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A Risk Assessment Framework for Hazmat Transportation in Highways by Colored Petri Nets

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***Abstract*—The management and control of vehicles transporting hazardous materials (hazmat) on congested highways has attracted growing attention from researchers in recent years. This paper proposes a decision support system (DSS) for monitoring hazmat vehicles, aimed at assessing two problems: evaluating the social risk induced by hazmat vehicles traveling in highways and selecting restoration procedures after an accident involving heavy vehicles. The proposed DSS can estimate in real time and offline the risk of hazmat transportation, by taking into account the type of transported hazmat, the traffic, and the density of populations living close to the highway. Two main modules of the DSS are specified: the risk assessment module and the simulation module (SM) that allows forecasting risk in different contexts and scenarios. In particular, the SM is realized by modeling the highway network in a colored Petri net (CPN) framework. In order to show the effectiveness and the applicability of the DSS, a prototype is described and applied to a highway in the North-east of Italy.**

***Index Terms*—Colored Petri nets (CPNs), decision support system (DSS), hazardous material transportation, simulation.**

I. Introduction

THE management of hazardous material (hazmat) transportation on road has attracted a growing attention by researchers in recent years. Indeed, hazmat transportation implies potentially high risks depending upon the nature of the hazmat carried and the physiochemical events associated with these materials, the localization and density of the affected subjects, the characteristics and state of roads, the density of the traffic, and the environmental conditions. Mitigation of transport risk requires the implementation of a variety of policy tools such as specializing in hazmat incidents emergency response teams [29]. Moreover, a number of transport safety measures aim at reducing the possible undesirable consequences of incidents involving accidental release of dangerous goods during transportation [4], [26], [30]. In this context, different decision makers and actors are involved in decision problems that can be seen under planning or control viewpoints [21]. Planning problems refer to long-term decisions (route design, resource allocation), in which there is no need of information in real time. On the other hand, control problems are related to the short term and/or real time decisions (routing of vehicles, emergency operations, restoration procedures after an accident) that need real-time information and dynamic models.

Research in the area of planning problems focuses on two main issues [29]: 1) assessing the risk induced on the population by hazmat transportation traveling on the road network [10], [11] and 2) identifying the route that minimizes transport risk [4], [7]. A popular measure is the number of people living within a threshold distance from the routes used by hazmat trucks. A model suggested by Batta and Chiu [3] emphasizes exposure to hazmats rather than the occurrence of an accident. Alternatively, incident probability is suggested as a risk measure by several authors [1], [12], [25].

For the second research issue, Kara and Verter [15] propose a bi-level programming model for the problem of designing a road network for hazmat transportation. Moreover, Erkut and Gzara [10] consider a bi-objective (cost and risk-minimization) version of the network design problem. Verter and Kara [29] provide a path-based formulation for the hazmat transport network design problem. Varying the routing options included in the model for each shipment can generate alternative solutions to the network design problem. In addition, Verter and Gendreau [28] focus on the tactical planning problem of a railroad company that regularly transports a predetermined amount of mixed freight (i.e., nonhazardous and hazardous cargo) across a railroad network.

Few contributions are relevant to the operational management problem for hazmat transportation. In particular, Minciardi and Robba [21] proposed a generic decision architecture for the management of vehicle fleets that transport hazmat. The solution takes into account the presence of different decision makers with the objective of the reduction of economic costs and the containment of risk for vehicles and infrastructures. Moreover, Centrone *et al.* [8] present a dynamic freeway model in a colored Petri net (CPN) framework that allows analyzing in real-time the risk of hazmat transportation in different routes.

This paper presents a decision support system (DSS) to be used by the highway planners for monitoring and controlling vehicles transporting hazmat and solving two operational problems: 1) assessing the risk induced on the population by hazmat vehicles traveling on highways and 2) selecting the optimal restoring procedures and routes of the heavy vehicles (HVs) after an accident.

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A decision-making process to choose the best option from a feasible set is present in just about every conceivable human task [23]. As there are various definitions for what a DSS is, there are various classifications for the different types of DSSs. According to Power [24], DSSs can be divided into five main categories.

1) *Communication-Based:* Emphasis is given to the communication and collaboration of a group of decision makers.
2) *Data-Based:* The DSS makes extensive use of databases, processes large amounts of data, uses queries and advanced methods, such as on line analytical processing.
3) *Document-Based:* The DSS is mainly used in knowledge management and retrieval systems.
4) *Knowledge-Based:* The DSS makes use of artificial intelligence and rules for automated decision making, and are also called expert systems.
5) *Model-Based:* The DSS gives major emphasis on mathematical models, simulations and optimization techniques that are used to optimize performances and objectives.

The proposed DSS is designed in a model-based framework and consists of three components: the data component (DC), the model component (MC) and the user Interface Component (UIC). The DC stores all information needed for the DSS to operate; the UIC allows the effective interaction of the user with the real system. Moreover, the MC contains all the models, algorithms, rules, and knowledge that are needed to provide decision support to users.

In the presented DSS, the MC consists of three modules: the risk assessment module (RAM), the simulation module (SM) and the decision module (DM). In particular, we specify the two main modules of the MC: the RAM and the SM. The RAM assesses in real time the social risk of transporting hazmat on the highways, by using the data coming from information and communication technology (ICT) tools. The social risk is defined as the risk of people that can be exposed to the consequences of an accident with hazmat release. Moreover, the SM is devoted to analyze the risk of hazmat transportation and to forecast the highway stretches where the risk can be high. Indeed, the simulation studies have proved to be useful domains for making decisions and assessing DSS implementations [5], [22]. In the presented DSS, the SM is based on a modular colored timed Petri net (CTPN) model of the highway network and includes the model of the accident and the restoration procedure after the accident. Hence, the DSS can be employed to suggest to hazmat transporters the safest route and to choose the best accident restoration policy with respect to the number of involved people and the evaluated social risk.

In order to show the effectiveness and the applicability of the DSS, we show a prototype implementation devoted to evaluate the risk related to the transit of hazmat in a stretch of the A4 highway in the North-east of Italy. Assuming that an accident occurs in a particular link of the highway, we evaluate and compare the risk in the links by applying different strategies to restore the normal traffic flow.

The remainder of this paper is organized as follows. Section II describes the DSS architecture. Moreover, Section III describes the proposed risk assessment and DMs. Section IV presents the SM described in a CTPN framework and Section V shows a DSS prototype applied to a case study. Finally, Section VI reports the conclusion.

