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Hazmat transport: A methodological framework for the risk analysis of marshalling yards

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Abstract

A methodological framework was outlined for the comprehensive risk assessment of marshalling yards in the context of quantified area risk analysis. Three accident typologies were considered for yards: (i) “in-transit-accident-induced” releases; (ii) “shunting-accident-induced” spills; and (iii) “non-accident-induced” leaks. A specific methodology was developed for the assessment of expected release frequencies and equivalent release diameters, based on the application of HazOp and Fault Tree techniques to reference schemes defined for the more common types of railcar vessels used for “hazmat” transportation. The approach was applied to the assessment of an extended case-study. The results evidenced that “non-accident-induced” leaks in marshalling yards represent an important contribution to the overall risk associated to these zones. Furthermore, the results confirmed the considerable role of these fixed installations to the overall risk associated to “hazmat” transportation.

Keywords: Major accident hazard; Quantitative risk analysis; Dangerous goods; Hazmat transportation; Marshalling yards; Railway

1. Introduction

In recent years important advances were achieved in transportation risk analysis (TRA). This is confirmed by several conference sessions specifically dedicated to “hazmat” transportation problems, by the relevant number of papers appeared in literature and by publications that, due to their comprehensive examination of the subject, may be considered as milestone references [1–3].

TRA is characterized by the fact that risk sources are mobile; it has become a well-defined area of quantified risk analysis (QRA), parallel to chemical process quantified risk analysis (CPQRA). Traditional techniques for the calculation of risk have been specifically adapted to TRA and “ad hoc” models have been developed for it, as those proposed, for instance, in [1–9].

Though there are still some topics of TRA to which scarce attention was paid till now and for which, as a consequence, no general comprehensive methodological approaches are available. Referring to on-land road and rail transportation, one of these themes is surely represented by the risk assessment of holding and storage areas, as parking areas, temporary terminals for the transport of intermodal containers, and marshalling yards. In these areas, “hazmat” vehicles may stop and stay for relevant time frames before continuing their travel. Despite the availability of well-assessed methodologies for the evaluation of the risk caused by accidents involving in-transit vehicles, less attention was devoted to the development of rigorous techniques for the analysis of these “hot spots”.

As a matter of fact, when considering “hazmat” transport, the attention is focused on the “accident-induced” releases, since the kinetic energy of moving vehicles has the potential to cause the rupture of the vessel resulting in a relevant loss of containment as a consequence of the accident. In several approaches, this induced to neglect in TRA the possible influence of non-accident initiated leaks, similar to those occurring to plant vessels [2,3,6,10]. However, this choice is generally supported only by qualitative considerations and not also by a quantitative evaluation. Ignoring minor “non-accident-induced”

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leaks seems reasonable for travelling tank trucks and railcars, since in this case the spilled substance will be immediately dispersed in the atmosphere or on the ground due to the movement of the vehicle, without a major harm to people.

On the other hand, severe leaks will reasonably be detected during the travel and will cause the tank- or railcar to stop, causing a major hazard to local population. Moreover, when the vehicle is not travelling, the released substance may give rise to severe final outcomes, as toxic clouds, fires and explosions, even in the case of minor losses. As a matter of fact, the analysis of past accidents evidences that a relevant number of "non-accident-induced" releases resulting in major accidents took place in marshalling yards and in parking areas. An important review of past yard accidents performed some years ago [11], focusing on the number and characteristics of the accidental events as well as on the extent of their consequences, outlined the importance of risk due to "hazmat" transportation in marshalling yards. A more recent investigation [12] of the information reported by the Canadian Dangerous Goods Accident Information System (D.G.A.I.S.) [13] revealed that the percentages of accidents occurred during the in-transit phase of the transport and during the staying at a yard are equal, thus evidencing the necessity to address as risk sources both the railway lines and the yards. Moreover, some quantified area risk analysis (QARA) studies evidenced the relevance of the hazards coming from areas were "hazmat" railcars are handled, and the importance of the potential contribution of this risk component to the overall values of individual and societal risk in industrial areas [14,15].

Therefore, the exclusion of non-accident initiated leaks in TRA and in particular in the risk assessment of areas where vehicles stop and stay seems not justified. A further element that should be considered is that marshalling yards are often close to passengers railway stations, which are generally in the proximity of population centres. Moreover, these installations are usually not specifically dedicated to "hazmat" transportation, thus non-specific alarm, mitigation and emergency response systems may be present. All these factors suggest not to neglect the risk of these sites in an integrated approach to transportation risk management. However, to the knowledge of the authors, no thorough assessment of the risk caused by "non-accident-induced" releases is available in the literature. An approach to the problem is reported in a short section of the TNO "Purple Book" dedicated to shunting yards [3], but even in this reference a specific assessment of the expected frequencies of "non-accident-induced" releases is lacking.

The present study was dedicated to the development of a specific methodological approach for the comprehensive analysis of risk due to "hazmat" transportation in a marshalling yard. All the components of risk deriving from the different categories of possible accidents (in-transit accidents, shunting accidents, "non-accident-induced" releases) were examined. A particular effort was dedicated to develop an approach to the assessment of "non-accident-induced" release frequencies. Hazard and operability analysis and Fault Tree techniques were applied to obtain specific and reliable release frequency values for these events. The methodology was applied to the analysis of a case-study derived from actual data available on an Italian industrial area. Individual and societal risk due to the different accident categories possible in a marshalling yard were evidenced.

2. QRA of marshalling yards: theory and methodological approach

2.1. Accidents that may cause a "hazmat" release in a marshalling yard

The risk analysis of marshalling yards is complex, due to the variety of operations to which railcars are subject. A first possibility is that a train may simply pass through the marshalling yard (usually at reduced speed). A second case is that the train may be subject to a simple stop and stay, leaving after some time without undergoing any other operation. A further possibility is that the train be subject to a change-over of the locomotive or to the shunting procedure, which consists in the splitting of the arriving trains and the formation of new ones. In all cases but the first the time spent by a railcar in the yard can yield from a few hours to several days.

