

Generating Hazardous Material Risk Profiles on Railroad Routes

Phani K. Raj and Theodore S. Glickman

ABSTRACT

A risk estimation approach is described for generating a risk profile of the rail transportation of any hazardous material on any route. The approach emphasizes the risk attributable to accidents involving large releases (i.e., derailments and collisions on main lines and in yards). Risk profiles for various hazardous materials or for various routes can be combined. The approach makes use of a specially derived model for the probability distribution of the number of cars experiencing a release in such an accident. As an illustration this model is applied to a route on which chlorine and liquefied petroleum gas are transported. The approach also relies on a number of consequence models for the various scenarios under which the hazardous materials of interest may be released in an accident. The effects described by these models are combined with the population exposure estimates in the illustration in order to estimate the associated fatality levels.

There is interest in the risk of railroad accidents in which a large quantity of a particular hazardous material is released on the main lines or in the yards along a particular route. Such accidents are primarily derailments or collisions that occur when some equipment is in motion; they are sometimes referred to as "kinetic" accidents to differentiate them from the multitude of accidents caused by failed valves, overfilling, corrosion, leaks, and so forth in which the quantity of material released is usually smaller. To make the important distinction between those accidents that are more frequent but less severe and those that are less frequent but more severe, results will be given in the form of a risk profile, which is a plot of frequency versus consequence. In this case the consequence is the number of fatalities due to the effects of a release, and the corresponding frequency is the number of accidents per year in which that consequence is equaled or exceeded. Of course, risk profiles can be combined for various hazardous materials carried on a route or for various routes within a region.

The risk estimation approach used is based on the number of cars that release the hazardous material of interest in an accident. This approach may be construed as an updated and simplified extension of the method described previously by Glickman and Rosenfield (1). It is assumed conservatively that when there is a release from a car all of its contents are released. When the frequency and consequence have been estimated for every segment of the route for every possible number of cars that release their contents, the coordinates of each of the points on the risk profile are determined. Each such point corresponds to a different value for the number of cars that release their contents. The ordinate is the sum of the frequencies per year of the accidents on all segments in which at least that number of cars release their contents and the abscissa is the associated consequence value.

Symbolically, the risk profile is a plot of $F^*(I_X)$ versus $C(I_X)$ for every different value of I_X where I_X is the number of cars that release hazardous

material X in an accident; $F^*(I_X)$ is the expected frequency per year of accidents in which at least I_X cars release X [i.e., the upward cumulation of $F(I_X)$ values where $F(I_X)$ is the expected frequency per year of accidents in which I_X cars release X]; and $C(I_X)$ is the expected number of fatalities due to I_X cars releasing X in an accident.

ESTIMATION OF FREQUENCIES

The expected frequency per year of accidents in which a particular hazardous material is released from a given number of cars on a particular route segment is estimated from the overall expected frequency per year of accidents and the probability that the material is released from that number of cars. The results are then summed over all the route segments. Symbolically,

$$F(I_X) = \sum_s F_s P_s(I_X)$$

where

F_s = the expected frequency per year of accidents on segment s and

$P_s(I_X)$ = the probability that I_X cars release X in an accident on segment s.

A route segment may be a stretch of main line or a yard. The estimate of F_s on each main-line segment is computed from statistics on all kinetic main-line accidents, and the estimate of F_s on each main-line segment is computed from statistics on all kinetic yard accidents. The estimate of the distribution on each of $P_s(I_X)$ on each main-line segment is computed from statistics on all main-line derailment accidents and then is assumed (conservatively) to apply to other types of kinetic main-line accidents and to all types of kinetic yard accidents.

F_s on main-line segments can be computed on the basis of accident statistics, traffic volume data,

and route parameters [e.g., by multiplying the number of main-line accidents per billion gross ton-miles (BGTm) by the traffic volume per year in BGTm and then by the length of the route in miles]. For the illustration route, the main-line accident rate is 0.83 per BGTm on all segments. F_S is computed by converting this figure to a rate per billion net ton-miles and employing the volume and mileage data given in Table 1.

