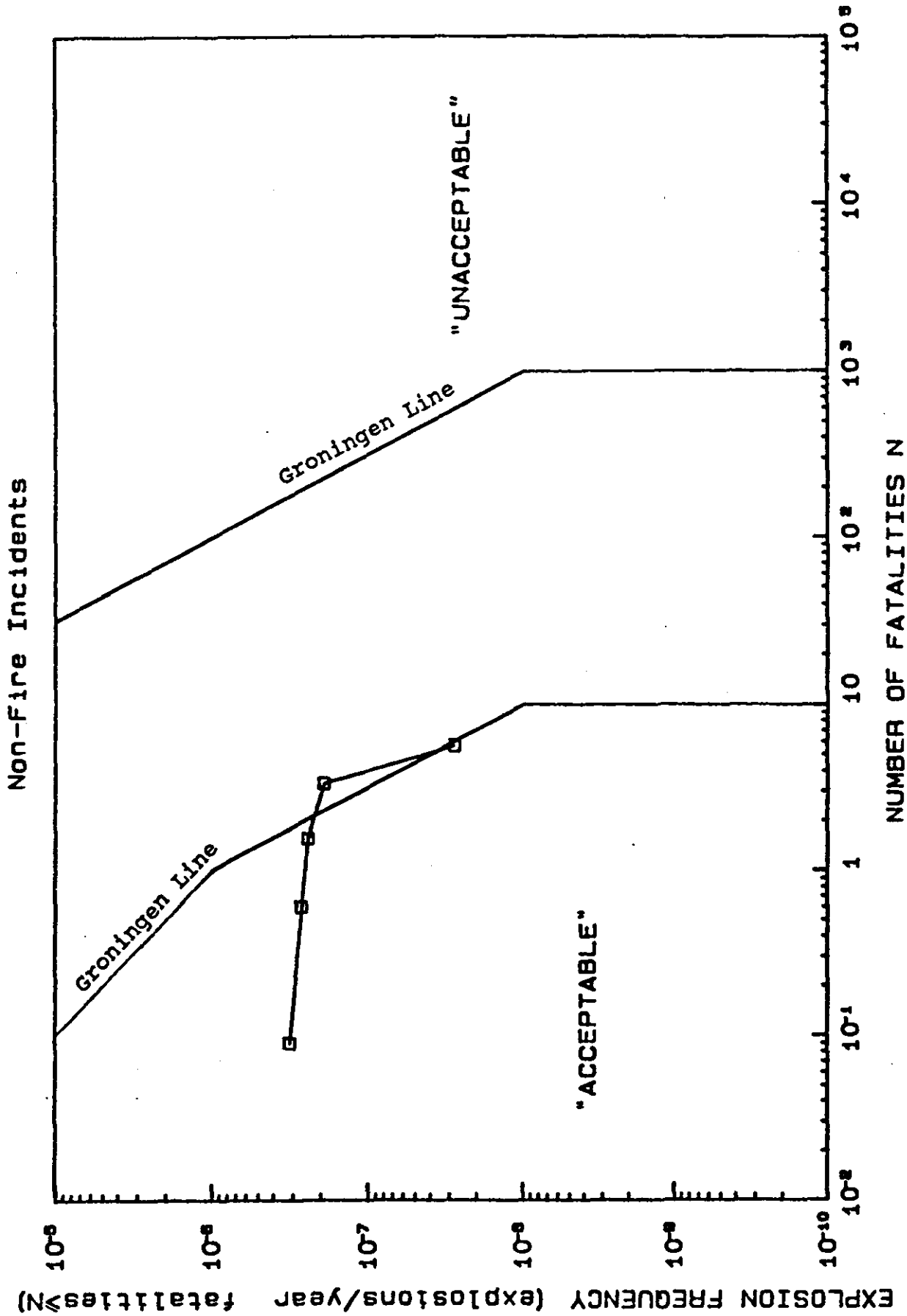
$= 3.74 \times 10^{-12}$ deaths/year

Societal risks from non-fire incidents are derived from the "explosion effects" model[11] and detailed here in Table 2 and Figure 1.

Table 2: Estimated frequency-size distribution of explosions of wagon loads (HD 1.1) in built-up areas and resultant fatalities: Rail Transport: - Non-fire Incidents

Mass of explosive te	Frequency (point) explosions/year	Fatalities	Frequency (cumulative) deaths > N/y
2.50	0.28×10^{-7}	5.62	0.28×10^{-7}
1.50	1.64	3.34	1.92
0.75	0.51	1.54	2.43
0.38	0.23	0.60	2.66
0.18	0.47	0.09	3.13
0.05	1.54×10^{-7}	--	4.67×10^{-7}

Figure 1: Fatality distribution (FN) curve for explosion of a munitions wagon in a built-up area: Rail transport: - Non-Fire Incidents



9.2 Rail Transport: Fire Incidents

The vast majority of explosives are sensitive to thermal stimuli. It is assumed here that all military explosives transported by rail are sensitive to thermal initiation. Suitable thermal initiation sources are absent in the normal transport environment. However, engulfing and sustained fires, as a result of accidents and faults, can cause initiation.

9.2.1 Identification of fires liable to cause explosion

In a similar fashion to the treatment of non-fire rail incidents, it is considered here that only those fires which result in casualties and/or extensive damage are likely to cause wagon fires capable of initiating military explosives. From the freight train accident (FTA) survey, conducted by the author and detailed in Chapter 4, Section 4.2, both crash and non-crash wagon fires are identified as potentially engulfing and sustainable, and therefore, liable to cause initiation of munitions.

Explosives cannot be conveyed with flammable liquids having flash points below 21 °C. These liquids are classed as highly flammable liquids by British Rail and include most dimethyl solutions, acetones and petroleum fuels. However, explosives can be conveyed with flammable liquids provided their flash points are between 21 °C and 55 °C. Flammable liquids within this category (British Rail class 3b) include some petroleum fuels, alcohol solutions and common liquids such as kerosene (paraffin). The author has been unable to obtain actual data on the proportion of rail

movements that involve both military explosives and flammable liquids. It is estimated from discussions with British Rail[1] that no more than about 60 movements out of a total of between 10000 and 11000 movements (per four weeks) have the possibility of conveying explosives and flammable liquids (i.e. a mixture of class 1 and class 3b goods). Therefore, the proportion of movements involving military explosives and flammable goods is thought here to be very small (much less than 0.5%) and British Rail[1] consider such traffic movements to be extremely unlikely. As a consequence of this, fires caused by the ignition of flammable liquids are not considered further. It is suggested that neglecting fires caused by flammable liquids will not greatly affect the risk values calculated here.

Fires occurring in locomotives are unlikely to spread beyond themselves or the immediate barrier wagon. Thus, locomotive fires as a source of wagon engulfment are also ignored.

Potential Incidents

a. Fires not associated with running-line accidents, causing casualties and/or extensive damage, resulting from, or leading to, sustained wagon engulfment.
c. Severe collisions and derailments, causing casualties and/or extensive damage, resulting from, or leading to, sustained wagon engulfment.

9.2.2 Frequency of fires

During 1986 a total of 53 FT fires occurred on British railways[8]. It is not known how many of these fires occurred on track passing through BUAs. However, it is argued in Chapter 4, Section 4.1.3, that about 17% of FT fires occur on track in BUAs. Assuming 1986 to be a typical year for FT fires on British railways (there is no evidence to suggest otherwise), and from the fact that FTs travelled 54×10^6 km during 1986, 10% of which was on track in BUAs, then

Frequency (fires/year) of FT fires in BUAs
$= 53 \times 0.17$
$= 9.01$ fires/year

The frequency of accidents can be expressed per unit time and per unit distance. Hence

Frequency (fires/km) of FT fires in BUAs
$= 9.01 / (54 \times 10^6 \times 0.1)$
$= 1.67 \times 10^{-6}$ fires/km

The above fire rate only applies to FT non-crash fires. This is a direct result of the way in which fires are recorded and classified by the Railway Inspectorate. Fires tend to be secondary features when classifying accidents. For example, collisions or derailments accompanied by subsequent fire are simply classed as collision or derailment accidents (for further details refer to Chapter 4, Section 4.1.3).

As noted in Chapter 4, Section 4.1.3, only about 18% of fires occur in non-powered rolling stock (i.e. wagons, etc.), and of these 40% are the result of leaking tank wagons laden with flammable liquids. Ignoring locomotive fires and FTs conveying tank wagons containing flammable liquids (see Section 9.2.1), then

Frequency (fires/year) of non-crash FT fires in BUAs (excluding locomotive fires and FTs conveying flammable liquids)

= 9.01 x 0.18 x 0.6

= 0.97 fires/year

Frequency (fires/km) of non-crash FT fires in BUAs (excluding locomotive fires and FTs conveying flammable liquids)

= $0.97 / (54 \times 10^6 \times 0.1)$

= 1.80×10^{-7} fires/km

From the FTA survey detailed in Chapter 4, Section 4.2, and from a number of fire reports received through the Cleveland County Fire Brigade[13] it is apparent that very few wagon fires are engulfing. The probability that non-crash train fires lead to wagon engulfment is estimated here to be between 0.05 and 0.15. This estimate is based on the estimation of the following.

A - The probability that fire is not detected until well established (0.20 - 0.30).

B - The probability that fire fighting is not undertaken or there is insufficient time to take effective action (0.20 - 0.40).

C - The probability that fire fighting is inadequate in preventing wagon engulfment (0.20 - 0.40).

The figures given above provide a rough guide to the probability of wagon engulfment given a wagon fire. A value of 0.10 is used henceforth. It can be argued that this estimate would be improved by the collection and analysis of FT fire data. However, the detail required to calculate a better estimate is not recorded in the vast majority of Railway Inspectorate accident reports and the author has been unable to find other data sources which would be of use.

Assuming that the causes of non-crash FT fires given above remain constant regardless of FT location, and that the probability of such fires leading to the engulfment of at least one wagon is 0.10, then the rate of FT fires causing wagon engulfment in BUAs can be estimated.

Frequency (fires/year) of non-crash FT fires leading to wagon engulfment in BUAs

$= 0.97 \times 0.10$

$= 0.097$ fires/year

Frequency (fires/km) of non-crash FT fires leading to wagon engulfment in BUAs

$= 0.097 / (54 \times 10^{6} \times 0.1)$

$= 1.80 \times 10^{-8}$

As noted in the FTA survey only two FT crash fire reports were identified as not involving flammable liquids. Both of these incidents were the result of high speed collisions between rolling stock. It is suggested here that these incidents are the most likely crash fires to cause thermal initiation of explosives. This assumption is based on the fact that both incidents caused extensive train damage and were serious enough to warrant a public enquiry and investigation by the Railway Inspectorate.

The author has been unable to identify similar FT accidents during the period 1967 to 1984 (i.e. FT crash fires resulting from high speed rolling stock collisions), therefore it is assumed here that these incidents are the total of such accidents during this period. Hence, assuming that the likelihood of fire is the same regardless of FT location and therefore the FT fire rate per unit distance is the same in BUAs as in non-BUAs, and that

a. FTs travelled an average* of 59.2×10^6 km per year (1967 - 1984),
b. 10% of annual FT travel is through BUAs,

then the rate of FT crash fires in BUAs, as a result of collisions with rolling stock, can be calculated.

* approximate 10 year average 1975 - 1984

Frequency (fires/km) of FT crash fires in BUAs as a result of rolling stock collisions
$= 2 / (59.2 \times 10^6 \times 18)$
$= 1.88 \times 10^{-9}$ fires/km

Frequency (fires/year) of FT crash fires in BUAs as a result of rolling stock collisions
$= 1.88 \times 10^{-9} \times 59.2 \times 10^6 \times 0.1$
$= 0.01$ fires/year

Fires as a result of derailment, which have the potential to cause wagon engulfment and hence initiation of explosives, are considered here to be less likely to occur than similar fires resulting from collisions with other rolling stock. To support this assumption, between 1981 and 1988 no FT fires were recorded as being the result of

a. derailment followed by subsequent collision with rolling stock[1],
b. derailment followed by subsequent collision with massive objects[1].

In addition, during this period only 4 fires were caused by FT derailment alone. These fires involved flammable liquids.

As a consequence of the above, and in the absence of further data, only crash fires as a result of high impact collisions between rolling stock are calculated here. It is assumed that all fires resulting from collisions lead to the engulfment of at least one wagon. It is suggested that the elimination of other initiation possibilities will not greatly affect calculated risk values.

Hence

Frequency (fires/km) of FT crash fires leading to wagon engulfment in BUAs
= 1.88×10^{-9} fires/km

Frequency (fires/year) of FT crash fires leading to wagon engulfment in BUAs
= 0.01 fires/year

9.2.3 Frequency of Explosions

Regardless of fire type no more than 1 munitions wagon is engulfed per incident. The probability of wagon exposure for both crash and non-crash fires, based on an FT conveying 20 wagons of which 4 wagons are laden with military explosives, is taken as 0.2. Using the approach adopted in Section 9.1.3, sympathetic explosion/detonation of other wagon loads can be ignored. The affect of sympathetic explosion/detonation on calculated risk values is illustrated in Section 9.5.4.

The majority of munitions wagons are constructed almost entirely of wood. As a consequence of this, it is thought that the duration of engulfing wagon fires is much greater than that needed to cause most explosives to initiate. In the absence of data, specific to wagon fires, the probability of explosion given an engulfing wagon fire is considered here to be unity[7]. Now

loaded FT movements equal 0.5×10^6 km,
10% of distance is covered on track in BUAs,
one half of all loaded movements involve HD 1.1 munitions.

Assuming FT fire rates are the same regardless of load conveyed (excluding locomotive fires and flammable liquids), then

For Non-Crash Fires

Frequency (explosions/year) of FT explosions resulting from non-crash fires in BUAs

$= 1.80 \times 10^{-8} \times 0.5 \times 10^{6} \times 0.1 \times 0.5 \times 0.2$

$= 9.00 \times 10^{-5}$ explosions/year

Thus, it is estimated that there are 1×10^{-4} explosions per year in BUAs as a result of FT non-crash fires.

For Crash Fires

Frequency (explosions/year) of FT explosions resulting from crash fires in BUAs

$= 1.88 \times 10^{-9} \times 0.5 \times 10^{6} \times 0.1 \times 0.5 \times 0.2$

$= 9.40 \times 10^{-6}$ explosions/year

Thus, it is estimated that there are 1×10^{-5} explosions per year in BUAs as a result of FT crash fires.

For Both Crash and Non-Crash Fires

Frequency (explosions/year) of FT explosions resulting from FT fires in BUAs

$= 9.00 \times 10^{-5} + 9.40 \times 10^{-6}$

$= 9.94 \times 10^{-5}$ explosions/year

Thus, it is estimated that there are 1×10^{-4} explosions per year in BUAs as a result of FT fires.

9.2.4 Explosion consequences

The "explosion effects" model[11] developed at Loughborough is used here to calculate risk values in a similar manner to that detailed in Section 9.1.4. Assumptions "b" through to "h" listed in Section 9.1.4 are also valid for fire incidents.

As noted in Section 9.1.4, it is not known how many movements crew members undertake per year. It is assumed that no individual is involved in more than 2% of all annual movements. In the absence of data to suggest otherwise this assumption is also used here.

The probability of death from a crash and non-crash fire incident is assumed to be 0.2 and 0.1 respectively. Using these assumptions individual risk can be calculated.