It must be recalled that loading/unloading operations of the "hazmat" railcars does not usually take place in yards, but in dedicated installations that are normally inside production sites. The safety of these operations is usually addressed in the risk assessment of the site. Thus, loading and unloading operations of "hazmat" railcars will not be further considered in the present study.

As a consequence of operations that take place in marshalling yards, three kinds of events may cause a release of hazardous substances:

1. "in-transit-accident-induced" releases, caused by trains passing through without stopping there;
2. "shunting-accident-induced" releases, occurring to single railcars and to set of wagons subject to the shunting procedure;
3. "non-accident-induced" releases, which are not related to vehicular accidents (as collisions and derailments) but to the failure of the railcar vessels containing hazardous substances (e.g. gasket failure, rupture of valves, etc.).

The importance of these three categories of hazardous events (and the necessity to not neglect the last one) are confirmed by the results of the analysis of the D.G.A.I.S. accident database [12], which shows that about 40% of the incidental events occurring at yards are due to spontaneous leaks not initiated by vehicular accidents, while the remaining 60% are induced by collisions and derailments.

In order to quantify the risk due to each accident category, it is necessary to estimate the "hazmat" release frequencies related to these three types of accident and the accident consequences. These will be discussed in detail in the following sections.

2.2. "In-transit-accident-induced" releases

Well-defined procedures are available for the frequency and consequence assessment of this category of accidents. Reference procedures are suggested by several sources (e.g. [1,2,3]). The frequency of occurrence may be evaluated as the product of the vehicular accident frequency and the probability the accident is followed by a release. A wide range of in-transit accident frequencies is proposed in literature, expressed as events/km/train or events/km/railcar (e.g. see [2] and [16] and references cited therein). Specific data for different types of railway lines and for different average speeds are also available [2]. Data on the expected release probability given the accident are also reported by several sources (e.g. in [2,3,6]). Usually different values are reported for atmospheric and pressurized railcars. Generally these data are derived from the analysis of past accidents. In [17] and [18] results are summarized about a research study on the in-transit accident frequency and the corresponding release probability to be used in the Italian context. In the "Purple Book" [3] values adopted for Dutch case studies are reported.

Addressing the consequence analysis of these releases requires: (i) the definition of possible loss of containment events; (ii) the selection of an event tree following the release; and (iii) the consequence analysis of the possible scenarios.

It is well known that defining the loss of containment events (LOCs) associated to the accidents is the more critical step in the procedure, and a number of alternative approaches was proposed for the definition of the release categories and of the occurrence probability of each category [2,3,5,6]. The LOCs characterisation is usually different for atmospheric and pressurized railcars, since it heavily depends on the features of the vessels, though this distinction is not always applied.

Useful suggestions about the LOCs characterisation and the event trees for flammables are summarized in the "Purple Book" [3], though it can not be ignored that due to the scarce quality of the data usually available, the LOCs and also the event tree definition generally rely more on an expert-based subjective judgement, sometimes based on values adopted for fixed vessels, rather than on historical or theoretical investigations specifically performed on "hazmat" transportation accidents. In Table 1 the reference data adopted in the present study for the analysis of "in-transit-accident-induced" releases performed within the case study discussed in the following and concerning an Italian industrial area are summarized. The data in the table were derived from an extended literature review and from historical evidence performed in several previous studies [19,20].

Table 1
Reference data for the "in-transit-accident-induced" LOCs

Data	Atmospheric railcar		Pressurized railcar	
Accident frequency	1.0×10^{-8} (ev/railcar/km)			
Release probability	0.10–0.23		1/3 (0.10–0.23)	
No. of release categories	3		3	
	Φ (mm)	P_{occ}	Φ (mm)	P_{occ}
Release category 1	50	0.85	30	0.90
Release category 2	100	0.14	80	0.09
Release category 3	/	0.01	/	0.01

Φ = equivalent diameter of the hole associated to the release category, in mm; P_{occ} = occurrence probability of the release category.

Table 2
Expected shunting accident frequencies in some Italian marshalling yards

Marshalling yard	Handled railcars	Shunting accidents	Shunting accident frequency
	Railcars/year	Events/year	Events/railcar
Priolo-Targia	3537	0.143	4.0×10^{-5}
Livorno-Calambrone	3715	0.286	7.7×10^{-5}
Mantova-Frassine	11634	0.143	1.2×10^{-5}
Brindisi	3103	0.143	4.6×10^{-5}
National data	128380	6	4.7×10^{-5}

2.3. "Shunting-accident-induced" releases

The procedure for the assessment of risk due to "shunting-accident-induced" releases is similar to that adopted for "in-transit-accident-induced" releases. In this case the accident frequency, derived from historical evidence, is usually expressed as events per railcar handled in the yard, that is in events/railcar. The "Purple Book" [3] suggests for the shunting-accident frequency a value of 4.50×10^{-5} events/railcar. This value is in sufficient good accordance with frequencies calculated for four different Italian marshalling yards on the basis of historical data available to the Italian national railway board. Table 2 reports the values calculated for four Italian marshalling yards over a period of 7 years (1994–2001) and for all the Italian national railway network over a period of 2 years (2001–2002). As shown in Table 2, these data range between 1.2×10^{-5} and 7.7×10^{-5} events/railcar.

Though it has to be noticed that the values of the release probabilities, as well as the LOCs characterisation are different with respect to the case of the "in-transit-accident-induced" releases, since the lower speeds of the railcars during the shunting process turn out in minor energies available in shunting accidents for puncturing the railcar vessels. The "Purple Book" [3] reports some suggestions in order to take into account this factor. Table 3 reports the reference data adopted to analyze the case-study discussed in the following. These were derived from a literature review and from the analysis of past accidents carried out in several previous studies [19,20]. It must be remarked that, differently from in-transit-accidents, a catastrophic rupture was not considered a credible consequence of a shunting accident.

Table 3
Reference data for the "shunting-accident-induced" LOCs

Data	Atmospheric railcar		Pressurized railcar	
Accident frequency	4.45×10^{-5} (events/railcar)			
Release probability	0.10		0.01	
No. of release categories	2		2	
	Φ (mm)	P_{occ}	Φ (mm)	P_{occ}
Release category 1	50	0.90	24	0.90
Release category 2	100	0.10	80	0.10

Φ = equivalent diameter of the hole associated to the release category, in mm; P_{occ} = occurrence probability of the release category.

