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Towards a Decision Support System for Real Time Risk Assessment of Hazardous Material Transport on Road

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Abstract: Several emerging telematics technologies allow a new definition of the risk caused by the transport on road of hazardous material (hazmat), which can be more related to space and time varying factors. Since there are many varying factors (for example, the state of the road, of the weather, of the driver, of the hazardous material) which affects its degree, hazmat transport risk is by definition dynamic, so that conventional definitions of natural and industrial hazard and risk are not adequate. In addition, while the management systems related to the real-time planning of hazmat routing can be oriented towards the achievement of a minimum risk, on the other hand, with their decisions, they are the main actors that do influence the current value of risk on a territory. These aspects are discussed throughout this work and a proposal of decision support system integrating all these aspects is suggested, describing the necessary steps to develop it. Although the DSS is at a preliminary stage of development, an introductive demonstration of dynamic risk assessment is shown on a specific territory, namely the western districts of Liguria region (Italy) which are heavily interested by hazmat traffic, and characterized by transport infrastructures generally quite close to civil and industrial settlements.

Keywords: Decision support systems, real time risk management, hazmat, logistics, transport.

1. INTRODUCTION

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 is currently represented by hazardous material (hazmat) transportation.
The current situation and the predicted trend of hazmat transportation require a particular attention as regards the definition of the risk, with attention to exposure of the population and the possible impact over the environment.
Conventional approaches generally define the hazmat transport risk as an industrial risk with static components and with statistic components of the hazard. Since there are many factors (for example, the state of the road, of the weather, of the driver, of the hazardous material) which affects its degree,, hazmat transport risk is intrinsically dynamic, so that conventional definitions of natural and industrial hazard and risk are not adequate.
In our work, a new approach is introduced and discussed, in order to model and to assess properly the hazmat transport risk on road of petroleum products (class 3 of hazardous material classification made by Federal Motor Carrier Safety Administration, US [2001]) made by tank trucks. In particular, a dynamic evaluation of the likelihood that certain events (of assigned intensity) take place (i.e., the hazard) over the infrastructures of the considered territorial system is discussed. The preliminary activities towards the definition of a decision support system (DSS) for real time risk assessment of hazmat transport on road are also presented.
This DSS, which can be also classified as an Environmental Decision Support System (EDSS) (Rizzoli and Young, 1997), is based on three modules:

- the GIS based interface for the characterization of the problem and for the computation of the parameters involved in the formulation of the problem;
- a real-time database where data characterizing the risk are stored;

- the optimization module, defining the optimal tank truck routing.

It is worthwhile to underline that, in the proposed DSS, the aim is to support dynamic route guidance of hazmat transport, and the problem is formalized as a mathematical programming problem, where the decisional variables are related to the routing of a fleet of trucks. In other words, the final goal of our research is to support decision makers in the hazmat transport planning, which, in a modern view, should be oriented not only to cost minimization but also towards risk minimization.

Real-time hazmat transport risk assessment is so a pre-requisite to develop such a DSS, and the related methodological aspects are discussed in the next section.

Finally, a preliminary demonstration of real-time hazmat transport risk assessment is presented over a particular area, namely western districts of Liguria region (Italy) which are heavily interested by hazmat traffic, and characterized by transport infrastructures generally quite close to civil and industrial settlements.

2. METHODS

This work is part of a greater project (see acknowledgments) aiming to reduce the impact of hazmat transport on road by tank trucks of petroleum products. In this preliminary phase, a correct definition of hazmat transport risk is required. It should be observed that this definition could be related to the definition of both industrial and environmental risk. In fact, a tank truck transporting petroleum products can be viewed as a repository of a chemical product that, just as a conventional petroleum tank in a refinery, can represent a danger for the population. The main difference in this case, is that this danger is moving throughout a network of roads. So, while "static" pre-defined emergency plan and protocols are adequate to recover from an emergency in an industrial site that is settled in a precise geographic location with a clear definition of the possible interactions with the population and the environments, the same can not be assed for a moving hazard. In fact, the risk of hazmat transport dynamically changes in time and space as regards both the stress to which the hazmat transportation is subject to, to the possible impact an accident may cause. As an obvious example, a tank truck is subject to different stresses when traveling on a safe straight road with nice meteorological conditions or when traveling on a winding road during a storm. Similarly, as regards the possible consequences of an accident, obvious examples may be related to a tank truck moving either in a suburb area or on a bridge over a river, or moving over a flat land with no important groundwater resources. In addition, a dynamic representation of impacts would be also necessary; for example, the risk released by a truck passing a residential area is certainly related to time: at night or at the weekend the potential damage will be greater than during hours of business.

