Risk Assessment of Transportation of Dangerous Goods

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Abstract

Hazardous materials are defined to be the substances that can have harmful effects for human, environment and property. These risks exist due to the nature, the hazardous properties or the state of the above materials.

Industrial needs as well as several human activities depend on the daily transportation of dangerous goods. The percentage of road accidents in which hazardous materials are involved, increases every year. The consequences of the above accidents cannot be compared to the ones of simple collisions in terms of seriousness. Risks involved in transportation because of freight's hazardous properties (toxicity, flammability, corrosiveness etc) are probable to give an extended radius to the affected area during an accident.

A methodology for the risk assessment during road transportation of hazardous materials has been developed. Two critical factors have been taken into consideration. The first one is the probability of an outcome (release of toxic materials, different types of fires and explosions of flammable materials) during accident occurrence, which has been estimated through consequence analysis. The second is the consequences of the outcome (thermal radiation, overpressure, toxic load) and has been calculated through modeling.

1. Introduction

The transportation of dangerous goods involves risks and has a potential to harm not only the truck's driver, but also the population being present at a certain distance along the pathway of the truck. The above mentioned population consists of the off-road residents living along the pathway and the on-road drivers and passengers of the other vehicles moving near the truck carrying the dangerous goods. The consequences of a road accident involving dangerous goods can be different types of fires (pool fire, flash fire, jet

fire), explosions (vapor cloud explosion VCE, boiling liquid expanding vapor explosion BLEVE) and release and dispersion of toxic substances (toxic gas cloud).

The most important hazards during the transportation of dangerous goods are due to possible loss of containment. Release of flammable gases or vapors can end up to flash fire and VCE, while flammable liquids usually result in pool fires. Jet flames is another type of fire that can be provoked by immediate ignition of a flammable gas released during an accident. Also, the containment might undertake a BLEVE or other types of explosions. Generally, flammable liquids result in fires rather than explosions. Explosion hazards exist mostly in cases where the transported substances are quite unstable. If the dangerous good is toxic, its release would form a toxic gas cloud. Toxic and corrosive substances can spread during a release just like liquids do. Accident history has shown that the risks related to the transportation of dangerous goods can be of the same magnitude as those arising from fixed installations. Thus, the management of risks involved in the transportation of dangerous goods has become a necessary process [1].

The risk management process is a set of procedures that can be used in transportation of dangerous goods for mitigating the risks involved. The first step of the risk management process is the identification of all potential risks. The next step, which is the objective of the present paper, is the assessment of the identified risks, so as to supply decision makers with powerful tools for the third step of the process. At the third step decision makers should take into account the outcome of the risk assessment before selecting suitable and effective safety control measures leading to necessary risk reduction. Finally, the performance measurement of the proposed and implemented safety control measures, completes the circle of the risk assessment process by providing information as a feedback for the first step.

In general, a risk exists when three conditions are satisfied. First, a source of risk must be present, which can be a system, process or activity that can release a risk agent. Second, there must be an exposure process through which people may be exposed to the released risk agent. Third, a causal process must exist by which exposure to risk agent results in undesired consequences. The final output would be estimates of the possible undesired consequences to human health, including a characterization of the probabilities and uncertainties associated with these estimates. Based on the above, a complete risk

assessment consists of four interrelated but distinct steps: release assessment, exposure assessment, consequence assessment and risk estimation.
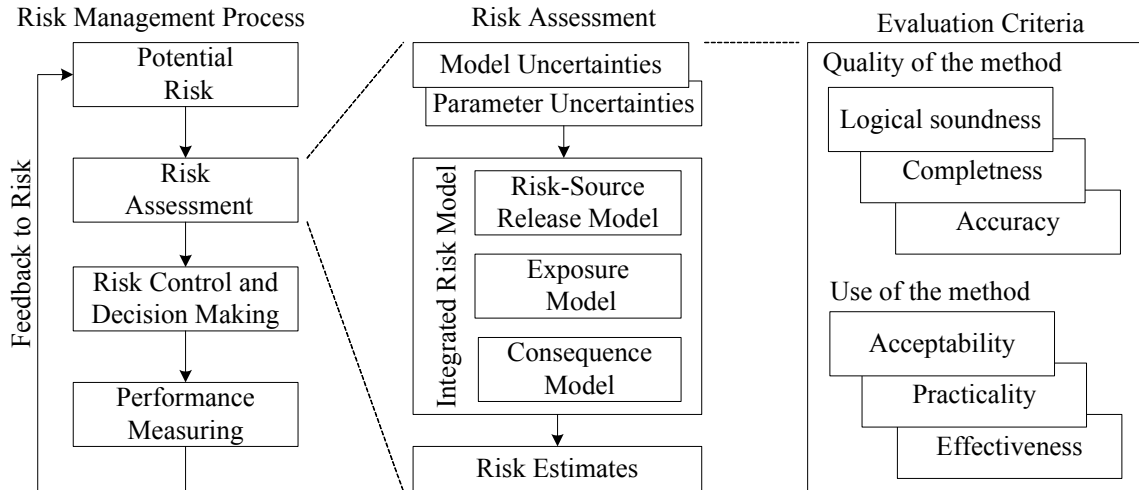