TABLE 1 Route Segment Data

Segment	Volume (10 ⁶ ton/yr)	Length (mi)	Speed (mph)	Population Density (No./mi ²)
1	17.7	18.9	30	2,800
2	17.7	21.3	45	127
3	17.7	39.3	45	41
4	17.7	20.0	45	48
5	17.7	13.3	45	141
6	17.7	32.4	45	89
7	17.7	11.6	45	26
8	17.7	20.0	45	51
9	21.2	30.8	45	110
10	23.1	27.8	45	19
11	23.1	16.0	45	18
12	23.1	21.9	45	23
13	23.1	35.4	35	103
14	42.7	38.0	30	602
15	31.7	31.2	45	65
16	31.7	24.5	45	196
17	31.7	19.4	45	22
18	31.7	18.8	45	65
19	31.7	9.4	45	112
20	21.3	18.8	30	268
21	21.4	11.3	30	868
22	29.5	14.1	30	1,104
23	37.7	4.2	30	1,789
24	35.5	7.3	30	1,016
25	35.5	23.9	30	113
26	35.5	17.8	45	73
27	35.5	17.8	45	37
28	35.5	8.9	30	594

F_S on yard segments can be computed from accident statistics and yard activity data (e.g., by multiplying the number of yearly accidents per million car classifications by the volume of car classifications per year in the yard in millions). The accident rate in each of the four yards along the illustration route is 6.56 per million classifications. The average speed in these yards is 10 mph.

The discrete probability distribution $P_S(I_X)$ can be computed sequentially from a number of other estimated constituent probability distributions that have to do with the size and makeup of the train, the severity of the derailment, and the impact of the derailment on the hazardous materials cars involved. This sequential approach has the advantage that sensitivity analysis can easily be performed later by varying any of the constituent probability distributions to represent different accident scenarios. Symbolically, the random variables for which the constituent probability distributions are estimated are as follows:

- J_X = number of cars of X derailed in a main-line derailment,
- N_D = total number of cars derailed in a main-line derailment,
- N_X = number of cars of X in the derailed train, and
- N_T = total number of cars in the derailed train.

The constituent probability distributions are then symbolized by the following:

- $P(I_X|J_X)$ = conditional probability that I_X of the J_X derailed cars of X release their contents,
- $P(J_X|N_D, N_X, N_T)$ = conditional probability that J_X of the N_X cars of X derail when N_D of the total of N_T cars derail,
- $P(N_D|N_T)$ = conditional probability that N_D of the total of N_T cars derail,
- $P(N_X|N_T)$ = conditional probability that N_X cars of X are in a train having a total of N_T cars, and
- $P(N_T)$ = probability that there are N_T cars in total.

Then $P(I_X)$ is computed according to the following sequence of formulas:

- Step 1. $P(I_X|N_D, N_X, N_T) = \sum_{J_X} P(J_X|N_D, N_X, N_T)P(I_X|J_X)$
- Step 2. $P(I_X|N_X, N_T) = \sum_{N_D} P(N_D|N_T)P(I_X|N_D, N_X, N_T)$
- Step 3. $P(I_X|N_T) = \sum_{N_X} P(N_X|N_T)P(I_X|N_X, N_T)$
- Step 4. $P(I_X) = \sum_{N_T} P(N_T)P(I_X|N_T)$

The result of the computation in each of the first three steps, as symbolized by the left side, is used in the computation in the following step. In effect, the first step estimates a conditional probability distribution for the number of cars that release X and each successive step removes one of the conditions until an unconditional distribution is estimated.

CALCULATION OF $P(I_X|J_X)$

It is assumed that the probability that I_X of the J_X derailed cars of X release their contents follows a binomial distribution. That is,

$$P(I_X|J_X) = \{J_X!/[I_X!(J_X - I_X)!]\}P_X^{I_X}(1 - P_X)^{J_X - I_X}, I_X = 0, 1, \dots, J_X$$

where P_X is the probability that any derailed car of X releases its contents. In other words, each of the J_X cars is assumed to be independent of the others and equally likely to experience a release.