3. "Non-accident-induced" releases

3.1. The approach to frequency calculation of "non-accident-induced" LOCs

As discussed above, scarce data are available on the LOCs intensity and on the expected frequencies of "non-accident-induced" releases, and no agreement is present in literature on the approach to the analysis of these events. A generic value of 5×10^{-7} events/railcar/year for the occurrence frequency of these LOCs is suggested by the "Purple Book" [3]. Other sources [2] suggest that this frequency (and also the LOCs characterisation) may be derived applying to the railcar the conventional techniques developed for the safety analysis of fixed installations, but do not provide frequency and loss intensity values that may be used in TRA studies. As a matter of fact, the lack of data and the absence of a specific procedure often lead to neglect these events in TRA studies.

In the present study a specific analysis was developed to characterize "non-accident-induced" LOCs and to estimate their expected frequencies and consequences. The problem was approached by the analysis of railcar design schemes using well known HazOp and Fault Tree procedures, whose theoretical foundations are extensively discussed in various literature sources (e.g. further details may be found in [21] and in references cited therein). Reference technical schemes and simplified process flow diagrams were derived for the railcar vessels used for the transport of hazardous materials as liquids (generally transported in an atmospheric railcar vessel) and pressure liquefied gases (shipped in pressurized railcar vessels). This was possible by a cross-check of the RID standards, of the current practice and of the technical information supplied by some railcar manufacturers. The results of this analysis are reported in Fig. 1, where the reference schemes of the atmospheric and the pressurized railcar vessel are shown.

3.2. HazOp analysis of railcar vessels

When performing the HazOp analysis of railcar vessels, a set of possible deviations of the process variables from the design values has to be considered. Since, excluding during loading/unloading operations that are not considered herein, there should be no flow from the vessel of the substance stored inside, the first examined deviation was "hazmat" outflow. The plausible deviations of pressure, level and temperature likely to cause a "hazmat" outflow were also taken into account. For each deviation the credible causes and the consequences of the event were derived. An example of the results of the HazOp analysis applied to the reference process flow diagram defined for an atmospheric railcar vessel is reported in Table 4.

Examining the consequences of the deviations, it was possible to identify five top-events, both for the atmospheric and the pressurized railcar vessel (indicated as TE0, TE1, TE2, TE3 and TE4 in the followings), corresponding respectively to a pinhole spill from the liquid phase, a minor release from the liquid phase, a major leak from the liquid phase, the catastrophic rupture of the vessel and a minor spill from the gas phase. In order to allow the quantitative characterization of the LOC consequences, nominal equivalent diameters were assigned to each top-event, on the basis of the available data on railcar compo-

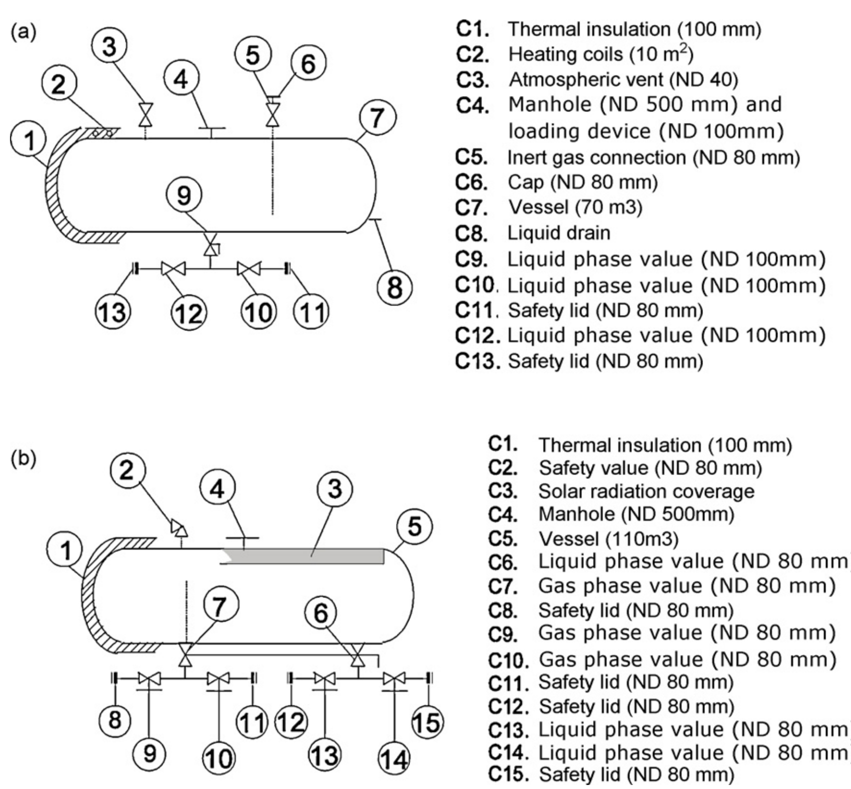

Fig. 1. Reference scheme for the analysis of expected LOCs and LOC frequencies: (a) atmospheric railcar vessel; (b) pressurized railcar vessel.

