Safety and Reliability – Bedford & van Gelder (eds)
© 2003 Swets & Zeitlinger, Lisse, ISBN 90 5809 551 7

Hazardous materials release analysis: probabilistic input for emergency response organisations

N. Rosmuller
Netherlands Institute for Fire Service and Disaster Management (Nibra), Arnhem, Netherlands

P.H.A.J.M van Gelder
Delft University of Technology, Faculty of Civil Engineering, Section of Hydraulic Engineering, Delft, Netherlands

ABSTRACT: In the Netherlands, substantial amounts of hazardous materials are transported by road. Quantitative risk analyses are conducted to indicate the risks associated with these transport activities. In general, classified release volumes accompanied by probabilities are used in these risk analyses. Still, the application is limited to risk analysis instead of also being used for emergency response planning objectives. The question is whether these classified quantities are in accordance with empirical data, both in release quantity and probability. Furthermore, it is interesting to link these risk analyses' results with emergency response activities. Based upon almost 550 hazardous material road accidents in the Netherlands during almost twenty years, retrieved from the FACTS database, a probabilistic analysis based upon bootstrapping is conducted. The results are compared with the classified used release data in a risk analysis. In addition, even more interesting is the use of these probabilistic results by fire fighting organisations. These organisations namely can use these results to derive their optimised preparation strategy on hazardous materials releases by road accidents.

1 INTRODUCTION

Hazards influence the level of safety. The more hazards there are, the less safe it is. In general, safety of an activity is operationalised using the term risk. Risk is the combination of probability and consequences of an accident (e.g. Kaplan and Garrick, 1981, Vlek, 1990). To operationalise risk, (transportation) risk analyses are conducted in which an iterative process is run (CPR, 1999). First, the system is described, preliminary hazard analysis is conducted, and scenarios are developed. With regard to these scenarios, probabilities and consequences are quantified as adequate as possible. The calculated risk forms the input for risk evaluation. Depending on the evaluation outcome (the risk is acceptable, unacceptable or additional enhancements are necessary) the risk analysis ends respectively, proceeds with additional analysis of certain enhancements.

To develop scenarios in transportation risk analysis, in particular event tree and fault tree analysis are used. The events or faults in these trees are quantified using database information or expert judgments. As an example, an event tree is visualised for a flammable gas (e.g. propane) transport (in bulk) activity by road tanker (based upon AVIV, 1993). In figure 1 it can be seen that starting at the left with the initial event (the accident), two events are possible: either a gas release or the gas stays within the tanker (the latter is less relevant for the consequences of people nearby the accident.

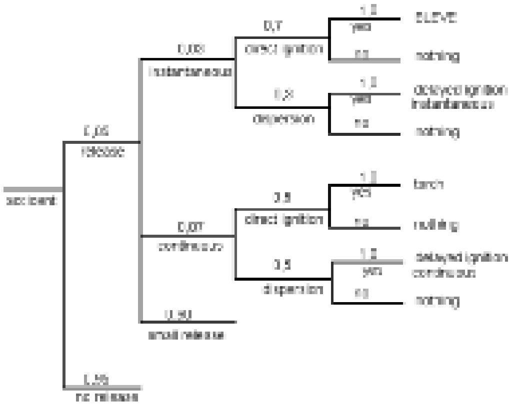

Figure 1. Event tree for flammable gas transport by road tankers.

Subsequently and proceeding to the right in figure 1, a gas release is classified in three categories:

- instantaneous (all the gas is released at once)
- continuous (a certain gas flow is released from the tanker)
- small (several litres or drops of the gas flew away).

For the instantaneous and continuous release categories, subsequently, the gas could either be ignited or dispersed. The two events determine which physical phenomenon results from the accident (BLEVE (boiling liquid expanded vapor explosion), instantaneous out flow with a delayed ignition, torch, or a continuous out flow with a delayed ignition). The physical phenomena are translated in numbers of fatalities by using data concerning the number of people nearby the activity (road) and meteorological circumstances.