In their report based on pre-1978 data, Nayak et al. (2) estimated that the value of the parameter P_X is related to train speed (v) in miles per hour according to the formula

$$P_X = 0.45 (v^{1/2}).$$

However, since 1978 the retrofitting of tank cars with head shields, shelf couplers, and thermal insulation has reduced the average percentage of derailed tank cars that release their contents from about 25 percent to about 7 percent in 1982, according to industry statistics (3), a reduction factor of about 0.28. Applying this factor to the previous formula yields an updated coefficient of 0.013 instead of 0.045. For the illustration route, where v ranges between 30 and 45 mph, P_X thus ranges between 0.071 and 0.087.

CALCULATION OF $P(J_X | N_D, N_X, N_T)$

It is assumed that every car in the train is equally likely to initiate the derailment, that all the cars containing X are blocked together, and that only adjacent cars derail. Then in the case in which the number of cars derailed exceeds the number of cars of X (i.e., $N_D > N_X$), the number of cars of X that derail cannot exceed N_X (i.e., $J_X \leq N_X$). If $J_X < N_X$, the conditional probability that J_X cars of X derail is the probability that they derail either in the front or at the end of the block. Each of these two possible outcomes has a probability of $1/N_T$, so the probability of one or the other is $2/N_T$. If $J_X = N_X$, the desired probability is the probability that the derailment was initiated in any of the $N_D - N_X$ cars in front of the block or in the first car of the block. Because each of these outcomes has a probability of $1/N_T$, the total probability is $(N_D - N_X + 1)/N_T$. Therefore, when $N_D > N_X$,

$$P(J_X | N_D, N_X, N_T) = \begin{cases} 2/N_T & \text{if } J_X < N_X \\ (N_D - N_X + 1)/N_T & \text{if } J_X = N_X \end{cases}$$

Similarly, when $N_D \leq N_X$, it can be shown that

$$P(J_X | N_D, N_X, N_T) = \begin{cases} 2/N_T & \text{if } J_X < N_D \\ (N_X - N_D + 1)/N_T & \text{if } J_X = N_D \end{cases}$$

CALCULATION OF $P(N_D | N_T)$

It is assumed that the probability that, in a main-line derailment, N_D of the N_T cars in a train derail follows a discretized gamma distribution. That is,

$$P(N_D | N_T) = [1/\Gamma(a) b^a] \int_{N_D}^{(N_D + 1) - 0.65} x^{a-1} e^{-x/b} dx$$

where

$$a = [E(N_D)]^2 / \sigma^2(N_D),$$

$$b = \sigma^2(N_D) / E(N_D), \text{ and}$$

$$\Gamma = \text{gamma function.}$$

The constant 0.65 arises from evaluating $P(N_D | N_T)$ for the case in which $N_D = 0$.

This assumed form for the probability distribution of the number of derailed cars generalizes from the result in the report by Nayak et al. (2), who argued that this distribution should be used to calculate the probability of the number of hazardous materials cars derailed. The same report concluded that the number of hazardous materials cars derailed depends primarily on the length of the train unless $N_T > 25$. The following formulas were estimated for the dependence of $E(N_D)$ and $\sigma^2(N_D)$ on train speed (v) in miles per hour:

$$E(N_D) = 1.7 (v^{1/2}) \text{ and}$$

$$\sigma^2(N_D) = 2.7 v.$$

For the illustration route, v ranges between 30 and 45 mph. Hence the estimate of $E(N_D)$ ranges between 9.3 and 11.4 cars, and $\sigma^2(N_D)$ ranges between 81 and 121.5.

CALCULATION OF $P(N_X | N_T)$

The probability that N_X of the N_T cars contain X in a randomly selected train is assumed to follow a Poisson distribution. Symbolically,

$$P(N_X | N_T) = (\mu^{N_X} e^{-\mu} / N_X!), \quad N_X = 0, 1, \dots, N_T$$

where $\mu = E(N_X)$. This assumption is made on the basis that the cars of X are more or less randomly assigned to trains and that they usually represent a small part of the total consist.

