A Risk Assessment Application of a Real Time Decision Support System Model for HAZMAT Transportation in a Sustainable Oriented Motorway Environment

Giampaolo Centrone[1], Maria Pia Fanti[2]
Gabriella Stecco[1] and Walter Ukovich[1]

[1] Dipartimento di Elettrotecnica, Elettronica ed Informatica
Università degli Studi di Trieste, Italy

[2] Dipartimento di Elettrotecnica ed Elettronica
Politecnico di Bari, Italy

Abstract. The transportation of hazardous material on congested motorways is an area of increasing concern for public safety and environmental awareness. This paper aims at developing a methodology with an original approach in making an attempt to encompass both professional experience and theoretical knowledge with application oriented studies from disparate areas related to the commercial transportation of HAZMAT on motorway, intimately linked with the "sustainable transportation" paradigm. The main objective is to assess quantitatively the acceptability of the Individual and Societal Risks connected with the transportation of HAZMATs. In addition, we propose a real time model of a Decision Support System for HAZMAT transportation on a sustainable oriented motorway environment. Finally, we offer an application of the proposed model. The case study involves a stretch of A4 motorway in the North-East of Italy.

1 Introduction

Economic globalization favors the increase of geographic mobility involving the expansion of transportation systems that is joined with the rise in land prices and the increase of air and noise pollution. In this world development [13], dangerous goods are used in many processes in industry all over the world and this has been justified by the economic revenue generated by their use. A dangerous good (named hazardous material or HAZMAT almost exclusively in the United States) is any solid, liquid, or gas that can harm people, other living organisms, property, or the environment. Due to its nature, every production, storage and transportation activity related to the use of HAZMAT have many risks for both society and environment and are often subject to chemical regulations. In this scenario, a new factor has acquired more and more importance: sustainability. Sustainability [5] is a systemic concept that relates to the continuity of economic, social, institutional and environmental aspects of human society. As HAZMATs are transported throughout the world in a great number of road shipments, their commercial transportation could be catastrophic and poses risks to life, health,

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property, and the environment due to the possibility of an unintentional release. Transportation of HAZMATs on road actually represents a potentially high risk in regard to the nature of the HAZMAT carried by trucks and the physiochemical events associated with these materials (radioactivity, explosion, toxicity, corrosion etc.), the localization and the density of the concerned (population, economic activities, buildings, networks, infrastructures, natural areas etc.), the characteristics and state of the roads (topography, layout, tunnels etc.), the density of the traffic, and the environmental conditions (weather, natural events etc.). While HAZMAT accidents are rare events, in a sustainable vision of development it is necessary to integrate risk mitigation and prevention measures into the transportation management in order to avoid the risks turning into real events. In spite of this issue, HAZMAT type, quantity, itinerary and delivery time are not precisely known by the public authorities, the highway and motorway companies, and the population. As a consequence, one of the main objectives of research in this field is to provide appropriate answers to the safety management of HAZMAT shipments, in collaboration with the principal parties involved in the goods transportation process. Researches in this area [6], focuses on two main issues: i) to assess the risk induced on the population by HAZMAT vehicles traveling on the road network; ii) to involve the selection of the safest routes to take.

