RISK ANALYSIS AND SAFE DISTANCES CALCULATION CONSIDERING ATMOSPHERIC PARAMETERS UNCERTAINTY

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***Abstract*— This work presents a computational tool, useful in risk assessment of hazardous material releases. It is based on a methodology that takes into account the stochastic uncertainty of atmospheric parameters. This is relevant for calculating risk of hazardous gases, particulate matter or bioaerosols diffusion when an accidental release or continuous emission occurs. This methodology can be applied to risk analysis of static sources (a stack or a fixed tank in a facility) or transportation accidents (road, train, maritime and pipeline transport) involving different scenarios. After carrying out a stochastic simulation based on well-known diffusion models (heavy and light gases or particulate matter), downwind concentrations are obtained so that individual and societal risks can be computed. This work contributes mainly to the formal presentation of the procedure, and the real application of the stochastic simulation avoiding large (prohibitive) computational effort, by introducing a translation algorithm and the Stochastic Reference Emitter (SRE) definition. This new approach also shows to be a fundamental step to organize a software prototype for risk assessment. Besides, taking advantage of the new computational capability a SRE-based algorithm for safe distances calculation is introduced. Finally, an example shows the main capabilities of the new tool.**

***Keywords*— Atmospheric parameter uncertainty, Consequence and vulnerability analysis, Risk assessment.**

I. INTRODUCTION

Road-accident rates are growing as industrial activity increases. For example, the extent of hazardous material transportation accidents is as important as releases from process equipments, stacks, tank releases, etc. In fact, 95% of cases reported in the 20th Century took place in the last 30 years (Planas-Cuchi *et al.*, 1997). Consequently, the available tools should be improved and new ones developed to compute risk indexes and to estimate safe distances when considering an emergency /contingency planning.

In a recent publication (Scenna and Santa Cruz, 2005), a method for a risk assessment study case considering the stochastic nature of meteorological parameters is presented. It demonstrates that it is possible to achieve good approximated distributions over the whole impact area using the Monte Carlo strategy. In order to improve the previous prototype, a special algorithm, capable of handling the long computing times associated with the simulation step is included together with a Stochastic Reference Emitter and a translation algorithm.

The following sections explain the main aspects of the risk calculation procedure. As it will be shown, we can model a toxic substance release as a consequence of a transportation accident or fixed emission, either involving single or multiple fixed sources. Moreover, safe distances can be easily calculated as a stochastic variability is considered.

II. CALCULATION STRATEGY FOR TRANSPORT RISK ANALYSIS

It is possible to define several indexes to represent risk analysis results. Common representations for individual risk are contour plots, profiles and/or different average indexes, such as maximum individual risk and average individual risk among others.

Societal risk includes quantification in terms of the number of affected people. Generally, it is represented as the Frequency-Number (F-N) curve, a plot of the complementary cumulative frequency versus the number of fatalities.

For risk definitions and risk estimation methodologies, see IEC (2002); TNO (1999); Christensen Møller *et al.* (2003).

For transport accident releases there are several aspects to be considered in a Quantitative Risk Analysis (QRA) (see Scenna and Santa Cruz, 2005): involvement of a dangerous-substance transportation vehicle in an accident, breakage occurrence and characteristics (type, size, etc.), release characteristics and calculation of the individual or societal risk and its distribution over the impact area.

Many works use a deterministic approach for each or some of the above-mentioned aspects (Batta and Chiu, 1988; Re Velle *et al.*, 1991; Erkut and Verter, 1995). Recent publications have made important contributions to solve the risk assessment problem (Leonelli *et al.*, 1999; Maschio *et al.*, 2004; Cozzani *et al.*, 2004; Gheorghe *et al.*, 2005).

Finally, the dependence of atmospheric parameter uncertainty in air dispersion models and the consequence analysis is considered in a previous work (Scenna and Santa Cruz, 2005). It was demonstrated that it is possible to achieve good approximated distributions over the whole impact area, using Monte Carlo strategy. The stochastic risk analysis problem on road transportation was modeled as follows.