If the shipment of hazardous material X on a route is more or less uniform throughout the year, the expected number of cars of X per train is estimated by dividing the annual number of cars of X on the route by the annual number of trains on the route. For the illustration route the estimates of $E(N_X)$ for the two hazardous materials of interest vary according to which segment of the route is being considered. These estimates are given in the following table.

Segment	Chlorine	LPG
1-13	0.141	0.832
14-21	0.046	0.089
22-28	0.045	0.001

Finally, it is assumed that the probability that there are N_T cars in a typical train is approximated by a normal distribution. That is,

$$P(N_T) = (1/2\pi)^{1/2} \int_{N_T - 0.5}^{N_T + 0.5} \exp \{-[x - E(N_T)]^2 / 2\sigma(N_T)\} dx$$

This assumption is made in the absence of any generally available information about the distribution of N_T .

For the illustration route the average number of cars per train is 88, and there is little variation in this number from one train to another. Hence on main lines $E(N_T) \approx 88$ cars and it is assumed that $\sigma(N_T) \approx 5$ percent of $E(N_T)$, or $\sigma(N_T) \approx 4.4$ cars.

ESTIMATION OF CONSEQUENCES

When a substantial quantity of a lethal hazardous material is released in an accident the most important consequence of concern is the loss of human life. The expected magnitude of this consequence may be estimated by multiplying the expected density of population in that area by the expected size of the lethal area. To be precise, the population density factor should include any on-scene professionals (train crew, fire fighters, and related emergency personnel) and the time of day should be taken into account when estimating the number of exposed individuals in the general public. Furthermore, the degree to which persons in the lethal area are vulnerable (depending on their preparedness, mobility, protection, and so forth) should be reflected. For expediency, however, residential county census data are used to estimate the population density along each segment of the illustration route. Estimates of the other factors affecting consequence magnitudes (i.e., the expected lethal areas for chlorine and LPG releases) were calculated using the models described hereafter.

CALCULATION OF LETHAL AREA FOR CHLORINE

Assuming that a fully loaded chlorine car carries 90 tons, the release rates for the four major release scenarios identified by Andrews et al. (4) are as follows:

1. A continuous release of chlorine vapor at

sonic velocity, at about 4 kg per second, from a relief valve.

2. A continuous release of liquid chlorine, at about 10 kg per second, from a stuck valve.

3. Extremely rapid to instantaneous release of all contents following a shell or head puncture at normal transport temperature (20°C). Seventeen percent of the released mass is estimated to flash to vapor, and the rest falls to the ground as saturated liquid at 240°K.

4. Instantaneous and catastrophic failure of the tank following heating and overpressurization after being subjected to a fire (for about 55 min with 90 percent of the shell insulation intact). The temperature of the liquid at the instant of tank failure is assumed to be 60°C. Thirty-two percent of the released mass, which flashes directly to form a saturated vapor cloud at 240°K, is released instantaneously into the atmosphere.

The principal hazard from a chlorine release is attributable to the highly toxic nature of the chemical. The gas phase presents hazards far from the release site because of dispersions of vapor in the atmosphere. Chlorine vapors are heavier than air and tend to disperse close to ground level. The liquid fraction on the ground presents a more local hazard due to burns from contact as well as toxicity. It is assumed that the lethal area is contained within a ground level concentration contour of 1000 ppm, corresponding to the findings of Andrews et al. (4).

Two relatively simple models for the dispersion of heavier-than-air gases were used to calculate the chlorine vapor dispersion area following an accident. Chlorine has about three times the density of ambient air and, when released, the vapor mass spreads laterally due to its heaviness, whereas it mixes with ambient air and moves in the downwind direction. The continuous release dispersion model in the Assessment Models in Support of Hazardous Handbook (AMSHAH) report (5) adequately describes the dispersion of a continuous release of heavy chlorine vapor from a tank car because (a) the source size is small and (b) most of the dispersion to reach the 1000 ppm level occurs when the vapor-air mixture has essentially neutral buoyancy. The model for heavy gas dispersion of instantaneously released vapor mass is taken from Raj (6). The hazard area formula that derives from the continuous release dispersion model is

$$A = (\pi/2)X_{\max}Y_{\max}$$

where

$$\begin{aligned} X_{\max} &= \text{maximum downwind dispersion distance and} \\ Y_{\max} &= \text{maximum semiwidth crosswind.} \end{aligned}$$