Figure 1: Evaluation criteria of risk assessment as a part of risk management process.

Release assessment consists of describing and quantifying the potential of a risk source. It includes a description of the types, amounts, timing and probabilities of the released hazardous substance. Exposure assessment consists of describing the conditions and characteristics of the population being exposed to risk agents released by a risk source. It includes a description of the frequency and duration of the exposure, the number, nature and characteristics of people that might be exposed and any other conditions that might affect consequences. Consequence assessment consists of describing and quantifying the relationship between exposures to risk agents and consequences on human health. It includes a specification of human fatalities or injuries. Risk estimation consists of integrating the results from release assessment, exposure assessment and consequence assessment to produce quantitative measures of health risks. It includes an estimated number of people experiencing health impacts of various seriousness, and probability distributions for expressing the uncertainties in these estimates.

The quality of the methodologies developed for risk assessment depends on three basic criteria: logical soundness, completeness and accuracy. Logical soundness ensures that every risk assessment is justified by theory and is based on well-developed mathematical disciplines such as probability theory and statistical analysis. Completeness ensures the

examination of all relevant aspects of risk and the absence of important omissions. Accuracy ensures that estimates of risk consequences are sufficiently precise and free from possible biases. Apart from the above criteria that evaluate the quality of risk assessment, acceptability, practicality and effectiveness should also be taken into account while developing a risk assessment methodology in order to evaluate the use of the method. Acceptability ensures that the risk assessment methodology fulfills the requirements of the end users. Practicality ensures that end users can implement the methodology in a real case situation with limited data and information. Effectiveness ensures that final estimates and measures of the level of risk are useful to decision makers in the risk assessment process.

2. Methodology

The necessary data for conducting a risk assessment for the transportation of dangerous goods are derived from the travelling risk source, the transportation network and the impact area (fig. 2). Risk assessment is structured as a process resulting from the interaction between the vehicle or travelling risk source, the transportation network and the impact area.

The vehicle or travelling risk source is characterized by the probability (P) of an outcome (i), such as fire or explosion, which, in case of an accident, depends on the type of dangerous good (dg) being carried [3].

The transportation network can be considered and viewed as a graph $G = (M, A)$ formed by the node set N_M and arc set N_A and a certain amount of shipments of some dangerous goods (dg) that are made yearly from node O (origin) to node D (destination). Also, the transportation route can be viewed as a linear risk source, since a release can occur at any point. This means that each point of the route can be considered as a point risk source. All arcs (A) can be divided into a number of links (N_l), each link (l) having the same properties across its length.

The impact area is characterized by population distribution and meteorological conditions. Population distribution can be made with accuracy by dividing the impact area into: (i) zones of polygonal shape, where people may be considered uniformly