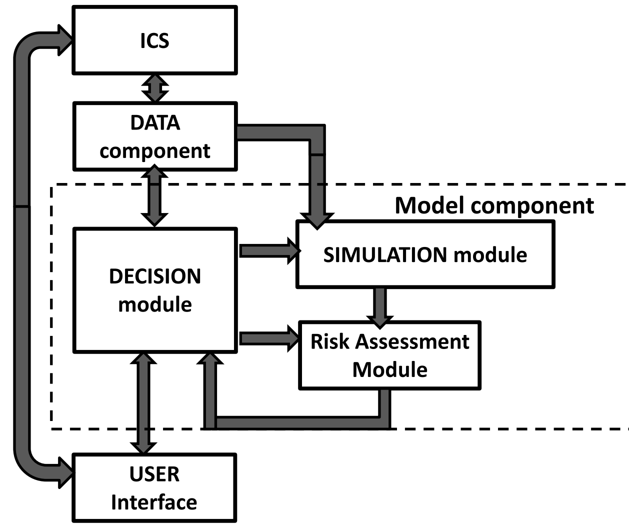

Fig. 1. DSS architecture.

II. DSS Architecture

In this section, we describe the structure of the DSS devoted to evaluate in real time the risk related to the transit of hazmat on highway networks and to take decisions about the traffic flow. The proposed DSS is model based and consists of three components: the DC, the MC, and the UIC. Fig. 1 concisely shows the main elements and the architecture of the proposed DSS and their connections: in particular it depicts the DSS components and the three MC modules, i.e., the RAM, the SM, and the DM.

The DC stores the information necessary for the DSS to operate. We distinguish three different kinds of data. The first and second kinds of data are stored in the DC: internal and external data. The internal data represent the data necessary to describe the system procedures, e.g., the time required for each activity, the number of available resources, the safety levels, etc. On the other hand, the external data are information coming in real time from the system: the current number of vehicles, the conditions of the roads, the accidents, the road maintenance works, the weather conditions, etc.

A third kind of data is used by the MC: they are the input and output data managed by the DM, the simulation models that are available for the simulation runs, the queue of the requests to be sent to the simulation server, the state of each request, and the results of the simulation.

The UIC allows the effective interaction of the user with the system by the information and communication system (ICS) that is based on the modern ICT tools. This module is the part of the DSS that is responsible of the communication and interaction of the system with the MC. Such a component is very important and the accuracy of the model is based on this interface. Indeed, the UIC communicates with the ICS that is able to interact with the real system and maintains the consistency between the stored data and the real system.

By means of the ICT tools belonging to the ICS, the DSS monitors the network, detects the events occurring in the system and sends the related information to the DC. The RAM can evaluate in real time the risk of the zones where there are vehicles transporting hazmat by considering the interaction among the transportation network (in this case the highway), the vehicles (the traveling risk source), and the impact area. On the basis of the risk assessment, the DM can modify and tune the rules for the network management.

Moreover, in consequence of the detected events and the model state knowledge, the DM may decide to trigger the simulation and to apply different restoration procedures. The reasons that can determine the start of the simulation are unpredictable event occurrences as well as critical situations of the model state that can exhibit queues, blockages, breaks, and all those occurrences that interact with the flow and management of materials and transporters. The simulation applies and evaluates the performances of the possible solutions proposed by the DM. Hence, the RAM uses the outputs of the simulation to evaluate the risk and the consequences of the possible scenarios.

More clearly, the DSS is devoted to be used by the highway planners and managers for two basic operations: 1) the DSS evaluates in real time the risk for the hazmat transportation by using the data provided by the ICS and detects the highway links characterized by a high-risk level and 2) the DSS triggers the simulation to forecast the risk for hazmat transportation and the accident consequences. In this case, the risk of hazmat transportation is evaluated using the outputs provided by the simulation that forecasts the accident consequences and provides and compares data about the possible restoration solutions.

On the basis of the simulation results and the RAM risk evaluation, the DM suggests the routing and restoration solutions to manage the network in different contexts. On the basis of the choices proposed by the DSS, the user transmits by the UIC the commands to the ICS that sends the corresponding messages to the network system.

The next sections focus on the specification of the two main modules of the MC: the RAM and the SM. Furthermore, a prototype of the DM in the case of accident involving hazmat transportation is presented.

III. Risk Assessment and DM

A. RAM Specification

In this section, we describe the module devoted to calculate in real time the risk related to the transit of hazmat in a highway network. We divide highway in a set of L links denoted by $L = \{L_i | i = 1, \ldots, L\}$, where each link is a highway stretch between two successive tollbooths. In addition, such a set of links is partitioned in $L = L_H \cup L_{\text{in}} \cup L_{\text{out}}$ where L_H collects highway links, L_{in} collects input links, i.e., the tollbooths to enter the highway, and L_{out} is the set of the output links trough which vehicles exit the highway.

The risk assessment is typically a process resulting from the interaction among the transportation network, the vehicles, and the impact area [11]. More precisely, it is possible to consider two types of risks: the individual risk and the social risk, i.e., the risk of the people that can be exposed to the hazmat accident consequences. In this paper, we consider the individual risk index due to a set $H = \{h : h = 0, 1, \ldots, H\}$ of H hazmat that are transported by HVs.

The main metrics to evaluate the individual risk are the following.

1) $R_i(h, \tau)$: The hazmat transportation risk of the highway link $L_i \in L_H$ at time τ.
2) $N_p(i, h, \tau)$: The number of people that are involved in an accident of a HV transporting hazmat h in $L_i \in L_H$ at time τ.

In order to calculate $R_i(h, \tau)$ and $N_p(i, h, \tau)$, the following indices are defined [11].

1) $f_i(h, \tau)$ [*Events/Vehicles*] is the relative number of the accident occurrence in a highway link $L_i \in L_H$ with respect to the traveling vehicles, involving the hazmat h, at a given time τ.
2) $\lambda_i(l)$ [*Events/Vehicles*] is the accident rate at the lth km of the highway link $L_i \in L_H$ [13].
3) $p_{\text{rel}}(h)$ is the probability of releasing the hazmat h as a consequence of an accident [6].
4) $N_{\text{CV}}(i, \tau)$: The number of common vehicles (CV) in L_i at time τ.
5) $N_{\text{HV}}(i, 0, \tau)$: The number of HVs that do not transport hazmat in L_i at time τ.
6) $N_{\text{HV}}(i, h, \tau)$: The number of HVs transporting hazmat h in L_i at time τ.

