ELSEVIER
Journal of Hazardous Materials 62 (1998) 59–74
JOURNAL OF HAZARDOUS MATERIALS

Risk analysis of hazardous materials transportation: evaluating uncertainty by means of fuzzy logic

S. Bonvicini *, P. Leonelli, G. Spadoni

Department of Chemical, Mining Engineering and Environmental Technologies, University of Bologna, Viale del Risorgimento 2, I-40136 Bologna, Italy

Received 28 July 1997; revised 17 January 1998; accepted 30 March 1998

Abstract

This paper provides an application of fuzzy logic to the risk assessment of the transport of hazardous materials by road and pipeline in order to evaluate the uncertainties affecting both individual and societal risk estimates. In evaluating uncertainty by fuzzy logic, the uncertain input parameters are described by fuzzy numbers and calculations are performed using fuzzy arithmetic; the outputs will also be fuzzy numbers. This work is an attempt to justify some of the questions the use of fuzzy logic in the field of risk analysis stimulates. This study provides, first of all, a condensed description of the fundamentals of the mathematical procedures which perform the risk measures calculations. Then, some basic concepts about fuzzy logic and fuzzy arithmetic are introduced, after which an explanation on how the uncertain input data can be represented by fuzzy numbers is made. Finally, test results of combined uncertainty and sensitivity analysis in the risk evaluation of a toxic gas release are presented and extensively discussed, in order to show which effect each uncertain input has on the output uncertainty.

Keywords: Fuzzy logic; Hazardous materials transportation; Individual risk; Risk analysis; Societal risk; Uncertainty evaluation

1. Introduction

Paraphrasing a famous statement of Albert Einstein, we can say that ‘‘so far as the input parameters in a risk analysis try to describe reality, they are not known with certainty, and so far they are known with certainty, i.e. they can be expressed by a single-point value, they do not refer to reality.’’ Since risk estimates are often used to evaluate the safety of an industrial plant, in order to find which additional safety

* Corresponding author. Tel.: +39 51 6443138; fax: +39 51 581200; e-mail: bonvi@dicm0.ing.unibo.it

0304-3894/98/$19.00
PII S0304-3894(98)00158-7

measures can reduce the risk, or to support public authorities in establishing emergency planning or new plant siting, in one word to describe reality and eventually to take decisions about how to modify it, it is better not to use for this aim a quantity, like an absolute risk value, which, using Einstein's words, does not refer to reality. In these situations uncertainty evaluation becomes a key variable which can not be neglected.

A first application of fuzzy logic to uncertainty estimation in an elementary and simple case of risk analysis can be found in Ref. [1]. Few introductory considerations about an application to uncertainty evaluation in transport risk analysis are presented in Ref. [2]. In this paper, instead, an extensive explanation shows how fuzzy logic can be used in the very complex and computing-time-intensive quantitative analysis of risk arising from road and pipeline transport of dangerous substances in a populated area; furthermore, results about a case study test are presented. In the case of transportation risk analysis, very often, there is only little and very sparse information available. In this case of data scarcity, where no highly reliable results can be expected, instead of using a computational intensive technique like the Monte Carlo simulation, a fuzzy logic approach, which needs only three model runs (one for the single-point risk value and two to find the curves delimiting the uncertainty band), could be a more advisable vehicle for evaluating uncertainty, so much that, to construct fuzzy numbers, little information can be sufficient.

The use of fuzzy logic in risk analysis is, to our knowledge, innovative. For this reason, it can stimulate perplexity, since some methodological objections need to be considered and discussed. In this sense, this work will also be an attempt to justify some of them and to put in evidence the potentialities this technique has in the field of risk analysis.

2. The risk models

In this section, a brief survey of the mathematical models used to calculate the individual and societal risk is given. A more extensive and complete description of these procedures is given in Refs. [3–5].

Since a road tanker release can occur in any point along the road on which the tanker is travelling, and a pipeline accident can take place everywhere along the pipeline route, a tanker or a pipeline conveying a dangerous substance can be considered as a 'linear risk source' equivalent to a great number of point-risk sources. First, it is necessary to characterise the point-risk source by defining the release cases, i.e. by assigning a hole size, a physical state of the outcome, a release rate, a release duration and a likelihood of occurrence to the possible accidents which may occur during the transport, and which have been chosen to classify all possible releases. Then, suitable meteorological conditions (given by the pairs 'atmospheric turbulence class–wind speed') have to be chosen. Afterwards, consequence models are used to calculate the spatial distribution of the physical effects of each pair 'release case–meteorological condition', i.e. concentrations if the hazardous chemical is a toxic one, thermal radiation and blast overpressures if it is flammable. The physical effects are then combined with proper exposure times to obtain the received doses which are converted in vulnerabilities, i.e. death probabilities of an average individual, through 'probit' equations. In this way, a vulnerability map, i.e. the vulnerability distribution around the risk point, is assigned to each pair ‘release case–meteorological condition’. These maps and the release case frequencies are the inputs for both the individual and societal risk models.

In a fuzzy logic approach, the characterisation of the release cases is strictly connected with the fuzzy representation of the input variables, as explained in the following sections.

2.1. The individual risk model

The individual risk at a test area point, i.e. a point corresponding to a real location of a geographical site, is given by the sum of the risks created at that point by all arcs of the linear risk source (i.e. the road or pipeline). In order to calculate the individual risk at point P due to an accident at point $Q(t)$, where t is a curvilinear route abscissa, the vulnerability maps are combined with the probability of occurrence of different seasonal situations, weather conditions and wind directions to obtain the unit risk maps. The unit risk $\bar{R}_{Q(t) \to O}$ due to the point risk source $Q(t)$ at a generic point O of the unit risk map for the ith release case is a parameter given by

$$\bar{R}_{Q(t) \to O}(i) = \sum_{j=1}^{N_{\text{seas}}} x(j) \sum_{k=1}^{N_{\text{met}}} \int_0^{2\pi} P_{\text{wind}}(j,k,\vartheta)\, v_{Q(t) \to O}(i,k,\vartheta)\, d\vartheta, \tag{1}$$