Table 4
Example of the results of the application of the HazOp technique to the analysis of reference schemes of railcar vessels: analysis of the reference scheme defined for the atmospheric railcar vessel

Deviation	Causes			Consequence
	C9 leakage (ext.)			
	C9 leakage (int.)	∩ C10 leakage (ext.)		
	C9 leakage (int.)	∩ C10 leakage (int.)	∩ C11 leakage	
	C9 leakage (int.)	∩ C10 leakage (int.)	∩ C11 not present	
	C9 leakage (int.)	∩ C10 not closed	∩ C11 leakage	
	C9 leakage (int.)	∩ C10 not closed	∩ C11 not present	
	C9 not closed	∩ C10 leakage (ext.)		
	C9 not closed	∩ C10 leakage (int.)	∩ C11 leakage	
	C9 not closed	∩ C10 leakage (int.)	∩ C11 not present	
	C9 leakage (int.)	∩ C12 leakage (ext.)		Pinhole leak (liquid phase)
	C9 leakage (int.)	∩ C12 leakage (int.)	∩ C13 leakage	
	C9 leakage (int.)	∩ C12 leakage (int.)	∩ C13 not present	
	C9 leakage (int.)	∩ C12 not closed	∩ C13 leakage	
	C9 leakage (int.)	∩ C12 not closed	∩ C13 not present	
	C9 not closed	∩ C12 leakage (ext.)		
"Hazmat" outflow	C9 not closed	∩ C12 leakage (int.)	∩ C13 leakage	
	C9 not closed	∩ C12 leakage (int.)	∩ C13 not present	
	More pressure	∩ C5 leakage (ext.)		
	More pressure	∩ C5 leakage (int.)	∩ C6 leakage	
	More pressure	∩ C5 leakage (int.)	∩ C6 not present	
	C9 not closed	∩ C12 not closed	∩ C13 leakage	Minor leak (liquid phase)
	C9 not closed	∩ C10 not closed	∩ C11 leakage	
	C9 not closed	∩ C10 not closed	∩ C11 not present	Major leak (liquid phase)
	C9 open by error	∩ C10 not closed	∩ C11 not present	
	C9 open by error	∩ C10 open by error	∩ C11 not present	
	C9 not closed	∩ C12 not closed	∩ C13 not present	
	C9 open by error	∩ C12 not closed	∩ C13 not present	
	C9 open by error	∩ C12 open by error	∩ C13 not present	
	More pressure	∩ C3 leakage (ext.)		Minor leak (gas phase)
	More pressure	∩ C4 leakage (int.)		
	More pressure	∩ C4 not closed		
More pressure	More temperature			Catastrophic rupture
	More level			Minor leak (gas phase)
More level	Wrong vessel loading			More pressure
Wrong vessel loading	Human error			More level
	Weight cell failure	∩ Volumetric recorder failure		
Less level	Other flow			Air enters vessel forming a flammable mixture
	Wrong vessel loading			
More temperature	Solar heating			More pressure
	Exposure to external fire radiation			
	Exothermic reaction			Solidification
Less temperature	Very low external temperature			Polymerization inhibitor precipitation

nents (e.g. the nominal diameters of pipes and connections) and of reasonable assumptions on the failure modes of components usually adopted in the literature (e.g. in the "Purple Book" [3]). An equivalent hole diameter equal to 1% of the nominal diameter of the pipes connected to the vessel was assigned to the pinhole spill (TE0), as usual in risk analysis. On the other hand, an equivalent diameter comprised between the 10% of the nominal pipe diameter and the 20% of its nominal cross section is generally suggested in the literature to model minor leaks (TE1 - liquid phase, TE4 - gas phase). A lbore rupture was adopted to model major leaks (TE2). Since the nominal diameter of the pipes more usually connected to atmospheric railcars is equal to 100 mm and of that of pipes connected to pressurized railcars is equal to 80 mm, this characterisation leads to the equivalent hole dimensions summarized in Table 5.

A preliminary consequence analysis, performed using the consequence analysis models provided by the TNO "Yellow Book" [22] and the EFFECTS 4.0 software [23], evidenced that the consequences of the expected outflow rates from top-events TE0 and TE4 are usually so small to produce no harm

Table 5
Equivalent diameter of release assumed for the "non-accident-induced" spills

LOCs	Equivalent hole diameters			
	General criterion as a function of the nominal pipe diameter Φ		Atmospheric railcar Φ (mm)	Pressurized railcar Φ (mm)
TE0	0.1Φ	(Liq. phase)	10	8
TE1	0.2Φ $(0.2\pi/4\Phi^2)$	(Liq. phase)	20 (45)	16 (36)
TE2	1.0Φ	(Liq. phase)	100	80
TE3	Catastrophic rupture	/	/	/
TE4	0.1Φ	(Gas phase)	10	8

to people and goods, thus resulting in a negligible contribution to risk, independently from their occurrence frequencies. Thus, these release modes were not further considered in the present analysis.

3.3. Fault Tree analysis of railcar vessels

In order to evaluate the expected occurrence frequencies of the top-events, the Fault Tree technique was applied to TE1, TE2 and TE3, both for the atmospheric and the pressurized railcar vessels. The fault trees were defined through a top-down procedure, stopping once primary events (i.e. events whose occurrence frequencies are known from historical experience) were reached. An example of the results obtained is reported in Fig. 2, that shows the fault tree obtained for the top-event TE2 (corresponding to a major leak) from the atmospheric railcar vessel represented by the reference scheme shown in Fig. 1(a).

The fault trees defined for the relevant top-events of both the atmospheric and the pressurized railcar require the characterization of 15 different primary events. Most of them correspond to the failure of a component of the railcar equipment (*volumetric recorder failure*, *weight cell failure*, *internal valve leakage*, *external valve leakage*, *rupture of connection*, *manhole leakage, insulation covering defect, vessel corrosion*). Two primary events are actually external events (*fire radiation, solar heating*). The remaining primary events are due to omissions or wrong actions of the operators during car loading operations (*human errors: valve not closed*, *valve open by error*, *absence of connection, exothermic reaction due to contamination or wrong loading*).