For each of these events, probabilities are used, based upon road traffic databases and hazardous material databases. From figure 1, it can be seen that given a road tanker accident, for example the BLEVE probability is 0,00105 ($0{,}05 * 0{,}03 * 0{,}7$).

Such event trees are generally used in hazardous material transportation risk analysis (see for example Saccomanno, 1993). An often applied application of such event trees is the routing of the hazardous materials itself in relation to the environment (see for example Leonelli et al., 2000). The transportation risk analysis focuses at quantifying event probabilities and less on the accident consequences. The consequences are extremely important for emergency response organisations such as fire brigades. The question here is how fire brigades can use the results of probabilistic analysis for their rescue activities (prevention, preparation and repression).

In this study, we will analyse opportunities for emergency response organisations to make use of probabilistic data concerning hazmat releases. First, various risk policies including probabilistic and deterministic approaches are described. Subsequently, real-life release amounts of road tanker accidents are analysed. The dataset is described in section 3 and analysed using a bootstrap technique in section 4. The bootstrap analysis should indicate the release amounts and according probabilities. Subsequently, opportunities are considered for fire fighting to make use of probabilistic hazmat data. Discussing the results and opportunities for further research concludes the paper (section 5).

2 RISK POLICIES

The risk policy of a country normally uses *individual risk* as a measure, which varies between 10^{-5} and 3.10^{-4} deaths per year for occupational, traffic and consumer risks. The individual risk is taken over the whole population at stake and a time period of one year. Although no general individual risk criteria are set, one tends to measure those against the *de minimis* of 10^{-6} to 10^{-5} deaths per year (Mumpower, 1986). In some cases, like high-speed train links, individual risk criteria are set in the Netherlands. The same is true for the zoning between hazardous chemical facilities and residential areas, at an individual risk contour of 10^{-6} deaths per year (the Dutch VROM-standard).

Apart from individual risk, also *societal risks* are defined. For social or group risks, the next step is to order the scenarios with increasing measure of potential consequences. The cumulative probabilities (or frequencies) for exceeding a certain number of deaths is then derived from the probabilities (F) of all scenarios contributing to the exceedance of a particular number of deaths (N). Graphically this is represented in an FN-curve. Orientation curves are defined for the group risk of hazardous chemical facilities (the Dutch VROM-type of curves, with a decreasing quadratic function expressing lower accepted frequencies with increasing potential number of deaths).

The societal acceptable risk is judged at a national level by placing an upper bound upon the expected number of fatalities per activity per year $E(N_{di})$. However limiting only the expected number of deaths does not account for risk aversion. Vrijling et al. (1995) have shown that risk aversion can be represented mathematically by adding a confidence requirement $\sigma(N_{di})$ to the norm:

$$E(N_{di}) + k \bullet \sigma(N_{di}) < \beta_i \bullet 100$$

where $k=3$; the risk aversion index and β_i a policy factor (β_i varies from 0.01 for involuntary no-benefit activities to 100 for completely voluntary direct-benefit activities).

The synthesis of this national risk criterion and the VROM-type of local societal risk criterion approach leads to an upper-bound to the FN-curve of the local activity, which is inversely proportional to the number of independent places N_A and the square of the policy factor β_i:

$$1 - F_{N_{dij}}(x) \leq \frac{C_i}{x^2} \quad \text{for all } x \geq 10$$

$$\text{where} \quad C_i = \left[\frac{\beta_i \bullet 100}{k \bullet \sqrt{N_A}}\right]^2$$

The numerical value of the tolerable frequency can, within certain limits, be tuned by the factor β_i.