1.1 Problem Definition

In Italy about 80% of road traffic is represented by the delivery of goods, and the overall trend in Europe seems to predict an increase of 30% within 2010. About 18% of this freight traffic is currently represented by HAZMAT transportation, but a clear awareness of HAZMAT transportation world flows on road and on the other transportation modes - as well as of the related security and safety aspects - is not present yet, at least from a social and economic point of view. Intelligent Transportation System technologies have also made possible the gradual reduction in journey times and thus opening up new economic horizons, with the conquest of wider markets. The freedom gained by the ease of movement, however, has a cost in terms of environmental impact, quality of life and safety. The risk is that the increasing demand for current and especially future can make that the cost is no longer sustainable. However, the actual accident risk and impact is not calculated. In addition, when, due to unforeseen events (traffic jams, accidents, etc.), they need to change route, they do not have any particular guidance on the safest alternative route. Motorways are one of the most important supporting infrastructures of transportation networks: they assure efficient and safe mobility of persons and goods in the world and represent the largest part of the built environment. Motorway is a term for both a type of road and a classification or designation. Motorways are *high capacity roads* designed to carry fast motor traffic safely. In the E.U. they are predominantly dual-carriageway roads with a minimum of two lanes in each direction and all have grade-separated access. Motorways are comparable with North American freeways as road type, and interstates as classification. In Italy, according to [3], HAZMATs transportation by road should require constant monitoring (tracking and tracing) of vehicles and cargo handled. This requirement involves a series of obligations to which must meet companies under the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR). As a consequence, motorway concessionaires must adopt real time systems to monitor HAZMATs carried and support the decisions on the transportation (MAS Monitoring - Alarm - Alerts).

2 Problem Solution

In Fig. 1 we propose a real time decision support system (DSS) model for monitoring of HAZMAT vehicles, aiming at solving the above stated problems.

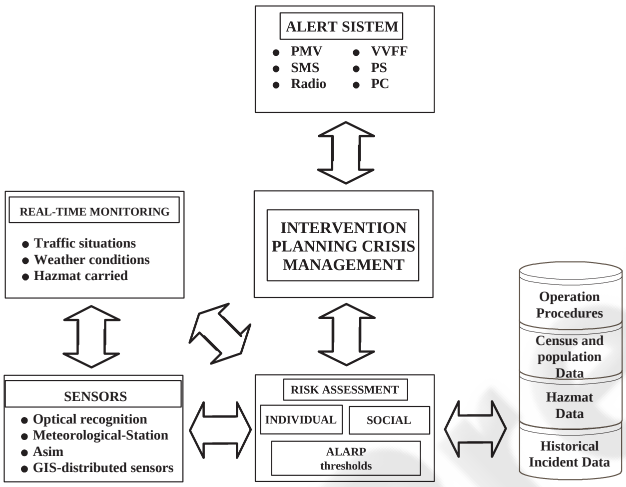
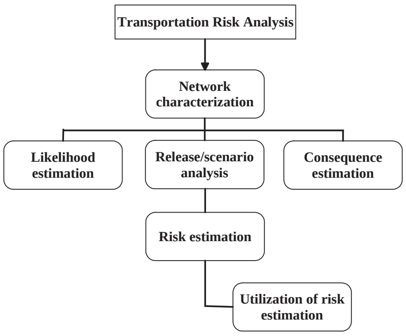


Fig. 1. The proposed System Architecture.

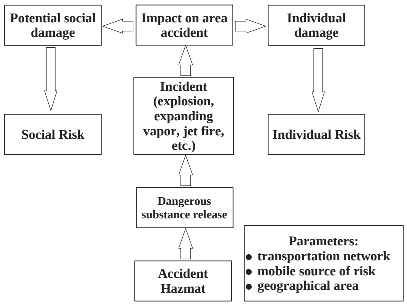
Such system should aim at calculating and evaluating in real time the individual and societal risk related to the transit of HAZMAT on the motorway network. Then, it should allow a monitoring in real time of the means transporting HAZMAT, a risk assessment derived from the carriage, the alert and notification of emergencies, and an anomalies reporting for a subsequent planned intervention. The model derives from the application of the quantitative risk assessment (QRA) methodology presented in Fig. 2(a).

We must take into consideration the following cause-effect chain which can be associated to a vehicle transporting one or more HAZMATs: the vehicle may be subject to a road accident (*accident*); the accident may cause the release of material transported (*release*); the release may cause a series of events (*incident*); the incident has an effect in the area surrounding the point accident. The model refers to damage to persons and in particular to death. The model of risk assessment derived from road transportation of HAZMAT is presented by a schematic representation in Fig. 2(b).

