Guangzhou-Shenzhen-Hong Kong Express Rail Link: An overview of the explosives aspects in a quantitative risk analysis for the road transport of cartridged emulsion explosives and accessories through a densely populated area.

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Abstract

The construction of approximately 15 km tunnels through rock involves the safe transport of substantial quantities of cartridged emulsion explosives, detonating cords and non-electric (shock tube) detonators through densely populated areas. Bulk explosives are manufactured on site and are not part of this study.

A risk analysis has been undertaken by ERM (Environmental Resources Management (ERM)) on behalf of MTR Corporation Ltd for the transport operations involved with these media. In support of this, the above authors participated in a review of explosives safety issues.

This analysis includes an assessment of prior incidents with similar explosives, the relevant physico-chemical properties of these energetic materials, available test data, credible insult scenarios during road transport, notably collisions, fires and damaged/off specification explosives and some possible approaches to mitigation. This paper will focus on the explosive emulsion aspects of the study.

The presentation is based on published reports which were part of a comprehensive overall QRA study conducted by ERM-Hong Kong Ltd [1].

Introduction

The Guangzhou-Shenzhen-Hong Kong Express Rail Link (XRL) is a cross-boundary transport infrastructure project providing high speed rail services between Hong Kong and Guangzhou and a connection to the national high-speed passenger rail network serving major mainland cities outside the Guangdong province.

This paper is concerned with the storage and transport of cartridged emulsions (gassed or sensitized by microballoons) - detonator sensitive - UN Classification 1.1D) through densely populated areas. This is part of a large Quantitative Risk Analysis study for the Express rail link in Hong Kong[1]. A group of experienced personnel with a background in explosives safety was engaged to assess the response of these energetic media to credible accident scenarios, specifically:

(i) Impact/ instantaneous friction e.g. as a result of a road collision
(ii) Fire – eg as a result of a tyre fire
(iii) Contamination/ material off-specification

Assessments were based on previous accident histories based on literature surveys, on the physico-chemical properties of the emulsion explosives, or by analogy with media considered less safe (ANFO in a fire scenario, and NG explosives generally).

Hazards of emulsion explosives

The explosives involved in this study were conventional packaged ammonium nitrate based water-in-oil emulsions, mechanically sensitized by microballoons or gassing agent: the water content in these systems would typically be in the range of 10-14 % w/w. No additional chemical sensitization (e.g. perchlorate) was to be used.

The hazards of emulsion and heterogeneous liquid explosives have been reviewed extensively elsewhere [ex 2,3,4,5]. In the absence of contamination or thermal insult, these media have been assessed as being not normally susceptible to scenarios typical of transport and storage:

(i) **Impact and Instantaneous Friction**: Unlike emulsion matrix, mechanically sensitized emulsions are susceptible to high velocity impact and shock. Minimum velocities for initiation tend to be in excess of 500 m/s. [6,7]. An illustration of the effect of high velocity impacts is given in Figure 1 (courtesy of Dr Roger Holmberg, EFEE).

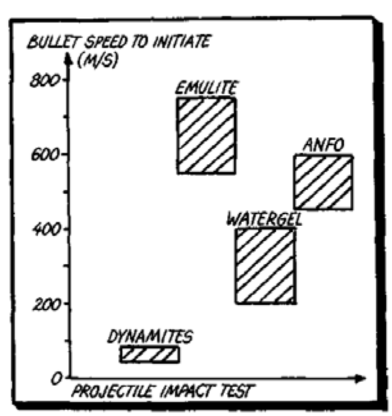

Figure 1: Bullet impact tests on a range of explosives

(i) **Deflagration** In the presence of appreciable water content and in the absence of chemical sensitizers, emulsions exhibit an elevated minimum deflagration pressure: in the presence of, for instance a perchlorate, these pressures are much reduced . In the context of transport and storage this minimum deflagration pressure would be substantially greater than storage pressures either in situ or in transport. [3,8,9]

(ii) **Thermal Explosion:** A worst and most conservative case for the thermal explosion scenario can be taken as an ANFO. By virtue of its water content providing a thermal buffer, due to both liquid heat capacity and latent heat of evaporation, the emulsions used in this operation can regarded as safe unless a critical temperature is exceeded and much of the water is driven off [2].