For Non-Crash Fires

Probability of exposure = 0.02 (particular individual)
Probability of death = 0.1
Frequency of explosions = 9.0×10^{-5} explosions/year

Hence

Individual risk (FT crew)
= $0.02 \times 0.1 \times 9.0 \times 10^{-5}$
= 1.80×10^{-7} deaths/year

For Crash Fires

Probability of exposure = 0.02 (particular individual)
Probability of death = 0.2
Frequency of explosions = 9.40×10^{-6} explosions/year

Hence

Individual risk (FT crew)
= $0.02 \times 0.2 \times 9.40 \times 10^{-6}$
= 3.76×10^{-8} deaths/year

For Both Crash and Non-Crash Fires

Individual risk
= $1.80 \times 10^{-7} + 3.76 \times 10^{-8}$
= 2.18×10^{-7} deaths/year

This is the risk to an individual member from a "pool" of train crew used in a single year. The number of deaths expected from the "pool" is 9.94×10^{-6} deaths per year (i.e. 1 death every 100 thousand years). This estimate assumes that there are 2 crew members per movement and that 1 crew member dies for every 10 explosions. Compared with non-fire incidents (see Section 9.1.4) it is considered that there is a possibility of escape prior to explosion.

Very few people reside within 20 m to 30 m of rail track. Based on an exclusion zone of 25 m, and assuming an average wagon load of 0.8 te (NEQ), the probability of individual exposure is calculated in Section 9.1.4 as 8×10^{-6}.

As shown in Chapter 6, Section 6.5.2, it is unlikely that the fire services will arrive in time to prevent explosion given an explosives laden wagon fire. In addition, due to a number of logistical problems evacuation is unlikely to occur. Even if evacuation is implemented the reduction in exposed individuals is thought to be negligible. Hence, evacuation of surrounding populations is not considered further.

For Non-Crash Fires

Exposure probability = 8.0×10^{-6}
Frequency of explosions = 9.0×10^{-5} explosions/year

Hence

Individual risk (members of the public)
= $8.0 \times 10^{-6} \times 9.0 \times 10^{-5}$
= 7.2×10^{-10} deaths/year

For Crash Fires

Exposure probability = 8.0×10^{-6}
Frequency of explosions = 9.4×10^{-6} explosions/year

Hence

Individual risk (members of the public)
= $8.0 \times 10^{-6} \times 9.4 \times 10^{-6}$
= 7.52×10^{-11} deaths/year

For Both Crash and Non-Crash Fires

Individual risk (members of the public)
$= 7.2 \times 10^{-10} + 7.52 \times 10^{-11}$
$= 8.0 \times 10^{-10}$ deaths/year

Societal risks from crash and non-crash fire incidents are derived from the "explosion effects" model and detailed here in Tables 3,4 and 5, and Figures 2 and 3.

Table 3: Estimated frequency-size distribution of explosions of wagon loads (HD 1.1) in built-up areas and resultant fatalities: Rail Transport: - Non-Crash Fire Incidents

Mass of explosive te	Frequency (point) explosions/year	Fatalities	Frequency (cumulative) deaths > N/y
2.50	0.54×10^{-5}	5.62	0.54×10^{-5}
1.50	3.15	3.34	3.69
0.75	0.99	1.54	4.68
0.38	0.45	0.60	5.13
0.18	0.90	0.09	6.03
0.05	2.97×10^{-5}	--	9.00×10^{-5}

Table 4: Estimated frequency-size distribution of explosions of wagon loads (HD 1.1) in built-up areas and resultant fatalities: Rail Transport: - Crash Fire Incidents

Mass of explosive te	Frequency (point) explosions/year	Fatalities	Frequency (cumulative) deaths > N/y
2.50	0.56×10^{-6}	5.62	0.56×10^{-6}
1.50	3.30	3.34	3.86
0.75	1.03	1.54	4.89
0.38	0.47	0.60	5.36
0.18	0.94	0.09	6.30
0.05	3.10×10^{-6}	--	9.40×10^{-6}

Table 5: Estimated frequency-size distribution of explosions of wagon loads (HD 1.1) in built-up areas and resultant fatalities: Rail Transport: - Crash and Non-Crash Fire Incidents

Mass of explosive te	Frequency (point) explosions/year	Fatalities	Frequency (cumulative) deaths > N/y
2.50	0.60×10^{-5}	5.62	0.60×10^{-5}
1.50	3.48	3.34	4.08
0.75	1.09	1.54	5.17
0.38	0.50	0.60	5.67
0.18	0.99	0.09	6.66
0.05	3.28×10^{-5}	--	9.94×10^{-5}

Figure 2: Fatality distribution (FN) curve for explosion of a munitions wagon in a built-up area: Rail transport: - Crash Fire Incidents and Non-Crash Fire Incidents

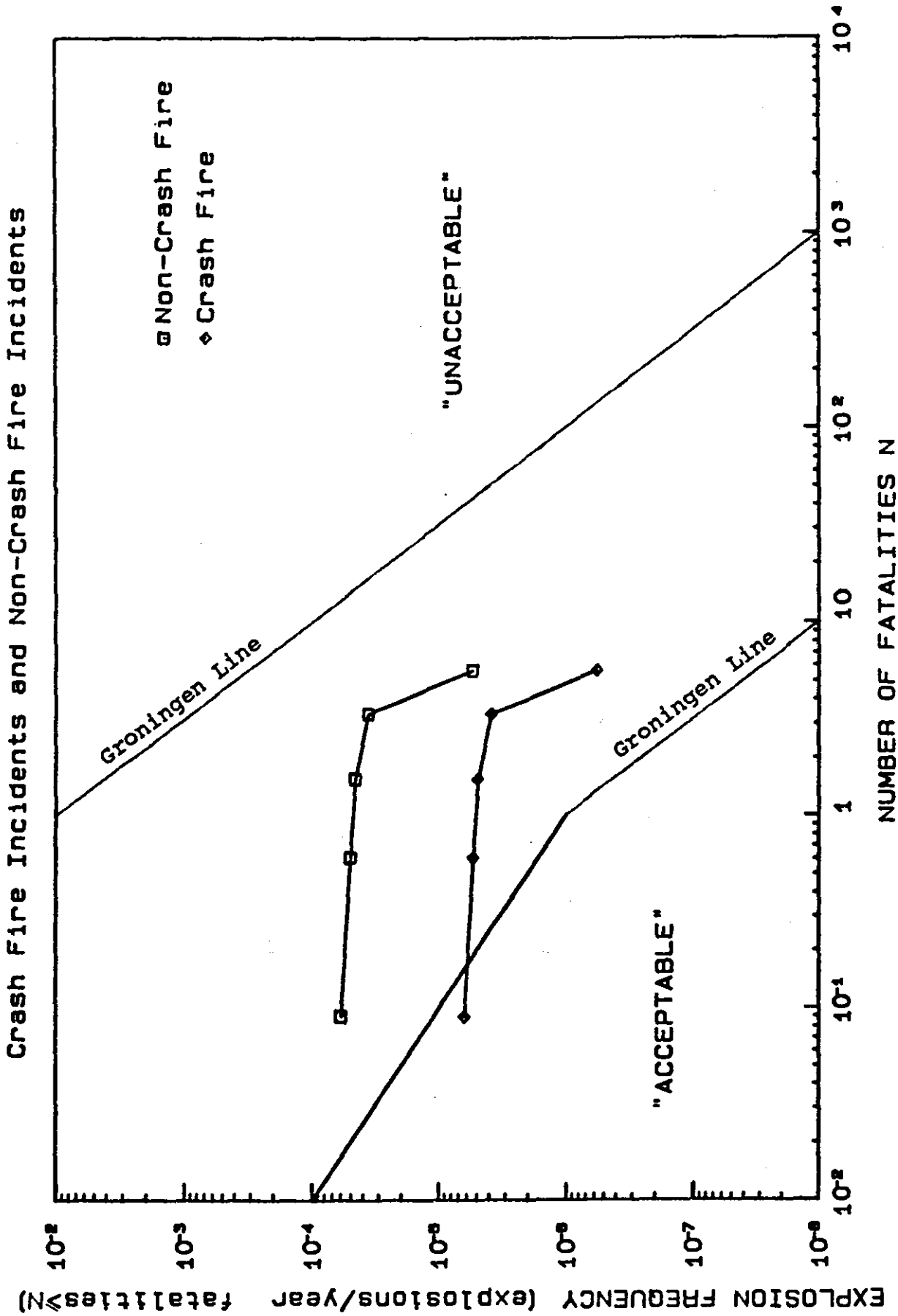
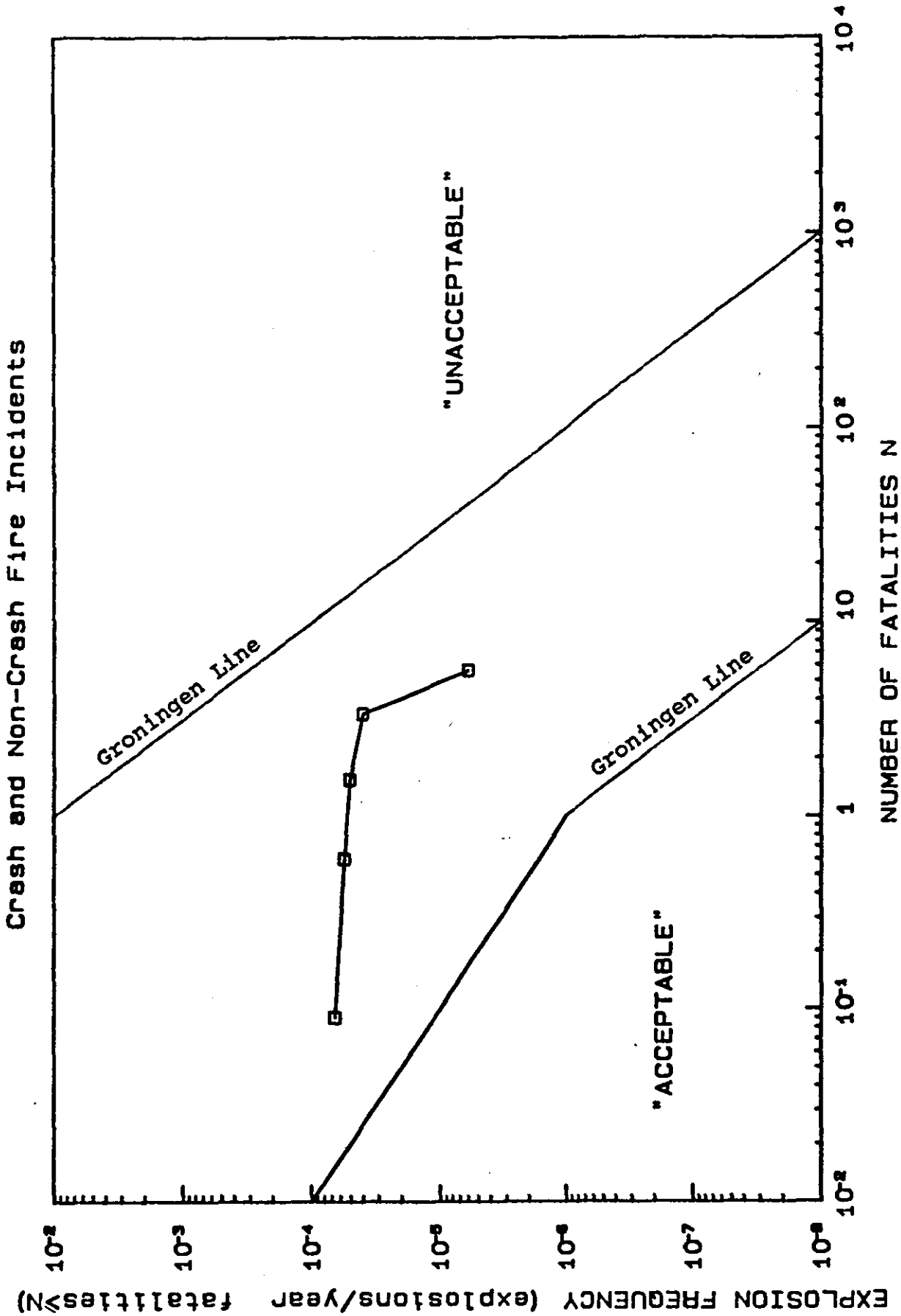


Figure 3: Fatality distribution (FN) curve for explosion of a munitions wagon in a built-up area: Rail transport: - Crash and Non-Crash Fire Incidents



9.3 Hazard Warning structure

The basic principles and applications of hazard warning structure are discussed in Chapter 8, Section 8.5. Two examples of its application are detailed for the road transport of military explosives. For completeness, two hazard warning trees are detailed here for the transport of military explosives by rail.

Regardless of mode of initiation, a major incident is considered to be an incident involving 30 or more fatalities. Realisation of a major incident relies upon explosion in a built-up area AND exposure of a major target. For road incidents the probability of major target exposure is given in Section 8.5 as 0.01. It is considered here that the probability of major target exposure on the railways is less than that on the roads. However, it has not been possible to find a reliable means of quantifying this reduction. Therefore, although it is acknowledged as an upper limit, the same probability of major target exposure, as used for road transport is used here for rail transport.

Both the "non-crash fire" and "crash fire" trees contain mitigating features of various strength. As noted in Section 8.5, strong mitigation is considered to be inherent in those features which have a low probability of failure. The dividing line between strong and weak mitigating features is taken as 0.1. Management may have some control over these features. Operational policy may be exercised to consolidate and maintain strong mitigating features while strengthening those which appear to be weak.

The principal mitigating features illustrated by the Hazard Warning Structures detailed here are as follows (see Figures 4 and 5.

	Failure probability
Non-exposure of a major target	0.010
Non-exposure of a level crossing	0.053
Insufficient closing speed	5.0×10^{-5}
Subsequent collision - rolling stock	0.026
Engulfing non-crash fire	0.100
Significant fire given crash	0.006

The strongest mitigating feature is related to speed. It is considered that this feature can be consolidated by the strict enforcement of speed restrictions and the emphasis of the dangers of excessive speed. For fire incidents, the strongest mitigating feature is "significant fire given crash" followed by "engulfing non-crash fire". Management can exercise very little control over these features, except to ensure thorough wagon maintenance, the awareness of train crew to their responsibilities when involved in accident/fire situations and the possible selection of wagons for fire retardation characteristics.

Subsequent collision following derailment is a strong mitigating feature over which management effectively has no control. In comparison, the "non-exposure" mitigating features are strong features over which management have limited control. Careful selection of movement routes minimising the number of major targets and level crossings together with the avoidance of built-up areas where practicable, may strengthen "non-exposure" features.