distributed with a density depending on the area being an urban, a suburban or a rural one, (ii) roads, where people are linearly distributed, (3) centers of aggregated population (CAP) e.g. schools, hospitals and commercial sites, where people can be considered as clustered [4]. Also, population distribution takes into account that people can be indoors at the occurrence of a release, sheltered from the accident consequences. Meteorological conditions are divided into N_k pairs of atmospheric stability class – wind speed. Also, the wind probability density distribution $p_{wind}(j,k,\theta)$ is the wind rise in the impact area, for each meteorological condition k and seasonal situation j. The angle θ is used to mark a generic wind direction [5].
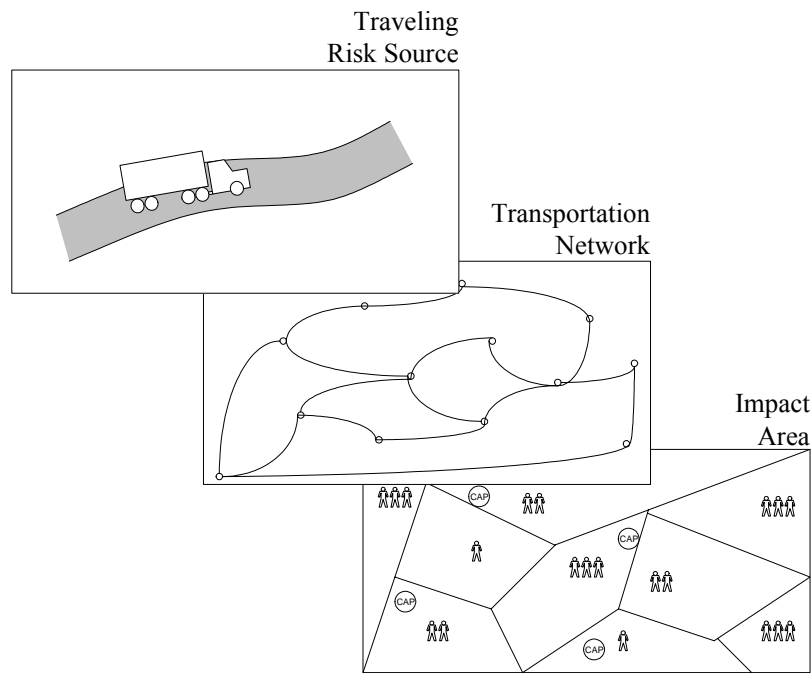

Figure 2: Interaction between data sources for transportation of dangerous goods risk assessment.

Risk Source Release Model

Release assessment involves quantifying the extent to which a risk source releases risk agents into the human environment. In transportation of dangerous goods the frequency of an outcome – fire, explosion, toxic gas cloud – during an accident is the above mentioned measurement. The frequency ($f_{i,j,dg}$) of an outcome (i) from an incident of

dangerous good (dg) transportation at seasonal situation (j) can be calculated by the following equation.

$$f_{i,j,dg} = f_{inc,j,dg} \cdot P_{i,dg} \qquad (1)$$

where $P_{i,dg}$ is the probability of an outcome (i) from an incident of transportation of a dangerous good (dg).

The frequency ($f_{inc,j,dg}$) of an incident (inc) of transportation of a dangerous good (dg) at seasonal situation (j) depends on the length (L_l) of the link, the number ($V_{l,j}$) of vehicles passing through link l, the fraction ($x_{l,j,dg}$) of vehicles carrying the dangerous good (dg) and the expected frequency ($f_{exp,j,l}$) of an incident on link l and at seasonal situation j [6].

$$f_{inc,j,dg} = f_{exp,j,l} \cdot L_l \cdot V_{l,j} \cdot x_{l,j,dg} \qquad (2)$$

The probability ($P_{i,dg}$) of an outcome (i) from the transportation of a dangerous good (dg) can be calculated through event tree analysis. For incidents involving LPG the event tree analysis [7] is presented in figure 3.
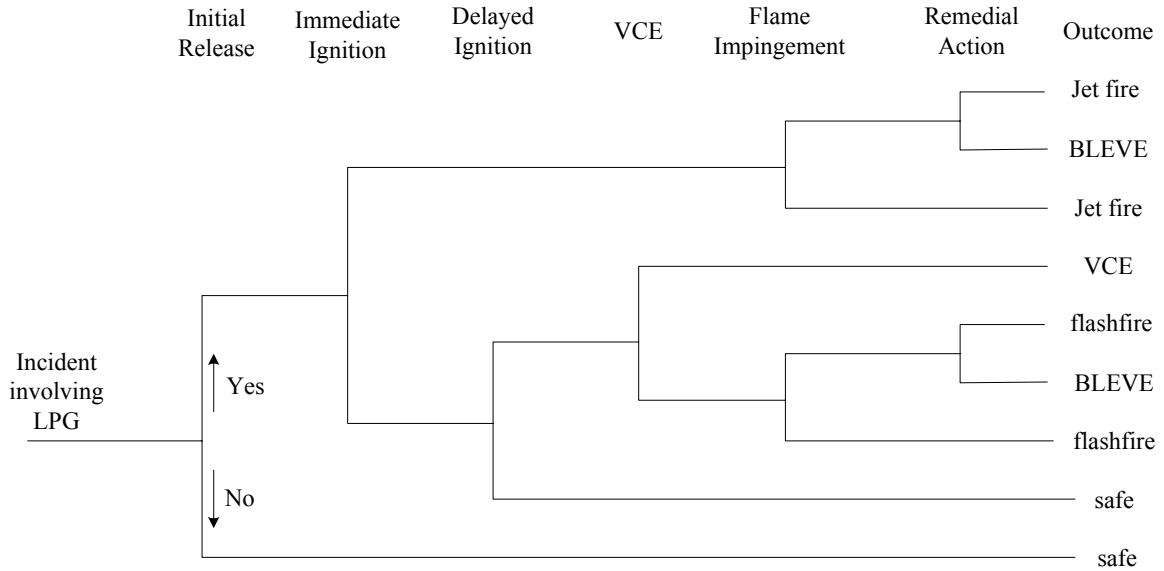

