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A framework for risk assessment and decision-making strategies in dangerous good transportation

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Abstract

The risk from dangerous goods transport by road and strategies for selecting road load/routes are faced in this paper, by developing an original site-oriented framework of general applicability at local level. A realistic evaluation of the frequency must take into account on one side inherent factors (e.g. tunnels, rail bridges, bend radii, slope, characteristics of neighborhood, etc.) on the other side factors correlated to the traffic conditions (e.g. dangerous goods trucks, etc.). Field data were collected on the selected highway, by systematic investigation, providing input data for a database reporting tendencies and intrinsic parameter/site-oriented statistics. The developed technique was applied to a pilot area, considering both the individual risk and societal risk and making reference to flammable and explosive scenarios. In this way, a risk assessment, sensitive to route features and population exposed, is proposed, so that the overall uncertainties in risk analysis can be lowered.

Keywords: Accident frequency; Hazardous materials; Societal risk; Transport

1. Introduction

The relentless drive of consumerism has required increased quantities of dangerous goods to be manufactured, transported, stored and used year on year, despite the relative recent move towards "inherent safe" materials [1]. A recent survey covering the time span 1926–1997 revealed reports of 3222 accidents involving hazardous chemicals, of which 54% are fixed installations, 41% are transportation accidents and 5% miscellaneous accidents [2]. Of the different way of transportation, rail has higher damage potential, as larger quantities are transported by this means. However, considering the damage it may cause

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to life and properties, transport by road is more hazardous, as roads often pass through populated areas, especially in developing countries [3]. The safety and efficiency of road transport is to be considered a strategic goal in particular in those countries, like Italy, in which about 80% of goods is transported by this means, with a 30% increase with reference to the 2010 forecast. Moreover, recent severe accidents, like the Monte Bianco tunnel and San Gottardo ones, have emphasized the problem, making it clear that the present system does not function optimally and that the risk connected to dangerous goods transport is comparable with the fixed plants one. Generally speaking, the concept of risk is the relation between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards [4].

The recent EEC Directive 96/82/EC implies the evaluation of risk in highly industrialized areas by means of quantitative area risk analysis techniques. It can be noted that certain dangerous substances are transported along particular Italian road sections in quantities that would exceed the threshold for safety notification or declaration, set down in Italy by Seveso II Directive, if stored in a fixed installation. On the other side, it must be remembered that EEC Directive 94/55/EC implies the harmonization of the different national legislation on transport of hazardous materials by road.

As reported by different researchers, a specifically tailored QRA methodology can represent an effective tool to assess the risk to people associated with the transport of dangerous substance. The selection of the best route for transport has been widely investigated [5] and was recently formulated as a "minimum cost flow problem", which consists of determining, for a specific hazardous substance, the cheapest flow distribution, honoring the arc capacities, from the origin to the destination nodes [6]. The risk from dangerous goods transport by road and strategies for selecting road load/routes are faced in this paper, by developing an original site-oriented framework of general applicability. Poor appreciation of factors related to road conditions such as road class, designated speed limits, traffic density, as well as of the population characteristics, is likely to result in a risk assessment insensitive to route specifics and over- or under-estimating the overall level of risk [7]. It was therefore chosen to develop a high level of detail in the frequency model, by considering in-depth the traffic accident environment; a "cautious best estimate" approach was employed adopting either realistic and directly detected assumptions, or conservative overestimating hypotheses. Contrary to other models [8,9], this approach considers the risk from normal traffic accidents in addition to the risk from the major hazard aspects of the transport of dangerous substances.

2. Theoretical

For an effective approach to risk modelling, a proper evaluation of the expected frequency is the starting point.

The frequency of an accident on the *i*th road stretch can be expressed by the following equations:

$$f_i = \gamma_i L_i n_i \tag{1}$$

$$\gamma_i = \gamma_0 \sum_{j=1}^{6} \mathrm{h}_j \tag{2}$$

where γ_i is the expected frequency on ith road stretch (accident km^{-1} per vehicle), L_i the road length (km), n_i is the vehicle number (vehicle), γ_0 the basic frequency (accident km^{-1}per vehicle) and h_j is the local enhancing/mitigating parameters.

The frequency of an accident evolving according to a scenario S, on the ith road stretch, can be expressed as:

$$f_{i,S} = \gamma_i L_i n_i P_S P_I \tag{3}$$

where P_S is the probability of evolving scenarios of type S, following the accident initializer (i.e. collision; roll-over; failure etc.) and P_I is the ignition probability for flammable substances involved in the accident.

In dealing with the magnitude of the accident, it seemed important to include both the motorists on the road and the off-route population.