(iii) **Detonation**: For conventional explosives, the onset of a stable detonation requires:

a. a sufficient energetic stimulus (shock, impact or via DDT (deflagration to detonation transition))
b. a diameter greater than the governing detonation failure diameter (dependent on the explosive and its confinement)

The absence of a sufficiently powerful stimulus ((i) above) precludes a shock/high velocity impact scenario leading to detonation via SDT (shock to detonation) . The inability for the emulsion to deflagrate at storage/ cartridge transport pressures eliminates concerns regarding DDT.

Scenarios in transport and storage of packaged emulsion explosives

Impact/ Instantaneous Friction

A number of projectiles impact studies on commercial explosives have been reported in the open literature [6,7]. These have largely been directed at examining possible domino effects on processing plants – whether an explosion or detonation in one plant component can propagate elsewhere in the process. From data available, fragment velocities have to be in excess of typical bullet velocities (500 m/s) in order to achieve explosive initiation. The required velocity is reduced at elevated temperatures [6] but it still outside any credible accident scenario envisaged here. Earlier studies have shown that the critical projectile initiation velocity for an emulsion is some tenfold greater than for a dynamite [7].

An extensive series of drop weight studies on NG explosives has been reported [10], in which a hammer was dropped onto cartridges to mimic the impact forces that cased cartridges would sustain on falling through a height in excess of 12 metres onto a hard unyielding surface. No ignitions were observed in 1150 trials, indicating an ignition probability below 0.001 (70% confidence level)

For the purposes of this study, and in the absence of more reliable data, the authors of this paper took the view that a probability for the emulsion would be at least a factor of 10 less giving a probability of 1(-4) (0.0001). A detailed literature search and record of accidents was unable to find a purely impact related accident that lead to a detonation with an emulsion explosive [11].

Fire/ thermal insult

In this scenario, the presence of voids is a secondary issue and the concern is whether matrix or mechanically sensitized emulsion can be made to explode or burn as a result of thermal insult. An earlier UK study [12] has addressed the question of probability of initiation due to fire for different classes of explosives. A guide figure for probability of 0.1 was suggested. It should be noted that the inventories of explosives being considered in this study can, at worst, be considered as semi-confined.

Given a sufficient thermal stimulus for a long enough duration it is inevitable that a dangerous condition may ensue as water is driven off as steam and the remaining material behaves as a hot, low density and/ or more refined ANFO with ammonium nitrate in a molten state. Consequences of any overheating will also be dependent on confinement i.e. whether evaporation of ammonium nitrate and then fuel can mitigate these. Taking this and the number of transport incidents that did not give rise to an explosion into account, the authors of this paper have suggested a probability of 0.5 as an upper estimate.

In relation to cargos comprising solely of ANFO and emulsion explosive five accidents were recorded which led to explosion [10].

Table 1 Fire related accidents with ANFO and emulsion explosives [11] – See also Appendix for more recent incidents

Year	Country	Type of Load	Type of Event	Cause
1959	USA	ANFO	Explosion	Vehicle Fire
1998	Canada	ANFO	Explosion	Vehicle crash/collision
1998	Australia	ANFO	Explosion	Vehicle Fire
2004	Russia	Emulsion	Explosion	Vehicle Fire
2007	Mexico	ANFO	Explosion	Vehicle crash/collision

In addition, a series of experiments has been reported [12] relating to the effect of fires on ammonium nitrate based explosives following the 1998 Walden, Ontario accident: the explosion could not be reproduced in these full scale fire studies. Based on the available information an upper limit of 0.5 for the probability of initiation of an emulsion explosive as a result of thermal insult was recommended. It was also concluded that exothermic reaction would be avoided if temperatures did not exceed 140 deg C and where this temperature was marginally exceeded the authorities might have 30 minutes or more to intervene and cordon off the affected area, given that the design of transport container and storage could include heat dissipation and insulation of load.