A qualitative analysis was applied to each fault tree, in order to determine the minimal cut sets (MCSs) and their order. For all the top-events of the atmospheric and pressurized railcar reference schemes, the MCSs resulted of the second order or of both the second and the third order. The quantitative analysis of the fault trees allowed the estimation of the expected occurrence frequency of each top-event as a function of the occurrence frequencies (or failure rates) of the primary events. In the absence of

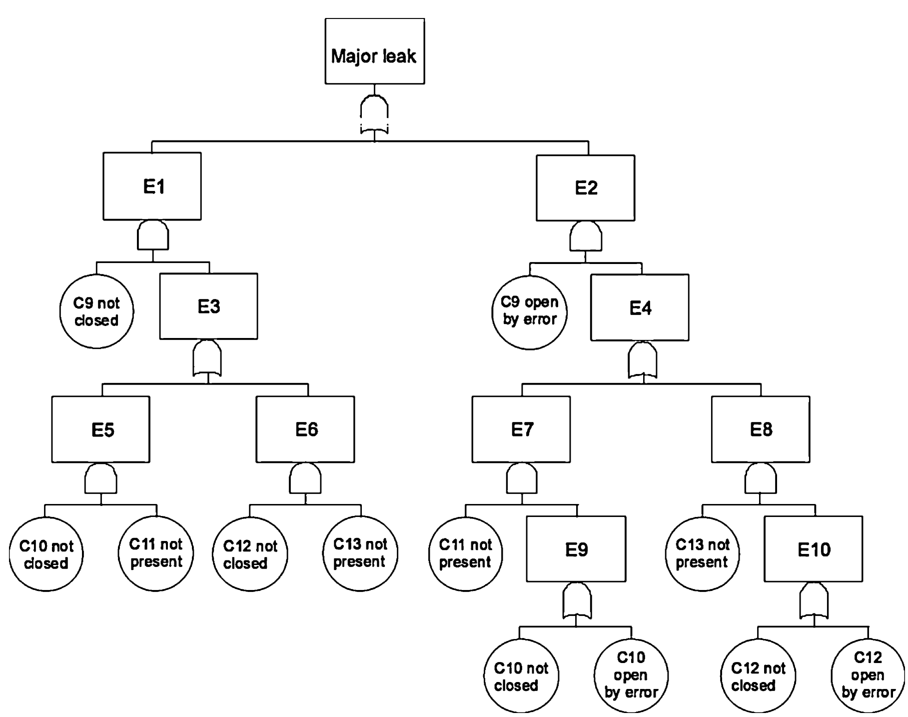

Fig. 2. Example of the results obtained by the Fault Tree analysis: TE2 (major leak) for the reference atmospheric railcar vessel shown in Fig. 1(a). E1: LOC through liquid line left open; E2: LOC due to wrong opening of liquid line; E3, E4: liquid line not closed; E5, E7: left-liquid line open; E6, E8: right liquid line open; E9: improper operation of valve C10; E10: improper operation of valve C12.

Table 6
Input data for the quantitative Fault Tree analysis: occurrence frequencies for primary events

Primary events	Expected occurrence frequencies (events/year)					
	CCPS [24]	Lees [16]	OREDA [25]	Rijmond [26]	Minimum value	Maximum value
Volumetric recorder failure	2.20×10^{-1}	1.14×10^{-0}	3.16×10^{-1}	2.00×10^{-1}	1.22×10^{-6}	1.14×10^{-0}
Weight cell failure	8.70×10^{-1}	3.75×10^{-0}	5.00×10^{-1}	4.30×10^{-1}	1.44×10^{-5}	3.75×10^{-0}
Human error	3.40×10^{-2}	1.00×10^{-3}	/*	/*	1.00×10^{-3}	3.40×10^{-2}
Valve leakage (external)	4.10×10^{-3}	5.00×10^{-3}	2.75×10^{-2}	8.76×10^{-5}	7.20×10^{-4}	5.42×10^{-2}
Valve leakage (internal)	1.09×10^{-3}	2.00×10^{-3}	8.06×10^{-3}	1.00×10^{-4}	1.09×10^{-3}	1.46×10^{-2}
Valve not closed	2.00×10^{-3}	2.75×10^{-3}	1.97×10^{-2}	1.00×10^{-3}	7.92×10^{-4}	3.85×10^{-2}
Valve open by error	2.00×10^{-3}	2.75×10^{-3}	1.97×10^{-2}	1.00×10^{-3}	7.92×10^{-4}	3.85×10^{-2}
Rupture of connection	6.10×10^{-3}	3.10×10^{-3}	1.48×10^{-4}	1.00×10^{-3}	7.92×10^{-5}	8.76×10^{-3}
Absent of connection	2.00×10^{-3}	3.00×10^{-3}	1.00×10^{-4}	1.00×10^{-3}	1.00×10^{-4}	3.00×10^{-3}
Manhole leakage	2.00×10^{-4}	2.00×10^{-4}	7.92×10^{-5}	/*	7.92×10^{-5}	2.16×10^{-4}

* Not reported.

failure rates specific for components of “hazmat” railcar vessel equipment, these were derived from literature data, examining in detail several available open databases. In Table 6 the minimum and the maximum values found for the failure rate of each primary event are reported, together with the values suggested by four authoritative literature sources [16,24–26]. The data in Table 6 were used in order to quantify, with the aid of the CARA Fault Tree 4.0 software [27], the occurrence frequencies of the top-events. The results obtained are reported in Table 7. The table also reports the reference values assumed in the analysis of the case study discussed in the following. The reference values were estimated using the primary event frequencies obtained from the more reliable failure frequency databases [24,25], also considering the release frequencies suggested by the “Purple Book” [3] for fixed storage vessels.

As shown in Table 7, the expected frequencies were calculated using both the lower-bond and the upper-bond value of the failure rates of the primary events, as well as using the homogeneous values given by the four qualified data sources identified. When one of these sources does not report a frequency value for a given primary event, the maximum value retrieved in literature was conservatively adopted. A sensitivity analysis was also performed, evaluating the contribution of each MCS to the corresponding top-event as the ratio between the occurrence frequency of the MCS and the occurrence frequency of the top-event. No critical components or operations were evidenced for the various MCSs from the results of the analysis carried out.

The occurrence frequencies in Table 6 show a wide variation, in general extended up to some orders of magnitude. As a consequence of the uncertainty of failure rates, the occurrence frequencies of the top-events show too a large variability, ranging over 2 to 5 orders of magnitude as shown in Table 7. However, if coherent values from the same data source are used, these variability intervals narrow and the difference among the top-event frequencies of the various literature sources reduces to less than one order of magnitude for all the top events, with the exception of the TE1 for both the atmospheric and the pressurized railcar, for which the difference still results of 4 orders of magnitude. However, it must be remarked that the low loss intensities corresponding to this category of releases limit the influence of these LOC events on the overall risk values. Thus, the use of the more conservative values for TE1 frequencies in the quantitative risk assessment of this release category may be accepted.