The number of fatalities N_S caused by the accident evolving according to a scenario S, on the ith road stretch, can be calculated according to following equations:

$$N_S = N_{S1} + N_{S2} \tag{4}$$

$$N_{S1} = k(vA_{L,1}) \tag{5}$$

$$N_{S2} = D(A_{L,2}) \tag{6}$$

where N_{S1} is the fatality number (fatalities), v the vehicle density on the road area (vehicle m^{-2}), k the average vehicle occupation factor, $A_{L,1}$ the road lethal area (m^2), N_{S2} the off-road fatality number (fatalities), $A_{L,2}$=lethal area (km^2) and D is the population density (inhabitants·km^{-2}).

When considering the different concurrent scenarios y and j (i.e. toxic release and delayed ignition), in order to avoid overestimation, the total lethal area will be considered as

$$A_{L,t} = A_y + A_j - [A_y \cap A_j] \tag{7}$$

3. A general framework

3.1. Field data collection

As already pointed out, a realistic evaluation of the accident frequency γ is to be considered an essential step in the risk assessment. As an example, an evaluation at a national level, making reference to National Institute of Statistics (ISTAT) data referred to 1999, can be performed starting from the following data: national road gasoline consumption 12.5×10^6 tonnes per year; average distance covered 10 km l^{-1}; yearly distance covered 1.95×10^{11} km per year; number of accidents 168×10^3; obtaining an accident frequency for cars corresponding to 8.6×10^{-7} accident per year km^{-1}. In a similar way, starting from the annual number of truck accidents (18×10^3 accident·per year) and an average yearly distance of 10^5 km per year·per truck, the truck accident frequency corresponding to 1.8×10^{-7} accident per year km^{-1} can be calculated.

When dealing with a particular route, a realistic evaluation of the frequency must take in account on one side inherent factors (such as tunnels, rail bridges, height gradient, bend radii, slope, characteristics of neighborhood, meteorological conditions) on the other side factors correlated to the traffic conditions (traffic frequency of tank truck, dangerous goods trucks etc.), suitable modifying the national frequency.

In order to provide a framework of general applicability for a road evaluation at local level, field data were collected on the selected highway, by systematic investigation, providing input data for a database reporting tendencies and intrinsic parameter/site-oriented statistics.

In the database on transport accident it seemed useful to include following descriptors: accident type; meteorological conditions; road intrinsic factors; substances involved; immediate sources of accident; immediate and underlying causes; emergency measures taken; immediate lessons learned.

3.2. Application to a pilot area

A pilot area was selected to this purpose, referring to the routes starting from the Genoa port area (the most important in the Mediterranean basin) towards the industrialized North Italian and Central Europe districts. Genoa-Milan A7 highway is characterized by high truck traffic (mainly ADR) and inherent factors determining to a major accident risk, with reference to both individual and social risk, defined according to European limits. As reproduced in Fig. 1, A7 highway is connected to A10 highway to the west and to A12 highway to the east. An alternative route towards Milano is represented by the highway Voltri-Alessandria A26, starting at the west side of Genoa and joining A7 highway after Serravalle exit. Historical frequencies, calculated for each highway stretch, are reported in Table 1. If compared with the historical accidents, it can be noticed that A7 highway is characterized by values higher at least an order of magnitude than the accident frequency calculated by other researchers for certain type of load threatening accidents [10], (6.0×10^{-8}), thus approaching the calculated values for urban road. The results can be ascribed to the already-mentioned particular characteristics of the route, with intrinsic hazard factors also due to its old construction time (1935).

As reported in Table 2, this assumption is confirmed by the average speed calculated for the different A7 highway stretches and vehicle type, making reference to the statistics obtained from the Italian Highway Society S.p.A.

Table 1
Accident frequency on the highway A7

Highway stretch	Length (km)	Yearly traffic (n)	Accident frequency (accident km^{-1})
1	1.9	10977375	8.63×10^{-7}
2	3	11541300	4.04×10^{-7}
3	2.9	10131670	6.47×10^{-7}
4	14.3	5648740	6.56×10^{-7}
5	5	4485485	13.4×10^{-7}
6	5.8	4395330	7.45×10^{-7}
7	6.6	4315395	4.56×10^{-7}