where N_{seas} and N_{met} are the numbers of different seasonal situations and meteorological conditions, respectively; P_{wind} is the probability density function of a given wind direction ϑ for a specified meteorological condition k and seasonal situation j and $v_{Q(t) \to O}$ is the vulnerability that a release i at $Q(t)$ creates at O when the meteorological condition is k and the wind direction is ϑ. In the case of a road transport, $x(j)$ is the fraction of the year that tankers travel on the road in a given season (the symbol $x_{\text{V}}(j)$ is used in this case); while, for a pipeline transport, it is the fraction of the season during which the pipeline is active (the symbol $x_{\text{p}}(j)$ is used in this case). The unit risk maps are then combined with proper frequency factors and translated along the route to describe the changes in the position where an accident can occur, i.e. the contributions of all point risk sources $Q(t)$ to the risk at P. Finally, they are summed for all release cases to obtain the global individual risk at P, IR_P:

$$\text{IR}_P = \sum_{i=1}^{N_{\text{rel}}} \left[\int_L f_{\text{rel}}(i,t)\, \bar{R}_{Q(t) \to P}(i)\, \text{d}t \right], \tag{2}$$

where L is the road (or pipeline) route, N_{rel} is the number of release cases and f_{rel} is the frequency of the ith release case, which has different expressions for the road and the pipeline.

The release case frequency for the road is given by

$$f_{\text{rel}}(i,t) = \lambda_R(t)\, p_{\text{rel}}\, p_{\Phi}(i)\, p_{\text{I}}\, n_{\text{V}}, \tag{3}$$

where λ_R is the average incident rate (incidents vehicle^{-1} km^{-1}), p_{rel} is the probability to have a release once an incident has occurred, $p_{\Phi}(i)$ is the probability of the release of a particular size, p_{I} is the ignition probability (for flammable substances only), and n_{V} is the number of yearly travelling tankers.

The release case frequency for the pipeline is calculated as

$$f_{\mathrm{rel}}(i,t) = \lambda_P(t)\, p_{\Phi}(i)\, p_{\mathrm{I}}, \tag{4}$$

where λ_P is the average release frequency (releases year^{-1} km^{-1}).

In order to perform the line integral of Eq. (2), it is necessary to represent the route as a polygonal curve of N_{seg} straight segments, each characterised by constant release frequency values. With this hypothesis, Eq. (2) becomes

$$\mathrm{IR}_P = \sum_{i=1}^{N_{\mathrm{rel}}} \sum_{l=1}^{N_{\mathrm{seg}}} f_{\mathrm{rel}}(i,l)\left[\int_{Li} \overline{R}_{Q(t)\to P}(i)\,\mathrm{d}t\right]. \tag{5}$$

2.2. The societal risk model

Societal risk can be represented by means of $F(N)$ curves, where F is the frequency of all accidents capable of causing the death of N or more persons. Apart from the vulnerability maps defined for each release case–meteorological condition, it is necessary to identify on a population map the: (1) zones of rectangular shape, where people may be considered uniformly distributed with a density depending on the area being an urban, a suburban or a rural one; (2) roads, where people are linearly distributed; (3) aggregation centres, e.g., schools, hospitals, and commercial sites, where people can be considered as clustered. Furthermore, the probabilities of each category of people being indoor have to be assigned.

At the point risk source $Q(t)$, a scenario is given by the combination release case i–seasonal situation j–meteorological condition k–wind direction ϑ. The number of fatalities $N_{Q(t)}^{\mathrm{scen}}(i,j,k,\vartheta)$ due to each scenario when an accident occurs at $Q(t)$ is evaluated according to the following equation.

$$\begin{aligned} N_{Q(t)}^{\mathrm{scen}}(i,j,k,\vartheta) &= \sum_{m=1}^{n_L} \rho_{L_m}(j) \int_{\mathrm{L}_m} \upsilon_{Q(t)}(i,k,\vartheta)\left[x_{L_m}(j) + \left(1 - x_{L_m}(j)\right)\alpha_{P,L_m}\right]\mathrm{d}L_m \\ &\quad + \sum_{n=1}^{n_A} \rho_{A_n}(j) \int_{\mathrm{A}_n} \upsilon_{Q(t)}(i,k,\vartheta)\left[x_{A_n}(j) + \left(1 - x_{A_n}(j)\right)\alpha_{P,A_n}\right]\mathrm{d}A_n \\ &\quad + \sum_{o=1}^{n_C} \upsilon_{Q(t)}(i,k,\vartheta)\left[x_{C_o}(j) + \left(1 - x_{C_o}(j)\right)\alpha_{P,C_o}\right] N_{C_o}(j), \end{aligned} \tag{6}$$

where n_L, n_A and n_C are, the numbers of lines, rectangles and points on the population map, respectively; ρ_{L_m} and ρ_{A_n} are the people densities corresponding to the mth line and the nth rectangle, respectively; N_{C_o} is the number of persons in the aggregation centre o; x_{L_m}, x_{A_n} and x_{C_o} are the fraction of people staying indoors and α_{P-L_m}, α_{P-A_n}, α_{P-C_o} are the mitigation factors deriving from being indoors on the generic line, rectangle or aggregation centre, respectively; eventually, $\upsilon_{Q(t)}$ is the vulnerability due to a release in the point risk source $Q(t)$ stored in vulnerability maps. To perform the integration steps of Eq. (6), each vulnerability matrix is linearly interpolated obtaining a continuous function. An efficient numerical algorithm based on the ‘circuitation theorem’ accelerates the surface integration that constitutes the slowest step of the procedure.