Contamination/ Off Specification Explosive

A view was taken that contamination of cartridged explosives or of the importation of these as off specification that might render the explosives more susceptible to insult was of very much lower probability (of order~1(-9)) than the impact or fire scenario was insignificant and did not warrant further investigation.

Fault tree analysis

The analyses carried out by ERM and earlier related studies [13,14,15,16] are discussed in detail elsewhere [1]: these include the probabilistic assessment data and only some aspects that apply to emulsion explosives are considered here. This paper is primarily concerned with the aspects of packaged emulsion explosives safety during transport in diesel powered light pick-up (LGV) trucks. These were to have the following safety related features:

- manual fuel isolation
- forward mounted exhaust and spark arrestor
- explosives compartment free of electrical wiring
- all wiring in fire resistant conduits
- protected fuel tank and design that avoided spillage accumulation
- water and carbon dioxide fire extinguishers
- fire resistant material on wheel covers
- fire screen between cab and load compartments and beneath the load compartment

Contributions from the hazards associated with crashes (fire and impact), non crash fires and spontaneous explosion have been considered.

The fault trees for the transport of emulsion explosives on contractor's trucks for both Expressway and non-Expressway travel are included in Figure 2. For both cases the probabilities are low and dominated by non-crash fires. More details of the non-crash fire analysis event frequency determination are given in Figure 3 with the implications of the analysis as a F-N curve presented in Figure 4.

Several aspects of Figures 2 & 3 are worth further discussion:

(i) **probability of initiation of explosives in a fire**: Emulsion explosives contain a considerable quantity of water. This, in the absence of chemical sensitizers, renders the explosive non-deflagrable at atmospheric pressure. Prolonged exposure to heat of fire will result in loss of water (as steam) and ultimately a sensitive hot liquid AN-oil mixture. Because of the less sensitive nature of conventional emulsions and this time scale to obtain a reactive medium a probability of 0.5 for initiation was chosen as a conservative limit, as discussed earlier.

(ii) **unsafe explosive & spontaneous explosion:** The probability of contamination in process or during transport or storage of emulsion cartridges which in turn lead to a more sensitive medium was considered to be very small and essentially non-contributory to the risk assessment. A guide probability for this event was ~ 1(-9).

(iii) **initiation by direct impact:** The emulsion cartridges are physically sensitized by the presence of voids. It is well established they can be initiated by high velocity bullet or sabot. In the context of this study, where worst case impact velocities will be substantially less, using the experimental data [6,7] the risk of direct impact initiation is small relative to the fire scenario

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(iv) **mitigation by quenching fire:** In the case of fire on a vehicle carrying explosives, evacuation of personnel and those in any damage zone that might be affected would be normal practice. In Figure 3 some allowance has been included for fire fighting for the specific explosives in a well insulated environment.

The results, F-N curves, for the full QRA are given in Figure 4 for both base and worst cases. . It should be noted that Figure 4 is an overall analysis but that the transport aspects are by far the major contributor to the fatality probability. It can be seen also that if the explosive transported was nitroglycerine based the probabilities would be a factor of at least 2 higher (impact sensitivity and susceptibility to initiation from thermal insult) and the operations would not normally be regarded as safe without further mitigation.