Note that the value of $\lambda_i(l)$ is strictly connected with the highway link topology, the traffic, and the weather conditions: then for each particular case it may be obtained from the highway historical data by statistical evaluation.

Here, the following simplifying assumptions are considered.

1) The accident rate $\lambda_i(l) = \lambda_i$ is constant along each link.
2) The exposure area of danger is centered at the point of the incident and is circular with a radius depending on the type of the substance.
3) The weather conditions are not taken into account.

Under these assumptions, the individual risk of hazmat transportation for a link $L_i \in L_H$ at time τ can be determined as follows [19], [20], [25]:

$$R_i(h, \tau) = N_{\text{HV}}(i, h, \tau) f_i(h, \tau) \quad \forall L_i \in L_H. \tag{1}$$

In addition, $f_i(h, \tau)$ is determined as follows:

$$f_i(h, \tau) = \lambda_i \cdot p_{\text{rel}}(h). \tag{2}$$

Moreover, the number of people $N_p(i, h, \tau)$ that are involved in an accident in link $L_i \in L_H$ with the release of hazmat h can be evaluated as follows:

$$\begin{aligned} N_p(i, h, \tau) = {} & \eta_i \left(\pi r_h^2 - 0.03 \cdot 2 r_h \right) \\ & + \frac{[N_{\text{HV}}(i, 0, \tau) + N_{\text{HV}}(i, h, \tau) + 2 N_{\text{CV}}(i, \tau)]}{l_i} 2 r_h \\ & \text{for } h = 1, \ldots, H \text{ and } L_i \in L_H. \end{aligned} \tag{3}$$

The first contribution of (3) gives an evaluation of the number of people living in the surroundings of the accident site assuming that the width of the highway links is equal to 0.03 km. Moreover, the second contribution estimates the number of people present in the highway link, assuming that one driver is in each HV and two people are in each CV.

B. Evaluation of Hazmat Transportation Risk by Simulation

The main task of the RAM is determining the frequency $f_i(h, \tau)$, the time-varying risk index $R_i(h, \tau)$, and the number of people $N_p(i, h, \tau)$. The DSS can obtain the values of such indices in real time from the data provided by the ICS. Alternatively, in order to assess an average value of the risk in different scenarios or to forecast the average risk of hazmat transportation in particular links, a simulation can be triggered by the DSS.

In particular, the simulation determines the following quantities at each time $\tau \in N$ for $0 \leq \tau \leq T$, where T is the duration of each simulation run and N is the set of natural numbers.

1) $N_{\mathrm{CV}}(i) = \left(\sum_\tau N_{\mathrm{CV}}(i, \tau)\right)/T$: The average number of CV in L_i.
2) $N_{\mathrm{HV}}(i,0) = \left(\sum_\tau N_{\mathrm{HV}}(i, 0, \tau)\right)/T$: The average number of HVs that do not transport hazmat in L_i.
3) $N_{\mathrm{HV}}(i,h) = \left(\sum_\tau N_{\mathrm{HV}}(i, h, \tau)\right)/T$: The average number of HVs transporting hazmat h in L_i.
4) $N_p(i,h)$: The average number of people that can be involved in an accident with the releasing of hazmat h in L_i.

Moreover, the average number of people that can be involved in an accident $N_p(i, h)$ for $h = 1, \ldots, H$ and $L_i \in L_H$ can be evaluated as follows:

$$N_p(i, h) = \eta_i \left(\pi r_h^2 - 0.03 \cdot 2r_h\right) + \frac{[N_{\mathrm{HV}}(i, 0) + N_{\mathrm{HV}}(i, h) + 2N_{\mathrm{CV}}(i)]}{l_i} 2r_h. \quad (4)$$

Finally, the average values of the individual risk are determined as follows:

$$R_i(h) = N_{\mathrm{HV}}(i, h)\, \lambda_i \cdot p_{rel}(h) \text{ for } h \in H \text{ and } L_i \in L_H \quad (5)$$

$$\overline{R_i} = \sum_{h=1}^{H} R_i(h) \text{ for } L_i \in L_H \quad (6)$$

where $R_i(h)$ is the risk averaged on the considered time intervals and $\overline{R_i}$ denotes the risk averaged on the all considered hazmat.

C. DM Specification

The core of the DSS is the DM that helps decision makers to estimate the impact of different procedures to deal with exceptional events or situations on the real system by taking into account the real-time traffic condition and the impact on the people.

The DM may be used in two different ways: real-time and offline applications.

In the first application, the DSS monitors the real-time traffic data available into the DC and sends such DATA to the RAM that estimates the risk indices (1) and (3).

Moreover, if the risk level overcomes a given guard threshold due for example to high-traffic congestion or an accident, then the DSS starts the following procedure.

1) The DSS launches an alert signal that communicates a dangerous situation.
2) Some rescue or recovery procedures that have been previously prepared in a suitable data base are considered.
3) For each alternative a set of simulations are executed in order to estimate the average risk indices (4)–(6).
4) A comparison is carried out also using appropriate diagrams.
5) The results are presented to the decision makers by the user interface module.

In the second offline application, the DSS can be used to find out the best rescue and recovery procedure to be applied at the step 2 of the presented procedure. In this case, the alternative strategies devised on the basis of the manager's experience can be evaluated and assessed by applying the steps 3–5 of the procedure.

IV. SM

This section describes the module devoted to modeling and simulating the highway network in a CTPN framework [14]. Hence, we first recall the basic elements of CTPN and then we describe the highway model.

A. Background on CTPNs

A CTPN is defined as a bipartite directed graph described by a six-tuple CTPN $= (P, T, Co, \boldsymbol{I}, \boldsymbol{O}, \boldsymbol{F})$, where P is a set of places, T is a set of stochastic timed transitions, Co is a color function that associates with each element in $P \cup T$ a nonempty ordered set of colors in the set of possible colors Cl. Moreover, function Co maps each place $p \in P$ and each transition $t \in T$ to the set of possible token colors $Co(p) \subseteq Cl$ and a set of occurrence colors $Co(t) \subseteq Cl$, respectively.

The matrices $\boldsymbol{I}$ and $\boldsymbol{O}$ are respectively the preincidence and the post-incidence matrices of dimension $|P| \times |T|$, where symbol $|(.)|$ indicates the cardinality of set (.). More precisely, $\boldsymbol{I}(p, t)(\boldsymbol{O}(p, t))$ is a mapping that associates to each set of colors of $Co(p)$ $(Co(t))$ a set of colors of $Co(t)$ $(Co(p))$. Moreover, each element of $\boldsymbol{I}(p, t)(\boldsymbol{O}(p, t))$ is represented by means of an arc from p to t (from t to p) labeled by function $\boldsymbol{O}(p, t)(\boldsymbol{I}(p, t))$.