The risk policy approach $E + k\sigma$ is a transparent approach which is easily understood by policy makers since the uncertainty is added in a linear way to the expected value with one additional degree of freedom (the risk aversion index k). The risk policy for flooding risk in the Netherlands is based on extreme quantile calculation. For flood risks from the sea a quantile of 1/10,000 years is used, and for flood risks from the rivers a quantile of 1/1,250 years is used. This approach is based on a cost-benefit analysis, but can also be formulated in the manner as described above. Instead of risk aversion indices of $k = 2$ to 3, the indices for flooding risks become 6 to 7, which is amongst others caused by the fact that probability density functions of extreme water levels have long right tails.

Fire fighting risk policies is less based upon probabilities. Moreover they are primarily focused at fighting the accident consequences. Once fire fighters have to come in action, an accident has occurred, hence the accident probability equals 1. There are various concepts in use for this focus on accident consequences. First, the worst-case concept meaning that the most negative consequences imaginable are described (Hirst and Carter, 2000). Although useful in giving a picture of disastrous consequences, this is not a concept to base upon an emergency response organisation. A more applied concept is the maximum credible accident approach. In using the maximum credible accident scenario, the central criterion is what constitutes a credible accident. Credible is defined as: an accident that is within the realm possibility (i.e. possibility higher than 1E-06/yr) *and* has a propensity to cause significant damage. As can been seen, the probability has already slightly been included in this approach. Another approach is that of the "representative scenario". Representative scenarios are those scenarios that up most challenge the emergency response organisations' capacity. These scenarios are developed from two perspectives: the hazardous activity and the emergency response capacity. In general, the accident consequences are determined and analysed with regard to the emergency response capacities. Those consequences that need maximum capacity within the limits of the emergency response capacity are leading. Because emergency response organisations are on average better equipped than just repressing average accident consequences, representative scenarios follow more or less a $E + k\sigma$ approach, in which k depends upon the hazardous activity and the accident consequences.

For the emergency responders with regard to hazmat transportation, in particular the release amounts are relevant. In combination with meteorological circumstances, the release amount determines for the bigger part the effect area (BZK, 1994) and the necessary emergency response logistics such as capacity to restore the remaining hazardous materials in tank units or evacuation plans (Zografos et al, 2000). In addition, the effect areas limit the opportunities to access accident sites, and thus the routing of emergency response vehicles.

Now that we have seen various risk policies, it is interesting to find out to what extend (probabilistic) data from transportation risk analysis are useful for emergency response organisations. To this end, we will use real life hazmat transportation data. First, we will describe this dataset. Subsequently, we will analyse this dataset to get an idea of the distribution of release amounts and the according probabilities.

3 DATA COLLECTION

To collect relevant data for empirical study we make use of the world's most extended hazardous materials accident database FACTS. Quite some research has been performed with this database. For instance, Rasmussen (1995) performed a study, based on accident case histories extracted from the databases Mhidas (SRD) and Facts (TNO) to identify relevant natural events causing accidents involving hazardous materials. A natural event is defined as an event originating from nature, which initiates accidents with hazardous materials. In the analysis, the accidents from the two sources were pooled and the analysis concerned a total of 232 accidents, which were analysed with regard to specific natural cause, geographical distribution and time trend. The analysis indicated that between 1% and 5% of accidents in industrial activities have natural events as a causative factor. The most often reported natural cause of accidents is "atmospheric phenomena" which account for 80% of the natural events found, lightning being the most common cause. Looking specifically at storage and processing activities lightning accounts for 61% of the accidents initiated by natural events.

Haastrup and Romer (1995) explored in systematic ways the problem of how many accidents involving hazardous materials actually occur in Europe, and to make a realistic estimate. A framework for predicting the total number of accidents was therefore developed and applied. The analysis was based on 535 unique accident descriptions (of which 107 were fatal accidents) from seven accident databases covering the nine-year period from 1984 to 1992. Two models were developed: the first model was based on ideas similar to "chemical reaction kinetics"; the second was more related to "estimations of an animal population". The models predicted an average of 87 accidents per year in contrast to the observed average of 59 accidents per year. For fatal accidents, the models predicted an average of 14 accidents per year, and the observed average is 12.