The hazard area formula from the heavy gas dispersion model is

$$A = X_e R_e + (\pi/2)R_e^2$$

where

$$\begin{aligned} X_e &= \text{downwind lethal hazard distance and} \\ R_e &= \text{cloud radius at the time concentration becomes lethal.} \end{aligned}$$

Table 2 gives the results of using these models. These results were computed assuming extremely stable weather with 3 m per second wind speed.

CALCULATION OF LETHAL AREA FOR LPG

The various scenarios for liquefied petroleum gas (LPG) releases that can be postulated to occur as a

TABLE 2 Expected Hazard Area Calculation for Release of Chlorine from a Single Tank Car

Release Scenario	Source of Release	Conditional Probability of Source, Given a Release ^a	Hazard Area (km ²)	Probability-Weighted Hazard Area (km ²) ^b
1	Pressure relief safety valve and top fittings	0.442	5.5 x 10 ⁻³	2.43 x 10 ⁻³
2	Bottom fittings and stuck relief valve when car is upside down	0.138	15.1 x 10 ⁻³	2.08 x 10 ⁻³
3	Shell and head punctures	0.319	1.2	0.383
4	Fire exposure and catastrophic release	0.200	1.8	0.360

^aBased on 1978-1983 railroad industry data.

^bTotal expected hazard area = 0.747 km².

result of an accident are similar to those identified in the case of chlorine releases. Geffen et al. (7) identified six major types of releases based on a fault-tree analysis of tank car failure and release modes. These release categories are as follows:

1. A continuous slow leak from the equivalent of a 2.5-cm-diameter opening, with a release rate of 2.2 x 10⁻³ m³ per second (leakage from cracks in welds may lead to this release scenario).

2. A continuous release of vapor from an opened or damaged valve, resulting from impact or puncture without a fire. The leak is from the equivalent of a 7.6-cm-diameter opening at a rate of 1.96 x 10⁻² m³ per second.

3. A small continuous leak with fire present in the vicinity. The estimated release rate is 10⁻² m³ per second.

4. Release from a safety relief valve with fire impinging on the LPG tank car. The rate of release of vapor from an upright car is estimated to be 0.11 m³ per second.

5. Major mechanical failure of the tank with all of the contents of the tank car released in seconds. In a majority of cases these releases would be ignited, but in some situations ignition may be delayed. Assuming that the initial lading temperature is 21°C, about 35 percent of the released mass flashes directly to vapor.

6. Explosive rupture of the tank caused by overheating of the tank wall by an impinging fire and internal overpressurization (BLEVE). All of the contents of the tank are released instantaneously. Temperature of lading before release (for an insulated tank car) is assumed to be 62°C. The percentage flash for this temperature is 60 percent.

Fire is the principal lethal hazard from LPG tank car releases. Several different types of fires can result: torch fires, pool fires, vapor fires, unconfined detonations in dispersed vapor, and fireballs. The other lethal hazard is mechanical in nature, arising from the fragmentation or rocketing of tank cars. The calculations of the hazard areas associated with the different types of fire hazard and mechanical hazard are described next.

Torch Fire

Torch fires result from the ignition of relatively small leaks of LPG from cracks, stuck vent valves, or relief valves operating normally. When the tank is exposed to an internal fire, torch fires pose

danger to railroad and emergency response personnel and other tank cars on which the flames may impinge.

The hazard distance extends roughly to the same distance as the length of the torch fire plume. The method by which the length of this plume can be calculated is discussed in the AMSHA report (5). In general, the torch fire plume length is between 100 and 200 times the hole diameter in the tank car from which the flammable gas is released under pressure. This torch fire plume length can be construed as the radius of the hazard area.