Figure 3: Event tree analysis for continuous LPG releases.

From the event tree analysis the probabilities of outcomes – jet fire, BLEVE, VCE and flashfire – during the transportation of LPG can be calculated by the following equations.

$$P_{jetfire,LPG} = P_r \cdot P_{ii} \cdot P_{fi} \cdot P_{ra} + P_r \cdot P_{ii} \cdot (1 - P_{fi})$$

$$P_{BLEVE,LPG} = P_r \cdot P_{ii} \cdot P_{fi} \cdot (1 - P_{ra}) + P_r \cdot (1 - P_{ii}) \cdot P_{di} \cdot (1 - P_v) \cdot P_{fi} \cdot (1 - P_{ra})$$

$$P_{VCE,LPG} = P_r \cdot (1 - P_{ii}) \cdot P_{di} P_v$$

$$P_{flashfire,LPG} = P_r \cdot (1 - P_{ii}) \cdot P_{di} \cdot (1 - P_v) \cdot P_{fi} \cdot (1 - P_{ra}) + P_{fi} \cdot (1 - P_{ii}) \cdot P_{di} \cdot (1 - P_v) \cdot (1 - P_{fi})$$

where P_r, P_{ii}, P_{di}, P_{VCE}, P_{fi}, P_{ra} are the probabilities of release, immediate ignition, delayed ignition, VCE, flame impingement and remedial action, respectively.

Exposure Model

Exposure assessment is the process of measuring the dose of risk agents received by population. Thermal radiation, overpressure and toxic load have been modeled for the calculation of the total dose which an individual receives at a certain distance.

For the estimation of the thermal radiation intensity (I) versus distance (x), the solid flame model is used [8],[9]. This model treats the flame as a solid shape and calculates the radiation which reaches a target at a certain distance to the flame, using a radiation heat transfer calculation incorporating a view factor (F_{view}), also called shape factor.

$$I = F_{view} \cdot E \cdot \tau \qquad (3)$$

The surface emissive power (E) depends on the pressure of the containment before vessel failure (P_{vo}), while atmospheric transmissivity (τ) decreases with the distance (x).

$$E = 235 \cdot P_{vo}^{0,39} \qquad (4)$$

$$\tau = 1 - 0,056 \cdot \ln x \qquad (5)$$

The thermal dose (D_{th}) is calculated from the following equation:

$$D_{th} = I^{4/3} \cdot t \qquad (6)$$

where t is the exposure time.

For the estimation of overpressure (P_{ov}), the TNT equivalence method is used, which calculates the overpressure at different distances from a vapor cloud explosion. The first stage is to calculate the portion of the release that will volatize and take part in the explosion. The flash fraction (F_{fr}) is given by the following equation:

$$F_{fr} = 1 - \exp\left(\frac{-C_p \cdot DT}{L}\right) \qquad (7)$$

where C_p is the specific heat, DT is the difference between ambient temperature T_a and boiling temperature T_b at standard pressure, and L is the latent heat.

The TNT equivalent (E_{TNT}) is calculated by the following equation:

$$E_{TNT} = M \cdot E_R \cdot 2 \cdot F_{fr} \cdot \alpha \qquad (8)$$

where M is the mass released.