Figure 4: Hazard warning tree for a major accident resulting from the rail transport of military explosives: Non-Fire incidents

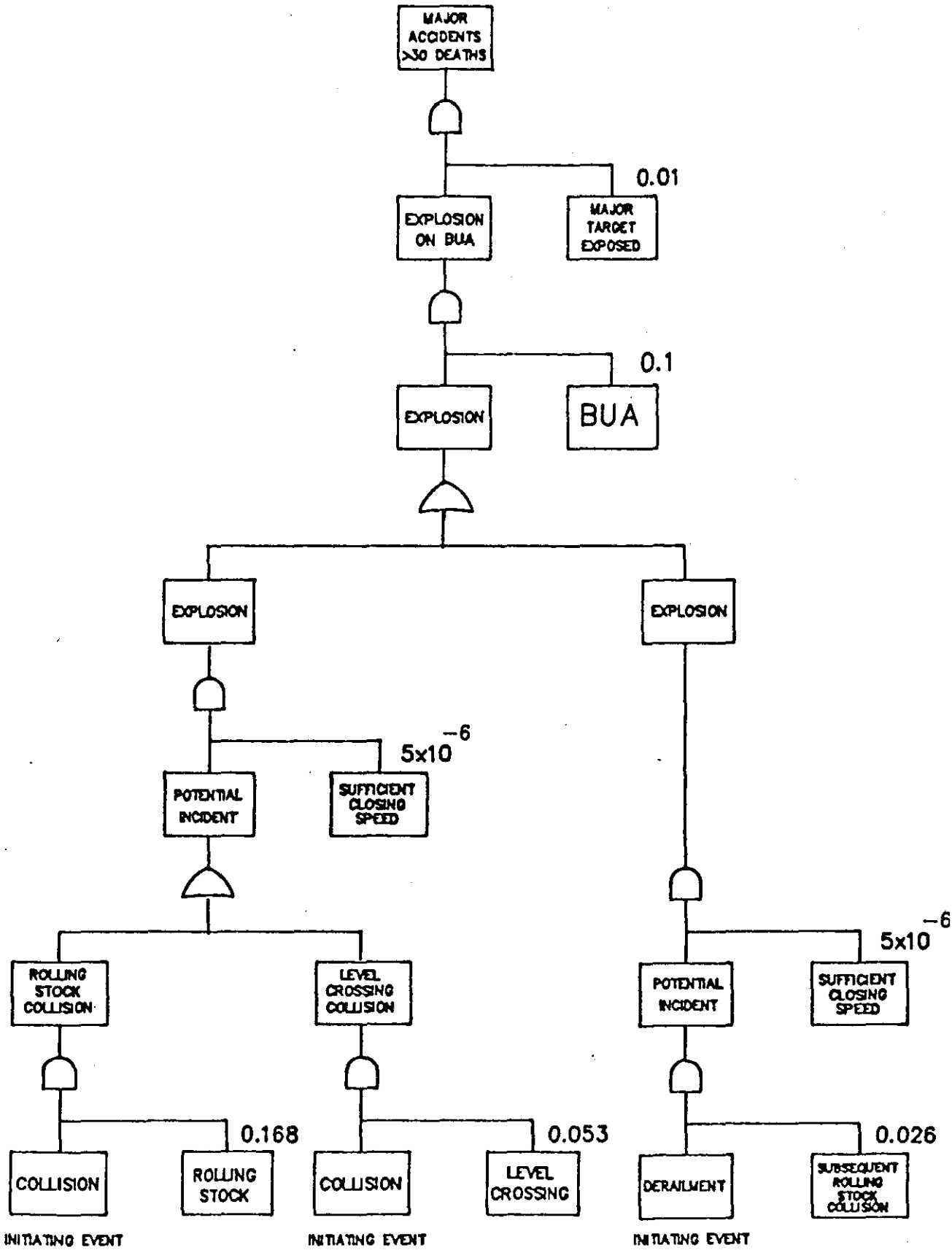
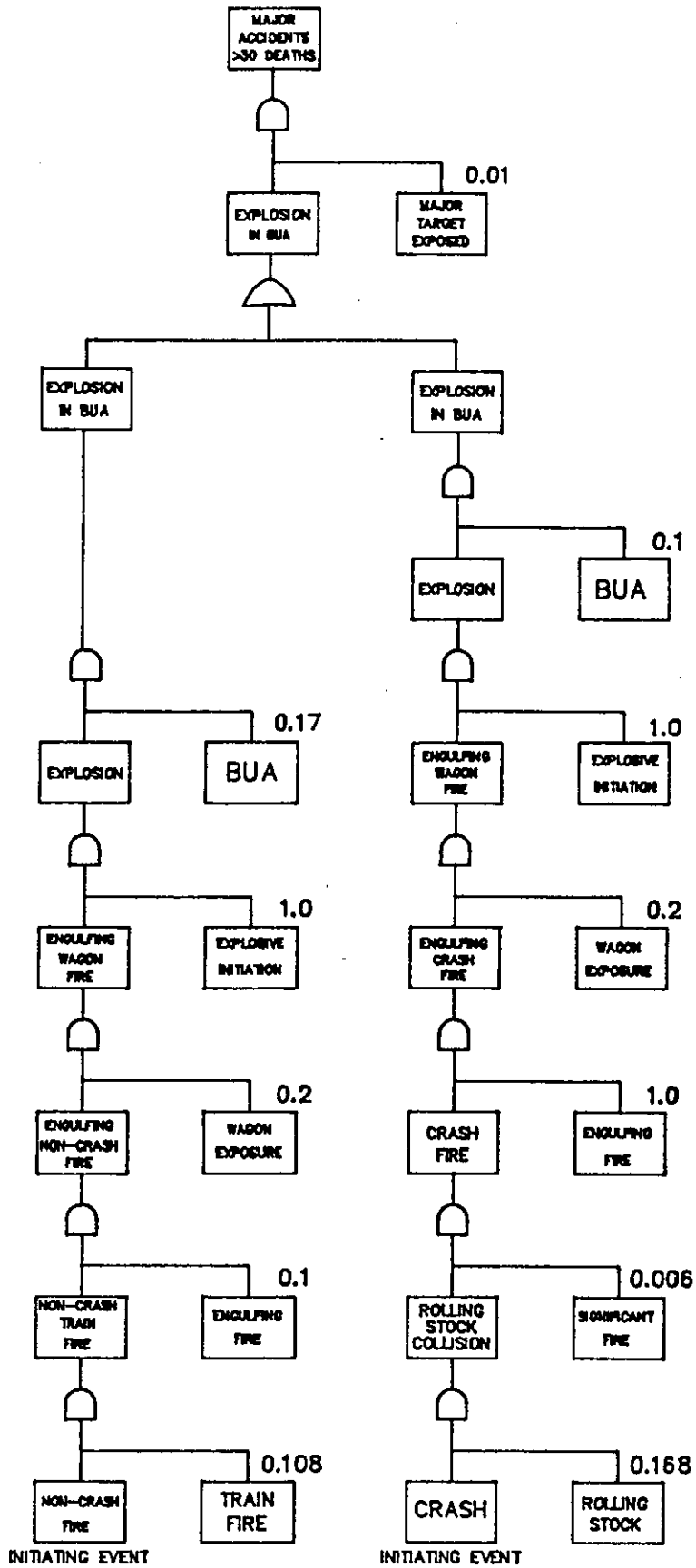


Figure 5: Hazard warning tree for a major accident resulting from the rail transport of military explosives: Fire incidents



9.4 Sensitivity Assessment

The problems of risk assessment sensitivity and the merits of sensitivity assessment are discussed in Chapter 8, Section 8.4. Most data used in risk assessments are subject to uncertainty. Unfortunately, it is rarely practicable to assess the effect of all data or combinations of data, and therefore, the assessment of a number of important estimates/values is usually adopted. This approach is useful for identifying and illustrating the relative importance of estimates/values. It is used here to illustrate the relative importance of impact initiation speed, passenger train fatalities, major target exposure and sympathetic explosion of rail wagons.

9.4.1 Explosives Vulnerability to Impact

For impact initiated incidents this report assumes that a minimum impact of 35 m/s is sufficient to cause munitions to initiate. Initiation variability exists and it is acknowledged that a small number of munitions initiate at impact speeds below 35 m/s. It is shown here that substantially increasing impact initiation speed reduces the risk values calculated in this chapter by an order of magnitude.

Note

It would be more usual to reduce impact initiation speed. However, due to the scarcity of data and the fact that most explosives have impact initiation speeds well above 50 m/s the only means of providing a meaningful analysis is to increase impact initiation speed.

Consider a minimum impact initiation speed of 40 m/s (90 mph). Using the method described in Section 9.1.3 the probability of FT collisions at 90 mph or more is approximately 5×10^{-6}. Similarly, for level crossing collisions with HGVs and cars; the probability that these occur at 90 mph or more is estimated here to be in excess of 1×10^{-6} and 1×10^{-5} respectively. Based on the annual number of road vehicle injury accidents an overall value of 9×10^{-6} is used here for all road vehicles (i.e. vehicles involved in injury accidents, 1986 - cars/taxis/LGVs 313,994 and HGVs/buses/coaches 26,910 - taken from Road Accidents Great Britain, The Casualty Report 1986 - HMSO).

As noted in Section 4.1.3, for impacts to occur with objects off the track at 35 m/s or more derailment would need to occur at speeds well over 40 m/s. Adopting this approach here; for impacts to occur at 40 m/s or more it is assumed that derailment would need to occur at 45 m/s or more. It is estimated from the survey conducted by Taig[4] that less than 0.01% of FT derailments occur at 45 m/s or more.

Hence

For collisions

Frequency (explosions/year) of FT explosions resulting from collisions with other rolling stock in BUAs
= 3.40×10^{-8} explosions/year

Frequency (explosions/year) of FT explosions resulting from collisions with road vehicles on level crossings in BUAs
= 4.20×10^{-9} explosions/year

For derailments

Frequency (explosions/year) of FT explosions resulting from derailment and subsequent collision with rolling stock in BUAs
= 9.53×10^{-9} explosions/year

Frequency (explosions/year) of FT explosions resulting from derailment and subsequent collision with massive objects off the track in BUAs
= 8.78×10^{-10} explosions/year

For both collisions and derailments

Frequency (explosions/year) of FT explosions resulting from non-fire incidents in BUAs
= $3.40 \times 10^{-8} + 4.20 \times 10^{-9} + 9.53 \times 10^{-9} + 8.78 \times 10^{-10}$
= 4.90×10^{-8} explosions/year

From the estimates given above individual and societal risks can be calculated.

Hence

Individual risk (FT crew)
= 9.80×10^{-10} deaths/year

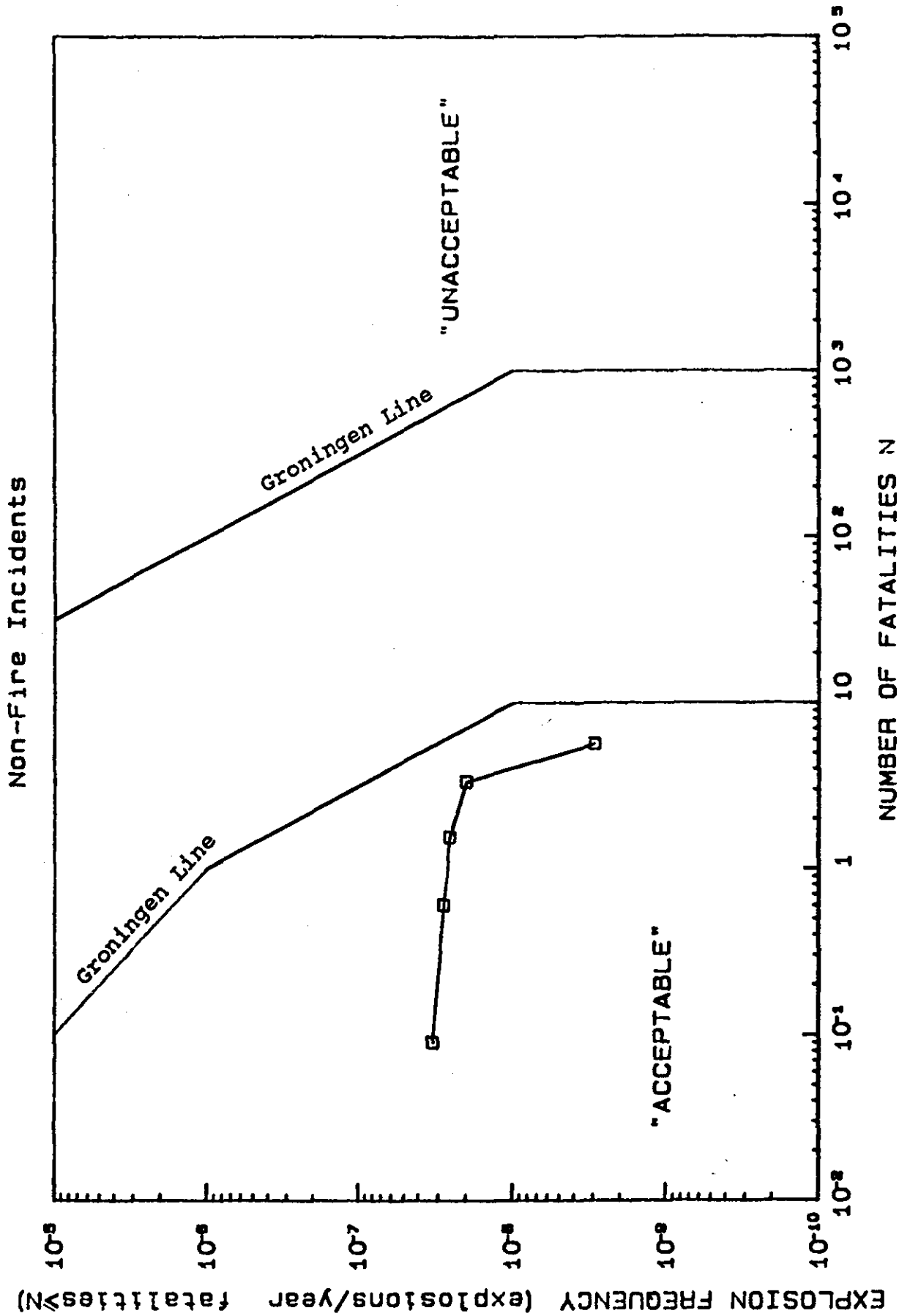
Individual risk (members of the public)
= 3.92×10^{-13} deaths/year

Both individual risks and societal risks are reduced by an order of magnitude (due to the adoption of the 40 m/s minimum impact initiation speed). Assuming the change in risk to be symmetrical (about the minimum impact initiation speed, 35 m/s), then for a 5 m/s reduction an order of magnitude increase in individual and societal risk could be expected. However, by reference to the impact data detailed in Chapter 4.0, Section 4.3, it can be seen that FT closing speeds are not evenly distributed about 35 m/s and therefore calculated risks are not symmetrically distributed about the minimum impact initiation speed. In fact using the method described in Section 9.1.3 it can be inferred that a reduction in minimum impact initiation speed is liable to increase risks by orders of magnitude. However, the increased individual risks remain acceptable for those working on and living near many chemical plants. Similarly, the increased societal risks are unlikely to compare unfavourably with the strict Groningen criteria and the risks considered by the Advisory Committee on Major Hazards[14] not to be "unacceptable".

Table 6: Estimated frequency-size distribution of explosions of wagon loads (HD 1.1) in built-up areas and resultant fatalities: Adjusted for greater impact initiation speed (40 m/s): Rail Transport: - Non-fire Incidents

Mass of explosive te	Frequency (point) explosions/year	Fatalities	Frequency (cumulative) deaths > N/y
2.50	0.29×10^{-8}	5.62	0.29×10^{-8}
1.50	1.72	3.34	2.01
0.75	0.54	1.54	2.55
0.38	0.24	0.60	2.79
0.18	0.49	0.09	3.28
0.05	1.62×10^{-8}	--	4.90×10^{-8}

Figure 6: Fatality distribution (FN) curve for explosion of a munitions wagon in a built-up area: Adjusted for greater impact initiation speed (40 m/s): Rail transport: - Non-Fire Incidents



9.4.2 Passenger Train Fatalities

The risk assessments performed in Sections 9.1 and 9.2 take no account of fatalities on other trains which may be involved in explosion incidents. In particular passenger train (PT) fatalities have been ignored. It is obvious that the number of expected fatalities from a munitions wagon explosion dramatically increases if PTs are involved in initiating incidents. This scenario is considered here for non-fire initiated explosions. It is shown that a large increase in the number of fatalities does not greatly increase societal risks.

Consider an impact initiating collision between an FT and a PT in a built-up area, where the PT is carrying 100 individuals. In addition to exposed members of the "non-travelling" public the incident causes passengers and train crew to be exposed to the effects of explosion.

Based on lung haemorrhage Eisenberg et al[15] estimate that a blast wave having a peak overpressure of 1.4 bar or more will cause 50% fatalities in those exposed. Similarly, a blast wave having a peak overpressure of 0.3 bar or more will cause 50% serious injuries from flying fragments and 10% of those injured will suffer fatal wounds. Doubts have been expressed over the accuracy of the equations given by Eisenberg et al (see Chapter 7.0, Section 7.1, page 262).

Using the relationship between peak overpressure and scaled distance, and from protection, however minimal, offered by wagons and wagon furniture etc., it is assumed here that no more than approximately 40% of passengers are exposed. From these assumptions the number of additional

fatalities resulting from explosions involving PTs can be estimated.

For example, consider the above scenario involving the explosion of 0.75 te (NEQ) of explosive.