Risk assessment is typically structured as a process resulting from the interaction among the transportation network (in this case motorway), the vehicle (or better the traveling risk source), and the impact area. The model evaluates simultaneously the consequences and the frequencies of occurrence of possible scenarios. This makes it possible to assess



(a) The Transport Risk Assessment Methodology.



(b) The Risk Assessment Model.

Fig. 2.

quantitatively the *individual risk* and the *societal risk* (if the distribution of the people liable to be exposed is at hand). A complete assessment of the risks due to HAZMAT by road would require to consider all the possible weather situations, all the kinds of accidents, with all the types of vehicle partially or fully loaded. Such an evaluation is completely impossible and some simplifications have to be introduced. The QRA model is based on the following steps: choice of a restricted number of HAZMATs, choice of some representative accidental scenarios implying those HAZMAT with their usual packagings, identification of physical effects of those scenarios for an open air or a tunnel section, evaluation of their physiological effects on road users and local population, taking into account the possibilities of escape/sheltering, determination of the yearly frequency of occurrence for each scenario.
$F(N)$ curves and their expected values are the major outputs of the QRA model. According to [7], *Frequencies / Gravity curves* ($F(N)$ curves) stand for the annual frequency of occurrence F to have a scenario likely to cause an effect (generally, the number of fatalities) greater than or equal to N and *Expected value* (EV) is the number of fatalities per year, obtained by integration of a $F(N)$ curve.

3 How to Characterize the Risk in Transporting of HAZMAT on Motorway Environment: A Case Study

In this section we present an application of the real time model for the calculation of the Individual and Societal Risks in a motorway environment.

The Transportation Network. We consider the motorway network of an Italian concessionaire, in the North-East of Italy, S.p.A. Autovie Venete. In particular we refer to the sections summarized in Tab. 1. The network under consideration has been modeled as a network with nodes and links where nodes represent exits / junctions of the motorway and links the stretches (sections) of motorway between two exits / junctions. Let N_{link} be the set of links of the motorway network and l a generic link. For each link,

Table 1. Link length, average population density, HAZMAT and number of vehicles carrying them on tested links.

Link	Length (Km)	Average Population Density ($inhab/Km^2$)	Substance type	Num. of Vehicles
S.Stino di Livenza - Portogruaro	12.8	214.35	Chlorine	2
Portogruaro - Latisana	13.5	166.05	Ammonia	2
Latisana - S. Giorgio di Nogaro	17.6	112.66	Hydrochloric Acid	2
			Nitric Acid	2

the following data have been obtained: length [Km], and average population density [inhabitants / Km], around the link. According to [18], the average population density has been calculated using a GIS (Geographical Information System) overlapping the geographical map of the municipalities on the motorway network of S.p.A. Autovie Venete in order to identify common cross on each link. Then, for each link, we have identified the municipalities involved and measured the kilometers of infrastructure that pass through each town in order to identify the weights for calculating the average density on the link. These weights have been derived by dividing the kilometers of infrastructure that affect each municipality with the total length of the link. Note the density of population in each Italian municipality, using data on the census of 2001 [9], we shall calculate the weighted average with weights determined in the previous step. Tab. 1 illustrates the links in discussion with the relevant data.

The Accident Probability. We use the Truck Accident Rate of Harwood [8] in order to calculate the accident probability ($\lambda_{inc}(l)$) in terms of $events/(vehicle * km)$. We can also calculate the rate of accidents on a single stretch of length unit road by using the number of accidents in a time period of ten years and the total distance traveled by heavy vehicles during the same period, data provided by AISCAT (Associazione Italiana Societá Concessionarie Autostrade e Trafori) [1].

$$TAR_{y_r} = \frac{A_{y_r}}{VKT_{y_r}} \tag{1}$$

where TAR_{y_r} is the average accident rate for trucks $events/(vehicle * km)$ on the Italian motorway network for year y_r; A_{y_r} is the number of accidents involving trucks on the Italian motorway network; VKT_{y_r} is the total distance traveled (vehicle-kilometers) by trucks on the network under consideration. Tab. 2 shows the number of accidents involving heavy vehicles, the total distance traveled and the *Truck accident rate* year by year from 1997 to 2007 and the summary data (extension, routes) for the years under consideration. The last row presents the data that we use in the model.