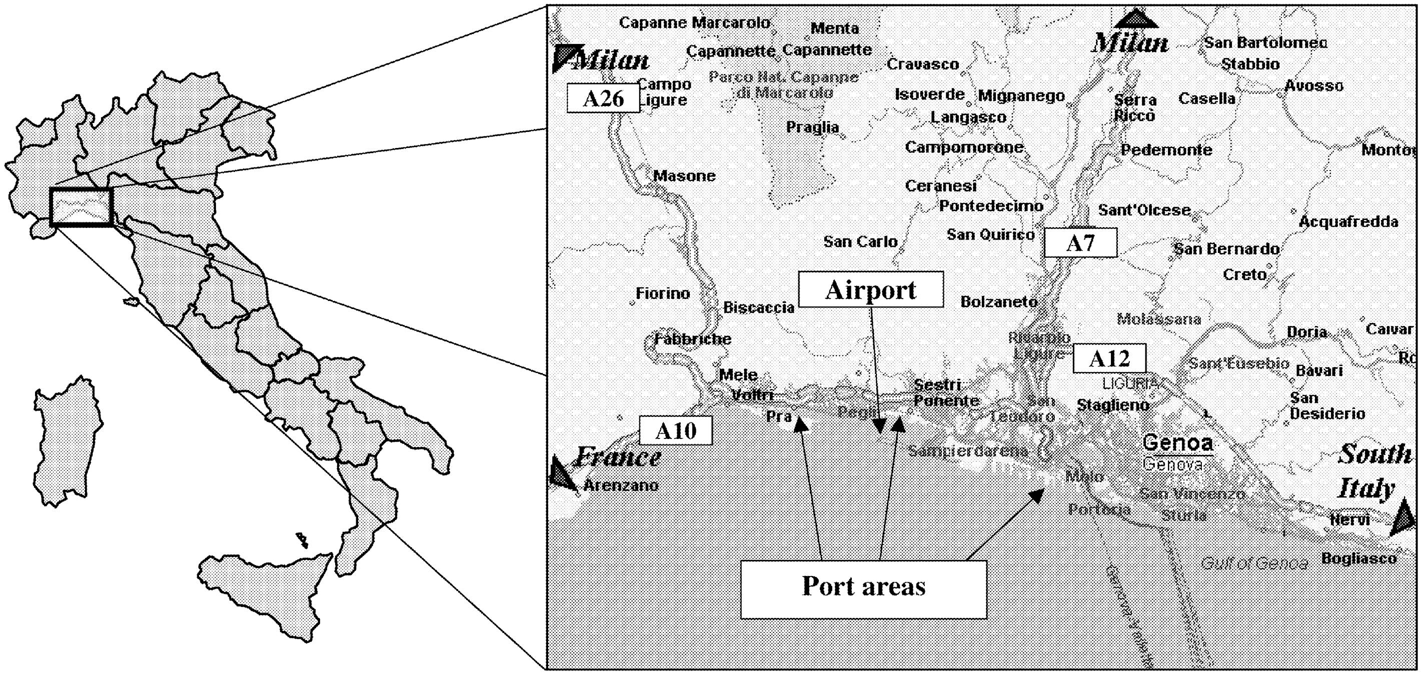

Fig. 1. Pilot area.

Table 2
Average speed on A7 highway, for the different vehicle categories

Highway stretch	Average speed (km per h)		
	Car	Truck	Total
Genoa Ovest-Connection A-7/A-10	84	67	83
Connection A-7/A-10–Connection A-7/A-12	80	64	78
Connection A-7/A-12-Bolzaneto	77	62	75
Bolzaneto–Busalla	80	64	77
Busalla–Ronco Scrivia	80	64	77
Ronco S.–Isola del Cantone	80	64	77
I. del Cantone–Piemonte	80	64	77

The statistical distribution of the accidents during the hours of the day, as resulting from on-site survey performed by the road policy of Genoa district over a suitable time span, is reproduced in Fig. 2.

In order to verify the existence of a correlation between accident and heavy traffic/ hazardous materials transport (ADR), a statistic elaboration over the same time span was carried out, considering as well the results reproduced in the same Fig. 2.

By considering the daily ADR traffic on the different highway sections, it results that the higher values of dangerous goods fluxes correspond to the intersection between the highways A10 (West riviera) and A12 (East riviera), in the stretch between the towns of Bolzaneto and Busalla and in the starting stretch, from the central port of Genoa (Genoa Ovest tollgate) to the connection between the highways A10 and A7. Globally, the considered highway can be divided into 22.63 km of straight stretch; 9.33 km of tunnels and 7.54 km of bends.

As a basis of comparison, the number of accidents in Liguria for the different vehicle categories was obtained by elaborating statistics obtained from ISTAT, as follows: motorcycles: 1024; cars: 5635; trucks: 444; other: 91.

The proportion of severe accidents on A7 highway north during the years 1995–1999 is in the range 27–40% of the total accidents, defining a severe incident as one involving death, serious injuries, a fire or explosion, or more than EUR 25000 worth of damage.

3.3. *Statistical elaboration of the data*

By elaborating the data collected on the field, over a suitable observation time, the immediate causes of the accidents on the highway A7 north, can be grouped as listed in Fig. 3.