Some values of the energy ratio E_R and the efficiency factor α are given in table 1 for some explosive substances [10].

Table 1.

Material	Energy ration	Efficiency factor
Hydrocarbons	10	0.04
Ethylene oxide	6	0.10
Vinyl chloride monomer	4.2	0.04
Acetylene oxide	6.9	0.06

Then the scaled distance (R) is calculated by:

$$R = \frac{x}{E_{TNT}^{1/3}} \qquad (9)$$
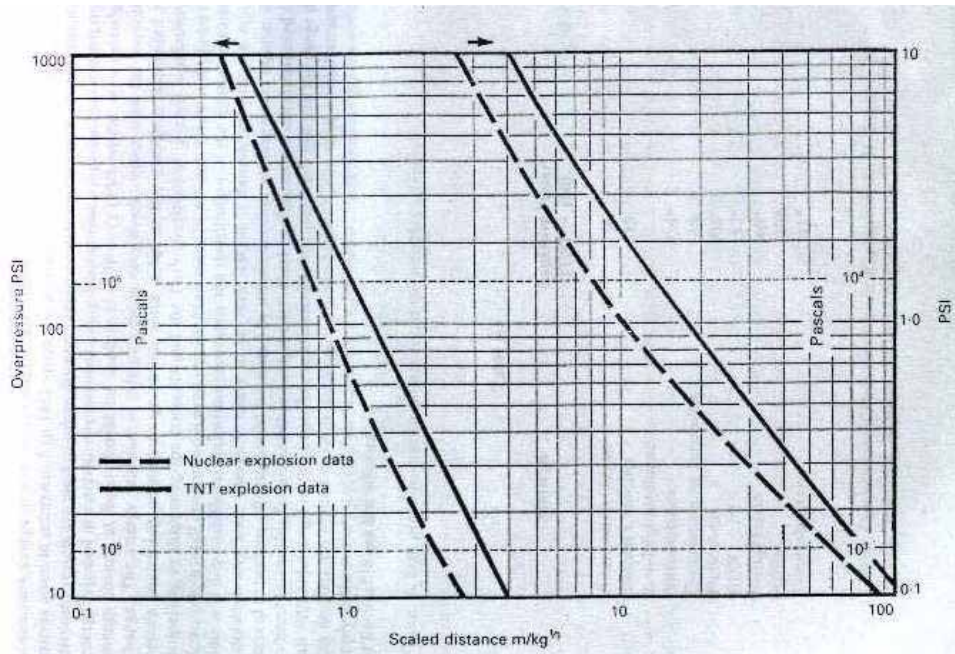
where x is the distance from the point of release

Figure 4: Scaled range versus overpressure.

The overpressure (P_{ov}) is obtained from figure 4 [10], and the impulse D_{ov} (dose) from equation (10):

$$D_{ov} = P_{ov} \cdot t_{ov} \qquad (10)$$

where t_{ov} is the positive phase duration.

For the estimation of toxic load, the Gaussian plume model is used for an instantaneous release where the concentration (C) at a position x,y,z and after a time t_r from the time of release can be calculated by the following equation [8]:

$$C(x,y,z,t) = \frac{Q}{(2\cdot\pi)^{3/2}\cdot\sigma_x\cdot\sigma_y\cdot\sigma_z}\cdot\exp\left(-\frac{(x-u_a\cdot t_r)^2}{2\cdot\sigma_x^2}\right)\cdot\exp\left(-\frac{y^2}{2\cdot\sigma_y^2}\right)\cdot\exp\left(-\frac{(h-z)^2}{2\cdot\sigma_z^2}\right) \quad (11)$$

where Q is the total mass released, h is the height of the centroid of the cloud from the ground, u_α is the air velocity, z_o is the roughness coefficient, and a, b, c, d, e are constants that depend on meteorological conditions.