Consider a truck accident, which produces a toxic substance release. The problem is depicted in Fig. 1.

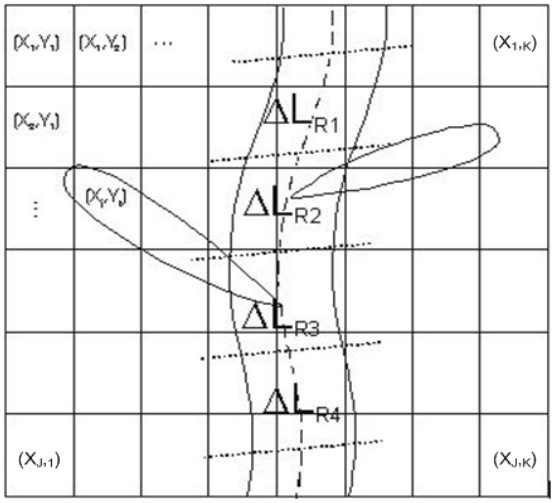


Figure 1. Discretization of the emission points and the receptor grid points.

The model is based on a simple representation of emitters and receptors (grid). ΔL_{Ri} are different road segments and the product "J . K" is the number of the receptor squares. The emitters are supposed to be placed in the centre of each road segment (ΔL_{Ri}), as the receptors are in the centre of each square.

The road is cut up into a number of segments and the surrounding area is divided into square sections (grid of receptors). Each road segment, ΔL_{Ri}, is considered as a potential fixed point source or emitter (a potential accident point placed in the centre of each road segment).

The expected pollutant concentration is calculated at each grid point or receptor (X_j, Y_k), with j = 1, … J; k = 1, ... , K, considering all the emitters. Assuming the linear composition of the emitter effects, every road segment contribution that affects each receptor must be added. Indeed, a suitable procedure for generating all possible stochastic variable values should be considered in this calculation. As a result, concentration histograms corresponding to each receptor (X_j, Y_k) can be achieved according to seasonal, annual, or other time horizons. Once these histograms are obtained, the scheduler has important data to compute the expected resource demands either for emergency planning or for risk assessment over the analyzed area.

Consequently, the concentration distribution, the maximum expected concentration, the most probable concentration value, the risk distribution, the expected individual or societal risk curves, among others, over each geographical area are easily obtained.

Usually, the breakage and release occurrence and characteristics (the most representative accident scenarios) are known by an event tree that covers all the possibilities.

In this way, the total risk is the addition of partial results corresponding to each branch of the adopted tree. So, the following formula is used.

$$R_{jk} = \sum_{m=1}^{M} EP_m \sum_{i=1}^{I} R_{mijk} \tag{1}$$

where M is the number of accident scenarios, I the number of road segments, and EP_m the scenario probability. For each scenario (m) and emitter (i), we have:

$$R_{mijk} = F_i \, \Omega_{mijk} \tag{2}$$

where F_i is the accident probability in each road segment (i) and Ω_{mijk} the accident consequence at each receptor (j, k) corresponding to the emitter (i) and scenario (m). The accident probability, F_i, can be calculated by multiplying the truck accident probability, p_i, the road segment length, ΔL_{Ri}, and the number of shipments per year, N_T.

$$F_i = p_i \, . \, \Delta L_{R_i} \, . \, N_T \tag{3}$$

The accident consequence Ω_{mijk} can be calculated as follows:

$$\Omega_{mijk} = \sigma_{jk} \Phi_{mijk} A_{jk} \tag{4}$$

where σ_{jk} is the population density in each square (j, k), A_{jk} is the area and Φ_{mijk} is a measure of the vulnerability of each receptor.