As is well known, various factors influence the accidents: mechanical, environmental, behavioral, physical, road intrinsic descriptors. The main points of interest resulting from Fig. 3 are the high proportion of incidents due to high speed, corresponding to 40.3 and the 21.7% drive errors. The striking high percentages of these factors are to be correlated in their turn to the intrinsic characteristics of the analyzed highway. In fact, the high proportion of bends characterized by small radii (<200 m) and steep descent, make it necessary to respect low speed (i.e. 40 km/h), which is not usual on this type of road. When dealing with Hazmat incidents, historical data reported by Hardwood et al. [11] show that the proportion due to traffic is 11%, while the proportion involving a truck failure (body, tank, valve or fitting) is

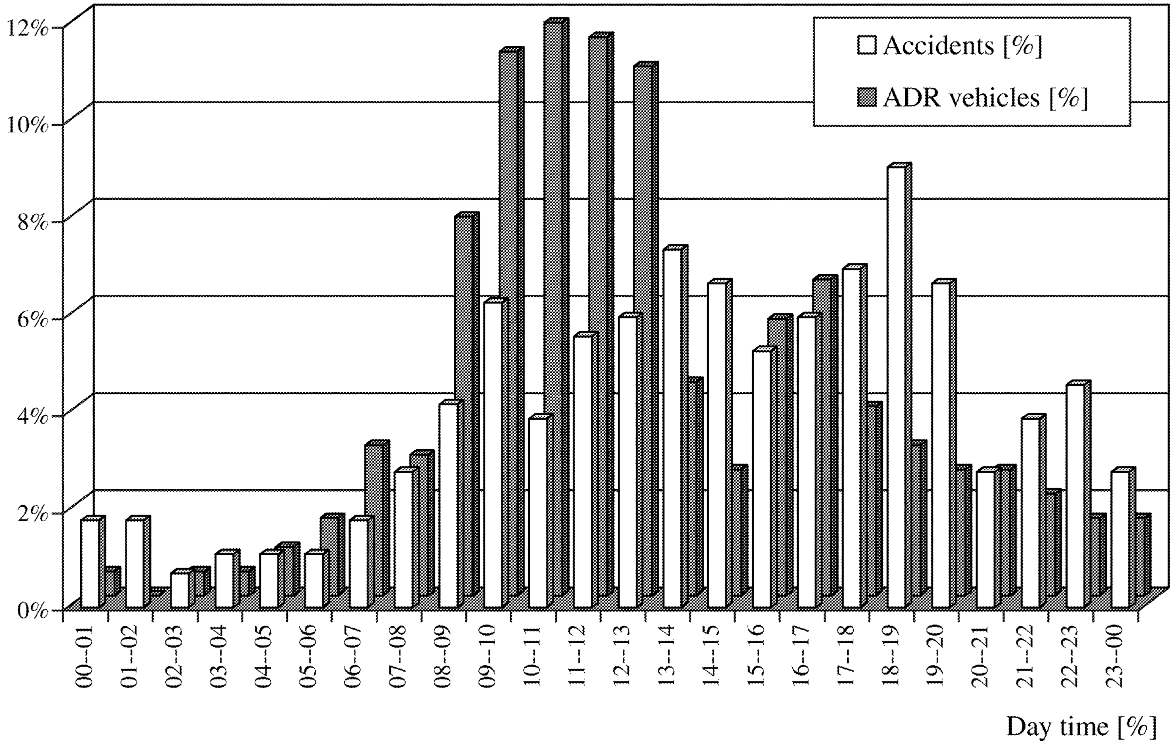

Fig. 2. Accident and heavy traffic (ADR) hourly distribution on A7 highway Genoa Serravalle.