In addition, a marking $\boldsymbol{M}(p)$ of place $p \in P$ is defined as a mapping $\boldsymbol{M}: P \rightarrow Cl$. More precisely, $\boldsymbol{M}(p)$ is a set of elements of $Co(p)$ also with repeated elements [14] corresponding to the colored tokens in p.

A transition $t \in T$ is enabled at a marking $\boldsymbol{M}$ with respect to color $c \in Co(t)$ if for each $p \in P$ it holds $\boldsymbol{M}(p)(c) = \boldsymbol{I}(p,t)(c)$. If an enabled transition $t \in T$ fires with respect to color $c \in Co(t)$, then we get a new marking $\boldsymbol{M'}$ obtained by the state equation: $\boldsymbol{M'}(p)(c) = \boldsymbol{M}(p)(c) + \boldsymbol{O}(p,t)(c) - \boldsymbol{I}(p,t)(c)$.

Finally, the temporization of the colored PNs is obtained here by attaching time to transitions: $\boldsymbol{F}[t(c)]$ specifies the distribution timing associated to each stochastic transition $t \in T$ with respect to color $c \in Co(t)$.

B. Highway Network Model

The highway network is modeled by the CTPN denoted by CTPN $= (P, T, Co, \boldsymbol{I}, \boldsymbol{O}, \boldsymbol{F})$: the structure of the model is modular and is built by a top–down approach [31]. In particular,

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the tollbooth subsystems and the highway lanes are singled out in a generic and modular approach. The set of places P is partitioned into the following subsets: $P = P_L \cup P_C \cup P_A \cup P_B$ where places $p_L \in P_L$ represent the highway stretch links, places $p_C \in P_C$ model the capacity of the link, places $p_A \in P_A$ model the capacity reduction or the blocking of a link for accidents or works in progress and places $p_B \in P_B$ model the tollbooths.

Each colored token in a place $p \in P_L \cup P_B$ of the CTPN is a vehicle traveling in the highway. Moreover, we consider that two types of vehicles are in the system.

1) CV, i.e., vehicles like cars, vans, and motorbikes with size less than 5 m or 1 vehicle equivalent (v.e.).
2) HVs, i.e., vehicles transporting freight or hazmat of 15 m or 3 v.e.

The token colors are defined by a pair denoting the vehicle type and the transported material. Hence, the color domain of each place $p \in P_L \cup P_B$ is

$$Co(p) = \{< cv, 0 >, < hv, h > \text{ for } h = 0, \ldots, H\} \quad (7)$$

where $h = 0$ means that no hazmat is transported by the vehicle.

Moreover, tokens in $p_C \in P_C$ are the capacity available in the link in terms of v.e. and tokens in $p_A \in P_A$ express the state of a lane (blocked or reduced). Hence, places $p \in P_C \cup P_A$ are marked by tokens with neutral colors denoted by symbol $< \bullet >$

$$Co(p) = \{< \bullet >\}. \quad (8)$$

Summing up the set of possible token colors is

$$Cl = \{< \bullet >, < cv, 0 >, < hv, h > \text{ for } h = 0, \ldots, H\}. \quad (9)$$

Furthermore, the set of transitions T is partitioned into the following subsets: $T = T_L \cup T_C \cup T_I$ where T_L models the travel of vehicles in the lanes, T_I models the vehicles that enter or leave the network and the payments at the tollbooth; T_C represent the occurrence of unpredictable events such as accidents, work in progress beginning, restore of the lane. Hence, the sets of the transition occurrence colors are the following:

$$Co(t) = \{< cv, 0 >, < hv, h > \text{ for } h = 0, \ldots, H\} \quad \text{for } t \in T_L \cup T_I$$
$$Co(t) = \{< \bullet >\} \text{ for } t \in T_C.$$

Fig. 2 depicts the CTPN modeling a generic link: places $p_{\text{LE}i}, p_{\text{LW}i} \in P_L$ represent the highway stretch of the east, west direction, respectively, $p_{\text{CE}i}, p_{\text{CW}i}, \in P_C$ are the corresponding capacities of V v.e. The events modeling the vehicles that enter the link are transitions $t_{\text{LE}i} \in T_L$. If transition $t_{C2} \in T_C$ fires, the event of a capacity reduction due to the maintenance or the restore of the highway occurs. In particular, in such a case V neutral tokens $< \bullet >$ leave $p_{\text{CE}i}$ and the link capacity decreases. Moreover, $t_{C1} \in T_C$ models the ending of the restoration works and, when it fires, v neutral tokens are added to $p_{\text{CE}i}$. If an accident occurs, then transition $t_{C4} \in T_C$ fires and place p_{A2} is unmarked: in this situation the lane is blocked since transition $t_{\text{LE}(i+1)} \in T_L$ is not enabled. The vehicles can travel again in the link when t_{C3} fires and place p_{A2} becomes marked. Furthermore, transitions $t_{Ii}, t_{Oi} \in T_I$ model the input and the exit of the highway through the tollbooth, respectively.

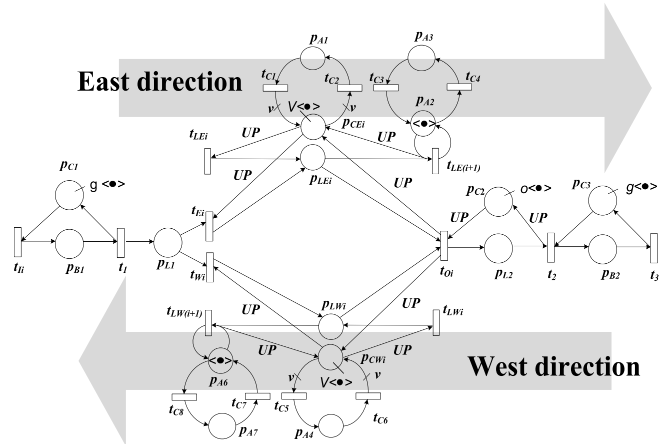

Fig. 2. CTPN model of the generic highway link L_i and the tollbooths.