In order to estimate the number of affected people, usually the probit methodology is used. The probit scale is a useful tool for measuring the expected percentage of affected people (Casal Fábrega *et al.*, 1996).

$$Y_{mijk} = a + b \ln \left(C_{mijk}^{\ n} \, \Delta t \right) \tag{5}$$

where Y_{mijk} is the probit unit (which is related to the probability of affected people); n, a and b are material-dependent constants; C is the concentration in ppm at each grid point (j, k) due to the emitter (i) and the scenario (m); Δt is the exposure time in minutes.

Ω_{mijk} can be obtained as follows:

$$\Omega_{mijk} = \sigma_{jk} PY_{mijk} \mathrm{A}_{jk} \quad (6)$$

where PY_{mijk} is the percentage of affected population (deaths) at each receptor (j, k) due to the emitter (i) and scenario (m), and it is a function of Y_{mijk}.

It is important to note that the calculation of the vulnerability (Φ_{mijk}) strongly depends on the stochastic meteorological conditions. Instead of considering only the worst or the most probable condition, we introduce distributions for wind direction, wind velocity and atmospheric stability. Then, the Monte Carlo simulation is used to obtain the concentration distribution for each receptor (j, k). Consequently, the total risk R_{jk} involves the whole relevant information about the problem. In fact, the whole set of scenario possibilities is covered for the Ω_{mijk} calculations.

It was found that high computing time is spent for fine discretization (grids) and road partition. For example, the time spent to solve the model for a chlorine transportation accident in the Rosario city orbital motorway was 8 hours (Scenna and Santa Cruz, 2005). Therefore, computing time becomes an obstacle for building up a general prototype for risk assessment, even for fixed sources when fine grids of the impact area are necessary. On the other hand, in order to obtain a general tool, other models must be implemented (particulate dispersion, UVCE, fire modeling) using this strategy. So, it is necessary to optimize this method. To do so, a special algorithm is presented to deal with this associated computational problem. This algorithm reduces computational time from 8 hours to 5 minutes (case studied in Section IV)

The New Algorithm for Stochastic Simulation

To reduce computational time we define an affected zone considering only one emitter called *Stochastic Reference Emitter (SRE)*. Then we determine all the receptors affected by the *SRE* using a Monte Carlo simulation. The shape and size of this zone (and the associated concentration distribution in each point) can be supposed to be invariant, because all the variables and all the values they can take have been considered. If we store all the concentration histograms and all the data corresponding to the receptors affected by the *SRE* in a database, we can easily determine the histograms for any receptor by a simple translation algorithm. This procedure reduces considerably the computing time without loss of accuracy.

In general, each receptor is affected by several emitters, so the algorithm must take into account the contribution of all these emitters. The algorithm works as follow (Fig. 2):

Input Data:

- All emitter and receptor coordinates are stored in the database.
- The *SRE* coordinates, simulation data and results (concentration histograms, wind direction, temperature, wind velocity, atmospheric stability) for all the trials are stored in the database.