Pool Fire

When all of the contents of an LPG tank car are released rapidly due to tank failure caused by mechanical puncture or impact, a significant fraction of the released mass flashes to vapor and the remaining volume drops to the ground as liquid. The liquid spreads on the ground. If, in addition, the liquid is ignited it forms an expanding pool fire. The principal hazard from this pool fire is thermal radiation from the fire.

The maximum size to which a burning pool expands on flat ground is given in a paper by Raj (8). Using this result along with the models reviewed by Raj (9), the following calculations are made for the pool fire hazard area resulting from one tank car release of LPG.

According to the fire thermal radiation models reviewed by Raj (9), the thermal radiation hazard distance (S) can be obtained by applying the inverse square law given by

$$S = \left[\frac{(\rho_L V_L \Delta H_C)}{4\pi t_b q_{haz}^0} \right]^{1/2}$$

where ρ_L is density of the liquid, V_L is the spilled volume of liquid, ΔH_C is the heat of combustion energy which is radiated, t_b is the duration of burning of the pool fire, and q_{haz}^0 is the radiant thermal flux level at which a fatality will result. Assuming that the duration of burn is 91 sec if one tank car of LPG is released [based on the result given by Raj (9) for the maximum size of a burning pool on flat ground] and that the lethal radiation hazard level is 20 kW/m² (the level at which serious second-degree burns can be inflicted), $S = 170$ m. Hence, the pool fire hazard area (πS^2) is 9.1×10^4 km².

Vapor Fire

If the instantaneously released liquid and vapor puff are not ignited immediately, the vapors produced disperse in the atmosphere as a heavy gas cloud puff. More vapor is generated by the boiling of the liquid spilled on the ground. During dispersion the vapor cloud is mixed with air and forms a flammable vapor cloud. Because of the presence of a variety of ignition sources in urban areas (and to some extent in rural areas) the probability of ignition of the vapor cloud increases continuously as a function of downwind distance.

Assuming that (a) ignition occurs only when the mean vapor concentration of the cloud is equal to one-half of the lower flammability limit and (b) the lethal hazard area is equal to the area swept by an ignited vapor cloud during dispersion, the area in question was calculated by means of the heavy gas dispersion model used for chlorine.

Vapor Cloud Detonation

Vapor clouds of propane dispersed in the atmosphere may detonate, even in the unconfined state, when

sufficiently energetic ignition occurs. It is less certain, however, whether a deflagration type of burning of an unconfined vapor cloud can transit to detonation. It is assumed that it is possible to induce detonation in an unconfined propane-air mixture.

The blast effects of detonation are calculated by using the trinitrotoluene (TNT) equivalent approach described by Geffen et al. (7). It is assumed that (a) only the instantaneously released vapor mass participates in the detonation, (b) only 10 percent of the released vapor mass will detonate, and (c) there is a 100 percent fatality rate in an area within which the peak overpressure is above 6.0×10^4 Pa. The overpressure-distance relationship is given by

$$p = 82.88 X^{-1.4362} M_{TNT}^{1/3}$$

where overpressure (p) is in Pascals, distance (X) is in meters, and TNT equivalent mass (M_{TNT}) is in kilograms.

Fireball

The exposure of an LPG tank to a fire results in the occurrence of two phenomena, collectively known as a BLEVE. First, the boiloff from the heat input is vented into the atmosphere through the relief valve. This gas outflow is ignited and forms a torch fire. Second, the tank wall not backed by liquid inside overheats and weakens. Failure of the tank wall is sudden, resulting in the rupture of the tank, instantaneous release of remaining contents, and then ignition of the contents released. This ignition results in the formation of a spectacular fireball.

The initial radius of this hemispherical ball of fire is given by the equation [from Geffen et al. (7)]:

$$r = 1.93 M_V^{1/3}$$

where r is in meters and M_V is the mass of propane vapor in the fireball (in kg). It is assumed that (a) the total mass of vapor vented before the BLEVE occurs is small compared to the lading mass, (b) about 60 percent of the released mass flashes to vapor (that is, the liquid in the tank just before release is about 50°C), and (c) the lethal thermal radiation hazard zone extends about 100 m beyond the edge of the fireball radius on the ground.