Dynamic risk assessment is needed since it is necessary to decide in a specific instant and in real-time the route minimizing the time/space varying risk. Dynamic risk assessment is also nowadays possible due to the several emerging telematics technologies allowing a more detailed definition of the dynamics components that affect in real-time the hazard.

A proposal of dynamics definition of risk for hazmat transport is so required. In the following subsections these aspects are introduced.

2.1 Conventional risk definition of industrial and environmental risk

Throughout this work, the following general definitions of hazard and risk are taken into account (U.S. Department of Transportation Research [2000]). Hazard is related to the intrinsic characteristic of a material, condition, or activity that has the potential to cause harm to people, property, or the environment, and it is often defined in terms of a probability. Risk is related to the combination of the likelihood and the consequence of a specified hazard being realized.

In the context of industrial hazards, risk is generally defined as a function (most frequently a product) of the likelihood frequency of a hazardous event and of its related magnitude in terms of damage on people, property or the environment.

In the context of natural hazards, the definition by UNESCO [1972] is generally adopted, which allows computing the risk on a set of territorial elements that may be damaged by a natural hazard, as a function (specifically, a product) of the likelihood of the hazard, of the value of elements (people, property, or the environment) at risk, and the so called vulnerability, that is the capacity of an element to resist to a hazard event.

It is quite evident that these two definitions are somehow equivalent: both of them include a term related to the probability of the hazard, and both include a term related to the strength of the effects on the elements that are in the geographic and temporal neighborhood of the event.

2.2 Risk definition of hazmat transportation

Both the previous definitions may be also adequate to the definition of hazmat transport risk taking into account that the probability of an event and its magnitude are time/space varying, since they are subject to several external/internal time/space varying factors. These varying factors represent the main difference with traditional environmental and industrial risk definition. In environmental and industrial risk definition the probabilistic component of the hazard is often the main relevant aspect, and since the occurrence of a catastrophic event can be hardly controlled. In hazmat transport risk definition the probabilistic evaluation of the hazard of a road tract is also important, but here the risk can be controlled in real-time, for example, by keeping hazmat trucks away from that road tract. In addition also the impact of the hazard, which is usually computed as a worst/mean scenario evaluation in environmental and industrial risks, in hazmat transport risk evaluation should be more properly monitored and assessed in real-time.

In general, the transport routes can be taken into account as risk sources represented by segments that, in turn, are obviously made of an infinite number of points that are also a source of risk.

There are several ways of quantifying hazmat transport risk, as shown by Erkut and Verter, [1998]. An accurate definition should include at least the characteristics of the following interacting factors: the transport network, the vehicles and the territory.

A frequent approach in literature for hazmat transport risk analysis is based on three separate stages:

1. to determine the probability of an accident involving the hazmat release;
2. to estimate the level of potential exposure, given the nature of the event;
3. to estimate the magnitude of the consequences (fatalities, injuries and property damage) given the level of exposure.

In these stages, probability and conditional distributions are computed. In practice, due to lack of information, the three stages process is not completely developed, and a worst-case approach, taking into account the potentially impacted population, is often used (Zhang *et al.* [2000]). Therefore, the expected consequence risk associated with a road link *l*, is often expressed as (Zhang *et al.* [2000]):

$$R_l = S_l P_l N_l \qquad (1)$$

where, R_l is the total risk from hazmat movement on link *l*, S_l the number of shipments on link *l*, P_l the probability of a release accident for a single shipment on link *l* and N_l the total number of persons who will be affected by a release accident on link *l*. The rarity of hazmat accidents makes it very difficult to calculate empirical hazmat accident probabilities for each link; general truck accident rates are sometimes used to estimate these probabilities.