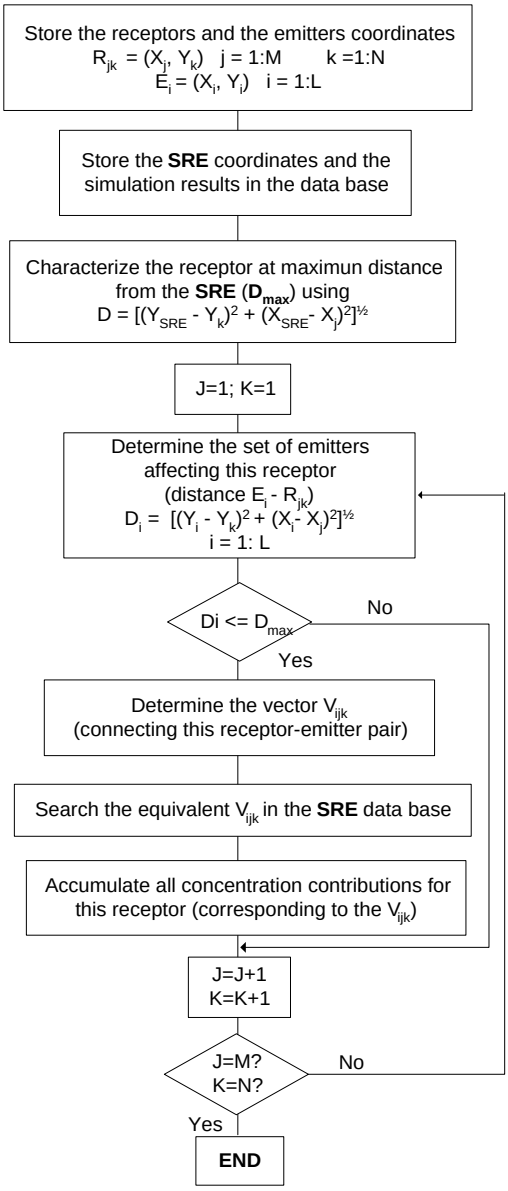


Figure 2. Simplified flow diagram of the translation algorithm

Calculations:

- Identify the receptor set in which the health criteria was reached or overcome. Characterize the receptor at maximum distance from the *SRE* in this set. This can be done by calculating the distances between the *SRE* and all the receptors (centers) according to Eq. (7).

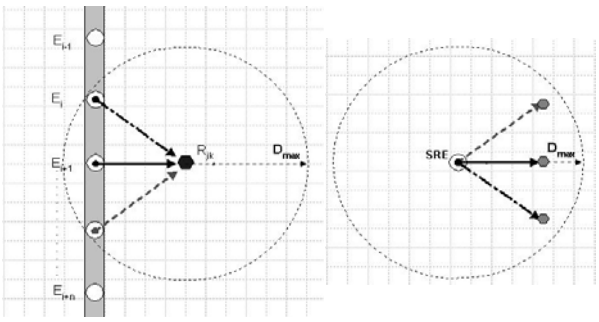
$$d_{ijk} = \sqrt{(Y_i - Y_k)^2 + (X_i - X_j)^2} \quad (7)$$

where (X_i,Y_i) and (X_j,Y_k) are the emitter and the receptor coordinates, respectively.

After the maximum distance (D_max) is calculated, the analysis is performed over a circle of D_max radius,

centered in the receptor under consideration. The road portion included in this circle (centered at the receptor) determines all the emitters affecting it (See Fig. 3 a,b).

- Select one receptor.
- Determine the set of emitters affecting this receptor.
- Find all the vectors (V_{ijk}) connecting each receptor-emitter pair (only those affecting this receptor) and calculate its magnitude and direction. Also store the emitter coordinates that meet that condition, thus characterizing all the emitters affecting each receptor (Fig. 3a).
- For the vector set satisfying the above condition, search the corresponding histograms in the *SRE* database according to Fig. 3b. Each one is found placing the vectors V_{ijk} at the *SRE* coordinates (origin) and determining the receptor coordinates.
- Accumulate all the concentration contributions for the receptor under analysis and store the final histogram.
- Repeat this procedure for all the receptors to be analyzed (area of interest).



a) b)

Figure 3. Graphical representation of the Translation Algorithm

III. RISK ANALYSIS FOR FIXED SOURCES

Risk calculation for fixed source releases can be solved as a particular case of the above described risk transport calculation model.

Again, total risk is the addition of all contributions due to the different scenarios, but now only one emitter is considered.

$$R_{jk} = \sum_{m=1}^{M} EP_m R_{mjk} \qquad (8)$$

where M is the number of possible scenarios, and EP_m the corresponding scenario probability.

Another important point is the calculation of safe distances. For safe distances definitions (Initial Isolation Distance and Protective Action Distance) see 2000 ERG (Brown *et al.*, 2000).

Once obtained all the receptors where the chosen critical health criterion is reached, distances between each receptor (j, k) and the emitter can be calculated (j = 1, … , M; k = 1, ... , N).

As previously pointed out, all data are stored in a database. It gives information about each vulnerable receptor, its geographic coordinates, concentrations obtained in each trial, meteorological variables, among others. So, each vulnerable receptor is individualized with a simply query to the database.