Each scenario of the point risk source has to be characterised by a number of fatalities $N_{Q(t)}^{\text{scen}}(i,j,k,\vartheta)$ and a frequency per unit length and unit angle, defined as

$$f_{Q(t)}^{\text{scen}}(i,j,k,\vartheta) = f_{\text{rel}}(i,t)\, x(j)\, P_{\text{wind}}(j,k,\vartheta). \tag{7}$$

In order to evaluate $N_{Q(t)}^{\text{scen}}(i,j,k,\vartheta)$ for a given scenario at a point risk source $Q(t)$, the population map is overlaid with the vulnerability maps, which are rotated to describe the changes in the wind direction. Once $N_{Q(t)}^{\text{scen}}(i,j,k,\vartheta)$ and $f_{Q(t)}^{\text{scen}}(\mathrm{i},j,k,\vartheta)$ at point $Q(t)$ are known for each scenario, $F_{Q(t)}(N(i,j,k))$, i.e. the cumulative frequency function per unit length at point $Q(t)$, can be evaluated by taking into account all wind directions. To simulate the change in the position where accidents can occur, the vulnerability maps are translated along the route, and for each route point $Q(t)$, the evaluation of $F_{Q(t)}(N(i,j,k))$ is performed. The last step of the procedure is to integrate $F_{Q(t)}(N(i,j,k))$ along the route obtaining $F(N(i,j,k))$, and, for fixed values of N, to sum the integrated values for all combinations of release case–meteorological condition–seasonal situation, in order to obtain the final $F(N)$ curve.

As in the individual risk model, the route is represented by a polygonal curve of N_{seg} straight segments, each characterised by constant release case frequency values. For each segment l, the outlined $F(N)_l$ calculus is performed, and eventually, the $F(N)_l$ curves are summed for constant N values to obtain the $F(N)$ curve for the whole route.

3. Fuzzy logic

3.1. Fuzzy sets

In this section, some basic concepts about fuzzy sets and their notation and terminology will be introduced (this is explained in more detail in Refs. [6,7]). A crisp set A (that is a classical nonfuzzy set) can be defined by a ‘membership function’ χ_A, which can assume only the values 0 and 1: for each $x \in X$, when $\chi_A = 1$, x is declared to be a member of A, and when $\chi_A = 0$, x is declared as a nonmember of A.

In the natural language, however, concepts very often contain some vagueness that does not allow to divide elements in such a sharp way between two groups, members and nonmembers. This vagueness could mathematically be represented by allowing the characteristic function to assume all values between 0 and 1, so expressing different grades of membership of each element $x \in X$ in A.

Apart from the membership function, a fuzzy set can also be fully and uniquely represented by its α-cuts. Given a fuzzy set defined on X, an α-cut is the crisp set that contains all the elements of X whose membership grades in A are greater than or equal to the specified value of α. If they are only greater than α, the crisp set is called a ‘strong α-cut’.

3.2. Fuzzy numbers and fuzzy arithmetic

If a fuzzy set A defined on the set of all real numbers R has the following three properties: (1) A is a fuzzy set whose largest membership grade is 1, (2) the α-cuts of

A for every $\alpha \in (0,1]$ are closed single intervals, and (3) the strong α-cut for $\alpha = 0$ is bounded; it is called a 'fuzzy number'.

Fuzzy arithmetic consists of performing arithmetic operations on fuzzy numbers in terms of arithmetic operations on their α-cuts, i.e. on closed intervals, using the rules and the notations of an area of classical mathematics called 'interval analysis'. Basically, the endpoints of the α-cuts, on which the operation has to be performed, must be combined according to the operation. The minimum and maximum values of the solution will define the lower and upper endpoints of the solution interval, respectively.

4. How to construct fuzzy numbers in transport risk analysis

Uncertainty evaluation in the area of risk assessment can properly be handled by means of fuzzy logic, since the significance of fuzzy numbers is that they facilitate gradual transition between states and, consequently, possess a natural capability to express and deal with uncertainties.

In this study, four variables have been considered uncertain for each mean of transport: the release frequencies, the release rates (or the release quantities), the residential air exchange rate and the probability of people being indoor.

Performing the transportation risk analysis, it was possible to find probability density functions for some uncertain inputs. As explained in Ref. [8], a connection between the 'degree of membership' and the 'probability of occurrence' has been established by means of a bijective transformation which turns a probability measure into a degree of membership. For these inputs, this 'transformation procedure' has been adopted to construct fuzzy numbers.

For the others, for which only little information and not probability density functions have been found, simple shapes, like triangular, trapezoidal, Gaussian or more generally symmetrical ones, have been used to represent fuzzy numbers, as suggested in Ref. [6].

4.1. Pipeline release frequency

Data for pipeline release frequencies and equivalence hole size probabilities have been taken from Ref. [9], where they are given for a pinhole, a medium hole and a guillotine breakage. In Table 1, the main features of the test case pipeline are summarised.

The total release frequency λ_P can be calculated from two different viewpoints. The first is that of the pipeline owner, who will assume values as low as possible to demonstrate the safety of his plant, and the second one is that of the pipeline opposers, e.g. people living close to it, who will assume values as high as possible: figures of 2×10^{-4} and 7×10^{-4} ev km^{-1} year^{-1} are obtained, respectively, from the 2 parties, which can be considered as the endpoints of the α-cut for $\alpha = 0$. Since a lognormal distribution is used to describe failure rates where there is quite uncertainty [10], a curve with a lognormal shape has been taken to represent the pipeline failure frequency. Through the above mentioned 'transformation procedure', this curve has been converted to a fuzzy number, which is shown in Fig. 1.

Table 1
Main features of the test case pipeline

Transported substance	ammonia
Diameter	200 mm
Wall thickness	11.1 mm
Earth cover	1.5 m
Year of construction	1990
Design flow	10.4 kg s^{-1} (3.28×10^{8} kg yr^{-1})
Isolation valve spacing	10 km

The probabilities p_{Φ} of the release being a pinhole, a hole or a guillotine rupture have been taken equal to 43%, 43% and 14%, respectively, and they have been considered as single-point values.

4.2. Pipeline equivalence hole sizes

The small and the medium hole diameters have been represented as fuzzy numbers. In the absence of further information, a simple normalised symmetrical Gaussian bell distribution, adjusted so that the α-cuts for $\alpha = 0$ are (0, 20) and (20, 200), respectively, was chosen for both, as shown in Fig. 2. Since the release rate is a square function of the hole diameter, the outflows will have an asymmetrical bell shape.