Moreover, as shown in Table 7, reference values may be estimated, also considering standard values suggested in the literature for fixed atmospheric and pressurized storage vessels [3]. The results confirm that, as expected, the release frequencies become lower with the severity of the top-event, confirming that major releases are rarer than minor LOCs. Although these frequencies cannot be directly compared with those corresponding to “accident-induced” leaks due to the different units, the values estimated are far than negligible. This point will be further discussed in the following, where the results of the performed case study will be analyzed.

Table 7
Results of the Fault Tree analysis: occurrence frequencies of the “non-accident-induced” releases

Top-events	CCPS [24]	Lees [16]	OREDA [25]	Rijmond [26]	Minimum value	Maximum value	Reference value
	Atmospheric railcars						
TE1	3.65×10^{-3}	3.32×10^{-3}	1.00×10^{-2}	5.70×10^{-6}	7.20×10^{-7}	3.68×10^{-2}	5×10^{-3}
TE2	4.79×10^{-7}	1.36×10^{-7}	2.29×10^{-7}	4.70×10^{-8}	3.77×10^{-10}	2.57×10^{-5}	5×10^{-6}
TE3	3.47×10^{-8}	1.99×10^{-7}	3.23×10^{-8}	3.90×10^{-8}	2.99×10^{-10}	4.45×10^{-8}	5×10^{-7}
	Pressurized railcars						
TE1	3.28×10^{-5}	5.50×10^{-5}	2.12×10^{-3}	7.00×10^{-7}	2.28×10^{-6}	7.99×10^{-3}	1×10^{-3}
TE2	3.88×10^{-7}	5.52×10^{-7}	1.13×10^{-6}	1.28×10^{-7}	1.35×10^{-9}	2.01×10^{-4}	1×10^{-6}
TE3	2.96×10^{-8}	1.33×10^{-7}	2.15×10^{-8}	2.60×10^{-8}	2.00×10^{-10}	1.40×10^{-7}	1×10^{-7}

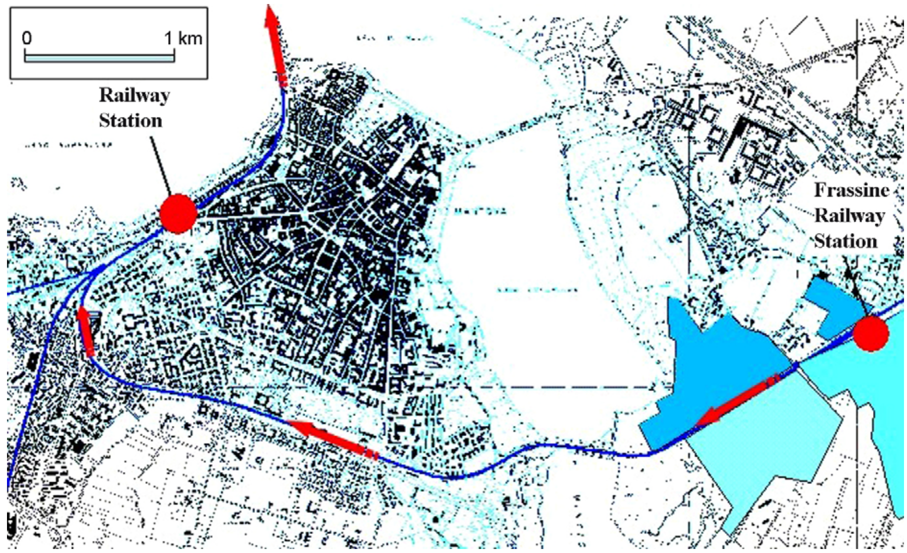

Fig. 3. The rail route of hazardous materials in the area of Mantova.

4. Analysis of case study

4.1. Definition of the case study

In order to understand the validity of the approach developed to frequency and consequence assessment of "non-accident-induced" releases within the methodological framework previously outlined for the risk assessment of marshalling yards, this was tested on several case studies, defined also in cooperation with the Italian National Railway Service. Besides testing the suitability of the comprehensive approach developed to the analysis of the risk due to marshalling yards, a further main aim of the case studies was to understand the importance of the contribution of "non-accident-induced" releases to the overall risk caused by marshalling yards were railcars carrying dangerous goods are present. The results obtained are discussed in the following, where a particularly significant case study was analyzed, concerning the railway station and marshalling yard of an Italian town, the city of Mantova.

Mantova is situated in the north of Italy, on a small peninsula extending into the lakes formed by the river Mincio and has about 50,000 inhabitants. It represents a beautiful artistic site, with important historical monuments in the downtown. However, an extended industrial area is present quite near to the town centre, where relevant quantities of hazardous materials are processed inside the plants and delivered to the end-users by railway. A marshalling yard is present in the industrial zone, close to the Frassine Railway station (as shown in Fig. 3), where trains carrying hazardous materials are composed. From Frassine these trains arrive to the marshalling yard of the station of Mantova, crossing densely populated areas. In the Mantova railway station a stay occurs (without shunting operations) before the railcars are sent by a single track line to Verona, from where they reach their final destination.

In order to perform the consequence evaluation for the "hazmat" railcars, the different chemicals shipped were grouped in 5 classes (named A, B, C, D1 and D2), each corresponding to different physical properties and hazardous rating. For each class a key substance was selected, as shown in Table 8. In the fourth column of the table, data representative of the actual railcar traffic for each key substance are reported, expressed as railcars yearly shipped [28]. Considering that a year has 8760 h and that each railcar stops in Mantova railway station for a mean time value of 2 h (that is for a fraction of the year equal to 2.28×10^{-4}), the number of equivalent railcars present in the railway station may be easily evaluated multiplying each railcar flux by the yearly fractional presence value. The results obtained are reported in the last column in Table 8.