Then, the distance distributions are calculated using equation (7) (for fixed sources subindex "i" is not necessary).

To calculate protective action distances, the ERPG2 health criterion is used in the filtering step. The initial isolation distance is calculated in the same way, with the life-threatening health criterion defined as an ERPG3.

In both cases, to calculate the protective action and isolation distances the 90-percentile can be selected.

For multiple fixed sources or transport accidents, Eq. (7) can be used for each emitter and all the receptors affected by them, in order to obtain distance distributions and their 90-percentile.

IV. STUDY CASE

The risk associated with the chlorine transportation in the orbital motorway of Rosario city is analyzed applying the new strategy (using the *Stochastic Reference Emitter* and the *Translation Algorithm*), in order to show their capabilities. Representative scenarios involving chlorine are selected from a typical event tree reported in the literature (Federal Motor Carrier Safety Administration-Class 2-Div.2.3-Poisonous gases accidents; Rhyne, 1994).

An annual base is used to generate the input distributions for the dispersion model ($^{\#}$DEGADIS). It is important to note that in urban areas the plume profile can be significantly different because of the potential effect of buildings around the release location. Also, it is very difficult to estimate many parameters, which are, input data to the proposed rigorous model. Nevertheless, the results can be considered a good approximation for QRA. More rigorous models (Lagrangian models) can be used but they are very expensive from a computational point of view and completely unaffordable for this stochastic approach.

Table 1 shows gas properties and simulation parameters used for this example. For more details see Scenna and Santa Cruz (2005).

The number of receptors is selected according to the population density variability, the areas of interest (hospitals, schools, etc.) and the degree of accuracy desired for the output distributions. In this case we adopt J=37 and K=34 and the grid squares length is 200.

Once downwind concentrations for each receptor affected by the *SRE* are obtained, distributions are calculated taking ten concentration intervals. So, only a vector with few numbers is stored in the result database. Then, the *Translation Algorithm* subroutine is run in order to generate the histogram concentration for all

receptors considering the corresponding emitters along the entire road.

Finally, risk distribution in the area of interest is computed using risk definitions and the probit equation.

Fig. 4 shows the risk distribution along the studied road, applying the new strategy. The conclusion is that although there are no significant differences between the results presented in Scenna and Santa Cruz (2005), now the computation time has been greatly reduced (from 8 hrs. to 5 min.).

Table 1. Gas properties and simulation parameters

Property	Value
Gas	Cl_2
Molecular weight (gr)	70.91
Boiling Point (ºC)	-34.3
Density (Kg/m^3)	3.672
IDLH (mg/m3)	29.5
Emission flowrates (kg/sec)	0.1 , 1 and 3
Concentration height measurement (m)	1.6
Temperature (ºC)	20
Atmospheric pressure (atm)	1
Relative humidity (%)	60
Number of calculations per emitter (trials)	2000
Population density (inhabitants/km2)	3000
Number of shipments (vehicles/day)	20
Road segment length - ΔLR_j (m)	200
Truck accident probability (accidents/ vehicle-Km-yr^{-1})	2.125* 10^{-7}
Exposure time (minutes)	60

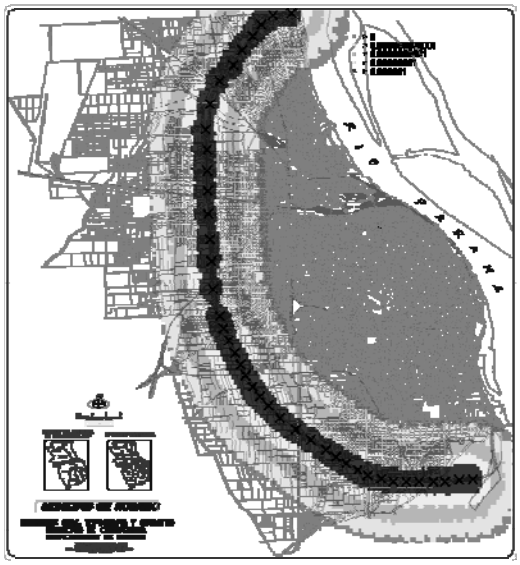


Figure 4. Risk distribution (with the SRE and Translation Algorithm strategy)

Distribution distances are presented, as mentioned in section III. First, the distance distributions for each flow rate are calculated. Then, their weighted average is obtained according to the probabilities given by the corresponding event tree. Finally, the 90-percentile is taken from the weighted distribution.