4.3. Road tanker failure frequency

The road tanker failure frequency can be expressed as $f_{\text{road tanker}} = \lambda_R \, p_{\text{rel}}$, where λ_R is the frequency (in ev km^{-1} $vehicle^{-1}$) that a tanker is involved in an incident and p_{rel} is the probability that there is a release once the incident has happened. Historical data

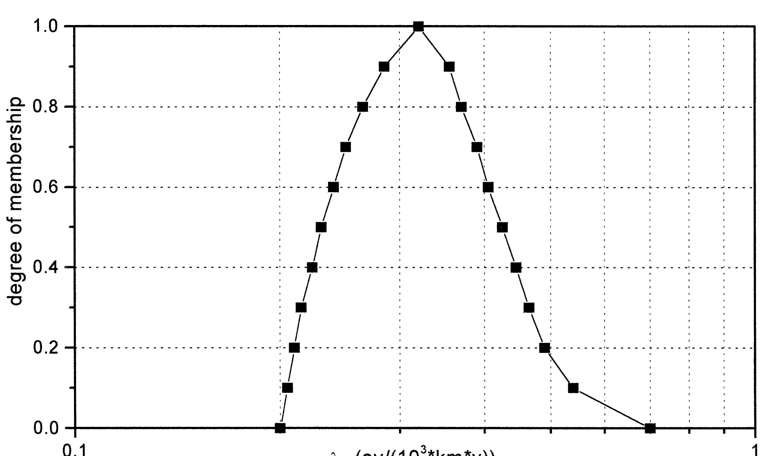

Fig. 1. Fuzzy representation of λ_P.

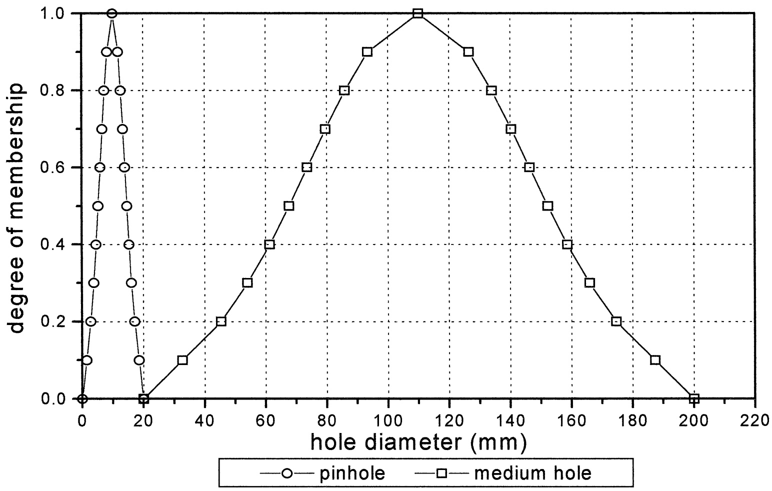

Fig. 2. Pinhole and medium hole diameters as fuzzy numbers.

both for λ_R and p_{rel} have been taken from Ref. [11]. An 80 km h^{-1} rural road has been considered in the case study test. In Fig. 3, the percentage of segments of 80 km h^{-1} rural road as a function of different λ_R ranges is reported as a bar diagram (very small percentages obtained from insignificant samples were omitted).

The average incident frequency for tankers on rural roads is about 0.2×10^{-6} ev km^{-1} $vehicle^{-1}$. In order to obtain the percentage of segments as a continuous function

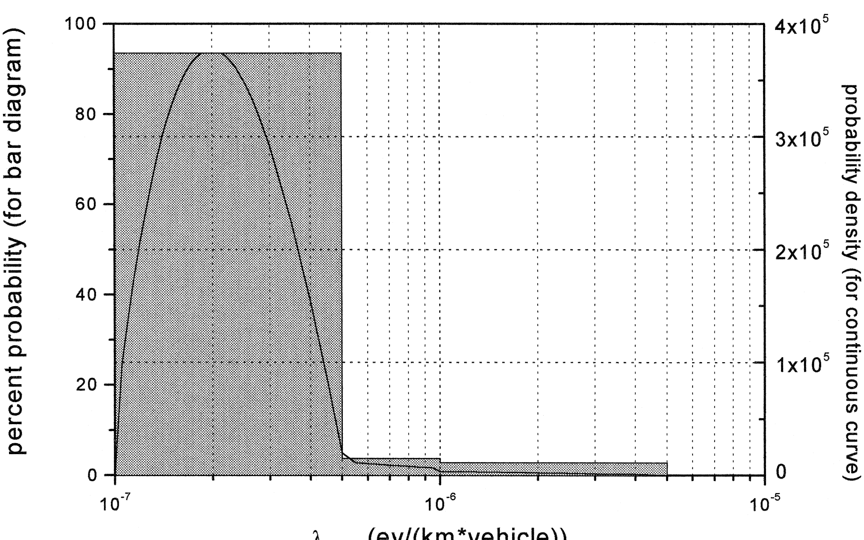

Fig. 3. Rural road segments (80 km h^{-1}) as a function of λ_R.

of λ_R, a curve, representing a probability density distribution, was drawn inside the bar graph, having a maximum when the abscissa equals the average incident frequency (Fig. 3). This curve has been converted to a fuzzy number by means of the above mentioned 'transformation procedure'.

In Ref. [11], the release probability is estimated as 1–3% for a thick-walled tanker. Values in this range or just outside can be derived by analysing historical data and from other published literature. Translating this data into fuzzy logic, the interval (1, 3%) can be taken as the α-cut for $\alpha = 0.4$. Since there is no other information about p_{rel}, a simple regular triangular shape was considered suitable for it, as suggested in Ref. [6].

The ammonia tankers travelling yearly on the road have been supposed to be 16 425; since road tankers have a capacity of 20 000 kg vehicle^{-1}, the road has an annual flux of ammonia of 3.28×10^8 kg year^{-1}, like the pipeline.