Rosmuller and van Beek (1999) explored the accident mechanisms and influence on accident consequences of clustering transportation line infrastructures. For highways, railways, waterways and pipelines they selected 115 hazardous materials accidents involving multiple transport modes. Subsequently they eliminated those accidents that involved crossings because they were looking for the influence of clustering, leaving 31 clustered line infrastructure accidents. In 12 cases accident propagation (one accident causes on the parallel line another accident) was at hand. In 4 cases the accessibility of the accident scene by emergency response personnel was influenced by the clustering (hampered (1) and improved (3)). In all 31 cases there was a traffic interruption on the parallel line. To examine the influence of clustering on accident consequences, these 31 accidents were translated in accident scenarios. For these scenarios, FACTS was searched again to find identical accidents (matches). For 29 cases a sufficient match was found. On a pair-wise matter, the number of victims (fatal and injured) were compared for the 29 clustered accidents and its match. From this analysis, using a sign-test, they concluded that:

- clustering seems to yield more fatalities than similar accidents on non-clustered accidents,
- clustering seems to yield more fatalities and injuries than similar accidents on non-clustered accidents.
- there is no difference in terms of injuries between accidents on clustered and non-clustered line infrastructures.

In 1998 a FACTS study was conducted (Van Gelder and Vrijling, 1998) to verify accident frequency of road tanker accidents in the Netherlands. In this study, accident frequency of road tanker vehicles carrying hazardous materials under pressure and atmosphere were verified. A dataset of 546 hazardous material accidents in The Netherlands during the period 1978–1997 was used to this end. In their risk analysis, given a significant hazardous material release from a road tanker accident (>100 litres), three categories were distinguished for the release amount with according probability of two road tanker types: atmosphere and pressure.

The dataset of Van Gelder and Vrijling (1998) will be used in this paper to analyse more in detail the release amounts and probabilities.

For fire fighting, the type of carriage (pressure or atmosphere) is relevant with regard to the accident threats. Based upon the specified hazardous material, we categorised the 546 accidents in pressure (94) and atmosphere (452). In total, 123 road tanker accidents with a hazardous material release occurred during 1978–1997 in the Netherlands. Not all the accidents had precise information about the release content. Sometimes the release amount was text like "almost anything" or "release amount unknown". These imprecise records (14) were deleted from the dataset. The remaining set had 103 accidents for road tankers carrying the hazardous material under atmosphere conditions, and 6 road tanker accidents that carried the hazardous material under pressure.

The atmosphere release amount was in the range from 0,001 to 30 m^3 (1 litre to 30,000 litres). Remind the release quantity in table 1 was more than 100 litres. The pressure release amount was in the range from 0,001 to 2,1 m^3. To be more precise, table 2 below shows the distribution of releases, given a release took place after a road tanker accident.

Table 1. Release quantity data of road transport (Van Gelder and Vrijling, 1998).

Tanker	Release quantity		
Atmosphere	Whole tank	5000 litres	500 litres
Probability	.15	.6	.25
Pressure	Whole tank	Puncture	Irrelevant amount
Probability	.105	.195	.7

Table 2. Release accidents.

Pressure		Atmosphere	
Litres	Freq.	Litres	Freq.
1	1	0–10	27
20	1	11–50	17
150	1	51–100	11
1000	1	101–500	17
1500	1	501–1,000	9
2100	1	1,001–5,000	10
		5,001–10,000	8
		> 10,000	4
	6		**103**

Here, we use this set to determine the average release amounts and the spread around the average (standard deviation). In addition we will generate the according probabilities and compare them to the data as used in Dutch transportation risk analysis.

4 BOOTSTRAP

The in section 3 described dataset is used in a self developed bootstrap tool, called TACAT (transportation accident consequences analysis tool). TACAT was developed to analyse the consequences of accidents, thereby using the number of accidents with certain consequences during a specified period of time (Rosmuller, 2001). Bootstrapping means that from a dataset, random a number of times with replacement (for example 10,000) a record is selected. In our application the release amount of a record (a hazardous material release accident) is stored, the record is replaced and a new record is selected.