For each relevant point of the route, a more detailed analysis can be performed to define the magnitude of the risk evaluating further aspects, such as for example, the area involved by the worst case of accident, the behavior of the emitted plume modeling it for instance as a Gaussian plume model.

Several important works address these aspects. Among others Leonelli *et al.* [1999], two original detailed procedures for the evaluation of individual and societal risk, have been introduced, which can take into account, integrating them in the same approach, different transportation modes, hazardous materials, meteorological conditions and seasonal situations, a non uniform wind probability density distribution and an accurate description of the indoor and outdoor population both on-route and off-route.

Among the Geographic Information System (GIS) based approaches, the work by Zhang *et al.* [2000] adopts map algebra techniques to combine airborne contaminant concentrations mathematically with the population distribution to estimate risk, for a release at any point on a network, for all parts of the study area.

2.2 The role of new emerging technologies in the risk definition of hazmat transportation

There is no doubt that a relevant role in the risk definition of hazmat transportation is carried out by new emerging technologies. Several specific technologies are both ready and often already installed on board to monitor the state of the hazmat and of the overall travel and to record it in a sort of on-board “black box”. The most relevant innovation in this respect is the possibility to know in real-time the exact truck position, and to transfer this information jointly with the real-time “black box” records at low price wherever it may be requested.

In this respect, wireless technologies, specifically, Global System for Mobile communication (GSM) and General Packet Radio Services (GPRS), coupled with Global Positioning Systems (GPS) represent well established and emerging technologies adopted to track in real-time a float of trucks. For example, the SIMAGE project by Di Mauro *et al.* [2002], which aims to develop a pilot system in some Italian district areas for the monitoring and control of the transport of dangerous substances mainly via road, is partially based on this technical solution.

It is quite evident however that GPRS and GPS are not the solution of their own, but they should be inserted in adequate information system, including GIS (Contini *et al.* [2000]) and optimization tools (Beroggi and Wallace [1998]). These aspects are briefly discussed in subsections 2.4 and 2.5.

2.3 A proposal of dynamic risk definition of hazmat transportation

The real-time monitoring of the actual routing of vehicles transporting hazmat, as well as of the state of the factors that can affect the magnitude of the hazard, allow to introduce a dynamic definition of risk due to hazmat transport.

In fact, an exhaustive definition of risk in this field should include both static and dynamic information affecting the definition of the current hazard of a transport. For instance, static information should include the basic features of the considered road segment (such as slope and turning) and territorial information (such as the proximity of a river basin, of urbanized areas, and so on). Instead, dynamic information should include traffic flow conditions (e.g., given by highway authorities), forecast or observed meteorological information, the current physical/chemical state (temperature, pressure etc...) of the transported hazmat, the current representation of impact and exposure and so on.

The proposed approach would aim to evaluate all the four main elements, which the literature indicates as the most important in the evaluation of the likelihood of the hazard, which are: the driver, the truck, the hazmat, the road. All four of them have static and dynamic components the most important of which are resumed in table 1. In addition, to compute hazmat risk, a dynamic representation of impacts would be also necessary.

One of the main objectives of our work is to take into account all of these important static and dynamic components with the objective to minimize the risk when hazmat transport can be scheduled in real time.

Table 1. The main factors affecting the hazard definition in hazmat transportation

Factors influencing risk	Evaluating static components	Evaluating real-time/ dynamics components
Driver	Training, Drive-Test, Medical-Test	Physiologic conditions
Truck	Periodic checks	Speed, wheel conditions ...
Hazmat	Conditions at start of route	Chemical and physical conditions
Rout segment	Type of road (municipal, highway etc...), characteristics (turning, slope, tunnels, bridges...)..	traffic flow, speed, meteo conditions, road-bed conditions, men-at-work and maintenance ...