The HAZMAT. in the next step, we select the HAZMATs that will be considered in calculating the risk. In particular, according to [16], we have considered substances that are more frequent or significant on the network under consideration. For each of these goods we obtained the following data (summarized in Tab. 3):

– the probability of release due to the accident ($p_{rel}(\nu)$) depending in general on the characteristics of the vehicle transporting the HAZMAT and on the type of accident where the vehicle is involved. This probability is taken from [2].

Table 2. Accidents and summary data year by year from 1997 to 2007.

		ROUTES	ACCIDENTS	TAR
YEAR	EXTENSION	$(veh. - km)$		
	KM	*Heavy*	*Heavy*	*Heavy*
1997	5371	$1.4428{*}10^{7}$	7825	$5.42{*}10^{-7}$
1998	5380	$1.5161{*}10^{7}$	8854	$5.84{*}10^{-7}$
1999	5380	$1.5974{*}10^{7}$	10024	$6.28{*}10^{-7}$
2000	5380	$1.6790{*}10^{7}$	9681	$5.77{*}10^{-7}$
2001	5388	$1.7254{*}10^{7}$	9647	$5.59{*}10^{-7}$
2002	5388	$1.7836{*}10^{7}$	9691	$5.43{*}10^{-7}$
2003	5388	$1.8359{*}10^{7}$	9198	$5.01{*}10^{-7}$
2004	5391	$1.9059{*}10^{7}$	8841	$4.64{*}10^{-7}$
2005	5432	$1.9184{*}10^{7}$	9005	$4.69{*}10^{-7}$
2006	5441	$1.9764{*}10^{7}$	9000	$4.55{*}10^{-7}$
2007	5446	$2.0229{*}10^{7}$	8613	$4.26{*}10^{-7}$
		$1.9403{*}10^{8}$	100379	$5.17{*}10^{-7}$

– the types of possible releases classified in relation to the size of the leakage hole ($N_{rel,t}(\nu)$) and the rate of release or the amount of material spilled ($p_{rel,t}$).
– the types of consequences of *incident* caused by different types of release of HAZMAT given the *accident* for a given type of substance ($N_{out}(\nu, r)$).
– the likelihood of occurrence of a final result given the *incident* ($p_{out}(i)$). This probability is derived for each triplet [substance - leakage - type of final outcome] from the information relating to incidents involving HAZMAT from 1997 to 2008 reported in the HMIS database [14]. This database contains detailed information on accidents involving HAZMAT in the U.S..
– the frequency of occurrence of a given scenario: $f^{scen}_{\nu,t}(i, r) = \lambda_{inc} \cdot p_{rel}(\nu) \cdot p_{rel,t}(r) \cdot p_{out}(i)$
– the lethal area radius of each pair [type of release - final outcome] calculated using the free software RMPComp distributed by U.S. EPA (Environmental Protection Agency) [15].

Assumptions. In the application we have considered the following assumptions.

1. $\lambda_{inc}(l)$ uniform throughout the link and constant for all links taken into consideration: λ_{inc};
2. exposure area of *danger circle* type [7] centered at the point of the incident with a radius depending on the type of substance, release and final outcome;
3. any person within the exposure area suffers from the same injury (death) in the same way regardless of the position, while people outside that area are not affected;
4. the seasons (j), the weather conditions on link $C^{t}_{met}(l)$ and the wind direction $\vartheta^{t}(l)$ are not taken into account;
5. the simulation is performed on a single moment in time;
6. risk neutral model ($\alpha = 1$) [17].