In this way, both the protective and the isolation distances are achieved (Fig. 5).

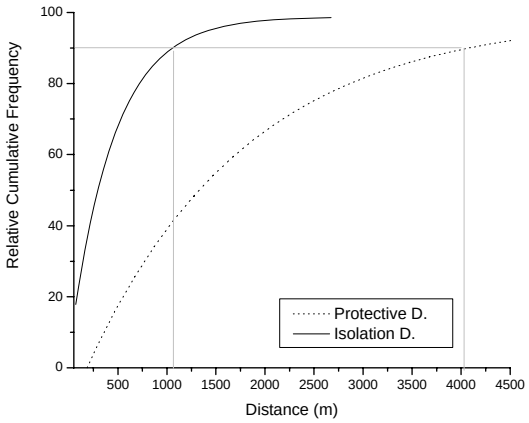


Figure 5. Protective and Isolation Distances for Chlorine transportation accidents

V. CONCLUSIONS

A risk assessment methodology which can consider the variability of meteorological parameters and different accident scenarios (an event tree) is described. The model can be used for static emission points (e.g. storage tanks, stacks, etc.) or for mobile sources, such as hazardous material transportation accidents. In this last case, the road is discretized in several segments.

In order to optimize computational time, simulation is carried out for the Stochastic Reference Emitter *(SRE)* and the output histograms are calculated considering all the trials. Every road segment is covered using the *Translation Algorithm*.

As previously said, the number of trials is proportional to the number of emitters and receptors. Consequently, computing time grows with the desired resolution (number of emitters and receptors). This problem is overcome by introducing the *SRE* and the *Translation Algorithm* which greatly reduce the computation effort and make building a software prototype for risk analysis using this stochastic approach possible.

It is evident that risk analysis for railway or maritime transport as well as for gas transport by pipelines can be solved in this way.

Although only gas diffusion scenario simulations have been shown in this work, Gaussian and particulate matter dispersion models will be added to the calculation module library in a future software prototype. Indeed, other models of interest for risk calculation (UVCE: Unconfined Vapor Explosions) can be modeled using the same strategy as that for gas diffusion. The theoretical background for the final software prototype implementation was presented in this paper.

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NOMENCLATURE

a,b,n	material-dependent constant in Probit equation
A_{jk}	grid square area
C_{mijk}	concentration in ppm at each grid point (j, k) due to the emitter (i) and the scenario (m)
d_{ijk}	distance between the emitter (i) and receptor (j,k)
EP_m	probability of scenario m
Fi	accident probability in each road segment (i)
I	number of road segments
M	number of accident scenarios
N_T	number of shipments per year
pi	truck accident probability
PY_{mijk}	percentage of affected people at each receptor (j,k) due to the emitter (i) and scenario (m)
R_{jk}	risk at the receptor (j,k)
R_{mijk}	risk at the receptor (j,k) due to the emitter (i) and scenario (m)
V_{ijk}	vector connecting the emitter (i) and receptor (j,k)
(X_i,Y_i)	emitter coordinates
(X_j,Y_k)	receptor coordinates
Y_{mijk}	probit number at the receptor (j,k) due to the emitter (i) and scenario (m)
Δt	exposure time in minutes
Φ_{mijk}	a measure of the vulnerability of each receptor
σ_{jk}	population density in each square (j, k)
Ω_{mijk}	accident consequence at each receptor (j, k) corresponding to the emitter (i) and scenario (m)
ΔL_{Ri}	road segments

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