In addition, Fig. 2 shows the net modeling an input and an output link. In particular, places $p_{B1}, p_{B2} \in P_B$ model the tollbooths; $p_{C1}, p_{C2} \in P_C$ are their capacities of $g < \bullet >$ v.e. (number of available tollbooth gates); $p_{L1}, p_{L2} \in P_L$ model the stretches between the tollbooth and the highway and the highway and the tollbooth, respectively. Transition $t_1 \in T_I$ models the fee payment, transitions $t_{Ei} \in T_I$, and $t_{Wi} \in T_I$ model the direction choice (east and west).

We assume that the firing times of transitions $t_{\text{LE}i} \in T_L$ have a triangular distribution and $\boldsymbol{F}[t_{\text{LE}i}(c)]$ for $t_{\text{LE}i} \in T_L$ and $c \in Co(t_{\text{LE}i})$ is a triple $[D_i, \delta_i, d_i.]$ where δ_i is the modal value, D_i and d_i are, respectively, the maximum and minimum values of the range in which the firing delay varies. Moreover, the firing times of transitions $t_{Ii}, t_{Oi} \in T_I$ and transitions $t_{Ci} \in T_C$ have exponential distribution and $\boldsymbol{F}[t(c)]$ denotes the average value of the delay time associated with transition t and color $c \in Co(t)$.

The arcs of the CTPN of Fig. 2 accordingly define the elements of matrices $\boldsymbol{O}$ and $\boldsymbol{I}$ with the following meaning.

1) If the arcs are not labeled, then the functions $\boldsymbol{O}(p,t)(c)$ and $\boldsymbol{I}(p,t)(c)$ make no transformation on the token colors for $p \in P, t \in T$ and $c \in Co$.
2) The arcs connecting transitions $t_{\text{LE}i} \in T_L$ and the capacity places $p_c \in P_C$ are labeled by function UP that transforms the token colors as follows:
$\boldsymbol{I}(p_c, t_{\text{LE}i})(<v, 0>) = <\bullet>$
$\boldsymbol{O}(p_c, t_{\text{LE}i})(<hv, h>) = 3<\bullet>$ for $h = 0, \ldots, H$
$\boldsymbol{O}(p_c, t_{\text{LE}i})(<v, 0>) = <\bullet>$
$\boldsymbol{I}(p_c, t_{\text{LE}i})(<hv, h>) = 3<\bullet>$ for $h = 0, \ldots, H$.

Indeed, if a CV has to enter a link, then one token of neutral color $<\bullet>$ must be in the link capacity place (1 v.e.). On the other hand, if a HV has to enter the lane, then three tokens of neutral color $<\bullet>$ have to be in the link capacity (3 v.e.). Analogously, if a vehicle of type v (hv) leaves the lane, then one token returns (three tokens return) to the available link capacity.

C. Accident Model

The vehicle flow can be interrupted by unpredictable events, such as accidents. We introduce a model to represent the interruption, also considering the possibility to

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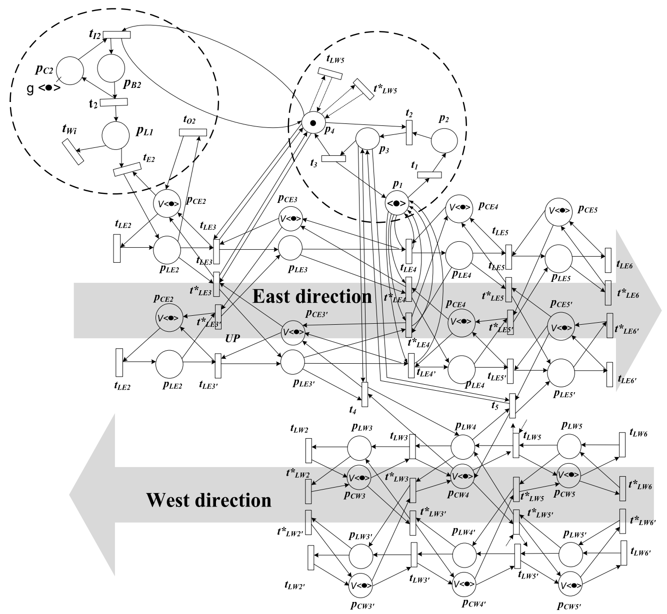

Fig. 3. CTPN model of the restoration procedure P4.

implement procedures to reestablish the normal traffic condition. Fig. 3 shows the CPTN model of the accident and the procedure necessary to restore the vehicle flow in two links L_3 and L_4 of a highway. The accident event occurrence is modeled by transition $t_1 \in T_C$: when transition t_1 fires, the vehicle flow is interrupted, because transitions t_{LE4}, $t*_{\text{LE4}}$, $t_{\text{LE4}'}$, and $t*_{\text{LE4}'}$ are disabled. Moreover, transition $t_2 \in T_C$ is associated with the time delay necessary to the highway operators for starting the restoration procedures. When the traffic condition is restored, t_3 fires and place p_3, if marked, enables the recovery procedures.

Here, we propose four strategies to reestablish the regular traffic flow.

P1: This procedure simply consists in waiting that the vehicles leave the highway.

P2: In this second restoration procedure, the vehicles that are in queue upstream the accident are directed toward the opposite carriageway after cutting the guardrail. Hence, the vehicles that remain trapped between the nearest upstream off-ramp and the accident place can move forward.

P3: The vehicles are routed to the first off-ramp upstream the accident place and, successively, they are reentered through the first on-ramp downstream the accident place by following an alternative road.

P4: The procedures P2 and P3 are simultaneously applied.

The model of the most complex restoration procedure P4 is shown in Fig. 3: the procedure starts when p_3 is marked and transitions t_4 and t_5 become enabled and can fire. The complete highway network is built up by connecting the described modules for each link.

V. DSS Prototype

In this section, we describe a prototype of the DSS devoted to assess the individual risk of a stretch in the A4 highway of the North-east of Italy, between the tollbooth of Villesse and the tollbooth of Venice (see Fig. 4). The data component such as the layout of the highway and the interarrival times are supplied by Autovie Venete s.p.a. that is the company managing the considered highway. As we enlightened in Section III, the DSS can be used in two basic applications: 1) the DSS evaluates in real time the risk of the hazmat transportation on the basis of data provided by the ICS and 2) the DSS triggers the simulation to forecast the risk for the hazmat transportation and the accident consequences in different scenarios. In this section, we show the second type of the application and describe the SM and the RAM of the DSS.