Individual Risk Calculation. The simulation was carried out on three adjacent links. As individual risk is the annual probability of an individual placed in a designated point

Table 3. Frequency scenarios.

HAZMAT	p_{rel}	**Release Type (Spillage)**	p_{relt}	**Incident Type (Cloud)**	p_{out}	**Incident Prob.**	**Scenario Frequency**	**Lethal area radius (Km)**
Chlorine	0.010	Small	0.94	Toxic	1	$9.40{*}10^{-3}$	$4.86{*}10^{-9}$	1.0
	0.010	Medium	0.04	Toxic	1	$4.00{*}10^{-4}$	$2.07{*}10^{-10}$	2.8
	0.010	Large	0.02	Toxic	1	$2.00{*}10^{-4}$	$1.03{*}10^{-10}$	5.6
Ammonia	0.025	Small	0.93	Toxic	1	$2.31{*}10^{-2}$	$1.20{*}10^{-8}$	0.2
	0.025	Medium	0.05	Toxic	1	$1.33{*}10^{-3}$	$6.88{*}10^{-10}$	1.0
	0.025	Large	0.02	Toxic	1	$5.32{*}10^{-4}$	$2.75{*}10^{-10}$	2.1
Nitric Acid	0.015	Small	0.93	Toxic	1	$1.39{*}10^{-2}$	$7.19{*}10^{-9}$	0.3
	0.015	Medium	0.06	Toxic	1	$8.82{*}10^{-4}$	$4.56{*}10^{-10}$	0.5
	0.015	Large	0.01	Toxic	1	$2.21{*}10^{-4}$	$1.14{*}10^{-10}$	1.9
Hydrochloric Acid	0.015	Small	0.92	Toxic	1	$1.38{*}10^{-2}$	$7.13{*}10^{-9}$	0.3
	0.015	Medium	0.05	Toxic	1	$7.37{*}10^{-4}$	$3.81{*}10^{-10}$	0.8
	0.015	Large	0.03	Toxic	1	$4.81{*}10^{-4}$	$2.49{*}10^{-10}$	2.6

Table 4. Geographical coordinates of the points chosen for Individual Risk calculation.

Point Location	**Latitude**	**Longitude**
Portogruaro Centro	45.78	12.83
Area di Servizio Fratta Nord	45.80	12.88
Latisana Ospedale	45.77	13.00
Muzzana del Turgnano Centro	45.82	13.13

of interest is affected by some degree of damage as a result of a specific incident [10], four points were chosen as "hot spots" at which to calculate the individual risk. Tab. 1 and 4 show respectively the links with the relevant substances circulating and the geographical coordinates of the points chosen for the calculation of individual risk. The network portion and the points under consideration are represented in Fig. 3.
For the calculations we have used the formula presented in [11] and [12] suitably modified to take into account the previous assumptions, the motorway environment and the real time events. More details can be found in [4]. Consequently, we made explicit that each event i belongs to the $N_{(out)}(\nu)$ of the general model may consist of a pair [type of release - final outcome] as in this case.

$$\text{IRP} = \sum_{i=1}^{N_{links}} \sum_{v=1}^{N_{veh}(l)} \sum_{r=1}^{N_{rel}(\nu)} N_{type}(l,\nu) f_{rel}(\nu,r) \cdot \\ \cdot \int_{L_l} \sum_{i=1}^{N_{out}(\nu,r)} p_{out}(i) \cdot V_{Q(x)v\rightarrow S}(i) dL_l \quad (2)$$

$$f_{rel}(\nu,r) = \lambda_{inc} \cdot p_{rel}(\nu) \cdot p_{rel,t}(r) \quad (3)$$

Fig. 3. Representation of points and the network portion under consideration.

Table 5. Simulation results - Individual Risk.