Doing this for example 10,000 times (replications) makes clear what the release amount on average are, how the amount is distributed and with the according probability. In addition, TACAT shows the effect of replications in order to clarify whether the outcomes are robust or may still fluctuate.

Figures 2 and 3 show the results of the bootstrap respectively the effect of replications for the releases resulting from road transportation under atmosphere.

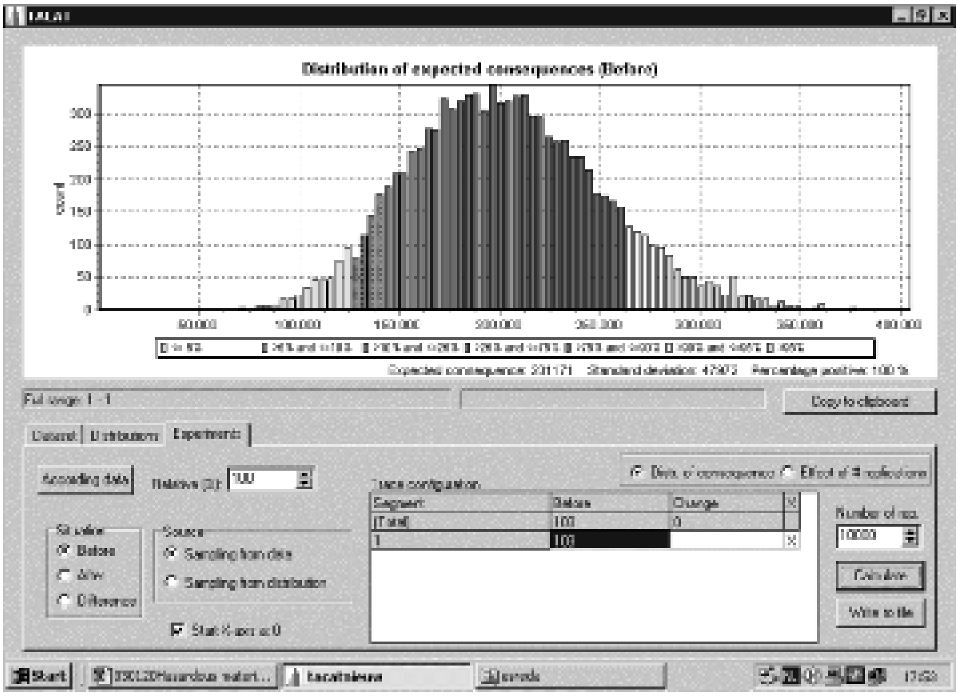

Figure 2. Results of the bootstrap analysis.

