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Risk analysis for road and rail transport of hazardous materials: a simplified approach

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Abstract

A simplified approach to transportation risk analysis for road and rail transport of dangerous goods is proposed, which is based on the use of a product databank, containing the impact areas for a number of pre-selected accidental scenarios, and on the selection of a few typical average values of the involved parameters, relevant to the type of transport activity and to the route. Such an approach enables also a non-specialist to very rapidly perform a transportation risk analysis, obtaining both individual and societal risk measures for the study case(s): the results may be used to support a decision making process, and/or as a basis for a more in deep analysis.

Keywords: Transportation risk analysis; Road transport; Rail transport; Hazardous materials

1. Introduction

A number of accidents involving a large number of fatalities, and some surveys carried out in the UK (HSC, 1991) and in Italy (Egidi, Foraboschi, Spadoni, & Amendola, 1995), clearly show that the risk associated to the transport of dangerous goods may be significant. The hazard mainly derives from the population at risk in the impact area (the routes may cross or pass by towns and villages) rather than from the scale of the accident, which is generally limited by the size of the containers.

From a theoretical point of view, transportation risk analysis (TRA) is simply derived from quantitative risk analysis (QRA) methodology, developed for the chemical process industry (CCPS, 2000), but the practical application of this well-known procedure to a moving risk source gives rise to a number of problems. In fact, most of the parameters involved in estimating the frequency and the consequences of the accidental scenarios, such as accident rate and population, generally change along the itinerary: accordingly, their values should be determined at each point of the route, repeating each time risk calculations. Such an approach is obviously impracticable, and the problem is managed by dividing the route into homogeneous portions where all the involved parameters can be considered constant (CCPS, 1995): as the length of the portions decreases both the accuracy and the complexity of the analysis increase.

Depending on the scope of the analysis, approximated as well as detailed approaches to TRA can be used. The former should be kept as simple as possible, in principle allowing also non-specialists to carry out the analysis and to immediately use its results for a basic evaluation of the risk level of the transport activity under exam. The latter should be kept as accurate as possible, enabling a specialist to properly assess the risk, to investigate about the presence of highly hazardous spots and to suggest effective mitigation measures.

The present work suggests a simplified and easy to use approach to rapidly perform a TRA for road and rail transport of dangerous goods.

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2. Simplified approach to TRA

A typical procedure for undertaking a TRA includes the following steps: (i) identifying a number of possible release scenarios; (ii) assessing the frequency of occurrence of each release scenario; (iii) assessing the probability that each release scenario will evolve into the possible outcome cases (jet-fire, pool fire, toxic cloud, etc.); (iv) determining the impact area relevant to each possible outcome case, calculated for a proper set of weather conditions; (v) estimating the expected number of fatalities for the population in the impact area.

In principle, these steps have to be repeated every time that any of the parameters involved in the above calculations changes along the itinerary. A first reasonable simplifying assumption concerns some of these factors, which may be regarded as route-independent. They are the release scenarios, the probability of a release scenario to occur following an accident and the probability of an outcome case to occur following a release scenario. In fact, two or three release scenarios, ranging from a small puncture to the catastrophic collapse of the container, may allow to cover most actual situations where a loss of containment occurs. The occurrence of a specific release scenario mainly depends on the initiating accident (collision, leakage from a valve, etc.) and on the features of the container (thickness, material, accessories, etc.). Given a release, the occurrence of one of the possible outcome cases will primarily depend on the amount of the spill and on the characteristics of the spilled product (physical state, pressure, flammability, etc.). This route-independent information can be derived from statistical analysis of appropriate sets of historical data.

Other parameters, such as the accident rate, the population and, to some extent, the weather conditions, which actually depend also on the time scheduling of the trips (season, and time of the day), can be regarded as route-dependent factors. Some reasonable simplifying assumptions are possible also in this case. The accident rate is usually given as a function of the type of road (highway, local, etc.), which can be easily identified for a given route; similarly, typical values of population densities can be associated to a few different types of built-up areas ranging from urban to rural ones, which can be still rather easily identified on a map.