Point Location	Individual Risk
Portogruaro Centro	$2.28{*}10^{-9}$
Area di Servizio Fratta Nord	$5.78{*}10^{-9}$
Latisana Ospedale	0
Muzzana del Turgnano Centro	$1.75{*}10^{-9}$

where $N_{veh}(l)$ is the number of different vehicle topologies on link l, $N_{type}(l,\nu)$ is the number of vehicles carrying the dangerous substance ν currently in transit on the link l, $N_{rel}(\nu)$ is the number of release cases of the dangerous substance ν, L_l is the route of link l and $V_{Q(x)_\nu \to S}(i)$ is equal to 1 if the point S is inside the *danger circle* centered at the point of possible accident Q related the triplet [substance - release type - final outcome]; 0 if the point S is external the same *danger circle*. Line integral was calculated using the method of Cavalieri-Simpson, dividing each of the three links in 10 intervals of equal length. Tab. 5 shows the results of the simulation.

From the evidence we can establish that the individual risk in the four points is acceptable according to the British ALARP threshold as the value is much lower than the limit value of 10^{-6} [10].

Societal Risk Calculation. In order to calculate the societal risk, we refer again to [11] and [12] suitably modified. For each link knowing the vehicles that are going through, we use (4) to obtain the $F(N)$ curves representation (for details see [4]).

$$F(N) = \sum_{i=1}^{N_{link}} \sum_{v=1}^{N_{veh}(l)} N_{type}(l,\nu) \cdot \sum_{i=1}^{N_{out}(\nu)} \int_{L_l} \delta^{N}_{scen}(i, C_{met}(l)) dL_l \qquad (4)$$

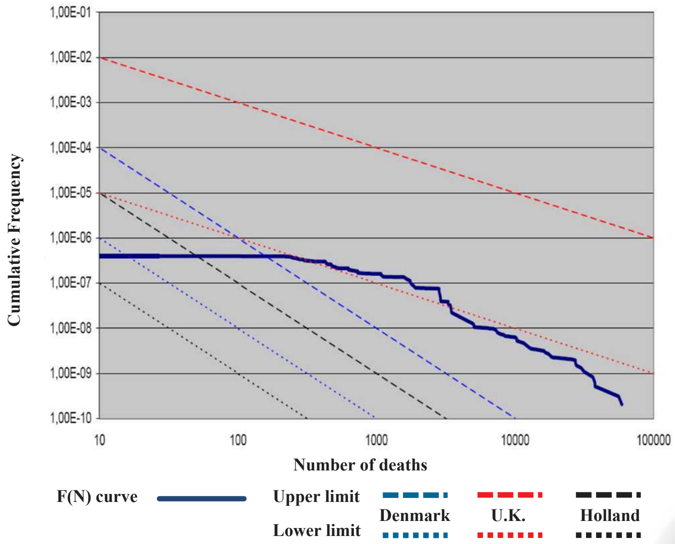


Fig. 4. Simulation results - Societal Risk.

The curve $F(N)$ is drawn in Fig. 4, referred to the simulation with different thresholds of acceptability [12].

It can be seen that at the moment of the simulation the societal risk, according to the British acceptability thresholds, is in the ALARP zone, whereas according to Dutch and Danish thresholds it is not acceptable.

4 Conclusions

The transportation of HAZMAT on congested motorways is becoming an area of increasing concern for public safety and environmental awareness. The risk to population and damage to environment is a major concern to the general public and government policy makers. Against these problems we present a methodology to perform the individual and societal risk assessment related to HAZMAT transportation in a sustainable oriented motorway environment. It constitutes an approach based on the GIS. The assessment criteria, based on the “sustainable transportation” paradigm, are structured into efficiency, cohesion and environmental criteria. The aim is assessing whether these risks are acceptable and possibly, if they were not, notify the situation through alert messages in order to take appropriate actions. We offered an application of the proposed real time model for the calculation of the Individual and Societal Risks involving in the case study a stretch of A4 motorway in the North-East of Italy. In spite of a limited number of trucks transporting HAZMAT on the motorway, the results of the application point out the concrete possibility to exceed the thresholds of the ALARP limits for the societal risk.
With regard to possible developments, the QRA methodology could be to extend, in

particular the model for calculating the individual and societal risk, to other situations of HAZMAT transportation by other transportation modes.