Fragmentation

Fragmentation debris from tank rupture can be hurled as far as 610 m according to Geffen et al. (7). It is assumed that the hazard area is of a length and width equal to the dimensions of a tank car.

Rocketing of BLEVED Tank Car

Rocketing of tank cars that "tear" circumferentially has been observed in some accidents. The distances to which parts of the damaged tub are hurled vary depending on several uncontrollable factors. An empirical correlation has been given by Nayak et al. (2) for maximum rocketing distance as a function of tank car capacity. A typical rocketing range is about 300 m. It is assumed that a rectangle having this range as its length, and width equal to the tank diameter, will form the lethal hazard area.

The results of all the calculations for LPG are summarized in Table 3, in which, as in the case of chlorine, the conditional probability of each re-

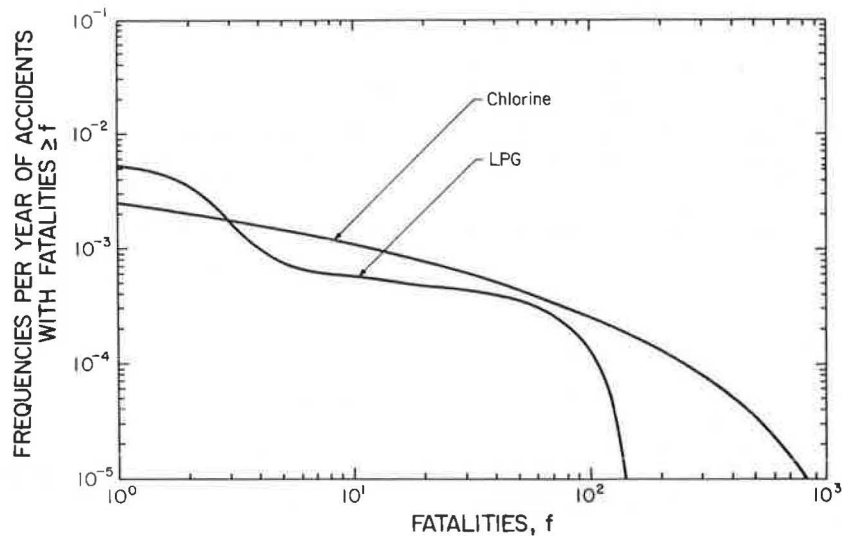


FIGURE 1 Risk profiles for chlorine and LPG on the illustration route.

TABLE 3 Expected Hazard Area Calculation for Release of LPG from a Single Tank Car

Release Hazard	Conditional Probability of Hazard, Given a Release	Hazard Area (km ²)	Probability-Weighted Hazard Area (km ²) ^a
Torch fire	0.580	1.2×10^{-4}	7.0×10^{-5}
Pool fire	0.288	9×10^{-2}	2.6×10^{-2}
Vapor fire	0.026	0.38	9.9×10^{-3}
Vapor cloud detonation	0.006	3.8	2.3×10^{-2}
BLEVE with fireball	0.050	8.7×10^{-2}	4.4×10^{-3}
BLEVE'd car rocketing	0.035	2.2×10^{-3}	7.7×10^{-5}
Missile debris impact	0.015	1.2×10^{-2}	1.8×10^{-4}

^aTotal expected hazard area = 6.4×10^{-2} km².

lease hazard is based on railroad industry data from 1978 to 1983. The final estimate of 6.4×10^{-2} for the expected lethal hazard area is about two orders of magnitude smaller than that for a comparable released mass of chlorine.

RISK PROFILES FOR CHLORINE AND LPG

The risk profiles for accidents involving chlorine and LPG tank cars on the illustration route, based on the calculated frequency and consequence estimates, are shown in Figure 1. Note that LPG poses a higher risk on this route if less severe accidents (one or two fatalities) are taken into account along with more severe ones but that chlorine has the greater risk beyond that point, becoming significantly more hazardous if only extremely severe accidents (50 or more fatalities) are considered. The largest number of fatalities expected in any chlorine release on this route is 613 with a frequency of 5.2×10^{-5} per year (once in about 20,000 years). There is a vanishingly small probability that more than one chlorine car will release its contents in an accident on this route. In contrast, the largest expected number of fatalities per release for LPG is 276 with a frequency of only 3.0×10^{-7} per year. This would occur from a release and ignition of the contents of four LPG cars on the most populated segment of the route. The expected number of fatalities per year on the route is about

twice as high for chlorine as for LPG (0.088 compared to 0.043).