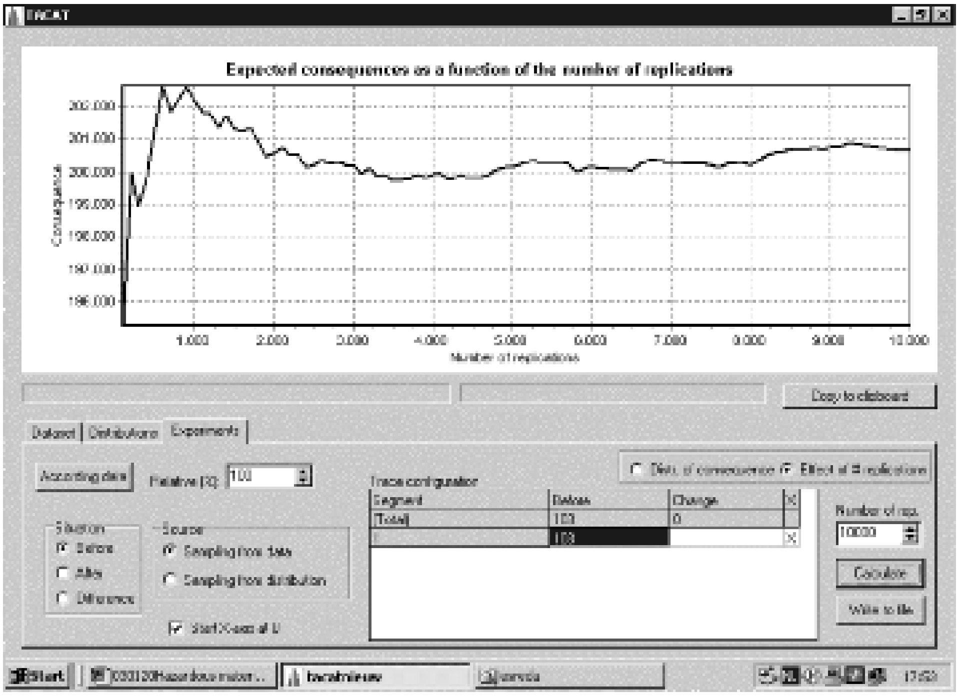

Figure 3. Effect of replications.

Table 3. Bootstrap results.

	Pressure	Atmosphere
Average	480 litres	2000 litres
Standard	1950	4800 litres
deviation	After 5000	After 4000
Stable	replications	Replications
Probability	Litres	Litres
0–5	0–180,0	0–1250
5–10	180,0–220,0	1250–1400
10–25	220,0–320,0	1400–1650
25–75	320,0–600,0	1650–2250
75–90	600,0–750,0	2250–2650
90–95	750,0–825,0	2650–2800
95–100	825,0–1100,0	2800–3600

Figure 2 shows that the average release amount (atmosphere) is somewhat less than 2000 litres (201,171 litres/103 accidents = 1953 liters per release) with standard deviation somewhat less than 480 litres (47,972 litres/$\sqrt{}$103 = 4726 liters per release). The probability is 25% to 75% that the release amount is between 1650 and 2250 litres. For other ranges the according probability can be seen from the screen-view. The according effect of replications shows that after about 4000 replications the release amount is between 2000 and 2010 litres and does not fluctuate (Fig. 3). Table 3 below summarises the bootstrap results for freight transport under conditions of pressure and atmosphere.

From table 3 we conclude that:

For a pressure road tanker accident, we can give a quantitative indication of the release volume with according probability in addition to the qualitative indication that have been used so far. On average 480 litres is released, and in 50% of the release accidents, the release volume is between 320 and 600 litres.

For an atmosphere road tanker accident, bootstrapping indicates a range of confidence levels for various release amounts including an average of almost 2,000 litres and a standard deviation of 4,000 litres.

With regard to the flammable gas event tree, we saw a .05 probability of a release. Flammable gas is transported under pressure. From the 546 FACTS accidents, 94 concerned transportation under pressure conditions and 6 of these 94 resulted in release. So these numbers are in the same range (about 5%). However, a .95 probability of no release might indicate that there are no victims, however emergency response organisations, in particular fire brigades, still have a serious activity to repress such accidents. See some of the recent hazmat road accidents in the Netherlands. Near the city of Ewijk (2001), three trucks collided. One of them contained hazmats. Even though there was no significant release (some litres that were condensed by the fire), the emergency response too more than 6 hours, the main traffic junction highway 50/highway 73 was closed for this time and road traffic over the whole eastern part of the country was disturbed, facing heavy traffic jams. Another hazmat accident took place at Highway 28 (2002), near the city of Utrecht. It concerned transportation in drums rather than bulk. Despite the facts that here was no release, still national traffic was disturbed heavily. In both cases, it was the lack of accurate data concerning the hazmat involved which introduced large uncertainties and very defensive emergency response tactics.