For each railcar, both "in-transit-accident-induced" leaks and "non-accident-induced" spills were considered, assuming for

Table 8
"Hazmat" rail traffic data through Mantova. R10, R11, R12, R20, R23: risk phrases following Directive 67/548/EEC and updates concerning the classification of dangerous substances

Class	Hazardous rating	Key substance	Railcars/year	Equivalent railcars
A	Flammable - R12 (excluding LPG)	*n*-Hexane	1901	0.43
B	Flammable - R11	Styrol	3600	0.82
C	Flammable - R10	Diesel fuel	6136	1.40
D1	Toxic by inhalation - R20	Styrol	3597	0.80
D2	Toxic by inhalation - R23	Acrylonitrile	736	1.68

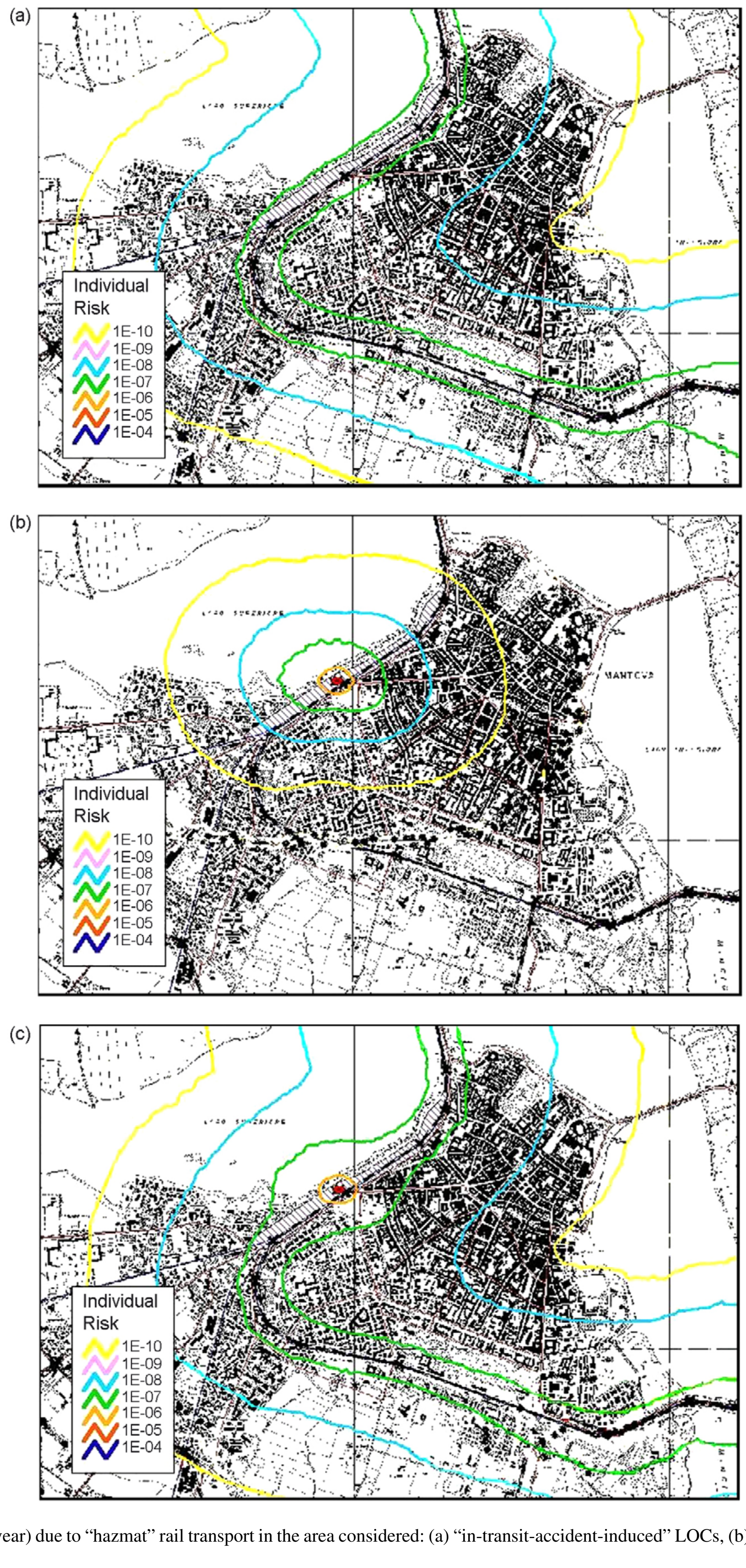

Fig. 4. Individual risk (events/year) due to "hazmat" rail transport in the area considered: (a) "in-transit-accident-induced" LOCs, (b) "non-accident-induced" LOCs, and (c) overall risk value.

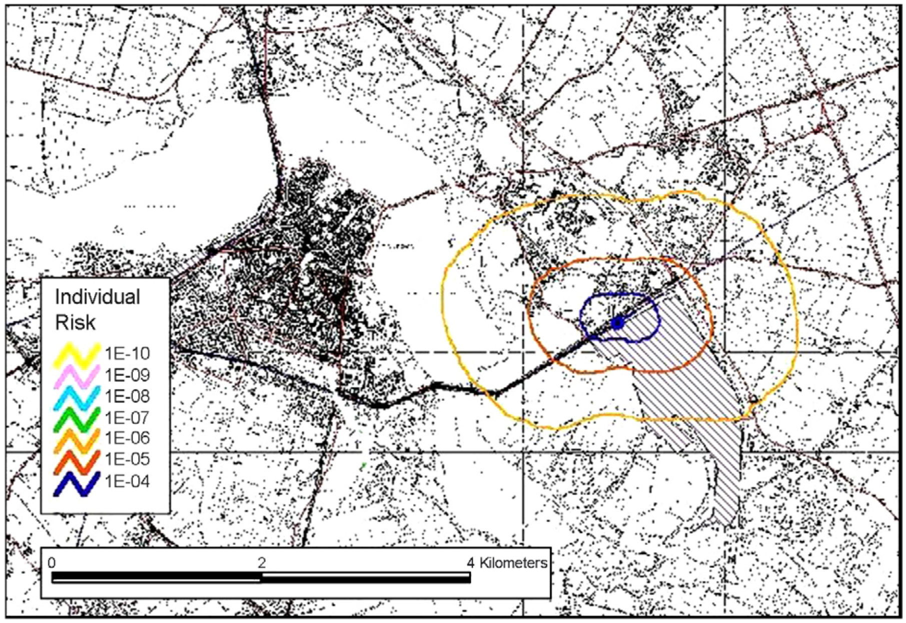

Fig. 5. Individual risk (events/year) due to the stay and to the shunting operations involving "hazmat" railcars in the Frassine marshalling yard.

the former the data values suggested in Table 1. For the "non-accident-induced" LOCs, the reference data in Table 7 were adopted. The release characterisation was performed using the data in Table 5, assuming for TE2 an equivalent release diameter equal to 20% of the nominal diameter.