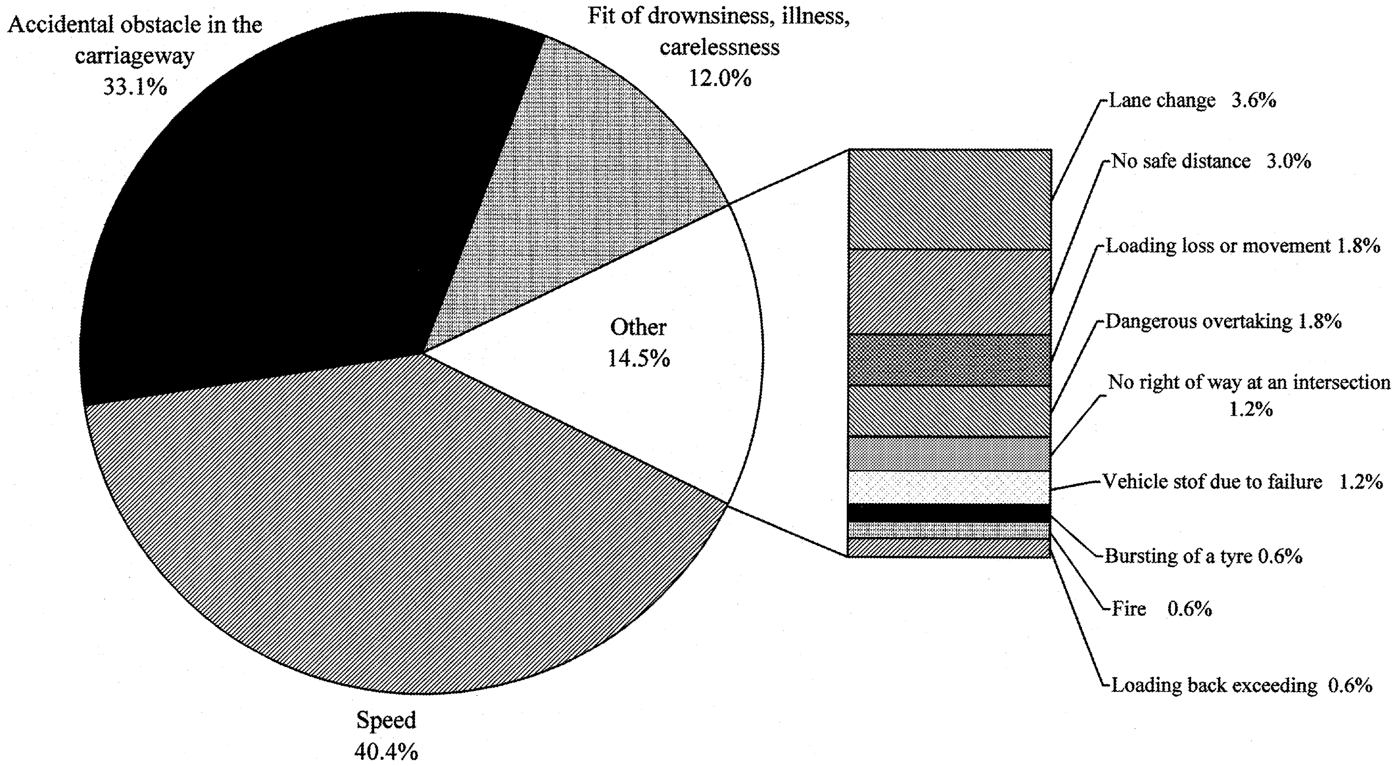

Fig. 3. Immediate accident causes.

as high as 44.5. It can be pointed out that, dealing with dangerous good transport, the main difference with process industry is the need of a noteworthy improvement in the inherent safety of the system and in the human factor.

A statistical multivariate analysis was performed by correlating historical accident data, directly collected on the field, with relevant intrinsic road factors and meteorological, traffic conditions.

The level of risk-related significance has been evaluated by using a two-sample test: by showing the difference between the observed distribution of the ranks of different sets of accidents (e.g. different by intrinsic characteristics of the road, meteorological conditions, etc.). This test has been used to indicate the significance in the difference between accidents and to select those events, which are "unusual" and thus contain "most valuable" information, with respect to certain parameters related to the accidents set [12].

A significative ($P < 0.05$) degree of correlation was highlighted making reference to the following parameters: h_1, h_2 geometrical characteristics; h_3 carriageway type; h_4 meteorological conditions; h_5 traffic intensity and typology. The number of accidents occurring in tunnel or road bridge was limited, allowing to obtain numerical results (h_6), which need further investigation. It is however clear that the data reported are to be considered more from the qualitative viewpoint, as well as that the results of risk modelling would be considered for the comparison of different alternatives, rather than in its absolute value. More accurate estimates could be developed if one has access to adequate historical accident data. An extension of the presented approach could be performed by analyzing a more complete and extended database, defining a "complete" database as an information pool which contains information on events of all possible characteristics, i.e. of all descriptor values and all possible combinations therefrom [12].

It must be also noted that we adopted a pseudo-linear relationship to describe, starting from field data, in a rather simple way, the interaction of various factors in influencing transport risk.

Tables 3–5 summarizes the results of the statistical elaboration of the different enhancing/mitigating factors, performed on the highway considered.

Table 3
Factors correlated to intrinsic road characteristics

Intrinsic characteristics	h_1	h_2	h_3	h_6
Straight road	1			
Road bend (radius > 200 m)	1.3			
Road bend (radius < 200 m)	2.2			
Plane road		1		
Slope road (gradient < 5%)		1.1		
Steep slope road (gradient > 5%)		1.2		
Downhill road (gradient < 5%)		1.3		
Steep downhill road (gradient > 5%)		1.5		
Two lanes for each carriageway			1.8	
Two lanes and emergency lane for each carriageway			1.2	
Three lanes and emergency lane for each carriageway			0.8	
Tunnel				0.8
Bridge				1.2

Table 4
Factors correlated to meteorological conditions

Meteorological conditions	h_4
Fine weather	1
Rain/fog	1.5
Snow/ice	2.5

Table 5
Factors correlated to traffic characteristics on the highway A7

Traffic characteristics	h_5
Low intensity $<$ 500 vehicle/h	0.8
Medium intensity $<$ 1250 vehicle h^{-1} with heavy traffic $<$ 125 truck per day	1
High intensity > 1250 vehicle h^{-1}	1.4
High intensity > 1250 vehicle h^{-1} with heavy traffic > 250 truck per day	2.4

4. Results and discussion

The study on the density of the population which might be exposed to Hazmat hazards from transport must include data on the population density along the route and on the so-called motorist density, taking into account, as well, the proportion which may be considered particularly vulnerable or protected. Otherwise, all individuals within a threshold distance from road stretches run the same risks regardless of their location.