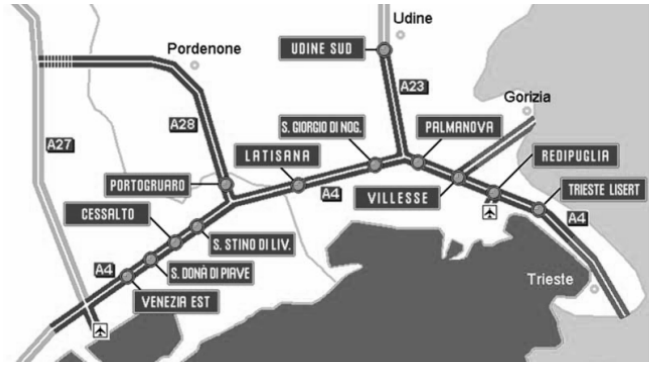

Fig. 4. Considered stretch of the highway.

TABLE I
Link Data

Link number	link	Length l_i [km]	Population density η_i [resident/km^2]	V_i [v.e.]
1	Villesse – Palmanova	10.2	164.55	4080
2	Palmanova-Udine	13	175.7	800
3	Udine – S. Giorgio	6.9	168.68	2760
4	S. Giorgio-Latisana	17.6	112.66	7040
5	Latisana - Portogruaro	13.5	166.05	5400
6	Portogruaro-S.Stino	12.8	214.35	5120
7	S. Stino-Cessalto	6.6	129.6	2640
8	Cessalto-San Donà	7.7	266.6	3080
9	San Donà-Venice	11.4	197.2	4560

A. SM Specification

The SM is realized by implementing the described CTPN model.

More precisely, the network is composed of $L = 9$ links L_i with $i = 1, \ldots, 9$ that are described by the data shown in Table I with reference to Fig. 4. In particular, the first and second columns list the links and the third column shows the corresponding length l_i for $i = 1, \ldots, 9$. Moreover, the fourth column of Table I shows the density population η_i [27]

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

TABLE II
CONSIDERED HAZMAT

Materials (h)	r_h [km]	$p(h)$
Petrol (1)	0.25	0.21
Diesel (2)	0.25	0.15
Hydrocarbon (3)	0.50	0.10
Hot transported substance(4)	1.00	0.10
Liquid oxigen (5)	0.25	0.07
Liquid nitrogen (6)	0.13	0.04
Other (7)	0.04	0.33

TABLE III
FIRING TIMES OF TRANSITIONS

link	t_{LEi} [min]	t_{Ii} [min]	t_{Wi} [min]	t_{Ei} [min]	t_{Oi} [min]
1	[5,6,8]	0.39	0.67	0.33	0.14
2	[6,8,10]	0.33	0.63	0.37	0.22
3	[3,4,5]	0.42	0.4	0.6	0.06
4	[8,11,13]	1.73	0.32	0.68	0.1
5	[6,8,10]	0.61	0.42	0.58	0.36
6	[6,8,10]	0.47	0.37	0.63	0.03
7	[3,4,5]	2.03	0.43	0.57	0.02
8	[4,5,6]	2.36	0.44	0.56	0.06
9	[5,7,9]	0.85	0.39	0.61	0.25

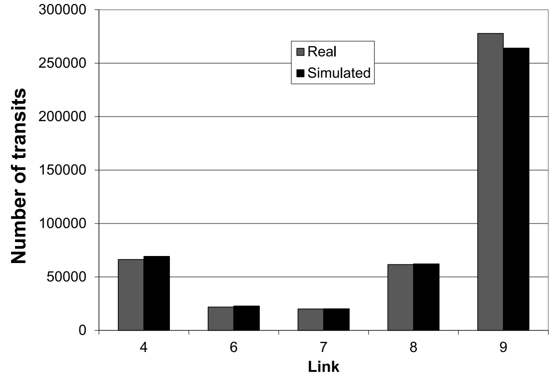

Fig. 5. Average real numbers of vehicles that pass through the tollbooth of link L_i and the average vehicle numbers obtained by the simulation.

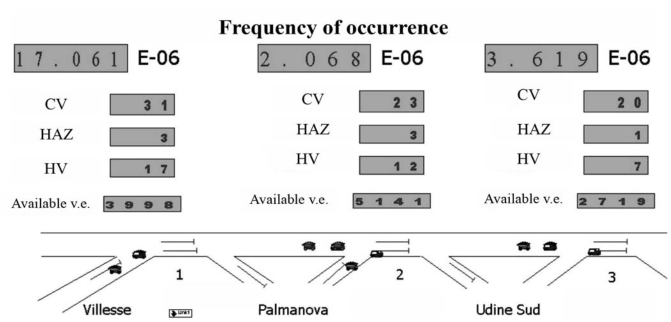

Fig. 6. Sketch of the highway traffic flow simulated in the ARENA environment.

referred to link L_i and the last column reports the corresponding link capacity $V_i = (l_i/5)n_c$ v.e. since 1 v.e. = 5 m and n_c is the number of lanes in the link (in the considered case study $n_c = 2$).

The assessment of the social risk is determined by considering H = 7 hazmat that are more frequent in the Italian highways. Table II shows the data concerning such hazmat: the first column reports the name of the hazmat and the associated label h in parenthesis, the second column shows the average lethal radius r_h that represents the distance within which the release of material h can be lethal, and the third column reports the probability $p(h)$ that a HV transporting hazmat is carrying material h. The inputs of the system are determined as follows: vehicles of color $< v, 0 >$ enter with a probability equal to 0.8, HVs of color $< hv, 0 >$ enter with probability 0.16 and HVs of color $< hv, h >$ with $h = 1, \ldots, H$ enter with probability $0, 04p(h)$.

The firing times with triangular distribution $\boldsymbol{F}[t_{\mathrm{LE}i}(c)] = [d_i, \delta_i, D_i]$ of transitions $t_{\mathrm{LE}i} \in T_L$ are reported in the second column of Table III and are determined as follows: $\delta_i = (l_i/100)\,60$, $D_i = (l_i/80)\,60$, and $d_i = (l_i/130)\,60$ min. Moreover, the third, fourth, fifth, and sixth columns of Table III show the average values of the exponentially distributed firing times of transitions t_{Ii},, t_{Wi}, t_{Ei}, and $t_{Oi} \in T_I$, respectively. The average values of the exponentially distributed firing times of transitions $t_{Ci} \in T_C$ that are associated to the unpredictable event occurrences are evaluated equal to 5.17×10^{-2} min on the basis of data of AISCAT [2].