5 EMERGENCY RESPONSE PREPARATION

Fire brigades have several goals in case of hazardous materials road accidents. Of course, they aim at rescuing potential victims and minimizing negative consequences as good as possible. Road tanker accident can result in victims due to the mechanic impact, due to the hazardous material and a combination of mechanic impact and the hazardous material. It is in particular the truck driver and fellow road users who could be stuck in their vehicles due to mechanic impacts. To rescue people from a mechanic impact, hydraulic machinery and equipment (e.g. scissors), are used. With regard to hazardous material victims, the truck driver, fellow road users and people nearby the road could be the victims. Gas teams should rescue these persons and minimize the consequences, using full protection with regard to clothing and breathing.

The hazardous material type of danger is relevant here. To minimise the negative consequences of a hazardous material road accident, it is essential that the volume to be released is as small as possible. The bigger the release, the greater the possible area in which negative effects might be sensible. Fire brigades have several strategies to minimises the effect area in case of a hazardous material release:

a) By stopping the leakage (for example by clothing a valve or freezing a hole in the tanker)
b) By covering the release volume so that dispersion by and ground is limited
c) By storing the hazardous material volume in an additional container (for example pump it over in an additional truck or available drums).

In particular with regard to the latter two strategies, it is relevant for the fire brigades to have an indication of the release amounts and the according probability so that they can prepare for routing and logistics.

In addition, evacuation plans could make use of the bootstrap results. Knowing release quantities and the according probability, one is able to determine in advance evacuation zones in case of an accident.

These evacuations zones are areas for which hazardous effect might occur with a certain probability. Evacuation is a far-reaching activity for citizens. Citizens have to leave their belongings behind and are aware of their vulnerability. Uncertainty and panic might result from evacuation. In order to limit such side effects, it is advisable to make use of probabilistic release data in contingency planning rather than to plan for the evacuation of an irrelevant too large area. And even in case of real life releases, evacuation areas could be based upon the probabilistic data regarding effect areas.

Still, a question for the preparation is what probabilistic data should be used by the fire brigades. On the one hand, it could be the frequency distribution directly retrieved from the database and using the $E + k\sigma$ approach. On the other hand, it could be the bootstrap approach followed by an $E + k\sigma$ approach. A key aspect would be the determination of k.

For the repression, neither of these approaches is sufficient. Once factual data about release quantities, meteorological data, and measurement results are available, these data should be leading in determining the safe zones in such cases.

6 CONCLUSIONS

Databases inhabit relevant data for (transportation) risk analysis. In particular accident frequency of hazardous material transportation activities are generated resulting in single values including for example the probability per release quantity, but preferably multiple values with uncertainty bounds are desired (Joshua et al. 1990, Hauer 1992, Stewart and Van Aerde 1990, Heydecker and Wu 1991, Heydecker 1991, Nembhard and Young 1995, Jovanis et al. 1987). Combining the stored hazardous material releases data and a bootstrapping technique enriches the generated data. As shown in this paper for hazardous material releases quantities, a distribution of release quantities is generated for both hazmat transportation under atmosphere and pressure conditions. In addition to the average release quantity, the distributions show the standard deviation and the confidence intervals per release range. Such probabilistic data can be used to formulate the appropriate risk policies and emergency rescue policy. Emergency response could use such release data for determining effect circles in term of victims and damage and subsequently determine their turn out routes. In addition, the training of fire personnel dealing with hazardous material release can be matched with the distributions of release quantities. In addition, emergency response organisations could match their logistics with these quantities. Despite the fact that using the bootstrap technique a richer picture of release quantities is presented, it is relevant here to memorise that, in case of a road tanker accident, in most cases there is no release at all. In these cases, uncertainty about the particular hazmat involved might still result in serious consequences for example in heavy traffic jams. Improvements in real time availability of hazmat transportation data and serious emergency response training is necessary with regard to the first quarters of an hour after a road tanker accident.