However, the most critical and time consuming step of a TRA is step (iv), i.e. the estimate of the impact area relevant to each possible outcome case, calculated for a proper set of weather conditions. This step, called "consequence analysis", generally involves the use of some computational code for estimating the thermal radiation, overpressure or concentration fields deriving from the outcome case under exam. Consequence analysis is a skilled specialist's task, requiring adequate computing support and time. In fact, one should bear in mind that, given a dangerous product, a container geometry and assigned transport conditions, the number of mathematical simulations will be $R \times O \times W$ where R is the number of selected release scenarios, O the number of possible outcome cases for each release, and W the number of weather conditions. In fact, meteorology affects the dispersion of the product, the most important parameters being the atmospheric stability class, the wind velocity and the temperature, which generally vary at any location during the day and with the season. To reduce complexity and time required to perform a TRA, the consequence analysis step should be separated from the others; this can be done by preliminarily performing the former for a number of products, under some typical weather conditions, estimating the impact areas where lethality is expected, and incorporating the results of such analysis in a database.

The resulting simplified approach can be summarised as follows. A limited number of release scenarios and of typical weather conditions are preliminarily defined. The probabilities of occurrence of each release scenario and of its evolution into the possible outcome cases are derived for the product, or for classes of similar products. Consequence analysis is performed to estimate the impact areas for each outcome case and weather condition: the obtained results are incorporated in a product data bank, which also includes the information about the probabilities of occurrence release scenarios and relevant outcome cases. The route is examined on a map, identifying the type of roads and built-up areas included: its total length is then divided into a proper number of segments, characterised by the same set of type of road and built-up area. Finally, risk calculations are performed to determine the risk, based on the number of trips carried out for each weather condition.

3. Route-independent information

In most cases, release scenarios are largely independent of transported product and of selected transportation mode: two to three release scenarios, ranging from a small leakage to the instantaneous discharge of all the transported product, can be assumed to cover all practical situations (CCPS, 1995). In the present study, taking into account that spills below a certain size (typically some ten kilograms) usually give rise to no or negligible consequences, two release scenarios (medium and severe) were assumed as a 30 min release from a 15 mm circular hole, and a release from a 220 mm hole, capable of emptying completely the container in a few minutes.

Information concerning the probability of a release size and of the outcome cases originated from such releases, for each transportation mode, can be derived from risk analysis (for example, applying fault tree analysis techniques) or from accident databases: in both cases, the available information is rather and affected by uncertainties.

Literature information (CCPS, 1995; Cozzani, Bonvicini, Vanni, Spadoni, & Zanelli, 2000) suggests the probability of the release size to primarily depend on the characteristics of the transport container (pressurised or not) and on the transport modality (road, rail, intermodal). The corresponding figures can be derived from the same sources, or from statistical analysis of accident databases.

Moving to the probabilities of the outcome cases following a release, even less information is available, especially for specific products. In fact, the number of transportation accidents occurring for a single product is usually very limited (with the exception of some very common materials, such as gasoline or LPG), and may not allow to draw consistent data. In these cases, grouping similar products may be appropriate to enlarge the database and derive more reliable data from existing records (for example, MHIDAS databases, OSH-ROM, 2001).

Associating the corresponding impact area to each outcome case requires to carry out the consequence analysis to estimate the thermal radiation, overpressure or concentration fields to be compared with suitable lethality thresholds. The procedure involves the calculation of the hazardous material dispersion into the environment, which depends on the meteorology (Pasquill stability class, temperature, wind velocity). The computational work can be substantially reduced if reference is made to some predefined sets of weather conditions: taking into account the monthly averages of temperature and wind velocities values in Italy (ISTAT, 1994), six meteorological sets were selected, deriving from the combination of three temperatures (5, 14 and 26 °C) and two wind velocities (3 and 6 m/s). Pasquill stability class was assumed to be D (neutral): this stability class has a probability of occurrence of more than 50% (Murphy & Zimmermann, 1998) and, in most cases, represents a reasonable conservative assumption. In fact, the stability classes giving rise to the worst consequences (stable E and very stable F classes) are more likely to occur at night time, when most people is relatively protected at home.

The hazardous materials transportation database includes, for each listed product, all the above data, which can be easily recalled and used in TRA calculations: this database, called TrHazDat, at the moment covers road and rail transportation of 29 dangerous products, selected among those more frequently transported in Italy.

4. Route-dependent information

This information includes factors such as the accident rate, the meteorological conditions and the population at risk.

The values of road and rail accident rates were derived from historical records, reported by the Italian Automobile Club (ACI, 1997) and obtained from the Italian Railways (FS, 1997), respectively. Road data consist of the number of accidents occurred in 1 year per 100 km of route, classified based on the road type, of the total extension of each road class, and of the number of accidents per 10 000 circulating vehicles. Based on this information, and applying a safety factor to account for the uncertainties, the accident rates listed in Table 1 were obtained. Due to the lack of more detailed information, a single average value, also listed in Table 1, is assumed for the whole railway network.