The average density on the route can be calculated starting from the collected statistical data relevant to average daily traffic, average speed and geometrical data of carriageway and lanes, in each highway stretch considered. A summary of the results is schematized in Table 6, together with the average population density along the route, resulting from the elaboration of the statistics supplied by ISTAT.

By comparing these data with the usual classification of the environment typology, it appears that the first three stretches can be classified as urban/sub-urban environment, while only the two last have rural characteristics.

Table 6
Average density on highway A-7

Stretch of A7 highway	On-route density (vehicle m^{-2})	Population density (person km^{-2})
Genoa Ovest–All. A-7/A-10	2.52×10^{-3}	2729
All. A-7/A-10–All. A-7/A-12	2.85×10^{-3}	1360
All. A-7/A-12–Bolzaneto	2.57×10^{-3}	2729
Bolzaneto–Busalla	1.40×10^{-3}	766
Busalla–Ronco Scrivia	1.21×10^{-3}	290
Ronco S.–Isola del Cantone	1.09×10^{-3}	119
I. del Cantone–Piemonte	1.07×10^{-3}	36

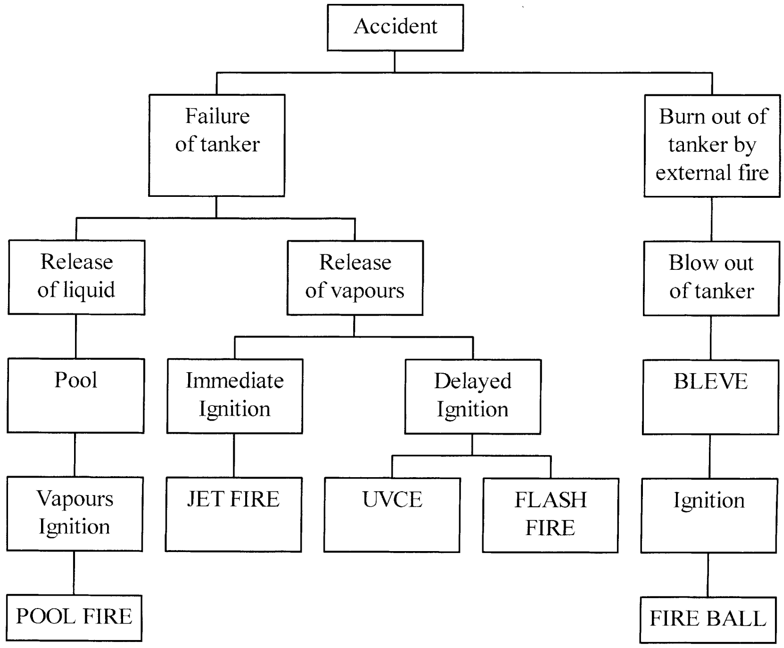

Fig. 4. Event tree of truck accident.

In order to evaluate correctly the number of on-road population involved in the accident, the response and the variations in the motorist density in consequence of an accident, were considered.

In particular, heavy goods vehicles were assumed to occupy 20 m of lane length and other vehicles 4 m. Two classes of motorist density are to be considered: the former refers to the carriageway, where the accident occurs, the latter considers the opposite carriageway, were the “ghoul effect” causes the slowing down of the traffic.

In order to evaluate the lethality area, the consequence model was applied making reference to the event tree reproduced in Fig. 4. It is clear that such approach can be implemented, taking into account more complex scenarios. For example, if the failure mode of a truck carrying LPG exposed to fire is catastrophic, then this will lead to a boiling liquid expanding vapor explosion. The immediate hazards from a BLEVE are blasts and projectiles. If the material is flammable then fire and explosion effects are a hazard. If the commodity is toxic then exposure is a hazard. [13].

Making reference only to flammable and explosive events, five scenarios were theoretically considered, i.e. BLEVE, unconfined vapor cloud explosion, jet-fire, flash-fire and pool-fire. Dealing with these scenarios, it seemed realistic to consider that owing to the congestion of the traffic and to the low protection supplied by cars and trucks, all motorists in the lethal area die. Making reference to off-road population a two steps model was considered [14], total lethality within the LD_{50} hazard range; 25% lethality between the LD_{50} and $LD_{0.1}$ ranges; no lethality beyond $LD_{0.1}$ range. The acceptability of risk and the judging criteria are commonly formulated depending on the current state of risk quantification methodology and a cost-benefit analysis, which is either explicit or implicit in the political debate where the limits were set [15].