ACKNOWLEDGEMENTS AND DISCLAIMER

The authors want to thank Mr. P.C. van Beek (department of Industrial Safety of TNO Dutch Organization) for Applied Scientific Research for his contributions to this paper. Any opinions expressed in this paper are those of the authors and do not necessarily reflect the position of Nibra or TU Delft.

REFERENCES

AVIV, 1993. Rapportage Externe Veiligheid Rail en Wegvervoer, Enschede [in Dutch].

BZK, Schadescenarioboek, Ministerie van Binnenlandse Zaken, Directie Brandweer en Rampenbestrijding, Den Haag 1994 [in Dutch].

CPR, Committee for the Prevention of Disasters. Guidelines for Quantitative Risk Assessment, Purple Book, CPR 18E. Den Haag, Sdu: 1999, (in Dutch).

Haastrup P., Romer H., 1995. An analysis of the database coverage of industrial – accidents involving hazardous materials in Europe, Journal of Loss Prevention in the Process Industries, 8 (2): 79–86 March, 1995.

Hauer, Ezra, Emperical Bayes approach to the estimation of unsafety: the multivariate regression method, Accident Analysis and Prevention, Vol. 24, No. 5, pp. 457–477, 1992.

Heydecker, B.G., and Wu, J., Using the information in road accident records, Proceedings of the 19th PTRC Meeting, 1991, London.

Heydecker, B.G., Unified statistical analysis of road accident time series using log-linear and Bayesian techniques, University of London, Centre for Transport Studies, Internal note, July 1997.

Hirst, I.L., and D.AS. Carter. A worst-case methodology for risk assessment of major accident installations, Proc. Safety Progress, Vol. 19, nr. 2, p. 78, 2000.

Joshua, Sarath C., Garber, Nicholas J. Estimating truck accident rate and involvements using linear and poisson regression models, Transportation Planning and Technology, 1990, Vol. 15, pp. 41–58.

Jovanis, Paul P., Chang, Hsin-Li. Modeling the relationship of accidents to miles traveled, Transportation Research Record, 1987, p. 42–51.

Kaplan, S. and B.J. Garrick, 1981. On the quantitative definition of risk, Risk Analysis, Vol. 1, No. 1, pp. 11–27.

Nembhard, D.A., Young, M.R. Parametric empirical Bayes estimate of truck accident rates, Journal of Transportation Engineering, July/August 1995, p. 359–363.

Rasmussen K., 1995. Natural events and accidents with hazardous materials, Journal of Hazardous Materials, 40 (1): 43–54 January 1995.

Rosmuller, N., and P.C. van Beek, 1999. Database analyses and transport corridors: Parallel lines for accident research, pp. 1–10, *16th ESReDA seminar on Safety and Reliability in Transport,* ESReDA, Oslo.

Rosmuller, N., 2001. Safety Analysis of Transport Corridors, Dissertation Delft University of Technology, Faculty of Technology, Policy Analysis and Management, TRAIL, 2001/6, Delft.

Saccomanno, F.F., et al., 1993. Risk uncertainty in the transport of hazardous materials, *Transportation Research Record,* No. 1383, pp. 58–66.

Stewart, A M. Van Aerde, M. Empirical analysis of Canadian gasoline and LPG truck releases, Journal of Hazardous Materials, v 25 n 1–2 Oct 1990. p 205–217.

Stewart, A M. Van Aerde, M. Enhancements and updates to the RISKMOD risk analysis model, Journal of Hazardous Materials, v 25 n 1–2 Oct 1990. p 107–119.

Van Gelder, P.H.A.J.M., J.K. Vrijling. Verificatie Kanscijfers TNO/AVIV Rapportage [in Dutch], Rapport TU Delft, December 1998.

Vlek, C.A.J., 1990. *Beslissen over risico-acceptatie,* Health and Safety council, The Hague, Repnr. A90/10.

Vrijling, J.K., van Hengel, W., and Houben, R.J. Acceptable risk as a basis for design, Reliability Engineering and System Safety, 59 (1998) 141–150.