While the continuous evaluation of static components has been the goal of major hazmat logistic companies for many years, the availability of emerging technologies mentioned in the previous section represents an important challenge to improve the decrease of the hazard by the monitoring of the dynamic components.

In this respect, a new definition of hazmat transport risk on road is required. In the work by Fabiano *et al.* [2002], a great emphasis is given to the evaluation of the expected frequency of an accident, which is at the basis of the computation of the hazard.

Specifically, on a given road segment *i* of length L_i on which n_i vehicles (for example each year) are passing, the frequency f_i of an accident can be computed by the following:

$$f_i = \gamma_i L_i n_i \quad (2)$$

$$\gamma_i = \gamma_0 \prod_{j=1}^{6} h_{i,j} \quad (3)$$

where γ_i is the expected frequency of an accident, which can be computed on the basis of the basic frequency γ_0 (accident km^{-1} per vehicle) and $h_{i,j}$ are local amplifying/mitigating parameters. Specifically, for each road segment *i*, six parameters $h_{i,j}$ are proposed: four parameters related to intrinsic road characteristics (turns, slope, number of lanes, bridge/tunnel), meteo and vehicle flow.

Meteo and vehicle flow are two parameters that have even more relevance to estimate the likelihood of the hazard if they can be both monitored in real-time and predicted in their evolution. Other two parameters, which play a similar important role, are velocity and availability of service of the road segment (for example men-at-work, that limit the service of the road segment, for example from two lanes to just one lane). So, in our approach, eight dynamics parameters affect the expected probability of an accident on a road segment.

In addition the approach is limited to the analysis to the transport of petroleum products and to two scenarios: explosion and release. In the first case, it is important to evaluate the magnitude of the event with respect to people that can be involved in the explosion (mainly represented by the driver himself, the other drivers on the road and the people living in the neighborhood), while in the other case it is important to evaluate the possible damage on the infrastructure (for example loss of service of the road) and of the environment (for example, pollution of a water basin). In addition, a dynamic representation of these impacts would be also necessary, but, as a simplifying assumption either worst case or probabilistic models of the impact may be taken into account.

2.4 A comprehensive decision support system architecture to support real time risk assessment and real time routing of hazardous material transport on road

Having accepted that a dynamic risk definition of hazmat transportation is needed, another aspect should be put in evidence. The dynamics of this risk can be controlled in real time. To establish the elements supporting this idea, some considerations about how hazmat routing is commonly planned and controlled are introduced hereinafter.

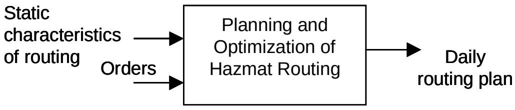

Figure 1. Simplified representation of a planning system for hazmat routing definition.

Figure 1 shows a simplified representation of a planning system, which supports the computation of the routing that should be performed by tank trucks in order to satisfy orders from customers. Specifically, referring to the particular case study treated within this work, in the case of distribution of petroleum products to the fuel stations distributed on a territory, each day a routing plan is defined according to the set of orders that have been received, to the characteristics of the road network, and with reference to the location of the demand. Usually this plan is supported by optimization modules that are able to compute an optimal solution of a vehicle routing problem (Christofides *et al.* [1979]), achieving objectives such as for example the minimization of the overall time of delivery.

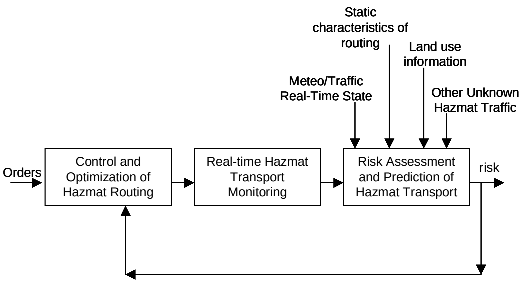

Figure 2. A modern view of risk based planning for hazmat routing definition.

Minimizing risk requires different approaches that should include the minimization of risk (Zografos and Androutsopoulos [2004]), the equity in the distribution of risk in the territory (Current and Ratick [1995]), and a real-time routing management (Beroggi [1994]). These aspects are the one on which we are currently investigating in order to make evolve the functionality of the planning system in figure 1, to the one shown in figure 2, which includes real-time decisional aspects.