4.4. Road tanker equivalence hole sizes

Ignoring releases below 2000 kg, in Ref. [11], three different ranges for the outflow quantities of a generic hazardous chemical have been considered: 2000–6000 kg, 6000–14 000 kg and 14 000–20 000 kg; the probabilities p_Φ of a release belonging to one of these ranges are 0.25, 0.35 and 0.40, respectively. In order to perform calculations and in the lack of any other information useful to obtain the diameter ranges, it has reasonably been supposed that it takes a tanker 60 min to release 2000 kg, 30 min for 6000 kg and 15 min for 14 000 kg; greater releases are assumed to be instantaneous. From these data, it is possible to evaluate the outflow rates for the small and the medium holes, and, knowing the mass flow rate (which depends on the particular chemical substance), to obtain the hole diameters corresponding to the above release quantities. The main results of these calculations, performed in the case of an ammonia tanker, are summarised in Table 2.

The diameter ranges in Table 2 have been taken as the α-cuts for $\alpha = 0$ of two normalised Gaussian bells, from which the corresponding release rates are easily obtained as fuzzy numbers.

The ammonia totally released through the large hole has also been represented as a fuzzy number. It has been supposed that the release quantities for all three rupture classes have the same fuzzy number shape; the total outcomes for the small and the medium holes have been calculated by multiplying the release rates by the release duration (for the latter ones a symmetrical triangular shape has been adopted, considering the ranges in Table 2 as the α-cuts for $\alpha = 0$). An analogous shape, as found for the

Table 2
Release rates characterisation for an ammonia tanker

Rupture class	Small hole		Medium hole		Large hole	
Release quantity (kg)	2000	6000	6000	14 000	14 000	20 000
Release duration (min)	60	30	30	15	instantaneous	
Outflow rate (kg/s)	0.56	3.33	3.33	15.56	/	/
Hole diameter (mm)	6.5	15.8	15.8	34.2	/	/

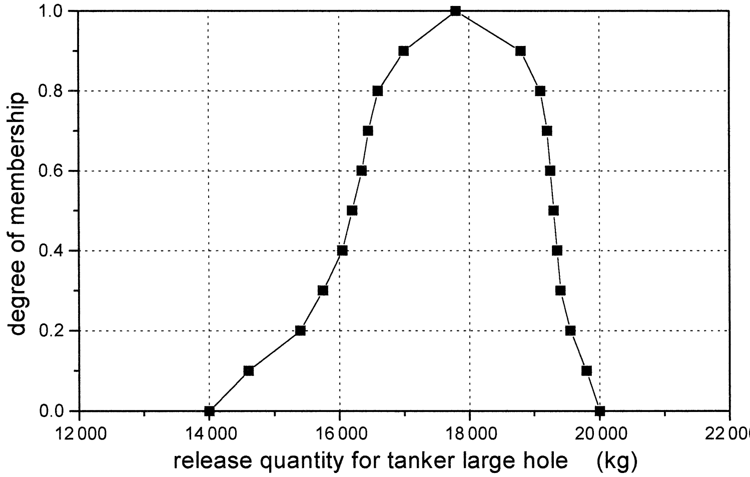

Fig. 4. Fuzzy representation of the release quantity for the tanker large hole.

first two rupture classes, has been considered also for the large hole release quantity, taking the interval (14 000, 20 000) as the α-cut for $\alpha = 0$, leading to the fuzzy number of Fig. 4.

4.5. Residential air exchange rate

In Ref. [12], the results of a statistical analysis about the probability distribution for residential air exchange rates are reported. It has been found that the experimental data

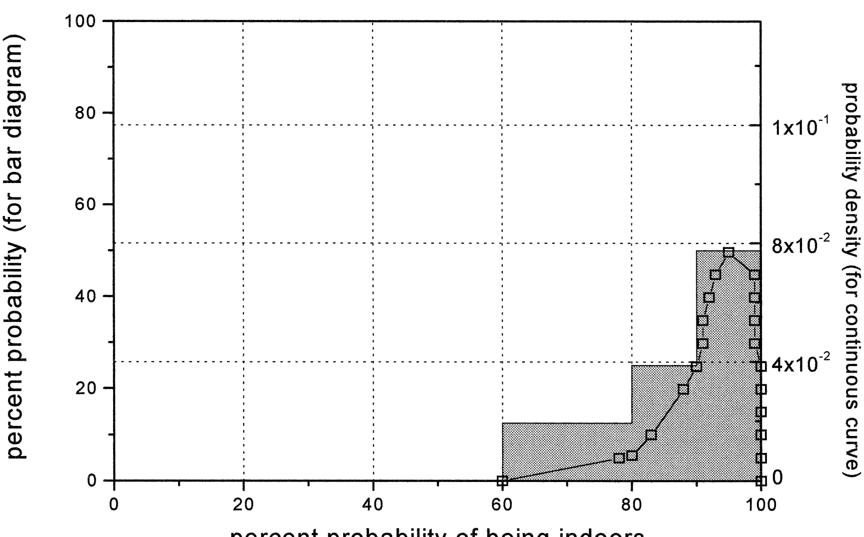

Fig. 5. Analysts' response as a function of the probability of people being indoor.

follow a lognormal distribution. In order to construct a fuzzy number, this probability distribution has been modified as to have the α-cut for $\alpha = 0$ a closed interval, and the above mentioned ‘transformation procedure’ has been applied to obtain a fuzzy number.

4.6. Probability of residential people being indoor

Not distinguishing between night and day, a 24-h average probability has being considered, taking data from Ref. [13], where four possible values, each reported by a different literature reference, are reported: 64%, 88%, 96% and 99%. Supposing each value to be expressed by 25% of risk analysts, then, 25% of them assign the indoor presence probability a value in the range [60, 80%] (12.5% in the range [60, 70%] and 12.5% in the range [70, 80%]), 25% in the range [80, 90%] and 50% in the range [90, 100%]. The risk analysts’ response percentage can be reported as a function of different indoor presence probability ranges, and a curve can be drawn inside this graph to obtain a continuous probability density function, as shown in Fig. 5. Applying the usual ‘transformation procedure’ to this curve, a fuzzy number is obtained.