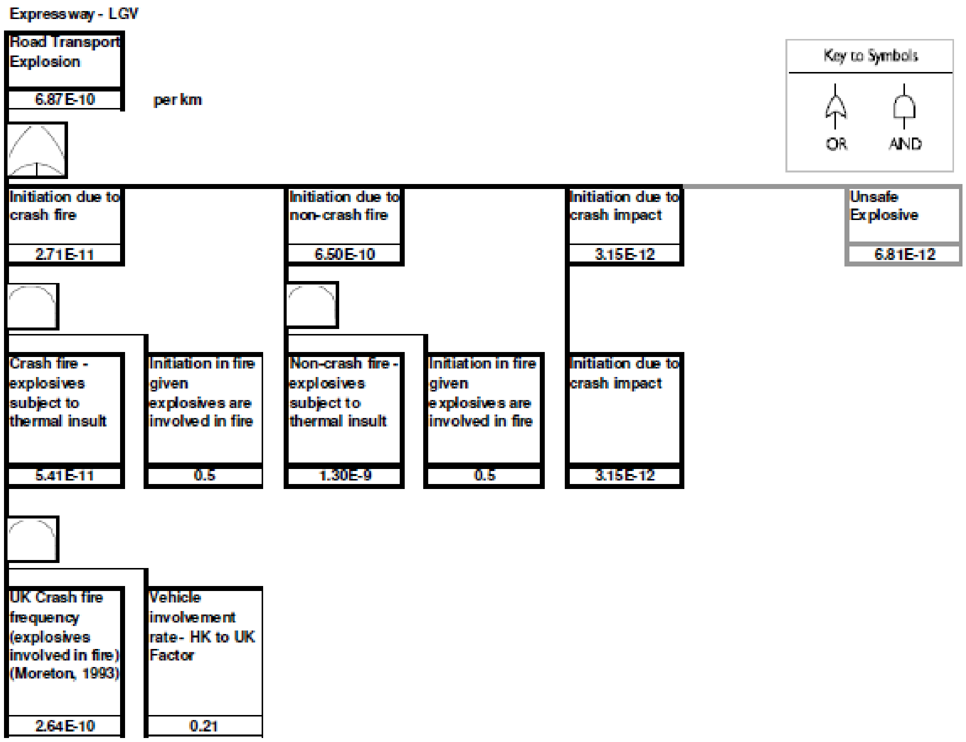
Mitigation measures

These were considered in the full study [1]. Alternative routes, explosives, load inventory, frequency, training and truck design/ safety features were examined. Of those measures whose effects could be quantified, there was little change in the F-N analysis.

Summary/ Conclusions

An explosives analysis has been undertaken as part of a much larger QRA study for the safe transport and storage of explosives in Hong Kong involved in the construction of two large rail tunnels. The outcome was an operation within ALARP guidelines. The critical consideration was the probability of a non-crash fire leading to an initiation and propagation to explosion/ detonation of the cartridged explosive. The consensus view on this probability was that it was, in contrast to nitroglycerine based explosives, less than 1 and a figure of 0.5 was adopted given the properties of the emulsion with large thermal sink in terms of water content and need for this to evaporate before exothermic chemical reaction could dominate.

It was also concluded that there had been no history of accidental explosions in the transport of cartridged emulsion explosives. Direct impact has been shown to be a minor contributor to any explosion risk. Guidance on the likely minimum temperature for ignition and for the time for this to be achieved in a fire is also discussed.