3. PRELIMINARY RESULTS

The aim of this research is to design and to implement a DSS for real time risk assessment of hazardous material transport on road. The project is currently evolving by steps. At the moment the modules shown in figure 3 have been implemented providing the possibility to track the transport within a GIS utility that can be accessed by a Web interface. In addition, preliminary computations of the real-time risk have been performed on historical data, since at the moment the DSS is not linked in real-time with meteo/traffic information.

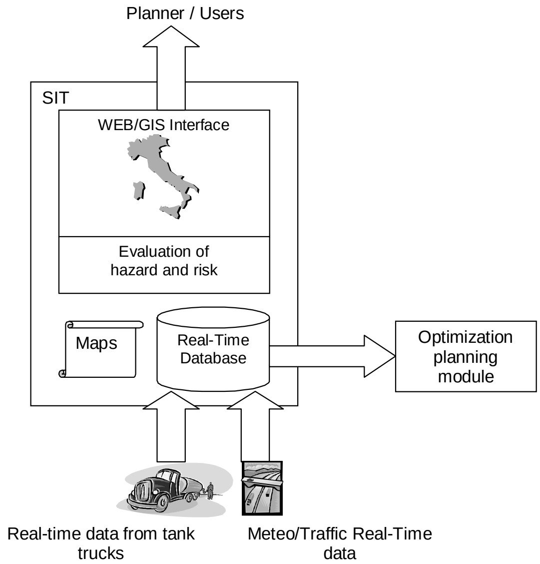

Figure 3. The preliminary modules of the DSS which have been implemented.

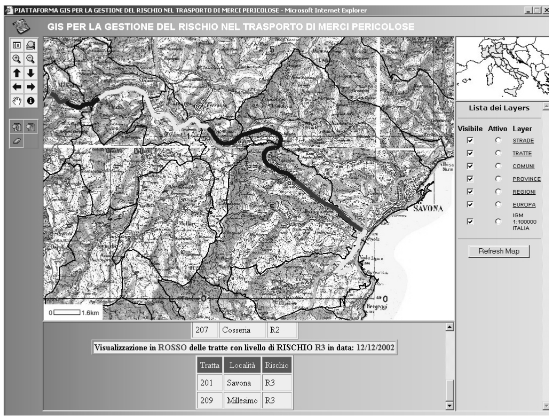

Figure 4. The WEB/GIS based interface of the DSS.

An example of graphic user interface developed for the DSS is shown in figure 4, where the results of the computation of the risk are shown for some road segments over a particular area, namely the western districts of Liguria region (Italy) which are heavily interested by hazmat traffic, and characterized by transport infrastructures generally quite close to civil and industrial settlements.

4. CONCLUSIONS AND FUTURE DEVELOPMENTS

The overall problem of hazmat risk transport is a complex interdisciplinary problem, that should be faced under many viewpoints one of which is the optimal risk-based planning of hazmat routing. Emerging telematics technologies and related new monitoring systems allow to improve the definition of risk, showing its real-time features and allowing to model its evolution. The proposed DSS aims to compute dynamic hazmat risk in real-time and it is based on a methodology starting from traditional static risk evaluations: dynamics components are introduced as a factor amplifying or reducing the accident expected frequency. In a comprehensive DSS, similar considerations should be taken into account in the evaluation of the magnitude, that is on the impact on vulnerable territorial elements. Once the DSS is verified on a greater set of historical and real-time information, it will be extended to be linked with or to enhance current route planning systems of hazmat transport.

Future developments are both technological and methodological. A technological aspect is related to the enhancement of the production of distributed information by the fleet of trucks adding sensors to monitor meteorological conditions (e.g. temperature and luminescence), information added by the driver (e.g. fog, accidents on the road), as well as information on the real-time health status of the driver himself. Methodological aspects will deal with the calibration of the model on a set of historical data and on the practical experience of drivers, and with the integration with route planning modules.

5. ACKNOWLEDGEMENTS

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