The local weather conditions along the route during the transportation are needed to properly select the meteorological set among those assumed to calculate the consequences of a transportation accident. The weather conditions can be estimated based on the meteorological data recorded at the closest meteorological station, taking into account also the influence of the time scheduling of the trips: this would allow to select up to three different sets of weather conditions from the reference ones, resulting from the combination of the three reference temperatures (5, 14 and 26 °C) with the appropriate value of wind velocity (3 or 6 m/s).

The population potentially falling in the impact area of a transportation accident includes on-route and off-route people, i.e. resident population, the former being usually less numerous than the latter. Most people lives in towns and villages, where the population density may be very high, and it can be assumed that the population density depends on the type of built-up area. Four different areas were identified, ranging from urban to very remote ones, and a proper population density value was assigned to each area, based on the size of the built-up area and the census records

Table 1
Average accident rates for road and rail transport in Italy

Road transport	Accident rate [No./(vehicle·km)]
Highway: two lines per each direction—no crossings	8.1×10^{-7}
State road: one wide line per direction—few crossing	1.6×10^{-6}
Provincial road: one line per direction—many crossings	1.0×10^{-7}
Urban street: inside built-up areas of towns and villages	1.2×10^{-6}
Rail transport	
Railway: any type	3.5×10^{-8}

Table 2
Average population densities for different types of locations in Italy

Class	Population density (No./km^2)
Remote: single houses—no built-up area	10
Rural: scattered houses—very small built up-area	200
Suburban: many houses—not very crowded built-up area	1500
Urban: many houses—very crowded built-up area	10 000

(ISTAT, 1992). The average population density values for the four types of differently populated zones are listed in Table 2.

The segmentation of the route is then performed, based on the accident rate and population data. This task is very simple for rail transport where the accident rate is assumed to be constant: looking at the railway layout on a map, the total length associated to each type of built-up areas is identified, and the route may be subdivided into a maximum of four segments.

The segmentation is slightly more complicated for road transport, where it is first necessary to identify to which road classes the various portions of the route belong, determining their length and the associated types of built-up areas. However, this task usually takes no more than some ten minutes, and allows to finally calculate the total extension of combination of road type and built-up area. Adopting four road classes and four population classes, as in the present case, the road route may be subdivided into a maximum of 16 segments; however, in most practical cases, the number is much lower (generally urban streets are not associated to remote or rural areas, highways do not cross cities or towns, etc.).

5. Application

A study case will be considered which consists in the road transport of 10 000 t/year of ethylene oxide from an industrial installation located near Priolo to the ferry terminal of Messina, in Sicily. Ethylene oxide is highly flammable, can explode, due to a decomposition reaction, even in the absence of oxygen, and is also toxic; it is transported in 35 m^3 tankers operated under pressure of nitrogen at about 1 MPa.

The route is shown in Fig. 1, and the details are reported in Table 3; it mainly travels on state roads and highways running through rural zones or close to towns, but crosses the town of Messina to reach the ferry terminal. The segmentation of the route was performed based on the information as read on the map,

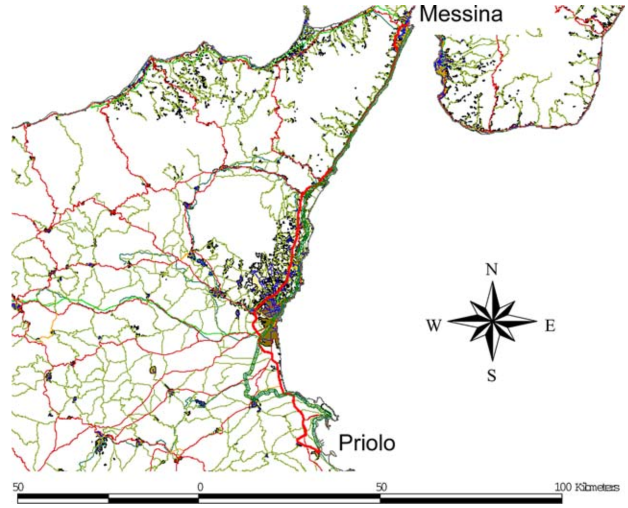

Fig. 1. Road and rail routes of the study case.

summarised in Table 3, and gave rise to the eight segments listed in Table 4.

Ethylene oxide transportation takes place all the year round, requiring 450 trips/year: due to the warm weather in Sicily, the temperature will be assumed as 14 °C for 8 months and 26 °C for the remaining 4 months, with high wind velocity (6 m/s).