The parameters σ_x, σ_y and σ_z are calculated by the following equations:

$$\sigma_y = a\cdot\left[u_a\cdot t + \left(\frac{L_y}{1.15\cdot a}\right)^{1/b}\right]^b \qquad (12)$$

$$\sigma_z = (10\cdot z_0)^{0.53\cdot x^{-0.22}}\cdot c\cdot\left[u_a\cdot t + \left(\frac{L_z}{1.15\cdot c\cdot 1.98^{\log(10\cdot z_0)}}\right)^{\frac{1}{d-0.059\cdot\log(10\cdot z_0)}}\right]^d \qquad (13)$$

$$\sigma_x = e\cdot x\cdot\left(u_a\cdot t_r + \frac{L_x}{1.15\cdot e}\right) \qquad (14)$$

where $2L_x$, $2L_y$, $2L_z$ are the length, width and height of the initial cloud, respectively.
For neutral meteorological conditions, the experimental values for constants a, b, c, d and e are given in table 2.

Table 2

α	b	c	d	e
0.064	0.905	0.20	0.76	0.13

Some values for the roughness coefficient (z_o) are given in table 3.

Table 3

Area	z_o
Plane land	0.03
Rural area	0.30
Suburban area	1.0
Urban area	3.0

The toxic load (D_{tl}) (dose) received by an individual is given by the following equation.

$$D_{tl} = C^n \cdot t \qquad (15)$$

Some values of constant n for various toxic substances are given in table 4 [11].

Table 4

Substances	Toxic load
Acrylonitrile, Sulphuric acid mist	$C \cdot t$
Ammonia, Chlorine, Hydrogen Fluoride	$C^2 \cdot t$
Hydrogen sulphide	$C^4 \cdot t$

Consequence Model

Consequence assessment is the process of describing and quantifying the relationship between exposures to a risk agent and the adverse health consequences that result from such exposures. The probit equation is used for the calculation of fatalities from exposures to certain amounts of doses from thermal radiation, overpressure and toxic load [11].

$$\mathrm{Pr} = -a + b \cdot \ln(dose) \qquad (16)$$

Values for constants a and b for each consequence are given in table 5 [11].

Table 5

Consequence	Dose	a	B
Thermal radiation	$I^{4/3} \cdot t$	14.9	2.56
Overpressure (impulse)	$P \cdot t$	46.1	4.82
Toxic load	$C^n \cdot t$	9.57	0.92

Risk Estimates

Risk estimation, also referred to as risk characterization, is the final step in risk assessment. Its goal is to produce measures for the health and safety risks that are being assessed. The measures are usually referred to as indices of risk. Typically, risk indices are simple numbers selected to characterize some important aspect of the risk. For the estimation of risks involved during transportation of dangerous goods, the individual and societal risk indices are used.

Individual Risk is the frequency at which an individual may be expected to sustain a given level of harm from the realization of specified hazards [12]. It is used to estimate the risk of a hypothetical "average" individual as a function of distance from the hazard. The individual risk The Individual Risk from travelling risk source is calculated by the following equation.

$$IR = \sum_{l=1}^{N_l} \sum_{dg=1}^{N_{dg}} \sum_{i=1}^{N_i} \sum_{j=1}^{N_j} f_{i,j,dg} \cdot \left[\sum_{k=1}^{N_k} \int_0^{2\pi} p_{wind}(j,k,\theta) \cdot \Pr(i,k,\theta) \cdot d\theta \right] \qquad (17)$$

Societal Risk is the relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards [12]. Societal Risk is usually expressed in the form of cumulative F-N curves, which are plots of the cumulative frequency (F(n)) of N or more people receiving the specified level of harm per year, against the number of people (N) receiving the specified level of harm. F-N curves are usually plotted on a log-log scale. In the calculation of societal risk, it is usual for the specified level of harm to be a fatality. Unlike in the calculation of individual risk, the number of people exposed to the risk is taken into account in the calculation of societal risk. Once both the frequency, f_i, and the number of fatalities, n_i, has been calculated for each event, it is possible to estimate the societal risk. To construct the F-N curve, the cumulative frequency F(n) is calculated from:

$$F(n) = \sum f_i \qquad (18)$$

where fi is the frequency of each event, and the sum is over all f_i for which n_i is greater than or equal to N. this is then plotted against N, the number of fatalities.

3. Conclusion

A numerical procedure for the calculation of individual and societal risk arising from the road transport of dangerous goods has been presented. It has been developed to support decision makers in safety management and safety control activities. Transport of toxic and flammable substances has been considered. In particular, the equation proposed for computation of individual risk takes into account both prevailing wind and prevailing seasonal situation. As far as societal risk is concerned, a modeling of the population distribution has been described, which takes into account population being indoors as well as differences between off-road and on-road population.

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