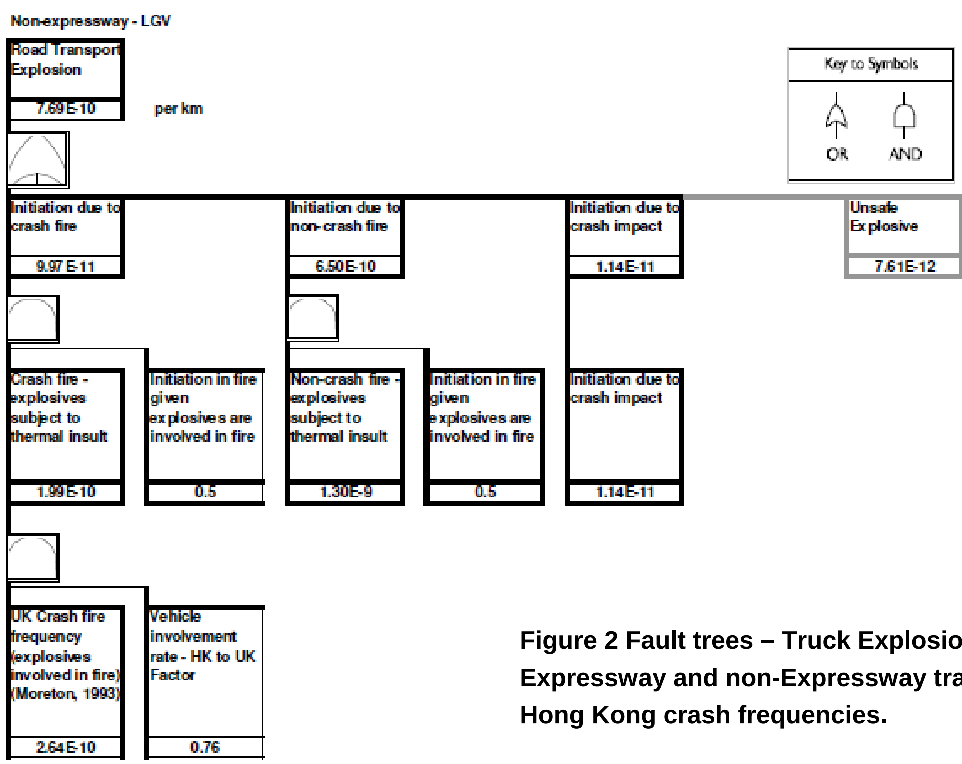


Figure 2 Fault trees – Truck Explosion Frequency per truck per km – Expressway and non-Expressway travel normalised to match UK and Hong Kong crash frequencies.