The CTPN model of the case study is implemented in the Arena environment [17] that is discrete event simulation software particularly suited for dealing with large-scale and modular systems. Moreover, the simulation validation is performed by determining the performance index $N_V(i)$, i.e., the average number of vehicles that exit through the tollbooth of L_i for $i = 4, \ldots, 9$ and by comparing the results of the simulation with the real data.

The selected index is deduced by 50 independent replications of 365 days with a transient period of five days and a 95% confidence interval. Since the half width of the confidence interval is about 5% in the worst case, the accuracy of the performance indices estimation is sufficiently confirmed. Moreover, considering the data supplied by Autovie Venete, we determine the real-average value $N_R(i)$ of vehicles that pass through the tollbooth of links L_i for $i = 4, 6, \ldots, 9$: the values of $N_R(i)$ are determined on the basis of 50 observations of 1 month. Fig. 5 depicts the indices $N_V(i)$ and $N_R(i)$ for $i = 4, 6, \ldots, 9$ and the comparison gives

$$N_V(i) - \rho_i \leq N_R(i) \leq N_V(i) + \rho_i \quad \text{for } i = 4, 6, \ldots, 9 \quad (10)$$

where ρ_i is the half width of the confidence interval of $N_V(i)$. Hence, the single mean test is applied [18] and the results prove that the simulation closely represents the actual system.

B. Simulation and DMs Application

Fig. 6 shows a sketch of a simulated link and shows how the DSS UIC can illustrate the actual situation and evaluate the index risk in real time. In particular, the data in the upper part of Fig. 6 report the link risk values at each time instant.

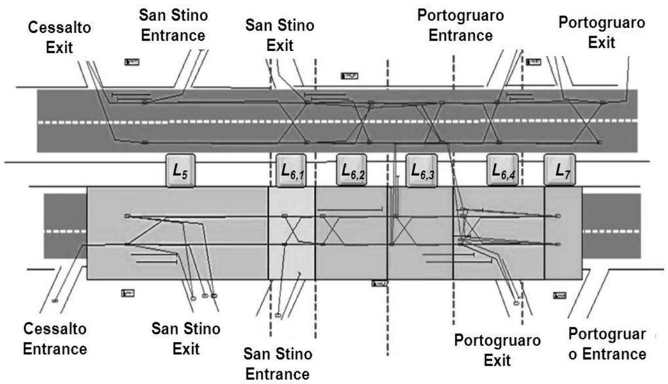

Fig. 7. Scheme of the sublinks considered in the accident analysis.

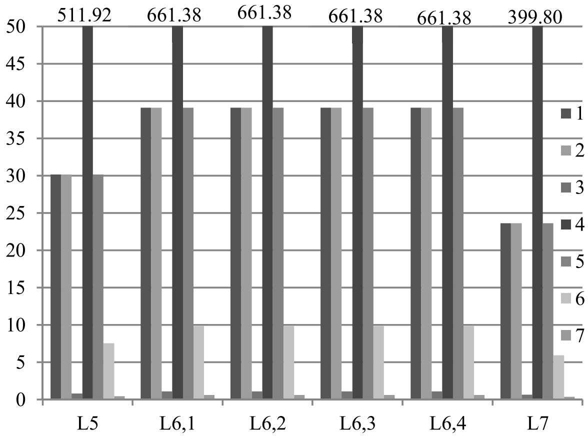

Fig. 8. Average number of people that could be involved in an accident (scenario SC1).

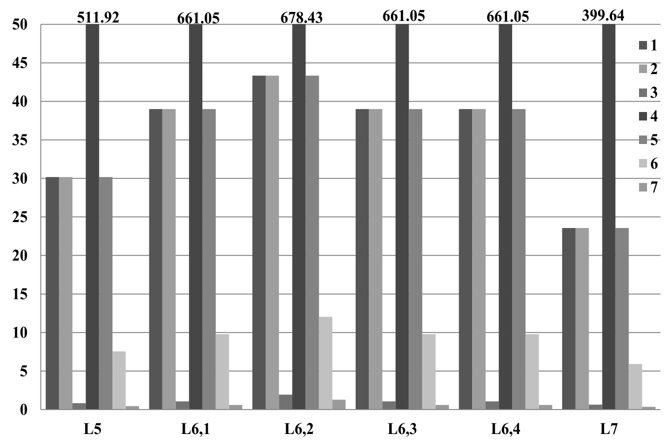

Fig. 9. Average number of people that could be involved in an accident if procedure P4 is applied (scenario SC5).

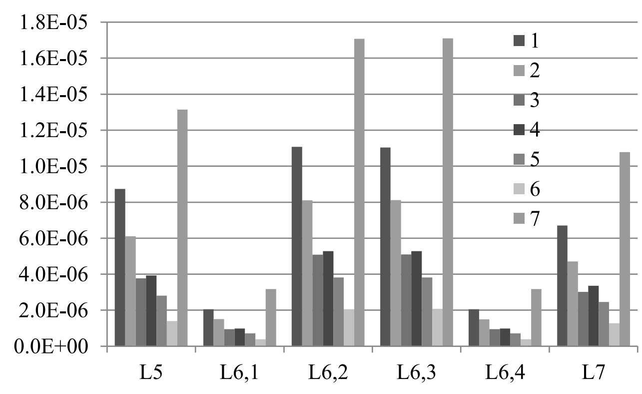

Fig. 10. Average risk $R_i(h)$ for $h = 1, \ldots, H$ in each sublink (scenario SC1).

Subsequently, the number of CV, hazmat HVs (HAZ), HV, and available capacity (in v.e.) of each link are depicted.

In the presented case study, we consider the offline application of the DSS in order to evaluate the risk and the number of the involved people in different critical conditions: 1) a high level of traffic is present in the highway and 2) a lane is blocked due to an accident. To this aim, the indices defined in Section III-B are calculated: the values of r_h and $p_{\text{rel}}(h)$ for $h \in H$ are reported in Table II and the accident rate λ_i is obtained by $\lambda_i = \text{TAR}\cdot l_i$ where TAR = 5.17×10^{-7} events/(vehicle·km) is the truck accident rate [13] per kilometer estimated from the data of AISCAT [2].

Moreover, the DM performs a simulation analysis considering five different scenarios.