The above-described technique was firstly adopted for the evaluation of individual risk, defined as “the frequency at which an individual may be expected to sustain a given level of harm from the realization of a specific hazard” [16]. For individual risk, we considered the upper acceptability criterion set down in The Netherlands in new situations or new developments, corresponding to 10^{-6} per year In order to compare this criterion with the Italian situation and verify its statistical validity, we elaborated data (20 years) from ISTAT, from which it results that the overall mortality rate, due to natural causes, is in the range 10^{-3} to 10^{-4} per year, for the most advantaged age bracket (i.e. people 5–45-year-old). Moreover, the individual risk of death due to accidental causes (including suicide and homicide) is about 5×10^{-4} per year. On this basis, the acceptability criterion of allowing an hazardous activity which adds less than 1% to the existing probability of death appears rather conservative for the Italian situation. Therefore, an in-depth evidence on the distribution of the risk along the route and on the localization of high spots was performed, with good accuracy and precision. On the other side, considering the potential for transported hazardous materials to cause multiple fatalities and the likelihood of the occurrence, the well-known societal risk can be modelled with the same approach, by the frequency of exceeding curve of the number of deaths (*F*/*N* curve) due

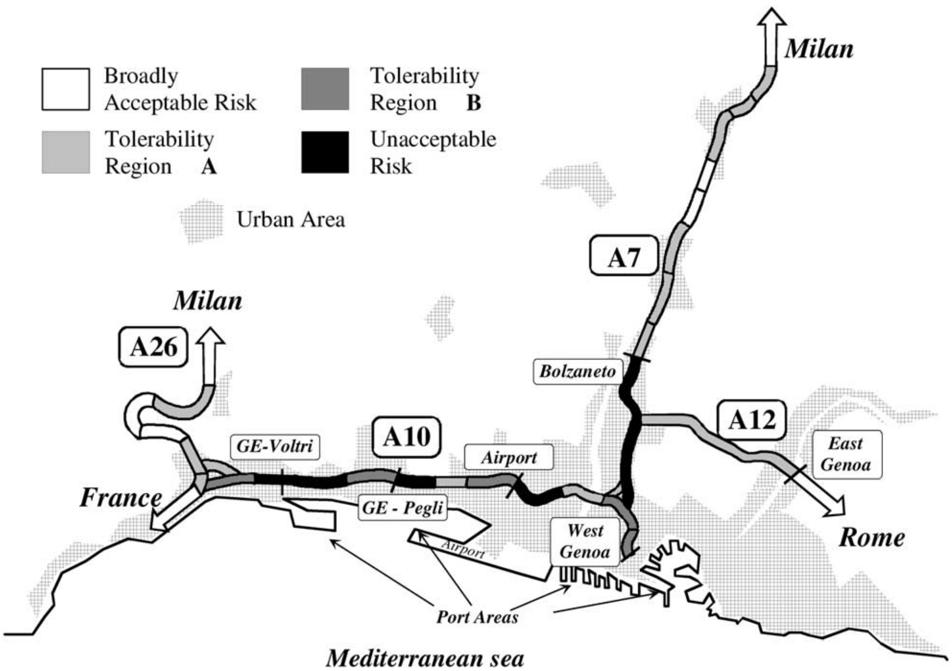

Fig. 5. Risk characterizing the different highway stretches.

Table 7
Acceptability criterion of the risk

Evaluation of the risk	Criterion	Explanation
Acceptable risk	$P < (10^{-5}/N^2)$	No need for detailed studies. Check that risk maintains at this level
Tolerability region A	$(10^{-5}/N^2) < P < (10^{-4}/N^2)$	Tolerable risk if cost of reduction would exceed the improvements gained
Tolerability region B	$(10^{-4}/N^2) < P < (10^{-3}/N^2)$	Tolerable only if risk reduction is impracticable or if its cost is grossly in disproportion to the improvement gained
Unacceptable risk	$P > (10^{-3}/N^2)$	Risk intolerable: risk cannot be justified even in extraordinary circumstances

to transport [17]. Societal risk analysis can lead, via the generation of expectation values (average number of lives lost) to the consideration of the need for, and cost benefit, of risk reduction measures, even if it involves many generalizing assumptions and averaging [14]. In all concepts, the most stringent of the personally and the socially acceptable level of risk determines the acceptable level of risk. So both criteria have to be satisfied [4]. It must be evidenced that the societal acceptable risk criterion is not standardized in the different EC countries. So, in the absence of a national statistical reference, we adopted again the *F*/*N* limit curves established in The Netherlands, dividing as well the so-called Alarp region into two bands. The results show that the risk associated with the transport of hazardous materials on the highways considered, in a number of stretches (Fig. 5), is at the limit of the acceptable level of risk set down according to the criterion schematized in Table 7, where *P* is the cumulative frequency per year and *N* the number of fatalities [18] (the hot-spots are, conservatively, indicated as characterized by unacceptable risk).