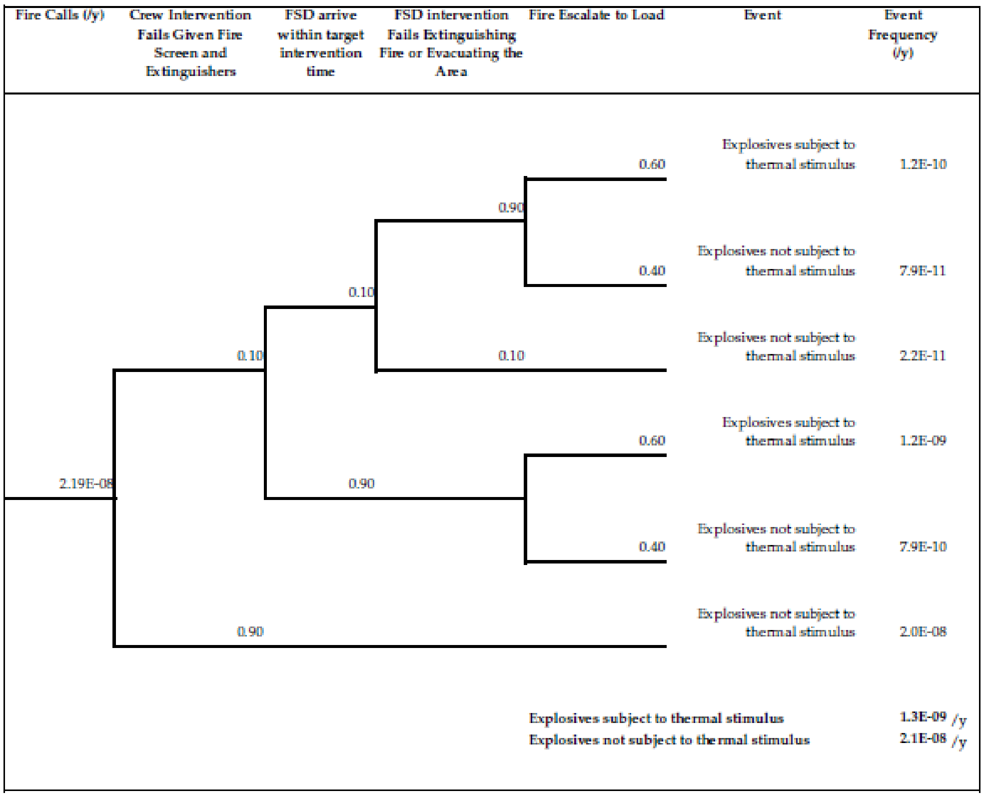


Figure 3 Event Tree for non crash fire scenario

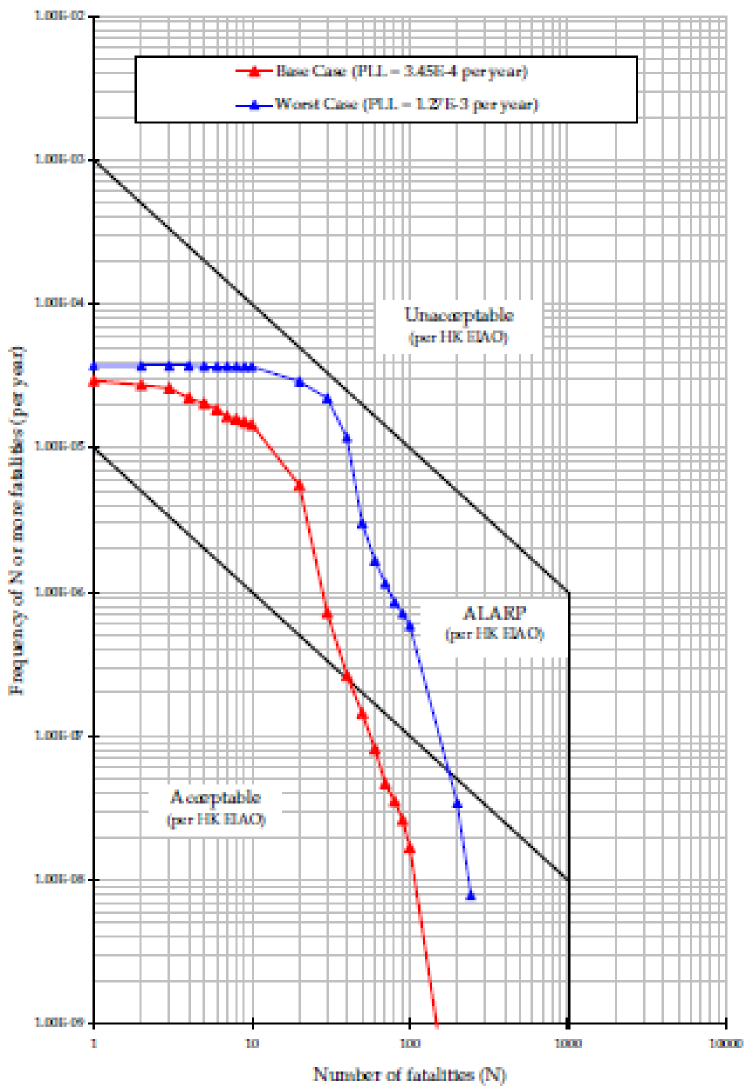


Figure 4 Overall Fatality Frequency vs number of fatalities for the transport of emulsion explosives for a base case and a worst case incorporating a 20% increase in the number of deliveries of explosives.

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Appendix

Since completion of the study there have been three other relevant ignition incidents in transport. All three incidents resulted in fire rather than explosion. Brief details are as follows:

Year	Country	Type of Load	Type of Event	Cause
2009	Canada	Watergel	Fire	Tyre fire
2010	Brazil	Cartridged emulsion	Fire	Brake Fire
2010	Saudi Arabia	ANFO	Fire	Vehicle crash/collision

Canada

A truck carrying a mixed load of explosives (watergel and detonating cord) caught fire as a result of a tyre blow out. Attempts to extinguish the fire failed. The crew withdrew to a safe distance. The load was consumed in the fire but there was no explosion.

Brazil

An explosives truck carrying 25 t of cartridged emulsion incurred a brake fire and rolled over. The driver, who was uninjured, tried but failed to extinguish the fire. He then allowed the load to burn itself out without further intervention.

Saudi Arabia

The transport contractor to a Saudi Chemical Company customer was transporting 18 tonnes of ANFO in a container when it rolled over and burnt out without exploding.