Number of exposed individuals = 40
Probability of death from blast = 0.5
Probability of death from fragments given serious injury
= 0.5 x 0.1 = 0.05
Fatality factor = 0.27 (see note)

Expected number of additional fatalities
= 40 x ((0.5 + 0.05) - (0.5 x 0.05)) x 0.27
= 5.67 deaths

Total number of expected fatalities
= 5.67 + 1.54
= 7.21 deaths

Note

The fatality factor is based on the expected reduction in deaths with respect to size of explosive consumed. e.g. for the maximum mean NEQ of 2.5 te, 5.62 members of the "non-travelling" public are expected to die compared with 1.54 for an NEQ of 0.75 te i.e. a reduction of 73%.

Table 7 lists the additional and total number of expected fatalities for various wagon loads.

Freight train collisions with PTs account for only 5.3% of all FT collisions with rolling stock. From Sections 9.1 and 9.2 it can be deduced that such collisions form only a small part of the estimated frequency of annual explosions in BUAs. The frequency of explosions per year from FT/PT collisions in BUAs is 1.80×10^{-8}. This compares with 4.49×10^{-7} explosions per year for all other non-fire initiated explosions in BUAs.

From Table 8 and Figure 7 it can be seen that allowing for passenger train fatalities does not greatly increase societal risks.

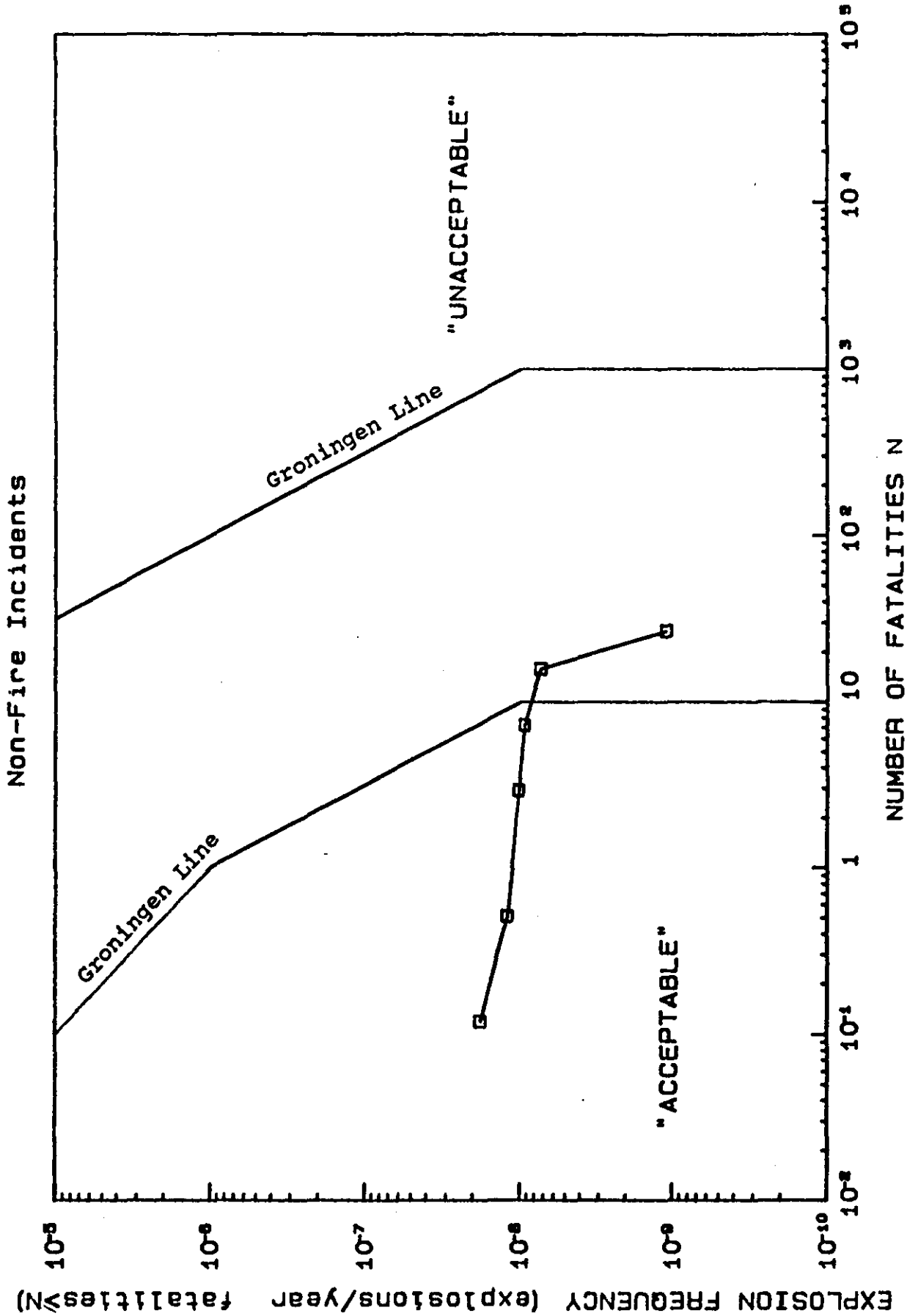
Table 7: Expected fatalities as a result of passenger train deaths

Load (NEQ) te	Additional Fatalities	Total Fatalities
2.50	21.00	26.62
1.50	12.40	15.74
0.75	5.67	7.21
0.38	2.31	2.91
0.18	0.42	0.51
0.05	0.12	0.12

Table 8: Estimated frequency-size distribution of explosions of wagon loads (HD 1.1) in built-up areas and resultant fatalities: Collisions with passenger trains: Rail Transport: - Non-fire Incidents

Mass of explosive te	Frequency (point) explosions/year	Fatalities	Frequency (cumulative) deaths > N/y
2.50	0.11×10^{-8}	26.62	0.11×10^{-8}
1.50	0.63	15.74	0.74
0.75	0.20	7.21	0.94
0.38	0.09	2.91	1.03
0.18	0.18	0.51	1.21
0.05	0.59×10^{-8}	0.12	1.80×10^{-8}

Figure 7: Fatality distribution (FN) curve for explosion of a munitions wagon in a built-up area: Collisions with passenger trains: Rail transport:
- Non-Fire Incidents



9.4.3 Major Target Exposure: Fatalities at Stations, Terminals and Marshalling Yards

It is shown here that although the numbers of expected fatalities increases at stations, terminals and marshalling yards (STM), the frequency of explosion is sufficiently low as to not greatly alter the significance of perceived societal risks.

Trains conveying explosives are known to be single destination trains and therefore train stops are kept to a minimum. Route details are not known and are obviously variable. As a consequence of this, it has not been possible to determine the proportion of time FTs accumulate passing through STM locations. However, it is estimated that 17% of FT travel time is spent in BUAs. Using this estimate, and assuming that no more than 1% of travel distance in BUAs occurs on track in STMs, then at these locations the frequency of explosions for fire and non-fire initiated causes is estimated to be two orders of magnitude less than the frequency of explosions at other BUA locations.

Consider a non-crash fire initiated explosion of a munitions wagon at an STM location in a BUA. Applying the above assumptions

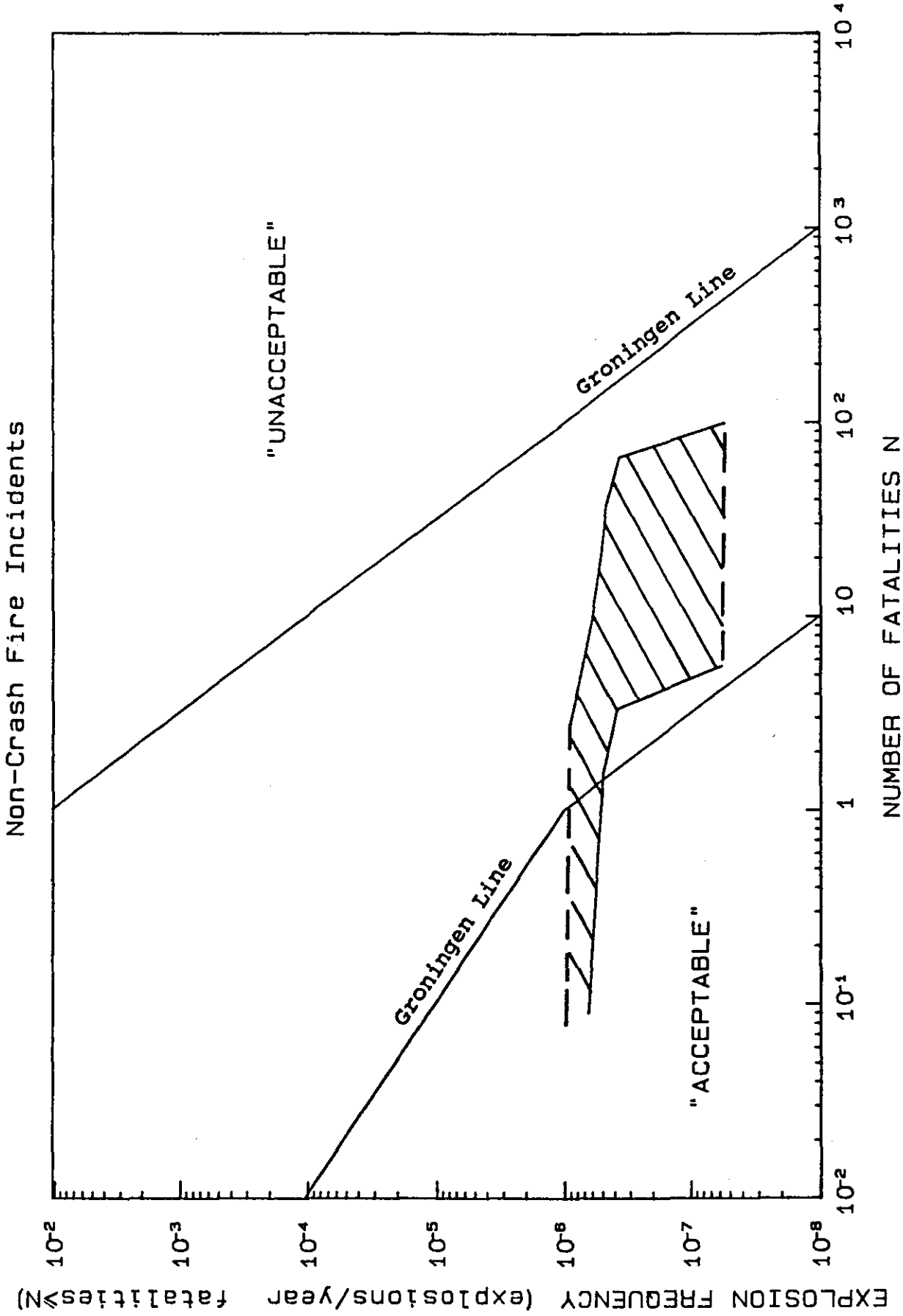
Frequency (explosions/year) of FT explosions resulting from non-crash fire incidents whilst passing through STMs in BUAs

$= 9.00 \times 10^{-5} \times 0.01$

$= 9.00 \times 10^{-7}$ explosions/year

The number of individuals present at STM locations is difficult to estimate with any certainty. It is suggested that STM populations may well increase exposed populations from as few as 2 individuals to over 100 individuals. As a consequence of this the frequency distribution curve shown in Figure 8 depicts a range of possible curves for the explosion of a munitions wagon. The frequency number (FN) curve range is plotted on the same scale as that used in Figure 2 (for non-crash fire initiated incidents) so that the societal risks can be compared.

Figure 8: Fatality distribution (FN) curve for explosion of a munitions wagon at an STM location in a built-up area: Rail transport: - Non-Crash Fire Incidents



9.4.4 Sympathetic explosion

Trains conveying military explosives typically consist of four wagons laden with explosives. In Sections 9.1.3 and 9.2.3 sympathetic explosion is ignored and it is assumed that only one wagon explodes for any given incident. However, allowing for sympathetic explosion, so that all four wagons explode, does not greatly increase individual risks. Furthermore, societal risks are only significantly increased for the higher death tolls. These increases in risk are shown here for non-crash fire incidents.

Average wagon load = 0.8 te (NEQ)
Average four wagon loads = 3.2 te (NEQ)

Following the same procedure as given in Section 9.1.4, then

Proportion of annual traffic = 0.01
Death circle diameter = 60.6 m
BUR distance per movement = 35 km
Frequency of explosions = 9.0×10^{-5} explosions/year

Exposure probability
$= (0.01 \times 60.6) / (35 \times 10^{3})$
$= 1.73 \times 10^{-5}$

Hence

Individual risk (members of the public)
$= 1.73 \times 10^{-5} \times 9.0 \times 10^{-5}$
$= 1.56 \times 10^{-9}$ deaths/year

The individual risk estimated above is similar to the individual risk of 7.20×10^{-10} deaths/year for a single wagon explosion estimated in Section 9.2.4.

From Table 9 and Figure 9, it can be seen that the increase in societal risks for a four wagon explosion compare favourably with the strict Groningen criteria. Compared with a single wagon explosion the risks, although greater, are comparable for low death tolls.

The risk estimates given here are based on the sympathetic explosion/detonation equation suggested by the ESTC[7] and used in this chapter.

i.e.

$$D = 0.8Q^{1/3} \quad .....1$$

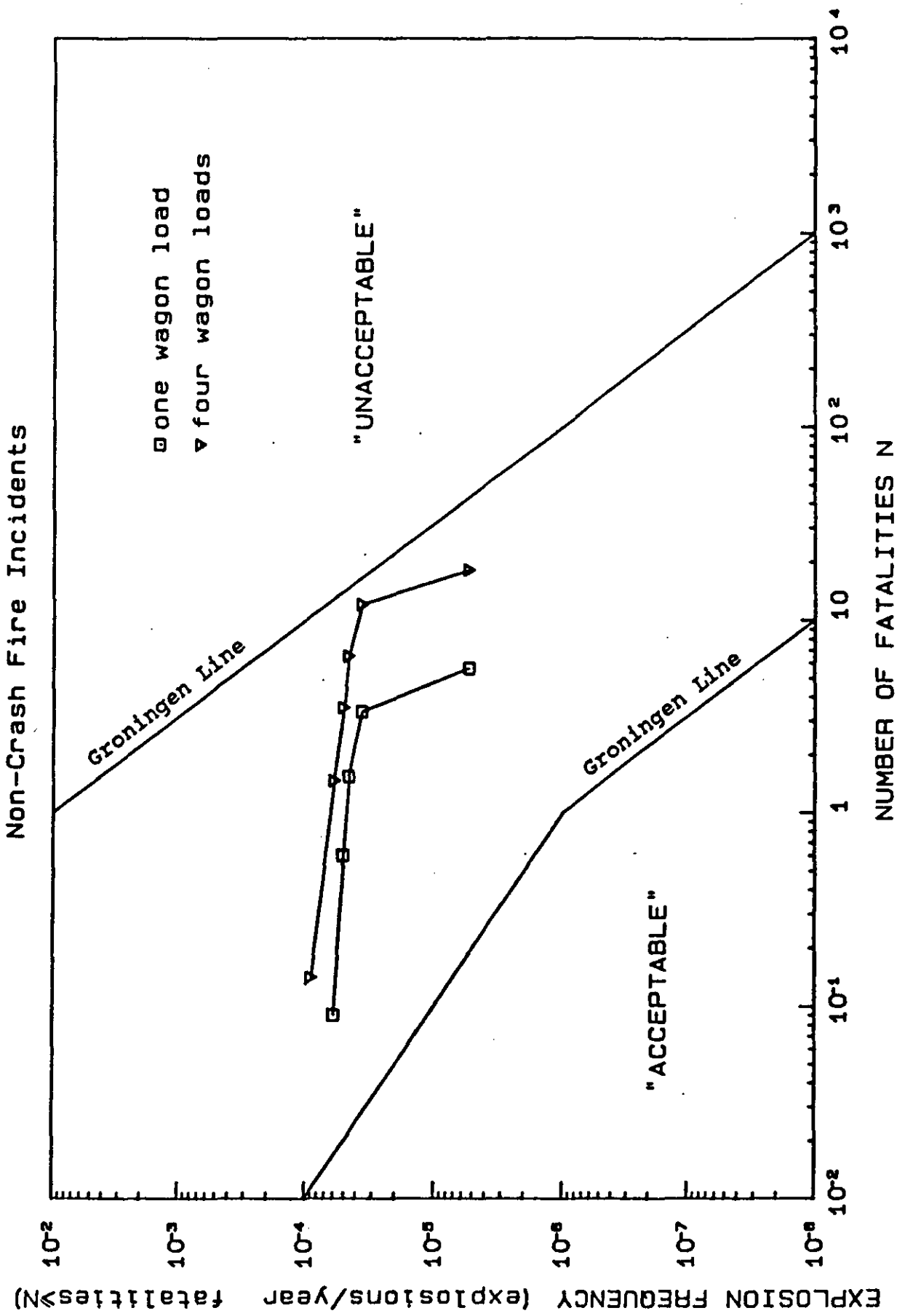
However, it is thought that for small distances, such as those between adjacent wagons (no more than about 2 m), sympathetic explosion/detonation will result from loads of 0.3 te or more[7]. Based on this assumption the estimated increase in individual and societal risks is less than that given by equation 1 above. This is because sympathetic explosion is only likely from 0.3 te (NEQ) or more of explosives. The load movement survey detailed in Chapter 4, Section 4.5, reveals that over 40% of explosive laden wagons contain less than 0.3 te (NEQ).