These results are to be considered carefully also owing to the fact that the stretches defined at major risk are common to different directions, namely Genoa port-North and East riviera-North. On this basis, the opportunity of limiting hazardous materials traveling during particular time bands, must be considered. As an example, making reference to the already-mentioned Fig. 2, about 53% of ADR traffic is focused in the time interval 8 a.m.–13 p.m. A second strategic opportunity consists in imposing a different highway route for hazardous materials transport. In this case-study, an alternative route is represented by A26 highway, from Genoa Voltri towards Alessandria. This highway actually collects the traffic from the west port of Genoa, from Multedo oil port and from the West riviera, but being more recent and characterized by lower intrinsic risk factors, it could gather also the traffic from East and Genoa central port. However, the practical utilization of this option is made difficult by the need of crossing a long urban stretch, while the risk of the transport of hazardous substances is lower if the route followed avoids centers of population. A solution for the risk reduction is therefore the construction of a slip road connecting Genoa central port and highway A26, even if the feasibility of this option is obviously constrained by economical and environmental impact issues. As a first attempt, Fig. 6 depicts possible alternative routes, selected on the basis of the developed risk based approach and connecting the port and airport areas with the highways A26 and A7, outside the urban area.

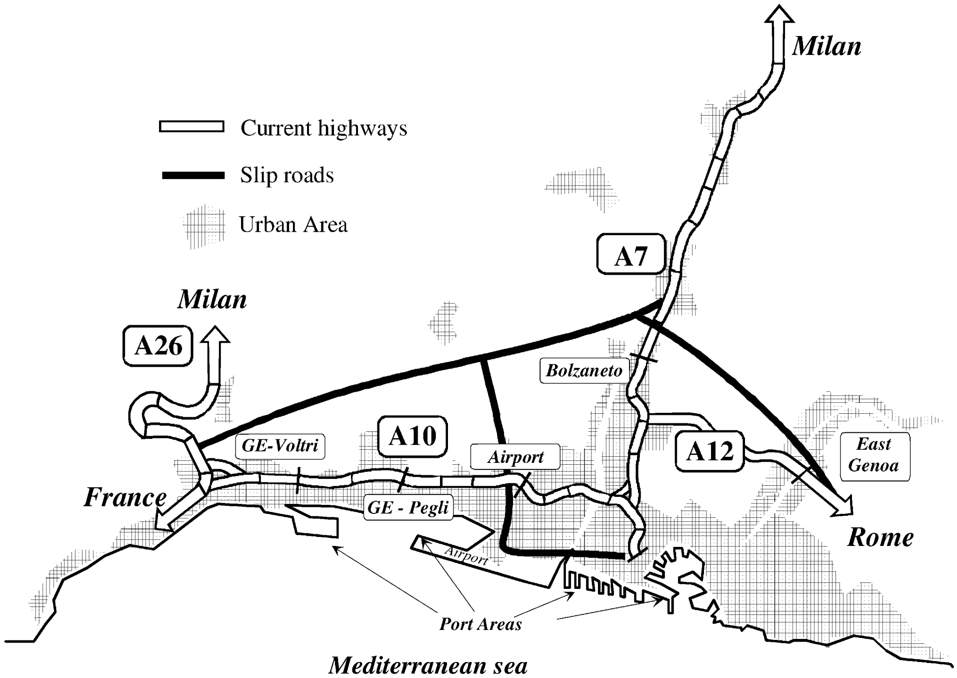

Fig. 6. Possible alternative routes.

5. Conclusions

The risk from transporting dangerous goods by road and the strategies proposed to select road load/routes are faced in this paper, by developing a site-oriented framework of general applicability. A methodological approach for the assessment of standard vehicle and dangerous goods truck flows was applied to a pilot area, allowing a statistical reinforced evaluation of intrinsic enhancing/mitigating parameters. In this way, a risk assessment, sensitive to route specifics and population exposed, is proposed and the overall uncertainties by the risk analysis can be lowered.

The developed model, of general applicability, may represent a useful tool not only to estimate transport risk but also to define strategies for the reduction of risks (i.e. distribution and limitation of ADR road traffic, improvement of highway section, alternative routes) and emergency management. In fact, one should not loose sight that the final goal is safety and that the tool based on the risk criteria approach is an instrument to measure an aspect of the whole situation.

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