Based on the above assumptions, the *F–N* curve relevant to the societal risk shown in Fig. 2 was calcu-

Table 3
Details of the route

Route	Length (km)	Road class	Population class	Length (km)
SP 95–96-114	12	Provincial road	Rural	12
SS 114	59	State road	Remote	43
			Rural	4
			Suburban	5
A18	76	Highway	Remote	56
			Rural	12
			Suburban	8
A20	9	Highway	Rural	4
			Suburban	5
Inside Messina	3	Urban	Urban	3

Table 4
Segmentation of the road route

Segment	Road class	Population class	Length (km)
1	Highway	Remote	56
2	Highway	Rural	16
3	Highway	Suburban	13
4	State road	Remote	43
5	State road	Rural	4
6	State road	Suburban	5
7	Provincial road	Rural	12
8	Urban	Urban	3

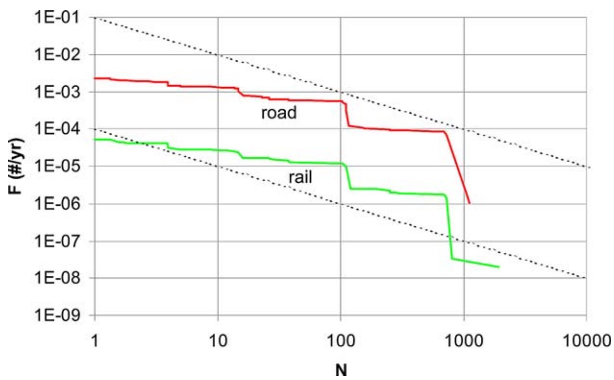

Fig. 2. Societal risk curves for the study case.

lated, which also shows, as dotted lines, the limit curves of the ALARP zone, according to HSC (1991). It can be observed that the *F–N* curve associated to the study case falls well within this zone, indicating that the risk is not too high, still being significant. This information may suggest that no further investigation should be devoted to this case. However, one may be interested in checking whether some risk reduction can be achieved by substituting road with rail transport. Assuming 70 m^3 rail containers, the number of trips reduces to 277 per year. The route segmentation is listed in Table 5, and the resulting *F–N* curve is also shown in Fig. 2. It can be observed that it lies about one order of magnitude below that of road transport,

Table 5
Segmentation of the rail route

Segment	Population class	Length (km)
1	Remote	106
2	Rural	24
3	Suburban	28
4	Urban	5

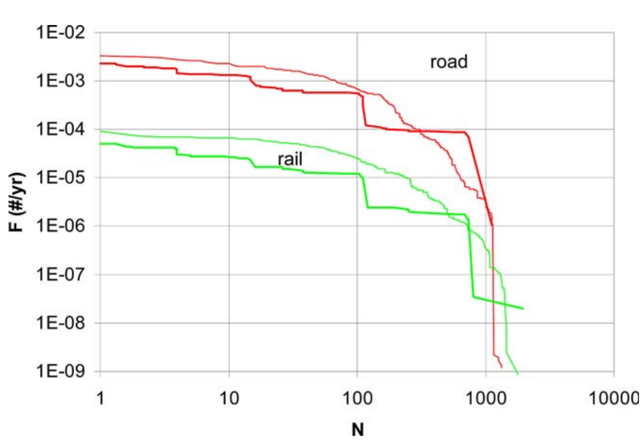

Fig. 3. Comparison of the *F–N* curves obtained for the study case using the simplified and rigorous approaches.

indicating that a considerable risk reduction is possible by changing the transport mode.

Fig. 3 compares the societal risk curves obtained using the simplified approach with those calculated by means of a more rigorous approach, based on accurate territorial information, such as local accident rates, population densities and weather conditions, described in details elsewhere (Bubbico, Di Cave, & Mazzarotta, submitted for publication). It can be noticed that, for both road and rail transport, the results obtained applying the short-cut procedure (thicker lines) are in rather good agreement with the others (thinner lines), thus confirming the validity of the proposed method.

6. Conclusion

The use of TRA as a decision tool for risk managers and authorities in order to permit or limit transportation activities involving dangerous substances is desirable but not yet adopted in most practical cases. In fact, the difficulty in collecting, organising and analysing the needed data, and the high number of consequence analysis calculations to be performed, make this type of analysis very long and discourages its use.

The use of the simplified but still rigorous approach here proposed allows to overcome these inconveniences and to perform a TRA obtaining very rapidly the relevant risk measures, which can be reliably used for a first assessment of the case. This is important to identify immediately the risk level relevant to a transportation activity, devoting a more detailed analysis only to the cases which actually deserve it; moreover, it can be also used to assess the possible risk mitigation arising from the selection of alternative routes or transport modes.

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