Thus, it can be concluded that accounting for sympathetic explosion (for the munitions train considered here) does not greatly increase individual risks although for the higher death tolls there is a significant increase in societal risks.

Table 9: Estimated frequency-size distribution of explosions of wagon loads (HD 1.1) in built-up areas and resultant fatalities: Adjusted for sympathetic explosion: Rail Transport: - Non-Crash fire Incidents

Mass of explosive te	Frequency (point) explosions/year	Fatalities	Frequency (cumulative) deaths > N/y
10.00	0.54×10^{-5}	18.02	0.54×10^{-5}
6.00	3.15	12.02	3.69
3.00	0.99	6.50	4.68
1.52	0.45	3.50	5.13
0.72	0.90	1.46	6.03
0.20	2.97×10^{-5}	0.14	9.00×10^{-5}

Figure 9: Fatality distribution (FN) curve for explosion of a munitions wagon in a built-up area: Adjusted for sympathetic explosion: Rail transport:
- Non-Crash Fire Incidents



9.5 References

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CONCLUSIONS

10.0 CONCLUSIONS, OBSERVATIONS AND RECOMMENDATIONS

Conclusion

It has been shown that the identification and quantification of transient hazards can be dealt with in a logical and organised manner through the application of quantitative risk assessment.

The methodology developed here is a useful tool for the identification and quantification of transient hazards. More specifically, the methodology is particularly useful for the assessment of risks from the road and rail conveyance of commercial and military explosives.

General Conclusions and Observations

Road and rail conveyance can provide accident environments having the potential to cause accidental initiation of commercial and military explosives. The likelihood of explosion is heavily dependent upon the accident and transport environments to which explosives are exposed. There have been a number of historical accidents involving explosives some of which have led to explosion. As a consequence of this, and because accident and transport environments are subject to change they need to be kept under review.

Stimuli most likely to cause accidental initiation of commercial and military explosives for both road and rail accident environments are fire, particularly non-crash fire, and impact. Explosions are much more likely to be associated with non-crash fires than crash fires and fire incidents than non-fire incidents. This conclusion is based on contemporary commercial and military explosives and current accident and transport environments.

Initiation of explosive loads conveyed both commercially and militarily by road and rail have the potential to damage surrounding environments and cause multiple casualties. Surrounding environments may be damaged and individuals injured as a result of blast overpressure, missile impact and/or thermal radiation. A number of techniques and models have been identified which can be used to evaluate the consequences of explosion alongside roads and rail track.

Further Work

Handling operations, such as loading and unloading, are not considered, and neither is temporary storage prior to handling. Investigation of these areas would complement the methodology developed here and enable not only transient hazards but also fixed hazards (associated with transport operations) to be assessed.

Further development of the explosion effects model, detailed in Chapter 7.0, would improve confidence in the estimation of fatalities. Main areas of concern include damage and injury assessment from fragmentation and thermal radiation. Of particular interest would be the extension of the model to incorporate HD 1.2 and HD 1.3 explosives.

Finally, the methodology developed here does not consider the transport of damaged or deteriorated explosives (i.e. "non-A1" explosives). It is known that such explosives are conveyed as and when necessary to refurbishment establishments and disposal sites. Investigation of these movements would add to the overall assessment of transient hazards.

ABBREVIATIONS AND NOMENCLATURE

ABL	Allegancy Ballistics Laboratory
ACDS	Advisory Committee on Dangerous Substances
ADR	European Agreement Concerning the International Carriage of Dangerous Goods by road
ANFO	ammonium nitrate fuel oil
ASI	accident severity index
BR	British Rail
BUA	built-up area
BUR	built-up road
BMT	blast/missile/thermal (range)
BWU	British weight units
CAD	Central Ammunition Depot
CIA	Chemical Industries Association
CIM	International Convention Concerning the Carriage of Goods by Rail
CM	closing momentum
CME	conveying military explosives
COTIF	Convention Concerning International Rail Transport
CPL	Classification, Packaging and Labelling of Dangerous Substances Regulations 1984
CS	closing train speed
CT	closing train tonnage
DMU	diesel multiple unit
ECP	Explosives and Chemical Products Limited
ECS	empty coaching stock
EEC	European Economic Community
EMU	electric multiple unit
ESTC	Explosives, Storage and Transport Committee

FL	freightliner
FN	frequency-number
FT	freight train
FTA	freight train accident (survey)
HD	hazard division
HGV	heavy goods vehicle
HMSO	Her Majesty's Stationary Office
HMX	cyclotetramethylenetetranitramine
HSC	Health and Safety Commission
HSE	Health and Safety Executive
ICI	Imperial Chemical Industries
IMO	International Maritime Organisation
JSODOC	Joint Service Ordnance Disposal Operations Centre
LDG	list of dangerous goods
LGV	light goods vehicle
LPG	liquefied petroleum gas
MC	motorcycle
MIRA	Motor Industry Research Association
MOD	Ministry of Defence
MPFSL	Metropolitan Police Forensic Science Laboratory
MV	munitions vehicle
NEQ	net explosives quantity
NG	nitroglycerine
OCTI	Central Office of International rail Transport
OECD	Organisation for Economic Cooperation and Development
OR	operational research
OSS	order of the secretary of state
OT	overturning

P	probability
p^o	peak overpressure
PAR	parcels train
PC	pedal cyclist
PED	pedestrian
PETN	pentaerythritol tetranitrate
Pr	probit
PSV	public service vehicle
PT	passenger train
RARDE	Royal Armament Research and Development Establishment
RDX	cyclotrimethylenetrinitramine
RI	Railway Inspectorate
RID	International Regulations Concerning the carriage of Dangerous Goods by Rail
RLSD	Research and Laboratory Services Division of the Health and Safety Executive
SRD	Safety and Reliability Directorate
STM	stations, terminals and marshalling yards
SVA	single vehicle accident
SWB	short wheelbase (wagons)
TNT	trinitrotoluene
TRRL	Transport and Road Research Laboratory
UKLF	United Kingdom Land Forces
UN	United Nations
x	mean
6	standard deviation
6^2	variance
#	constant (3.142)

APPENDICES

APPENDIX A: AN OVERVIEW OF THE REGULATIONS AND CONVENTIONS GOVERNING THE TRANSPORT OF EXPLOSIVES

As a consequence of the need to transport explosives, and because such materials are of a hazardous nature, the conveyance of explosives are regulated throughout the industrialised world by regulations aimed at

a. improving safety during transit,
b. reducing the frequency of accidents,
c. limiting the consequences of accidents.

The first set of regulations governing the conveyance of explosives in the United Kingdom (UK) were in the form of the 1772 Gunpowder Act. Numerous regulations have since been made, the latest being the Conveyance of Explosives by Road Regulations 1989. The following sections detail briefly the regulations which affect or have some relevance on the transport of both military and commercial explosives and related goods in the UK.

European and International Regulations

International transport regulations have been based on, or amended (or are in the process of being amended), so that they conform to the recommendations of the United Nations (UN) Committee of Experts on the Transport of Dangerous Goods. The UN committee, established on 15th April 1953, develop recommendations on the transport, classification, labelling and packaging of dangerous goods. There are ten current members of the committee; Canada,

France, the Federal Republic of Germany, Italy, Japan, Norway, Poland, the United Kingdom, the United States and the Soviet Union. Under the auspices of the UN these countries publish joint recommendations in the form of a book, entitled the Transport of Dangerous Goods, which is commonly known as the "Orange Book". In addition, pressure is exerted on other states, regional economic commissions and international organisations (e.g. International Maritime Organisation (IMO)) to bring existing and proposed transport practices into line with UN recommendations, thereby encouraging international conformity on the transport of dangerous goods.

Prior to any recognition of the UN committee the transport of dangerous goods by road and rail in Europe was governed to a large extent (and still is) by two international conventions.

1. The International Regulations Concerning the Carriage of Dangerous Goods by Rail (RID),

2. The European Agreement Concerning the International Carriage of Dangerous Goods by Road (ADR).

The RID regulations are incorporated in Annex I of the International Convention Concerning the Carriage of Goods by Rail (CIM). CIM is administered by the Central Office of International Rail Transport (OCTI) in Berne, Switzerland. In its 1984 version CIM was supplemented by the Convention Concerning International Rail Transport (COTIF). CIM was established in 1890 and by the 1950's RID was considered the basic source of reference for the transport of dangerous goods in Europe.

In September 1957 the ADR regulations were formulated by a Working Party of the Inland Transport Committee under the auspices of the Economic Commission for Europe. The regulations were published in 1959 supplementing the Convention Covering the International Carriage of Goods by Road (CMR), adopted in Geneva in 1956. Provisions within the agreement were to a large extent based on those previously incorporated into RID, thereby ensuring conformity between road and rail transport. As a consequence of this both RID and ADR contain similar information and deal primarily with

a. general regulations,
b. listing dangerous substances and articles,
c. marking and labelling,
d. packaging,
e. classification,
f. loading/unloading
g. documentation,
h. safety tests,
i. vehicle requirements.

Over the last decade those administering RID and ADR have seen many amendments to their original provisions. More often than not these have been recommended by the UN Committee so as to aid international conformity. However, even within the European Economic Community (EEC) most member states, although abiding by RID and ADR, have their own additional laws, regulations and interpretations of RID and ADR. These differences between EEC members (at present) prevent not only European harminization of regulations governing the transport of hazardous goods but also international harminization. For example, the UK is not bound (at present) by ADR on the transport of explosives. However, UK regulations are based on UN recommendations and therefore it is expected in the near future that ADR will

conform or mirror closely the regulations adopted in the UK. Similarly, it is hoped that RID will soon reflect UK regulations on the transport of explosives by rail.

United Kingdom Regulations

In the UK the transport of dangerous goods by road is governed by four sets of regulations. The first three refer to the transport of dangerous substances in general and the fourth the conveyance of explosives. All four are based on UN recommendations and are being continually revised so as to maintain conformity with ADR to which the UK is a signatory. The regulations are essentially

a. The Dangerous Substances (Conveyance by Road in Road Tankers and Tank Containers) Regulations 1981,

b. The Classification, Packaging and Labelling of Dangerous Substances 1984 (CPL),

c. The Classification and Labelling of Dangerous Substances for Conveyance by Road in Road Tankers, Tank Containers and Packages 1988,

d. The Conveyance of Explosives by Road Regulations 1989.

It can be seen that all four regulations are relatively recent. Over the last 5 to 10 years the Health and Safety Executive/Commission (HSE/HSC), the Explosives Storage and Transport Committee (ESTC) and Her Majesty's Explosives Inspectorate have been up-dating and amending previous regulations and legislation in order to conform with UN

recommendations. At present the CPL regulations on having adopted UN recommendations find themselves differing with ADR on substance classification. The CPL regulations include a ninth class, "miscellaneous dangerous substances", which cover harmful substances not categorised by the existing eight classes. There are also differences in the classification of toxicity and flammability. For example, the ADR regulations tend not to be as strict on toxicity as the CPL regulations[1]. Other differences exist between CPL and ADR, but these, it is thought, will be removed with the forthcoming revision of ADR to conform with UN recommendations.

Prior to the introduction of The Conveyance of Explosives by Road Regulations 1989 explosives were governed by Order of the Secretary of State (OSS 11), dated 20th September 1924 and made under the Explosives Act 1875. Military explosives were (and most remain - see below) governed by a separate regulation under the direct control of the Ministry of Defence (The Conveyance by Road of Military Explosives Regulations 1977 No. 888). With the introduction of the new regulations both commercial and military explosives fall under the same provisions aiding conformity (i.e. The Conveyance of Explosives by Road Regulations 1989). The new regulations do not, however, apply to the UK Armed Forces or visiting Armed Forces, although where practicable they are expected to comply with the regulations. In comparison, all MOD civilians and contractors must conform to the regulations unless exempt in writing by the Secretary of State for Defence.

The CPL regulations not only apply to the transport of dangerous substances by road but also to the transport of dangerous substances by rail. However, for commercial explosives British Rail have their own regulations. These are incorporated into a publication known as the "List of Dangerous Goods" (LDG) and more specifically the Byelaws Relating to Explosives (1989). For military explosives, conveyance is governed by Statutory Instrument 1977/888, "The Conveyance by Rail of Military Explosives Regulations 1977". British Rail's LDG classifies all dangerous goods in accordance with UN recommendations; except LDG has a tenth class specifically for the transport of dangerous chemicals in small quantities. In comparison, RID has only eight classes (similar to ADR) and differences exist (with LDG) on the categorisation of toxicity. Continual revision of RID to incorporate UN recommendations should soon alleviate these differences. In addition to the LDG regulations British Rail encourage safe practices amongst their employees by issuing a working manual to all staff engaged in the handling and conveyance of dangerous substances. The manual is commonly known as the "Pink Pages" and contains pertinent information on classification, labelling, loading/unloading, marshalling and action to be taken in the event of an incident involving dangerous substances (BR 30054).

Although to a large extent the UK complies with UN recommendations on the transport of dangerous goods, a major difference exists in the area of hazard identification marking of vehicles and packages. In the UK the HAZCHEM system has been adopted. For tanks and tank containers orange, white and black placards measuring 400 mm x 700 mm are affixed to the side and rear of vehicles, so that, in the event of an accident at least one placard can easily be seen. The scheme was pioneered in Cleveland in 1974 and proved extremely useful to the emergency

services. Initially HAZCHEM was used voluntarily throughout the UK under the auspices of the Chemical Industries Association (CIA) until it was finally incorporated as a requirement in 1981 under the Dangerous Substances Regulations. Information contained on the placards includes

a. emergency action code,
b. hazard warning sign,
c. substance identification number,
d. contact point for specialist advice,
e. name of manufacturer or consignor.

The emergency action code details appropriate measures to be taken, such as, evacuation, the use of breathing apparatus and/or special clothing, whereas, the hazard warning sign provides a pictorial representation of the main hazard associated with each substance. The identification number corresponds to the UN numbering system aiding rapid and precise substance identification. In addition, the contact number(s) and name of the body responsible for the load is included so as to aid emergency and clear-up operations. A typical HAZCHEM panel for the marking of road and rail tankers is shown in Figure 1. Marking of packages in the UK is also based on the HAZCHEM system, but only the substance identification number and hazard warning sign are employed.

The HAZCHEM scheme has not been adopted in its entirety for the transport of commercial or military explosives either by road or rail. Due to the need for security road vehicle placards only depict information relating to the hazard, whereas, rail wagon placards also identify the mass of explosives conveyed. At present the placarding of road and rail vehicles used to transport explosives in the UK differ not only with respect to the information given but

also pictorially from the HAZCHEM scheme (and each other) (see Figure 2).