5. Test results

In order to show which graphical representation can be assumed by the final risk measures evaluated by means of fuzzy logic and how they can be interpreted, calculations have been performed on a case-study area, where the wind angle probability has been taken uniformly distributed. This area is shown in Fig. 6, from which the road and pipeline routes and the population distribution can be derived. Calculations have been

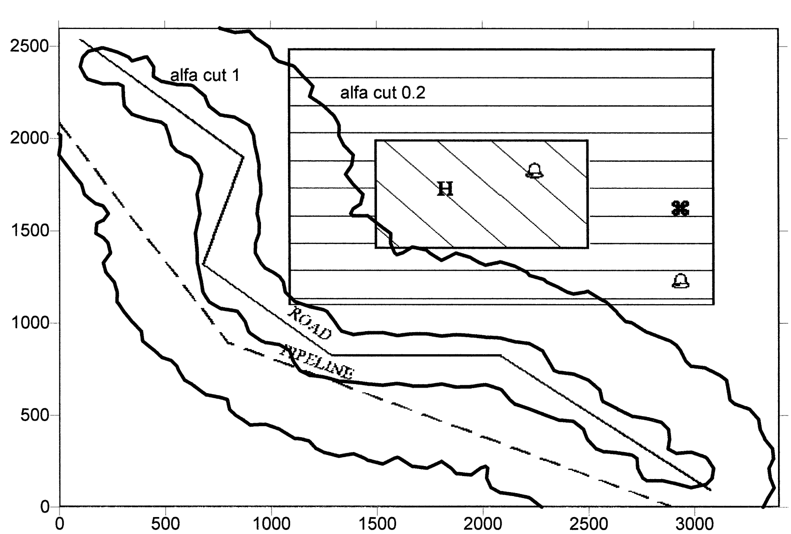

Fig. 6. Case study test area: (diagonal brush) suburban area, 8.33×10^{-3} persons m^{-2}; (horizontal brush) rural area, 2.27×10^{-3} persons m^{-2}; (bell) schools, 240 persons in each one; (**H**) hospital, 200 persons; (four-leaf clover) commercial site, 400 persons; on road population: 0.06 persons m^{-1}; and road transport individual risk (1×10^{-6} level contours).

performed for both the road and the pipeline. The results reported in this work mainly refer to the road.

The individual risk is a point function, and for each point, it can be represented as a fuzzy number. The road individual risk as a fuzzy number is reported in Fig. 7 for point (1800,1700) where the hospital is situated.

However, a more useful representation of it can be given by means of level contours. For a fixed risk level, two contours can be generally drawn for each α-cut, corresponding to the lower and the upper α-cut endpoints, respectively. In Fig. 6, the 1×10^{-6} level contours for the road transport of ammonia are mapped for $\alpha = 1$ and for $\alpha = 0.2$ (the one corresponding to the lower endpoint of the α-cut 0.2 is not reported, since in every area point inside this curve the risk is below 1×10^{-6}).

The single-point risk curves can be obtained by taking for each input variable the value corresponding to the α-cut 1, while for the uncertainty bands, by taking the values corresponding to an α-cut with $0 \leq \alpha < 1$. The α-cut level to which relate the uncertainty band can be chosen arbitrarily; in this case study, the uncertainty bands corresponding to the α-cut 0.2 are presented. It is worth noting that the uncertainty band corresponding to the α-cut 0.2 contains not only all uncertainty bands at α-cuts levels with $\alpha > 0.2$, but also the risk curves resulting from all possible combinations of the uncertain input data values taken at different α-cut levels with $\alpha \geq 0.2$. Through the 'transformation procedure' proposed in Ref. [8], the output fuzzy numbers representing risk values can be converted to statistical entities which can be viewed as an estimate of the output probability density distributions. In this way, the uncertainty range corresponding to each α-cut is put in relation with an interval of the probability estimate; in Ref. [8], it has been demonstrated that the α-cut corresponding to a specified level $\alpha*$ is greater or equal than the probability estimate interval delimiting the $(1-\alpha*)$ 100 percentile. This means that, for instance, the α-cut for $\alpha = 0.2$ is greater or equal than the probability estimate interval delimiting the 80% percentile, i.e. the region where 80% of risk analysts would draw the risk curves. For example, looking at Fig. 7, more than

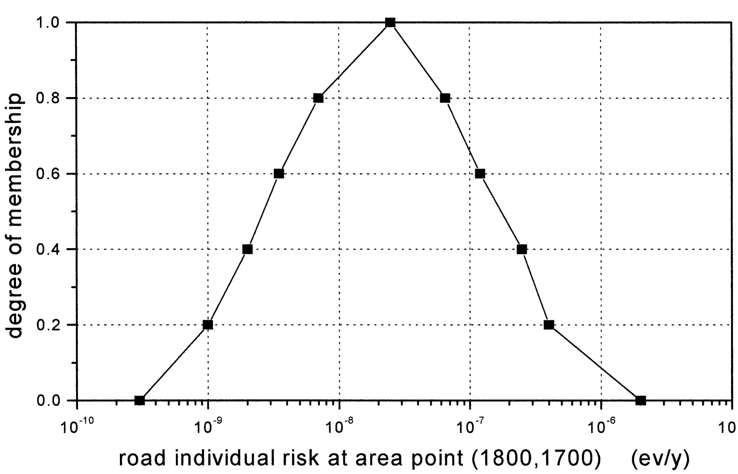

Fig. 7. Road individual risk at area point (1800,1700) as a fuzzy number.