Sensitivity analyses of the chlorine and LPG risk profiles were performed to evaluate (independently) the effects of reducing the release probability (P_x) and conducting emergency evacuation. In the latter case it was assumed that the exposed population is reduced by 85 percent within 1 hr of the release. For chlorine, a tenfold decrease in the release probability yielded a threefold decrease in the frequency per year of accidents resulting in at least one fatality and a five- to sixfold decrease in the frequency per year of accidents resulting in at least 100 fatalities. For LPG, a tenfold reduction in the release probability resulted in a tenfold decrease in the frequency of accidents causing at least one fatality and a larger decrease at higher fatality levels. Similar results were obtained for the effects of emergency evacuation.

In other words, the payoff from actions taken to reduce the probability of release (e.g., tank car retrofitting) and to reduce the vulnerability of the population (e.g., prompt evacuation) is in general higher for more severe accidents, but the specific relationship between the payoff and the actions depends on the hazardous material in question.

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Use of Risk Analysis in Enhancing the Safety of Transporting Hazardous Liquefied Gases

Risto Lautkaski

ABSTRACT

Three risk analyses were performed on the land transportation of hazardous liquefied gases in Finland. The gases considered were chlorine, anhydrous ammonia, sulphur dioxide, and liquefied petroleum gas. The accident file of Finnish State Railways allowed a detailed classification of railway accidents into 14 categories. The estimated conditional probabilities were then combined with the actual traffic data to give the probability of a tank wagon being involved in a railway accident. Structural analyses of the wagons were performed to estimate the probability of leakage when an accident occurs. A review of road accidents involving heavy vehicles was performed to assess the damage probabilities of road tankers. The estimation of the accident probabilities was complemented with calculations of gas dispersion and evaluations of the population density along the transportation routes. Risk analysis was an instructive way of going through all the factors contributing to the accident risk. In this way it was possible to suggest a number of measures by which accident risk could be reduced. The following changes, based on those suggestions, have been implemented: (a) construction of the manway nozzle in transportable pressure vessels has been improved; (b) installation of head shields and buffer override restraints has been continued; and (c) tank wagons carrying hazardous liquefied gases are positioned in the middle of a train. The risk studies also provided background material for national instructions for emergency preparedness and response to accidents involving hazardous materials.

Two-thirds of Finnish land territory is covered by forest. It is therefore not surprising that the national pulp and paper industry has traditionally provided a major part of exports.

Bleached pulp is produced at 18 mills situated throughout the country. The principal bleaching agent, chlorine, is produced at only two pulp mills; liquid chlorine produced at four plants is hauled by rail to the remaining 16 mills. The annual shipment of liquid chlorine ranges from 140 000 to 175 000 tonnes.

The pulp industry has become a consumer of liquid sulphur dioxide. Sulphur dioxide is recovered at a copper smelter and part of it is liquefied and carried by rail and road to pulp mills. About 50 000 tonnes are shipped annually.

Nitrogen fertilizers are produced at four plants. These plants are the major consumers of anhydrous ammonia in Finland. Almost all anhydrous ammonia is imported by tanker ships and by rail. The domestic overland shipments amount to 150 000 to 200 000 tonnes annually, of which more than 90 percent is carried by rail.

Two Finnish oil refineries produce about 100 000 tonnes of liquefied petroleum gas (LPG), which is carried to the customers and cylinder-filling plants in rail tank wagons and road tankers.

Because of Finland's geographical position and because Finnish railways have the broad Soviet gauge, some Finnish harbors constitute an important link in the trade of petroleum products and basic chemicals between the Soviet Union and some Western