Unlike the UK most European countries have adopted the UN system of marking vehicles and packages to warn of the hazards of dangerous substances (see Figure 3). The system is known as the Kemler Code and takes the form of two or three digits identifying main and subsidiary hazards. At present there are no plans to harmonise the two systems, although the UK HAZCHEM system has been used to some extent in France and Germany. It should be noted, that the Kemler Code is a mandatory part of both ADR and RID regulations and therefore, must be complied with for all trans-frontier shipment between the UK and continental Europe.

Table 1: List of useful references

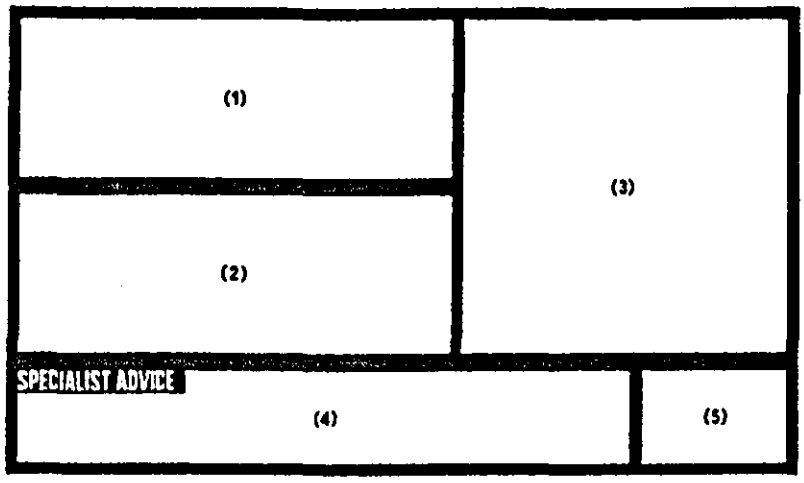
Gunpowder Act 1772
Explosives Act 1875 (amended 1923)
Explosives Storage and Transport Committee (formed 1925)
Notes on the conveyance by road of military explosives regulations (1977 - leaflet 19).
Notice to crews of road vehicles carrying military explosives including ammunition (1984 - leaflet 20).
Conditions for the use of freight containers for the conveyance of military explosives (1983 - leaflet 21).
Notice to crews of road vehicles carrying military explosives including ammunition (1989 - F MOV 773).
Hazardous load warning sheet for road movement of explosives (1989 - F MOV 774).
Health and Safety at Work Act etc. 1974.
The European Agreement Concerning the International Carriage of Dangerous Goods by Road (1990 - ADR).
The International Regulations Concerning the Carriage of Dangerous Goods by Rail (1990 - RID).
Statutory Instrument 1977/888 - The Conveyance by Road of Military Explosives Regulations 1977.
Statutory Instrument 1977/889 - The Conveyance by Rail of Military Explosives Regulations 1977.
Dangerous Goods by Freight Train and Passenger Train or Similar Service BR 22426 (revised).
The Dangerous Substances (Conveyance by Road in Road Tankers and Tank Containers) Regulations 1981.

Table 1: continued

The Classification and Labelling of Explosives Regulations 1983 (CLER).
Working Manual for Rail Staff (1987 - BR 30054).
The Classification, Packaging and Labelling of Dangerous Substances 1984 (CPL - amendments 1986 and 1988).
The Classification and Labelling of Dangerous Substances for Conveyance by Road in Road Tankers, Tank Containers and Packages 1988.
Recommendations on the Transport of Hazardous Goods (United Nations - fifth revised edition 1988)
The Conveyance of Explosives by Road Regulations 1989.

Figure 1: UK hazard warning panel for road tankers, rail tank wagons and road/rail tank containers: HAZCHEM system

a. Hazard warning panel arrangement



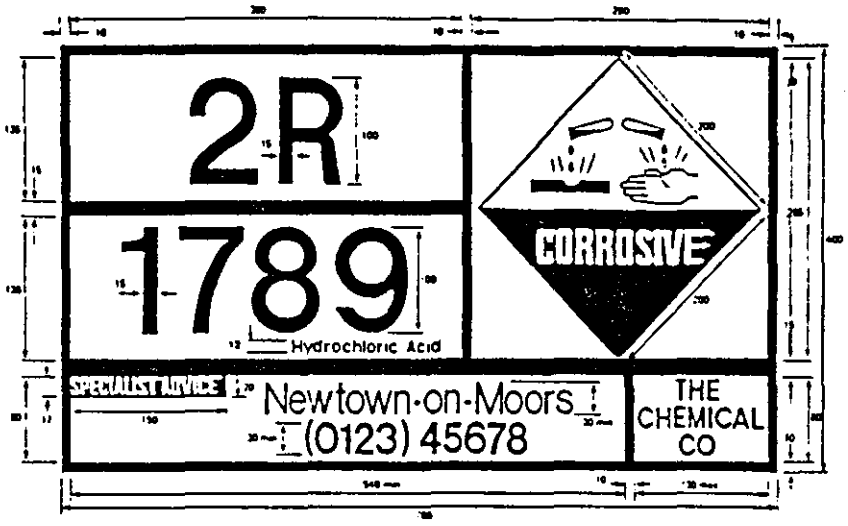
Note

a. Space (3) is orange, all other spaces are white.
b. All boarders and characters are black.
c. The following information shall be shown on each hazard warning panel.

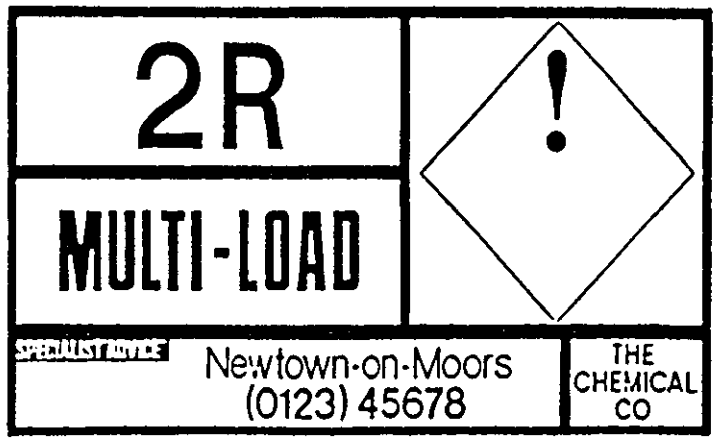
(1) Emergency action code (HAZCHEM code). The code consists of two or three characters. The first character (figure) indicates the correct fire-fighting medium (1-jets, 2-fog, 3-foam, 4-dry agent). The second character (letter) indicates the correct emergency response, personal protection and whether the substance can be violently reactive (P,R,S,T- dilute, W,X,Y,Z- contain, S,T,Y,Z- breathing apparatus, P,R,W,X- breathing apparatus, full body protection and gloves, P,S,W,Y - violently reactive, explosive decomposition, ignition of flammable gas/vapour, rapid combustion, rapid generation of steam, etc). The third character (letter) indicates whether evacuation should be considered (E- consider evacuation, omission of letter- evacuation is not deemed necessary).
(2) Substance identification number (SIN) (these are listed in the United Nations recommendations on the Transport of Hazardous Goods).
(3) Hazard warning sign (these are listed in the United Nations recommendations on the Transport of Hazardous Goods but may differ in the UK by national legislation).
(4) Telephone number or text indicating where specialist advice can be obtained at all times whilst the substance is being conveyed.
(5) Name of manufacturer or owner of substance, his house symbol or both (otherwise left blank).

b. Typical hazard warning panels

single load



multi-load

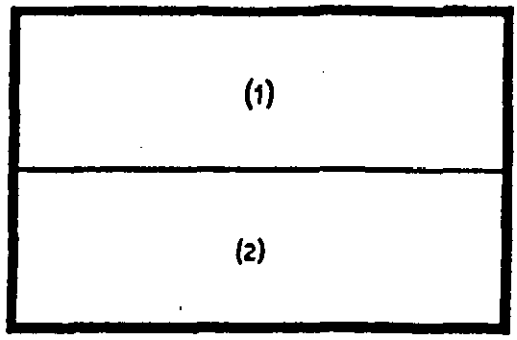


Source:

Guide to the Dangerous Substances Regulations 1981.
London Fire Brigade.
Working Manual for Rail Staff (BR 30054).
Recommendations on the Transport of Dangerous Goods (United Nations).

Figure 2: European hazard warning panel for road tankers, rail tank wagons and road/rail tank containers: Kemler code

a. Hazard warning panel arrangement



Note

a. Spaces (1) and (2) are white.
b. All borders and characters are black.
c. The following information shall be shown on each hazard warning panel.

(1) Hazard identification number (Kemler code).
(2) Substance identification number (SIN) (these are listed in the United Nations recommendations on the Transport of Hazardous Goods).

b. Typical hazard warning panel

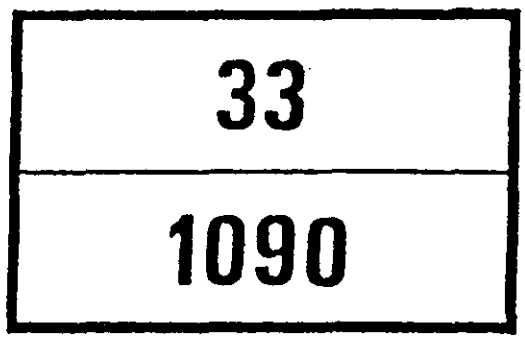
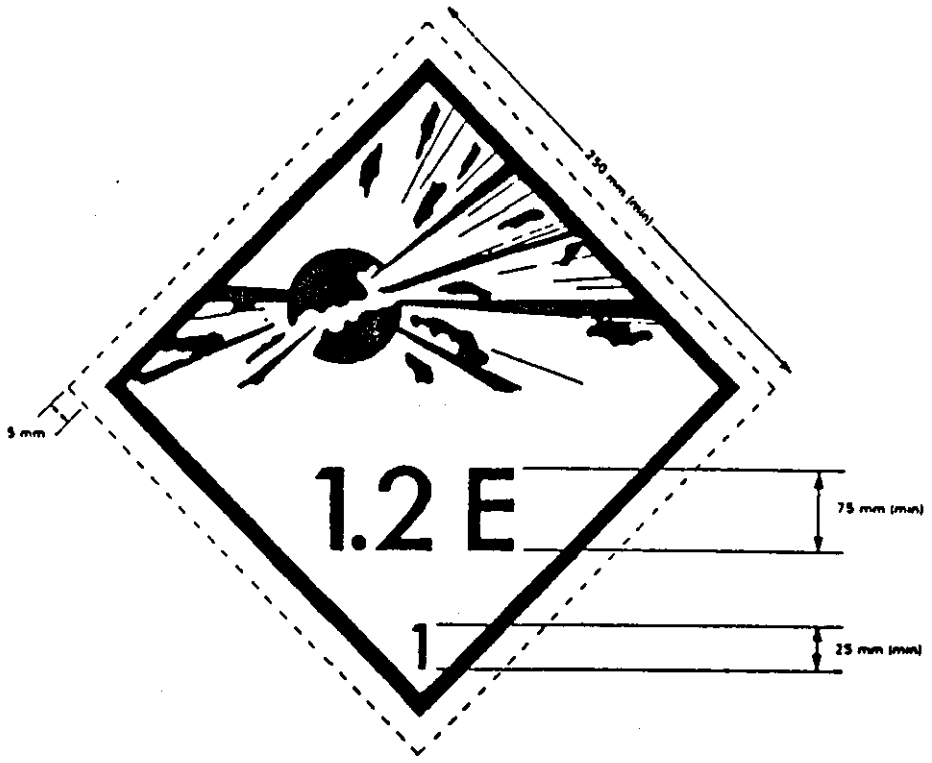
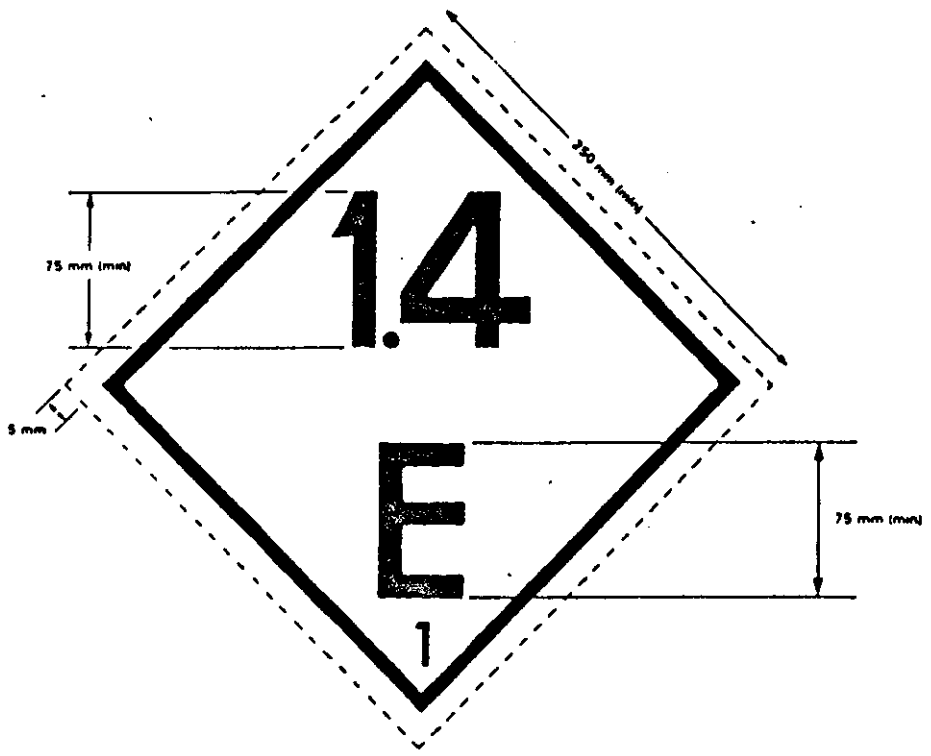


Figure 3: UK hazard warning panel for heavy goods vehicles conveying commercial/military explosives

a. hazard divisions 1.1, 1.2, 1.3



b. hazard division 1.4



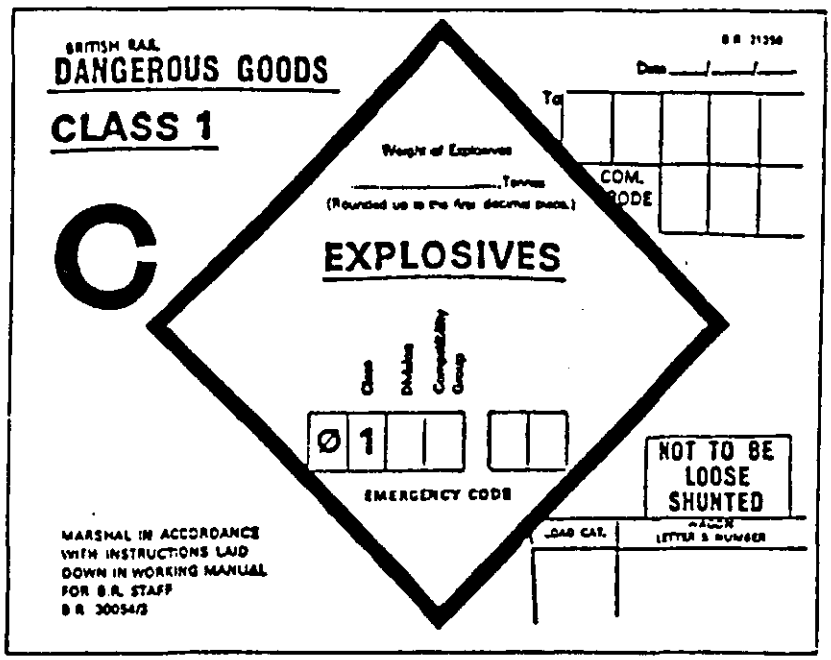
c. hazard division unknown

Note

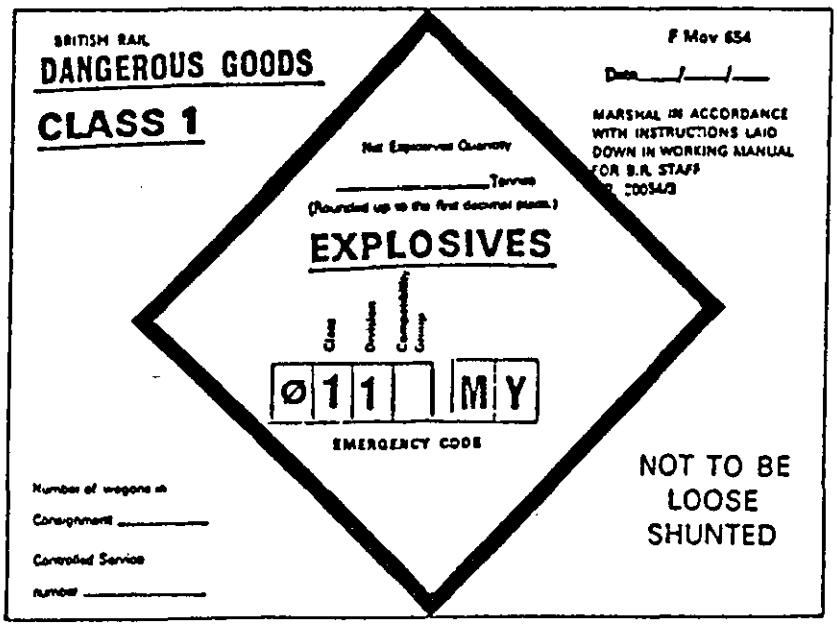
a. Basic panel colour orange.
b. All borders, characters and illustrations are black.
c. One panel affixed each side of vehicle, trailer, semi-trailer or freight container in which explosives are conveyed.
d. In addition to the placards illustrated one blank rectangular reflectorised orange plate (300 mm x 400 mm, 15 mm black border) affixed to the front and rear of vehicle.