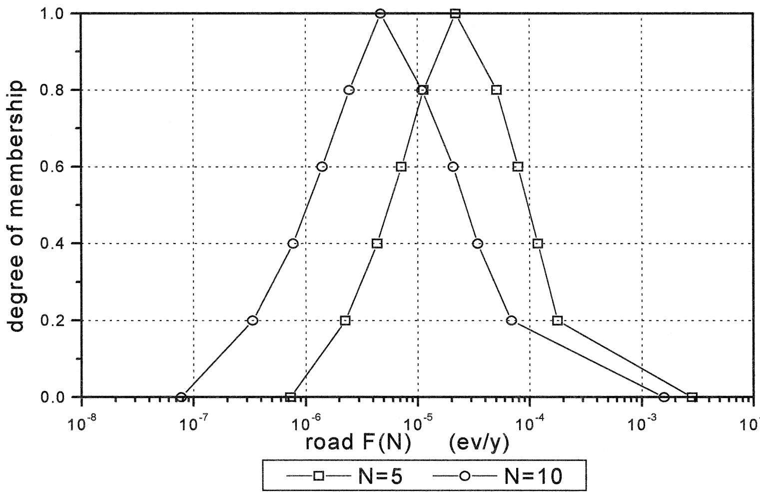

Fig. 8. Fuzzy representation of road F.

80% of risk analysts would say that the road individual risk at the area point corresponding to the hospital is between 1×10^{-9} and 3×10^{-7} ev year^{-1}; while, considering Fig. 6, more than 80% of risk analysts would say that the road individual risk is above 1×10^{-6} inside the outer contour line.

In a fuzzy logic analysis, the societal risk, too, represented by means of $F(N)$ curves, is a function of α, so that a tridimensional graph is possible for it, being the two

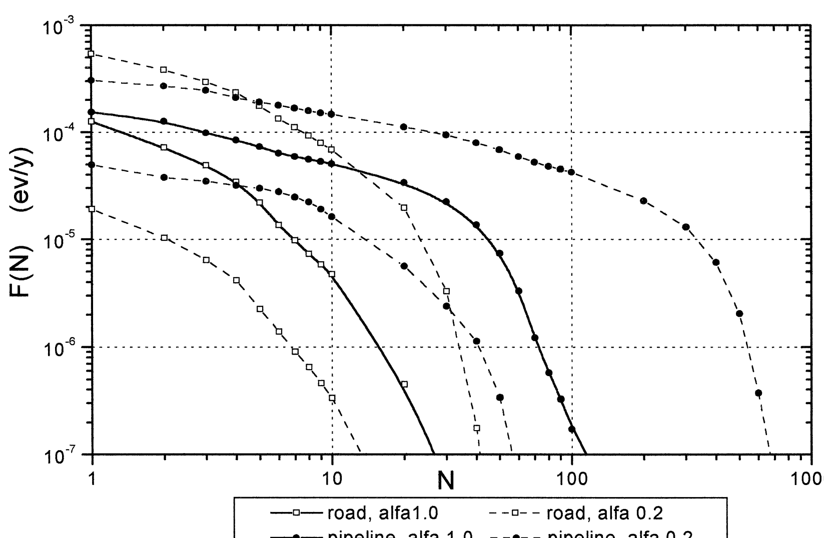

Fig. 9. $F(N)$ curves for the road and the pipeline.

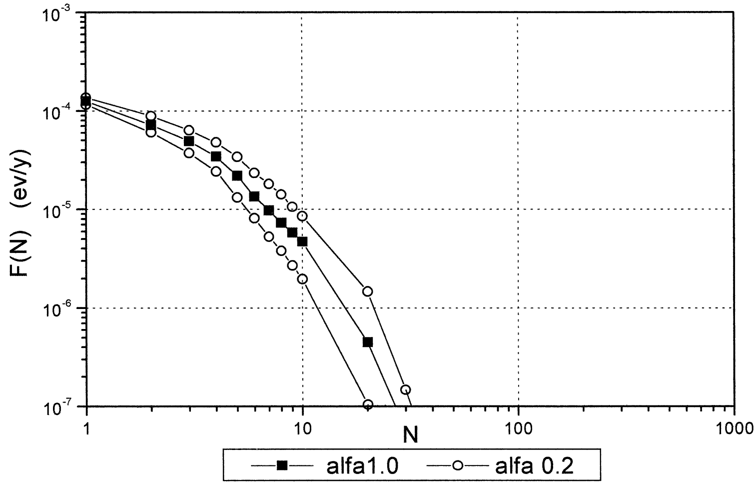

Fig. 10. Road $F(N)$ (release frequency as fuzzy set).

horizontal axes F and N and the vertical axis α. Since tridimensional figures are difficult to read, sections of the $F/N/\alpha$ graph at constant N values (Fig. 8) or at constant α values are generally more useful. The latter ones are the most important, since they show the single-point curve, drawn at $\alpha = 1$, and the uncertainty band, corresponding to $\alpha = 0.2$ (Fig. 9).

Fig. 9 has been drawn considering the release frequencies, the release rates, the buildings air exchange rate and the probability of people being indoor as fuzzy numbers

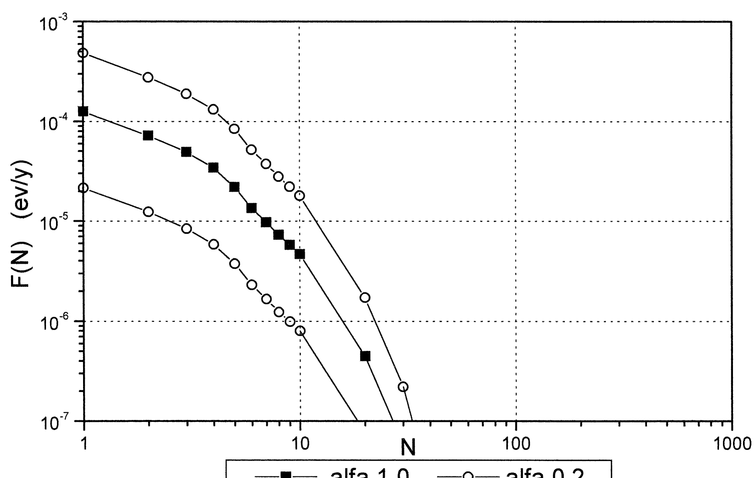

Fig. 11. Road $F(N)$ (release rate as fuzzy set).