For all incident types, the post-release event tree suggested in [3] was adopted for the flammable liquids (classes A, B, C). A pool fire was considered as the only consequence of the release of these substances, due to their low volatility, and an ignition probability of 0.13 was adopted. Standard models were used to estimate the pool fire consequences; for toxic substances, standard methodologies for consequence analysis were applied to model the atmospheric dispersions [22].

Data concerning the density and the distribution of population, as well as meteorological conditions affecting the impact areas of atmospheric dispersions, were derived from a previous study of the risk due to fixed installations in the area [28].

The calculation of the risk indexes in the area of concern was performed using the ARIPAR-GIS software [14,29]. The particular features of this software allowed the separate calculation of the contribution of each accident category to the overall risk indexes. Further details on the ARIPAR-GIS software are reported elsewhere [30].

4.2. Results of the case study

First of all the individual risk caused by "accident-induced-in-transit" LOCs was evaluated. The results are shown in Fig. 4(a). The individual risk results of about 1×10^{-7} events/year on the railway line and thus also in the yard.

Fig. 4(b) shows the individual risk due to the "non-accident-induced" releases. A value of 1×10^{-5} events/year is reached within the railway station, which is all other than negligible, being comparable or even higher than values typically recorded for fixed installations where relevant quantities of substances (as those listed in Table 8) are stored. As a matter of fact, the risk results about two orders of magnitude higher than the value due to that calculated for "accident-induced-in-transit" releases. The overall individual risk values are shown in Fig. 4(c), that evidences that the risk curves are deformed around the yard, confirming that ignoring this "hot spot" in the risk assessment would lead to underconservative results. This is further confirmed by the results of the analysis of the Frassine marshalling yard. The yard is characterized by a longer mean stay of the railcars (considered of 8 h in the present study) and by shunting operations for the composition of the trains. Fig. 5 reports the individual risk contours calculated for the marshalling yard considering only the contributions of "non-accident-induced" and of "shunting-accident-induced" releases. As shown in the figure, the individual risk caused by these events is of 10^{-4} events/year inside the yard. This is mainly due to the longer mean stay time conservatively assumed, that resulted in a higher number of equivalent railcars considered present in the yard.

Fig. 6 shows the societal risk, expressed as *F*/*N* curves, calculated for the rail transportation of dangerous goods through Mantova (the reference area considered for calculation is that shown in Fig. 3). The *F*/*N* curves were evaluated both for the "in-transit-accident-induced" releases and for the "non-accident-induced" spills. It can be noticed that the societal risk due to the "in-transit-accident-induced" releases is, in terms of frequency F, higher by an order of magnitude than the societal risk of the "non-accident-induced" releases. Thus, the overall *F*/*N* curve, which considers all LOC categories, nearly coincides with that caused by the "in-transit-accident-induced" releases. This may be justified considering both the location where accidents may occur and the population distribution in the area of impact of the accidental scenarios. As a matter of fact, the impact area of "non-accident-induced" releases is limited to the

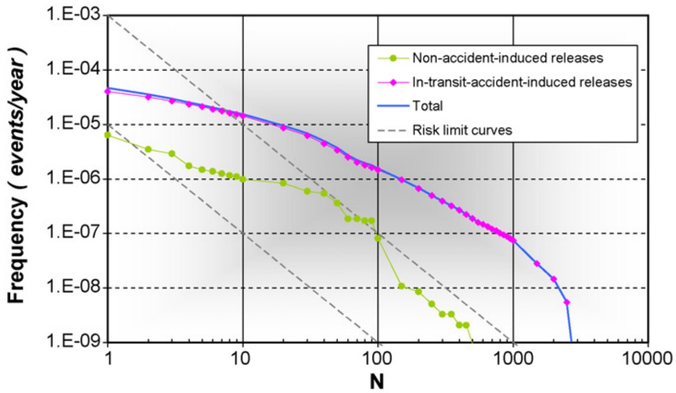

Fig. 6. "Hazmat" rail transport in the area considered for the case-study: societal risk expressed as *F*/*N* curves.

yard and the nearby zones, while "in-transit-accident-induced" releases may occur on the whole railway line, that runs along the most populated areas of the town. In addition, it may be noticed that, although the overall *F*/*N* curve due to "in-transit-accident-induced" LOCs is above the tolerable risk zone as defined by the Dutch risk acceptability criteria [31], also the *F*/*N* curve due to the only contribution of "non-accident-induced" releases falls inside the ALARP zone. These results confirm the importance of including "non-accident-induced" releases in the analysis of marshalling yards and railway stations in the assessment of individual and societal risk due to "hazmat" transportation.

5. Conclusions

In this paper a methodological framework was outlined for the comprehensive risk assessment of marshalling yards in the context of quantified area risk analysis; within the proposed framework "in-transit-accident-induced" releases, "shunting-accident-induced" spills and "non-accident-induced" LOCs are taken into account.

The outlined approach was applied to an extended case study. The results confirmed the relevant contribution of "non-accident-induced" releases to the overall risk of marshalling yards and, further, the relevant role of the risk due to these installations to the global risk associated to "hazmat" transportation, in particular in the presence of shunting operations and of relevant mean railcar stay duration. Moreover, the results confirm that the presence of marshalling yards may cause risk values comparable or even higher to those generated by fixed installations. Thus, the exclusions of marshalling yards from the application of the "Seveso-II" Directive (96/82/EC)" seems not to have a risk-based justification.

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