Figure 4: UK hazard warning panel for freight wagons conveying commercial and military explosives

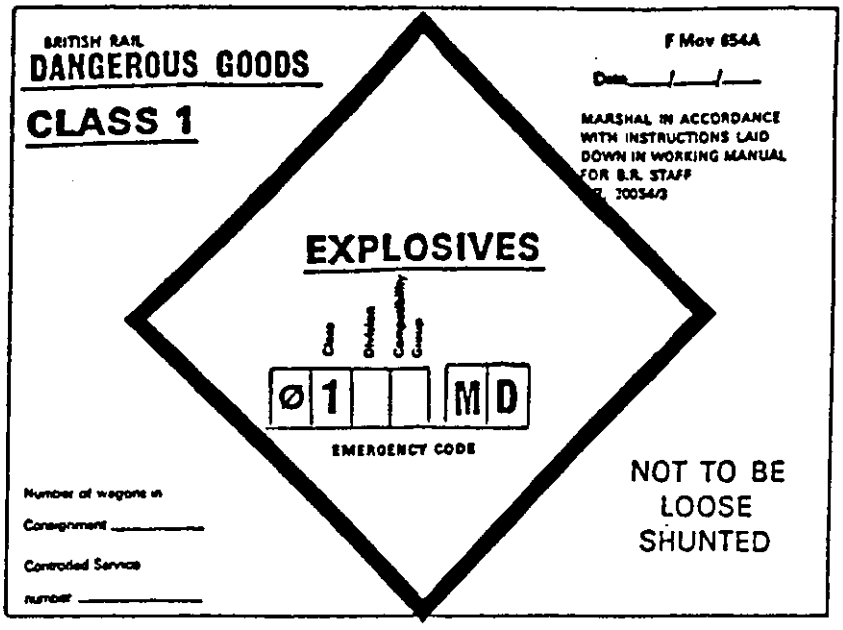
a. commercial



b. military (hazard division 1.1)



c. military (hazard divisions 1.2, 1.3, 1.4)



Note

a. Basic panel colour white.
b. All borders and characters are black.

TRANSPORT OF HAZARDOUS GOODS: THE LEGAL SITUATION

Anxiety stemming from the perceived risks associated with the transport of hazardous goods has tended to increase over the last decade in direct relation to the increase in the quantities transported. A multitude of international organisations have responded to this by initiating studies and establishing regulations in order to ensure the safe transport of such goods[1]. However, the majority of the work performed by these organisations (i.e. Economic Commission for Europe of the United Nations, OECD and IMO) coexists with, or merely forms a component part of, existing international regulations (often termed conventions), which are themselves affected by national laws and legislation. Resulting from the relaxation of national boundaries and the introduction of the free movement of goods throughout the European Economic Community (EEC), effective from 1992, harmonization of the laws relating to the transport of hazardous goods have taken on a new importance.

At present most member states of the EEC have adopted international conventions covering the transport of hazardous goods (as previously discussed). Unfortunately individual member states have repealed, altered and/or included additional rules over many years causing a jungle of rules and amendments specific to each state. As a direct result of this it is not surprising that the EEC have a major task in finding common ground so that all 13 member states can be bound by a single convention. The task is hindered in the main by the three systems of law, international, national and community law. National laws of individual states often contradict and/or prevent the formation of community laws and therefore, weaken the

communities voice in international circles. In addition, it is often difficult to determine current laws in force and distinguish between instruments which are binding or merely recommendations. Furthermore, laws and recommendations are continually being revised and amended adding to the confusion already present.

It is not the intention of this work to discuss in depth legislative procedures or the interrelation of international, national and community law. This area itself has been the subject of many extensive studies. The most recent being published in 1987 by the European Foundation for the Improvement of Living and Working Conditions[1]. The book categorises and clearly defines all the legal aspects of the transport of dangerous goods throughout the EEC and is very informative. Thus, the following sections address the obligations and liabilities of consignors and carriers without in-depth reference to specific laws and legislature.

Obligations associated with the transport of hazardous goods

Legal distinctions regarding the obligations of consignors and carriers are found in most of the national laws of industrial countries. However, the obligations of intermediaries, such as, drivers, businesses undertaking storage, loading and packaging are ill defined (with the exception of the Federal Republic of Germany), and are therefore difficult to interpret clearly due to the complex legal systems involved.

Obligations of the consignor are in the main based on international conventions covering the transport of hazardous goods. National laws often extend or repeal certain consignor responsibilities, but in general the following obligations are enforced:

a. preparation of detailed transport documents, including a declaration that all regulations applicable to the consignor have been observed,
b. ensure that packaging, marking and labelling of the load meets the regulations concerned,
c. inform the carrier of the exact contents of the load and provide written instructions on the safety precautions and measures to be taken in the event of an accident.

In addition to the obligations above, in the UK and most European countries the packaging of goods must be supervised by the consignor.

Similarly, obligations conferred on the carrier are based on international conventions, modified to varying degrees by national law. The main responsibilities of the carrier take the form of

a. an obligation to use transport suitable for the conveyance of dangerous goods which comply with specific technical requirements,
b. be in the possession of a current authorisation or operators certificate relevant to the goods being transported,
c. obtain from the conveyer relevant transport documents,

d. employ only qualified personnel and ensure they understand the safety precautions to be taken in the event of an accident,
e. take sufficient measures to ensure that packaging is intact and that goods are correctly loaded and secured.

In addition to these obligations, UK carriers must possess a current haulage operators certificate and drivers must satisfy specific training requirements. A certificate of competence detailing the class or classes of hazardous goods a driver has been trained with must be held. A special licence is also needed for the carriage of goods when using heavy goods vehicles in excess of 3.5 te (unladen). Training of drivers elsewhere in Europe tends to be sparse or practically non-existent, apart from the gaining of a heavy goods vehicle licence. It is apparent that safety could be improved by the implementation of compulsory vocational courses similar to those used in the UK, where drivers of road tankers conveying more than 3000 litres undergo additional specialised training. Progress is currently being made in this area by many other countries, although the majority of the effort appears to be coming from the UK, namely, the Chemical Industries Association (CIA) and the Road Transport Industry Training Board.

Liabilities associated with the transport of hazardous goods

The liabilities of consignors, carriers and intermediaries is extremely difficult to ascertain clearly. This is because both transport and environmental law is involved together with various legal systems (international, national, etc.) which are highly technical and constantly being amended. National courts have tried to differentiate between contractual relations of the transport parties, tortious liability, whereby the existence of fault is presumed, and the need to compensate third parties regardless of fault. However, such differentiation is hard to distinguish. For example, many risks are not covered by contracts, fault is often hard to proportion and the limit of liability difficult to assess. In addition to these problems there is often a thin dividing line between the need for a victim to prove fault and the need for a defendant to prove that no action by him gave rise to damage suffered by the victim. From the points raised above it is clear that simplification of the various laws in force would improve the present situation, if only in clarifying the liabilities of consignors, carriers and intermediaries.

Contractual liability of carriers usually refers to the safe passage of goods. If damage to the goods is sustained whilst in the care of the carrier then usually the injured party can claim compensation without proving fault. The carrier may, however, be exempted from making reparation for the damage caused if he can prove:

a. circumstances were beyond his control,
b. fault was on the part of the consignor,
c. orders issued by the consignor or claimant led to the damage,
d. goods were inherently defective causing damage.

The amount of compensation payable by the carrier is limited to the weight and volume of the goods transported, unless, the carrier is guilty of wilful or serious negligence. In comparison, once the carrier has taken responsibility for the goods, the contractual liabilities of the consignor are removed. This assumes that the consignor has correctly fulfilled his own obligations, as previously outlined, otherwise blame maybe attributable to the incompetence and/or negligence of the consignor.

It is generally agreed that the parties involved in the transport of dangerous goods should be liable for the consequences of failure to competently perform their obligations. However, the greatest difficulties arise when damage is caused to third parties unconnected with the transport contract, such as, the general public and the environment. In the UK liability for such damage is based on the tort of neglect which constitutes a breach of duty to ensure an undesired event does not occur. This duty has been extended to incorporate the "neighbour" and "proximity" principles, whereby, courts proportion blame on the fact that there was a duty to third parties and that damage was foreseeable. However, compensation is not obligatory in all incidents that cause damage. The gravity and likelihood of occurrence is often taken into account and certain risks considered acceptable if measures to avoid their consequences are deemed to be disproportionate in terms of cost (with respect to the social benefits usually gained).

Generally, the compensation paid to innocent third parties by UK courts is very comprehensive. The payment usually includes not only direct costs but all indirect costs, such as, loss of earnings and mental anguish etc.. UK courts have also been known to increase compensation excessively as a means of punishing the defendant, although in some cases full compensation has not been granted in view of the defendants circumstances. Expenses resulting from emergency and cleaning operations also qualify for compensation provided the measures taken are deemed necessary. It should be noted, that if for any reason the offender is not known or the damage is not direct and identifiable, the victim will (usually) be denied all compensation. If the victim dies, direct ascendants, descendants or collateral relatives can claim compensation on the victims behalf, acting as the deceased dependents. Compensation for persons on board the vehicle causing damage are covered by the contractual liability of the consignor and carrier, together with laws enforced internationally and nationally on the obligations of those engaged in transport operations. With respect to employees of the offending consignor or carrier, provided that they are free of any blame, then injuries sustained whilst performing their duties can be compensated through appropriate unions and legislation on accidents at work. At present compensation for environmental damage is much more reserved. Such damage affects the whole community and therefore usually requires local authorities or governments to act on the publics behalf. However, compensation is often not forthcoming, courts cite that no specific interests are directly affected and therefore, there is no case to answer.

It is obvious from the points raised above that greater clarity and harmonization of laws and conventions would help simplify the rules by which obligation and liability are assessed. Such action would provide greater legal certainty and clearly identify consignor, carrier and intermediary responsibilities leading to easier attribution and identification of fault.

Reference

1. The European Foundation for the Improvement of Living and Working Conditions. (1987).
   Transport of Dangerous Goods.

APPENDIX B: ROAD AND RAIL ACCIDENTS INVOLVING EXPLOSIVES

Road Accidents: UK

Date: 12 October 1957

Time: Early morning

Location: Five miles from Brecon on the main Brecon to Abergavenny road (A40 ?).

Accident: EXPLOSION, non-crash fire.

Deaths:

Injuries: Driver and mate were treated for shock.

Description: A non-crash lorry fire caused the ignition and explosion of 3.5 tons of "blasting powder (TNT)". The lorry was en-route to a mining site in Aberdare when the driver stopped the vehicle to de-mist the wind screen. Both driver and mate smelt burning and decided to summon the fire brigade and warn approaching traffic. Two cottages suffered roof, wall and window damage ("roofs fell-in"). Broken windows were reported up to 3 miles away from the blast and a crater 15 feet deep and 42 feet wide was made in the road. Driver and mate were 100 yards away when the explosion occurred.

Source: The Times (Sat. Oct. 12 1957).

Date: 15 September 1981
Time: Evening/night
Location: Motorway M4, Berkshire-Hampshire border.
Accident: Non-crash fire
Deaths:
Injuries:
Description: A commercial HGV in a convoy of 3 HGVs caught fire on the M4 motorway. The HGV was laden with 20 tons of unprimed USAF "cluster bombs" en-route from Barry Docks South Wales to RAF Welford in Berkshire. Fire started as a result of rear brake drum overheating. Flames were seen coming from the rear and underside of the lorry. Police, fire brigade and bomb disposal experts attended the scene. The fire took 3 hours to extinguish and a 15 mile stretch of motorway was closed for eight hours. The load was transferred to another "British Road Services" lorry to continue its journey.
Source: The Times (Wed. Sept. 16, Thur. Sept. 17 and Thur. Nov. 5 1981).

Date: 13 December 1982
Time:
Location: A17, Long Sutton (near Spalding), Lincolnshire
Accident: Vehicular collision
Deaths:
Injuries:
Description: An RAF HGV conveying Martel air-to-surface missiles collided with a commercial HGV on the A17 at Long Sutton. The load consisted of ten missiles each weighing one tonne. No fire or explosion accompanied the accident. The area was "sealed-off" and traffic diverted. Service personnel supervised the transferral of the load to another HGV in a 6 hour clear-up

operation.

Source: The Times (Tue. Dec. 14 1982).

Date: 22 March 1989

Time: Explosion between 09.40 and 09.45

Location: Fengate Industrial Estate, Peterborough.

Accident: EXPLOSION, non-crash fire.

Deaths: 1 (fireman)

Injuries: 81 (11 firemen and 70 office and factory workers).

Description: A 7.5 ton Iveco Ford HGV laden with between 750 kg and 800 kg of commercial explosives caught fire causing its load to ignite and consequently explode. The load consisted of gelignite (powergel), and up to 750 detonators and fuses. The HGV was en-route from Nobels Explosives, Lichfield, to Le Maitre, a fireworks factory in Cambridge. The HGV stopped in the yard of a factory on the Fengate Industrial Estate. Smoke and flames were seen coming from the rear and underside of the vehicle including its rear door. The first emergency call was received at 09.36 and the first fire appliance arrived 4 minutes later. Within about 2 to 4 minutes of 4 fire-engines, support vehicles and 50 firemen arriving the load exploded. People standing about 75 yards away were said to be knocked off their feet by a warm blast. A large number of detonators were scattered across a wide area. Severe damage was caused to 20 buildings, several fire-engines and about 100 other vehicles. Buildings up to 300 yards away were severely damaged. Nearby walls collapsed, and roofs fell-in. Glass, brick and metal objects were thrown through the air showering

surrounding buildings and cars. Secondary fires were caused to a number of surrounding vehicles. The explosion created a crater 3 metres across and a little under half a metre deep. The dead fireman was only yards away from the HGV when the explosion occurred. One other firemen was severely injured and admitted to intensive care. A total of 81 people were injured, injuries to 13 were so severe as to warrant a stay in hospital.
An inquiry into the cause of the incident is to be published and made public sometime in 1990.