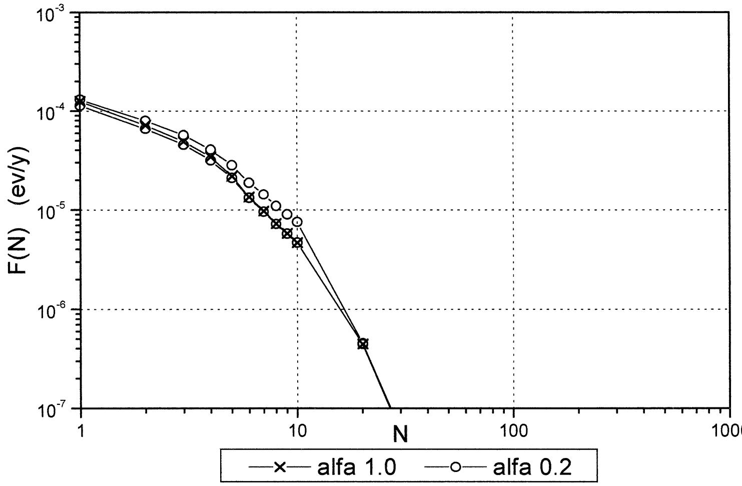

Fig. 12. Road $F(N)$ (air exchange rate as fuzzy set).

all together. In order to perform a sensitivity analysis, i.e. to see which of these variables mainly contribute to the amplitude of the uncertainty band, they have also been considered as fuzzy numbers one at time. Results for the road are shown in Figs. 10–13. From them, it can be immediately derived that the uncertainty about the residential air exchange rate and the probability of people being indoor does not influence at all the total road risk uncertainty, and that, among the road release rates and release frequencies uncertainties, mostly the latter ones contribute to it for small N.

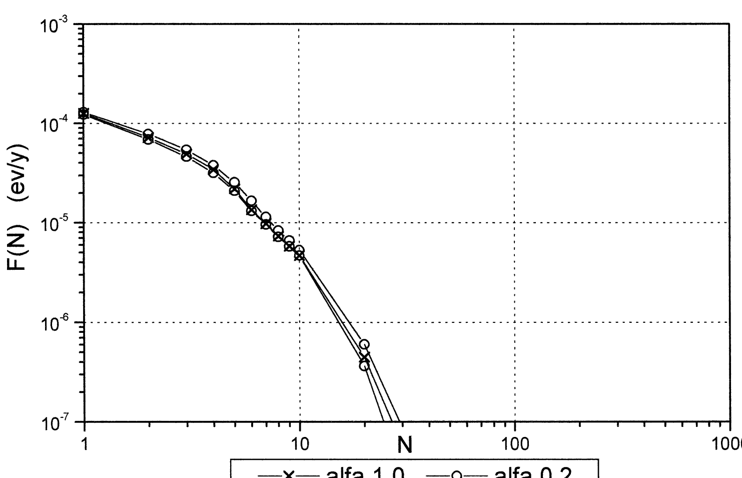

Fig. 13. Road $F(N)$ (probability of being indoor as fuzzy set).

6. Conclusions

In this paper, a new methodology of evaluating uncertainty in risk assessment has been presented, based on fuzzy logic, and has been applied to risk estimation for the transportation of toxic substances by both road and pipeline. If computer power and good probability density functions for all uncertain inputs are available, the traditional statistical analysis based on the Monte Carlo method can successfully be applied to evaluate uncertainty. Since there is very often only little and very sparse input data available in hazardous materials transportation risk analysis, a simpler and less computational intensive procedure like fuzzy logic can be a useful alternative approach for quantifying uncertainty ranges.

It is also worth noting that the fuzzy logic methodology allows, like the Monte Carlo method, the identification, from all uncertain variables, of those which most greatly influence the output, and the rapid evaluation of the effect that changing the values of these variables has on the final result. The importance of this flexibility makes the proposed technique useful in land use planning, safety management and safety control activities, since decision makers can quickly test the suitability of alternative choices in the adoption of preventive and protective measures.

References

[1] J. Quelch, I.T. Cameron, Uncertainty representation and propagation in quantified risk assessment using fuzzy sets, J. Loss Prev. Proc. Ind. 7 (6) (1994) 463–473.
[2] S. Bonvicini, P. Leonelli, G. Spadoni, Uncertainty evaluation using fuzzy logic in risk analysis of hazardous materials transportation, Proceedings of the SRA-Europe Annual Meeting, Stockholm, Sweden, 1997, pp. 237–245.
[3] R. Fiore, Metodi per la quantificazione del rischio: un'applicazione al trasporto stradale di sostanze pericolose, PhD Dissertation, University of Bologna, 1994, Italy.
[4] G. Spadoni, P. Leonelli, P. Verlicchi, R. Fiore, A numerical procedure for assessing risks from road transport of dangerous substances, J. Loss Prev. Proc. Ind. 8 (4) (1995) 245–251.
[5] P.Leonelli, G. Spadoni, A new numerical procedure for calculating societal risk from road transport of dangerous substances, Proceedings of the SRA-Europe Annual Meeting, Guilford, UK, 1996, pp. 243–246.
[6] G.J. Klir, Bo Juan, Fuzzy Sets and Fuzzy Logic—Theory and Applications, Prentice-Hall, Upper Saddle River, NJ, 1995.
[7] D. Dubois, H. Prade, Fuzzy Sets and Systems: Theory and Applications, Academic Press, New York, NY, 1980.
[8] D. Dubois, H. Prade, Unfair coins and necessity measures: toward a possibilistic interpretation of histograms, Fuzzy Sets Sys. 10 (1983) 15–20.
[9] EGIG, Gas Pipeline Incidents, Report 1970–1992, European Gas Pipeline Incident Data Group, 1993.
[10] CCPS, Guidelines for Chemical Process Quantitative Risk Analysis, Centre for Chemical Process Safety, Ache, New York, NY, 1989.
[11] L.H. Brockoff, A risk management model for transport of dangerous goods, EUR14675EN, JRC, Ispra, Italy, 1992.
[12] D.M. Murray, D.E. Burmaster, Residential air exchange rates in the United States: empirical and estimated parametric distributions by season and climatic region, Risk Analysis 15 (4) (1995) 459–465.
[13] TNO, Methods for the determination of possible damages, CPR 16E, The Director-General of Labour, the Hague, NL, 1992.