References

1. AISCAT: Rapporto incidentalitá rete autostradale italiana 1997-2007. Statistiche Aiscat, Associazione Italiana Societá Concessionarie Autostrade e Trafori, (2008)
2. Brown, D.F., Dunn, W.E.: Application of a Quantitative Risk Assessment Method to Emergency Response Planning. Computers & Operations Research, 34 (2007) 1243–1265
3. CEI: Road traffic and transport telematics Standards framework. Review of the applications and technological trends, normative references Annex to CEI UNI 70031 (2001) 1–18
4. Centrone, G.: Modeling a real time decision support system for HAZMAT transportation in a sustainable oriented motorway environment. Ph.D. Thesis, Universitá di Trieste (2009)
5. Centrone, G., Coslovich, L., Pesenti, R., Ukovich, W.: Social responsibility and sustainability in motorway Corporate Governance. International Journal of Environment and Sustainable Development 7 (2008) 94–113
6. Centrone, G., Pesenti, R., Ukovich, W.: Hazardous Materials Transportation: a Literature Review and an Annotated Bibliography. In: Bersani, C., Boulmakoul, A., Garbolino, E., Sacile, R. (eds.): Advanced Technologies and Methodologies for Risk Management in the Global Transport of Dangerous Good. NATO Science for Peace and Security Series, Vol. 45. IOS Press, Amsterdam (2008) 33–62
7. Erkut, E., Tjandra, S.A., Verter, V.: Hazardous materials transportation. In: Barnhart, C., Laporte, G. (eds.): Transportation, Handbook in OR & MS, Vol 14. Elsevier (2007) 539–621
8. Harwood, D.W., Russell, E.R., Viner, J.G.: Procedure for developing truck accident and release rates for hazmat routing. Journal of Transportation Engineering 119 (1993) 189–199
9. ISTAT: Quattordicesimo censimento generale della popolazione italiana (2001). http://cartema2.istat.it/home_cartema/iisstart.htmh
10. Jonkman, S.N., van Gelder, P.H.A.J.M., Vrijling, J.K.: An overview of quantitative risk measures for loss of life and economic damage. Journal of Hazardous Materials 99 (2003) 1–30
11. Leonelli, P., G. Spadoni, G.: A new numerical procedure for calculating societal risk from road transport of dangerous substances. In Proceedings SRAEurope Annual Meeting (1996) 243–246
12. Leonelli, P., Bonvicini, S., Spadoni, G.: Hazardous materials transportation: a Risk-analysis-based routing methodology. Journal of Hazardous Materials 71 (2000) 283–300
13. Nederveen, A.A.J., Konings, J.W., Stoop, J.A.: Globalization, International Transport And The Global Environment: Technological Innovation, Policy Making And The Reduction Of Transportation Emissions. Transportation Planning and Technology 26 (2003) 41–62
14. PHMSA - U.S. Department of Transport: HMIS database. (2006) https://hazmatonline.phmsa.dot.gov/IncidentReportsSearch/Search.aspx
15. RMP*Comp 1.07 http://www.epa.gov/OEM/content/rmp/rmp_comp.htm
16. Rossetto, A.: Sviluppo di un sistema DSS per il monitoraggio e l'analisi quantitativa del rischio nel trasporto di merci pericolose in autostrada. MSc. Thesis, Universitá di Trieste (2008)
17. Slovic, P.: Perception of risk. Science (1987) 280–285
18. Zhang, J.J., Hodgson, J., Erkut, E.: Using GIS to assess the risks of hazardous materials transport in networks European Journal of Operational Research 121 (2000) 316–329