Source: The Daily Telegraph (Thur. Mar. 23, Fri. Mar. 24 1989), The Times (Thur. Mar. 23, Fri. Mar. 24 1989) and The Daily Express (Thur. Mar. 23 1989).

Road Accidents: Worldwide (excluding UK)

Date: 4 June 1971
Time:
Location: Waco, Georgia.
Accident: EXPLOSION, crash fire.
Deaths: 5
Injuries: 33
Description: A car collided with a semi-trailer truck conveying commercial explosives. Gasoline and diesel split onto the road and ignited. Both vehicles were engulfed in flames and the load exploded. A total of 5 people were killed, these included 3 emergency service personnel and 2 bystanders.
Source: National Transportation Safety Board (US).

Hazardous materials special investigation. PB87-917001, NTIS.

Date: 12 June 1983
Time:
Location: Autobahn, near Schweinfurt, West Germany.
Accident: Crash
Deaths:
Injuries: 2 soldiers
Description: A United States Army lorry conveying munitions overturned in a crash on a West German autobahn. The lorry shed its load of 3 Hawk missiles (conventionally armed). Ordnance disposal personnel attended the scene. The accident was not accompanied by fire or explosion but the autobahn was closed for more than 4 hours.
Source: The Times (Sat. Jun. 11 1983).

Date: 1 August 1984
Time:
Location: Denver, Colorado.
Accident: Single vehicle accident
Deaths:
Injuries:
Description: A semi-trailer truck conveying Navy torpedoes overturned on an intersection between two major interstates near Denver. Diesel fuel split onto the highway but did not ignite and no explosion occurred. The fire services attended the scene.
Source: National Transportation Safety Board (US). Hazardous materials special investigation. PB87-917001, NTIS.

Date: 10 May 1985
Time:
Location: Bonnieville, Kentucky.
Accident: Crash fire
Deaths:
Injuries:
Description: A semi-trailer truck conveying military explosives collided with a parked car on interstate 65 near Bonnieville. The fuel tank of the truck ruptured and an estimated 30 US gallons spilt onto the road and ignited. The load of plastic explosives ignited and burnt intensely. The fires services attended the scene and extinguished the fire with water. No explosion occurred.
Source: National Transportation Safety Board (US). Hazardous materials special investigation. PB87-917001, NTIS.

Date: 4 August 1985
Time: 03.30
Location: Checotah, Oklahoma, USA.
Accident: EXPLOSION, crash fire.
Deaths:
Injuries: 49
Description: A semi-trailer truck loaded with military explosives collided with the rear of a car on interstate 40, 1 mile from the centre of Checotah. The load consisted of 10 MK84 894 kg general purpose bombs (2000 lb.) each filled with approximately 430 kg of tritonal. On collision the fuel tank of the car ruptured spilling diesel onto the road which subsequently ignited. Despite the efforts of the truck driver fire quickly engulfed both the car and truck. Police received an

emergency call at 03.34. On arrival at the scene the police found both vehicles to be engulfed in flames. Three fire-engines were present and preparing to withdraw when the first of three explosions occurred at 03.45. The second explosion occurred shortly after 04.00 and the third, and most powerful, at 04.22. The third explosion left a crater almost 11 metres across and just over 8 metres deep. Firemen over 300 m away were knocked to the ground. Damage was caused to residences over 1.5 km away. The majority of damage consisted of broken windows, damaged roofs, door frames collapsed ceilings and weakened exterior and interior walls. A nearby school (224 m away) was substantially damaged, 22 homes required major reconstruction and 11 homes needed re-building. In addition to the explosives truck and car a fire-engine was completely destroyed. One bomb, 80%-90% burnt-out, was thrown between 45 m and 55 m. Two other bombs were also scattered away from the site, a one metre end section was found approximately 50 m away. Both the driver and passenger of the car suffered injury. The passenger being admitted to hospital for second degree burns and abrasions/bruises. The driver of the truck was also slightly injured. Eight emergency personal were injured, the worst suffering face abrasions and a ruptured eardrum. In total 49 people were injured, most as a result of smoke and tritanol fume inhalation. Checotah evacuated its population of 5,000 people at 06.00 due to the threat of further explosions. The evacuation was completed at 07.45 and people were allowed to return to their homes at 12.30. Road-side

fires were extinguished by 09.30 and the road re-opened at 12.00. Clear-up operations were completed on 7th August.

Source: National Transportation Safety Board (US). Hazardous materials special investigation. PB87-917001, NTIS.

Rail Accidents: UK

Date: 22 October 1969

Time: 22.18

Location: Chelmsford Station

Accident: Derailment

Deaths:

Injuries:

Description: The 8th wagon of a class 6 special FT conveying military explosives derailed at 45 mph. The FT consisted of 27 covered wagons hauled by a diesel-electric loco. The first 5 wagons and the last wagon were empty, the other 21 were loaded with just over 117 tons of ammunition and pyrotechnics. No wagon contained more than 7 tons. Press reports suggested that "mortar bombs" were being carried and a track-side transformer was hit. Extensive track, signalling and platform damage was caused. Both up and down lines were blocked. A hot axle box overheated and caught fire after derailment. Explosives were removed by the Army. Clear-up operations took over 7 hours.

Source: Railway Inspectorate report, HMSO. The Times (Thur. Oct. 23 and Fri. Oct. 24 1969).

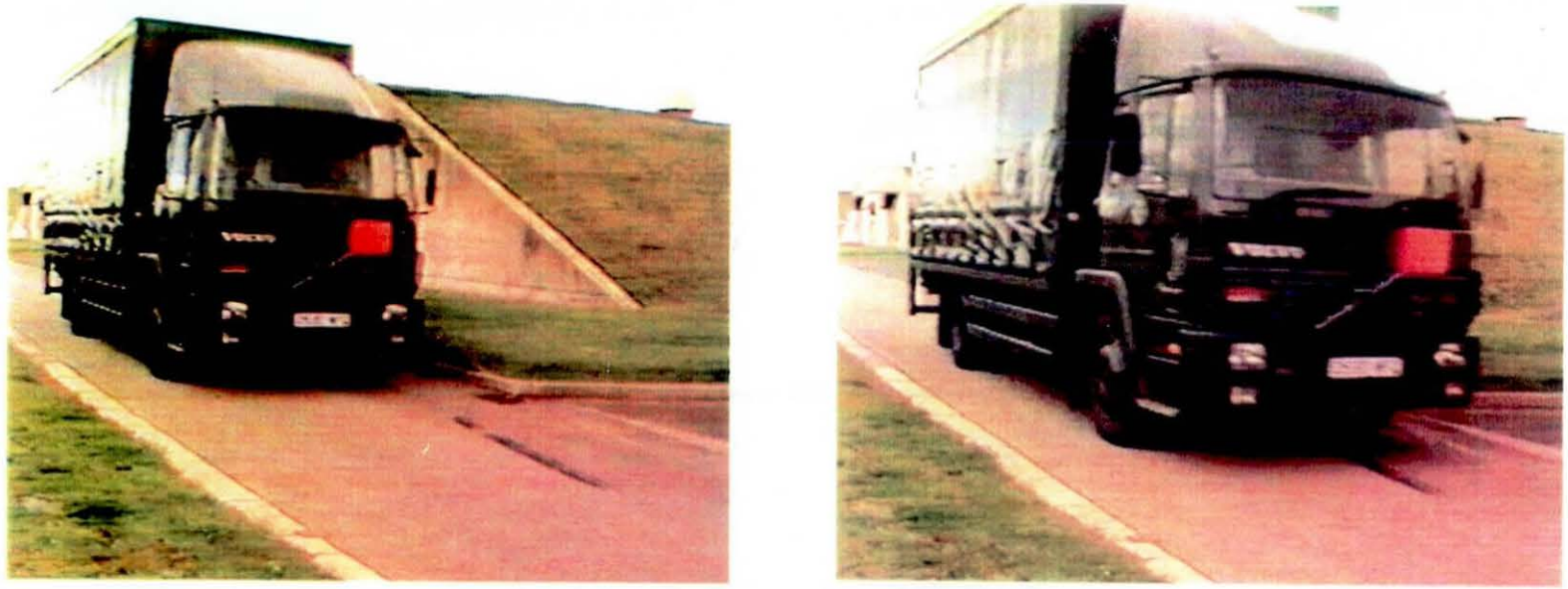
Date:
Time:
Location: Parkway Station, Stoke Gifford, Bristol.
Accident: Collision
Deaths:
Injuries:
Description: An ammunition laden FT derailed in sidings at Parkway Station as a result of being hit by another FT. No fire or explosion accompanied the accident. The accident caused local politicians to demand an inquiry. Parkway station is in a densely populated area of Bristol (nearby housing estate).
Source: The Sunday Express (Oct. 1987)

Rail Accidents: Worldwide (excluding UK)

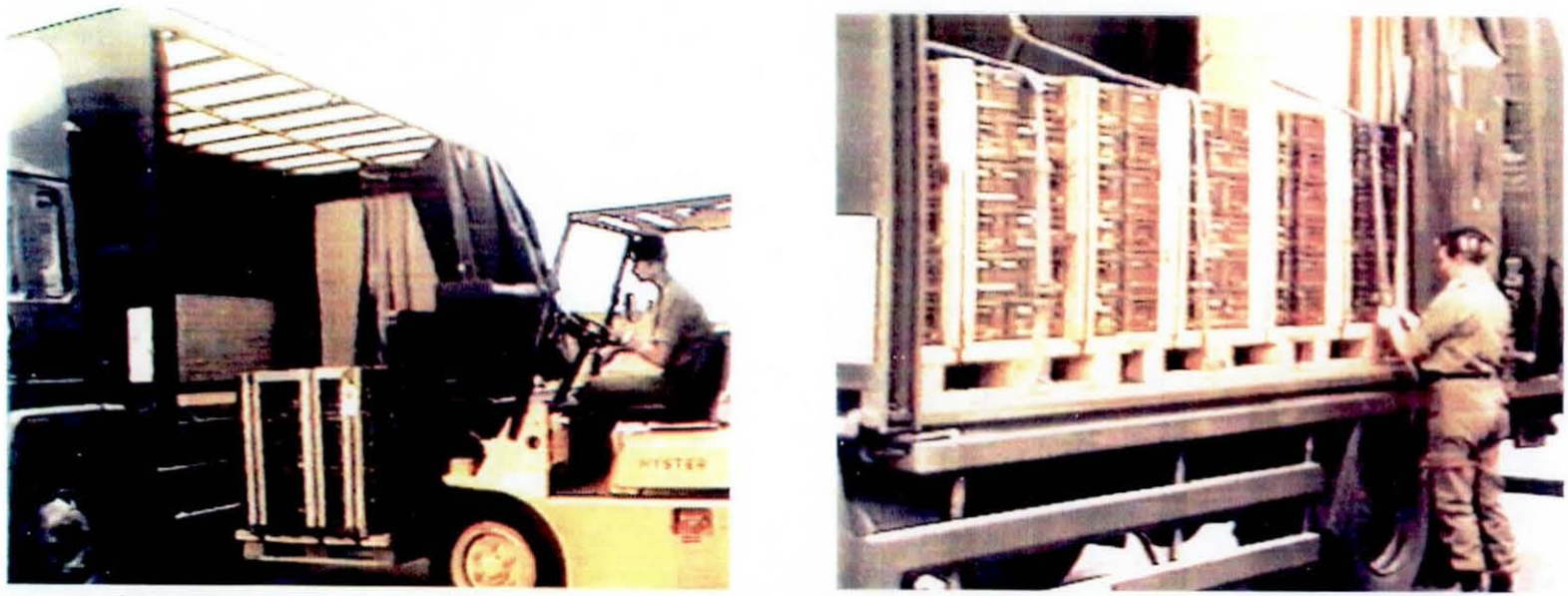
Date: 12 November 1987
Time:
Location: Iri, South Korea.
Accident: EXPLOSION, non-crash fire.
Deaths: 57
Injuries: 1300
Description: A watchman asleep in a freight car knocked over a candle igniting surrounding materials. The fire spread causing the trains load of dynamite to explode. The explosion occurred at a crowded station. Ten thousand people were made homeless.
Source: HSE

APPENDIX C: TYPICAL VEHICLES USED FOR THE CONVEYANCE OF COMMERCIAL AND MILITARY EXPLOSIVES

Road Transport



(1) Rigid 2-axle HGV, 5 te NEQ (military)



(2) Loading and securing typical palletised munitions.

Photographs: Chemfreight Training Ltd. video 'Explosives in Action' ©

(3) Rigid 2-axle HGV, 5 te NEQ (commercial)

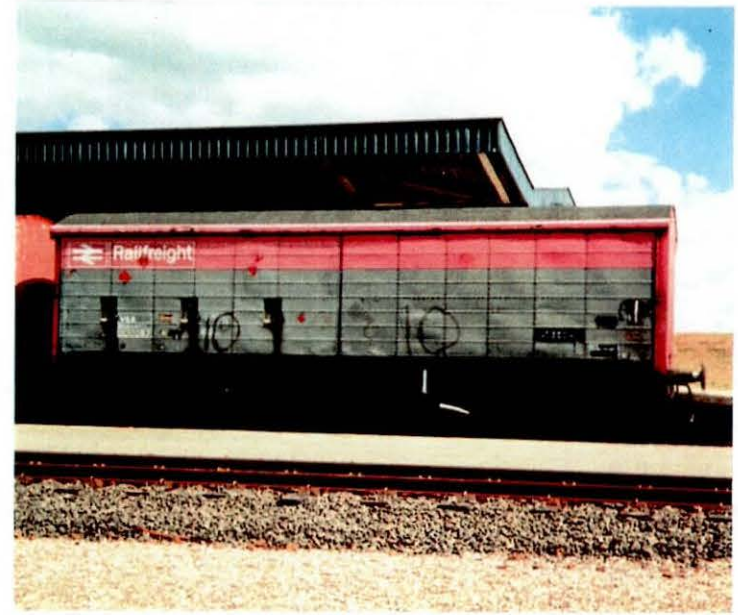
(4) Articulated 4-axle HGV, ISO container, 16 te NEQ (commercial)

Photographs: Courtesy of Pennine Transport

(1) 12 te ventilated goods wagon, air braked (military)

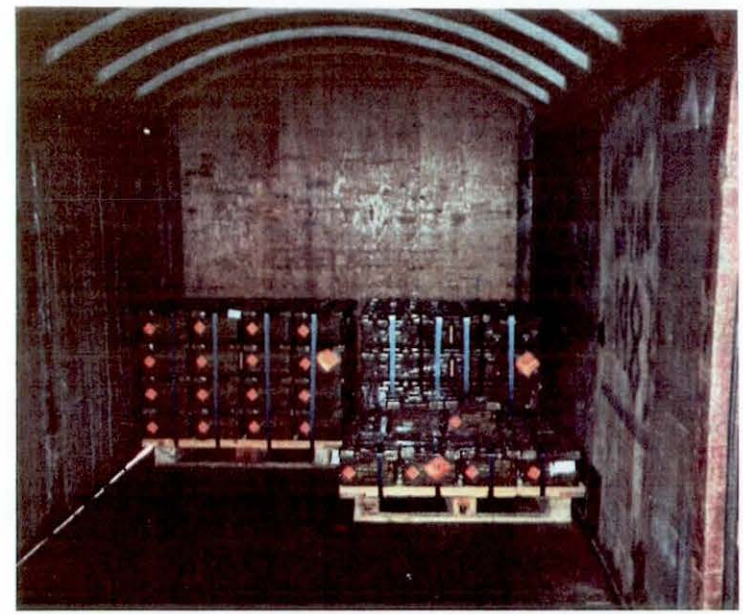
(2) Unloading palletised munitions.

Photographs: kind permission of Lt. Col. (Ret'd) Gillies, CAD Kineton



(3) 29.5 te goods wagons, air braked (military/commercial)

(3)



(4) Interior of 29.5 te goods wagon, palletised munitions prior to unloading.

Photographs: Kind permission of Lt. Col. (Ret'd) Gillies, CAD Kineton