1) SC1: High level of traffic where the average delay times of the input transitions are decreased to the 80% of the values shown in Table III.
2) SC2: The scenario SC1 with an accident in the link L_6 where the procedure P1 is implemented.
3) SC3: The scenario SC2 with an accident in the link L_6 where the procedure P2 is implemented.
4) SC4: The scenario SC2 with an accident in the link L_6 with an accident in the link L_6 where the procedure P3 is implemented.
5) SC5: The scenario SC2 with an accident in the link L_6 where the procedure P4 is implemented.

In the scenarios SC3, SC4, and SC5 we assume that the accident occurs in the link with the highest accident probability, on the basis of the historical data provided by Autovie Venete: the kilometer 6.4 of link L_6. The analyzed zone includes the neighboring links L_5 and L_7. In order to analyze the stretch with a high resolution, the zone of the accident (i.e., link L_6) is split into four sub-links as shown in Fig. 7: $L_{6,1}$ and $L_{6,4}$, are stretches of 1 km; the sub-links $L_{6,2}$ and $L_{6,3}$ are stretches of 5.4 km. We assume that the accident occurs between the sub-links $L_{6,2}$ and $L_{6,3}$, so that it is possible to evaluate in detail the consequent traffic evolution in the zones near the accident.

Figs. 8 and 9 show the average number of people that can be involved in an accident with the spillage of hazmat $h \in H$ in the two most different scenarios SC1 and SC5. The figures show that the number of people increases in the case of SC5 in link $L_{6,2}$, where the accident occurs: obviously the number of vehicles increases in the link after the accident. Moreover, it is apparent that the number of people remains nearly constant in the other links in the two scenarios.

Moreover, the Figs. 10–14 depict respectively the average risk $R_5(h)$, $R_7(h)$, and $R_{6,j}(h)$ for each sub link $L_{6,j}$ with $j = 1, \ldots, 4$ evaluated by the simulation and (5). The graphs show that the risk values are very different for each transported

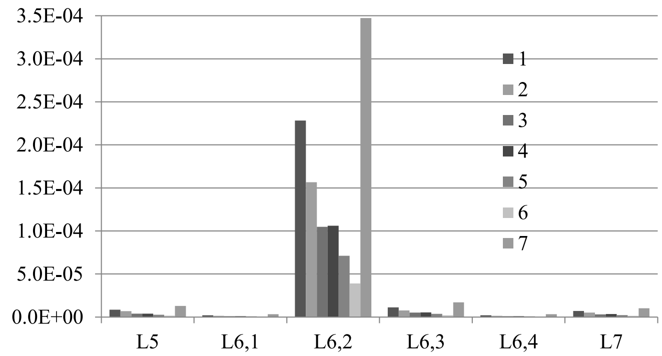

Fig. 11. Average risk $R_i(h)$ for $h = 1, \ldots, H$ in each sublink after the accident if procedure P1 is applied (scenario SC2).

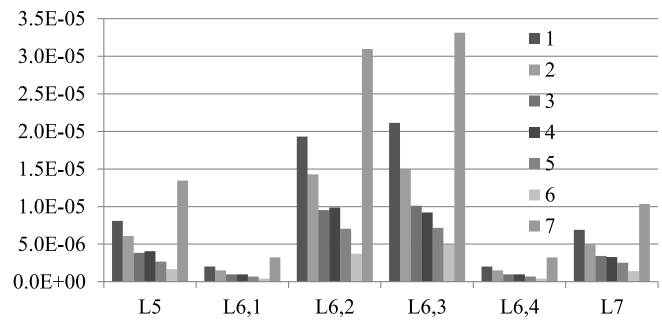

Fig. 12. Average risk $R_i(h)$ for $h = 1, \ldots, H$ in each sublink after the accident if procedure P2 is applied (scenario SC3).

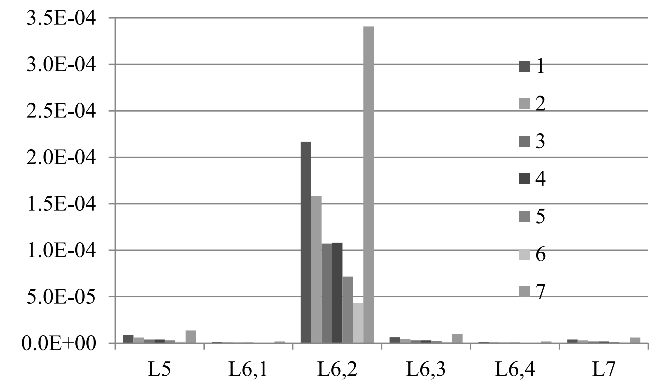

Fig. 13. Average risk $R_i(h)$ for $h = 1, \ldots, H$ in each sublink after the accident if procedure P3 is applied (scenario SC4).

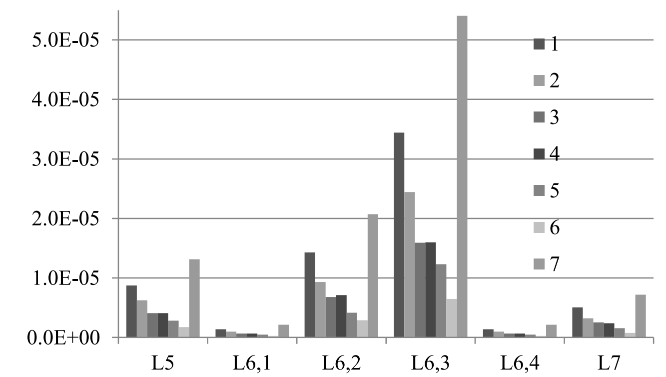

Fig. 14. Average risk $R_i(h)$ for $h = 1, \ldots, H$ in each sublink after the accident if procedure P4 is applied (scenario SC5).

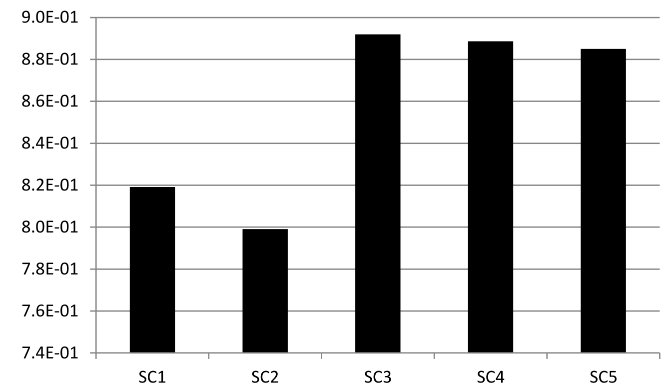

Fig. 15. Average risk $\overline{R_5}$ of L_5 after the accident.

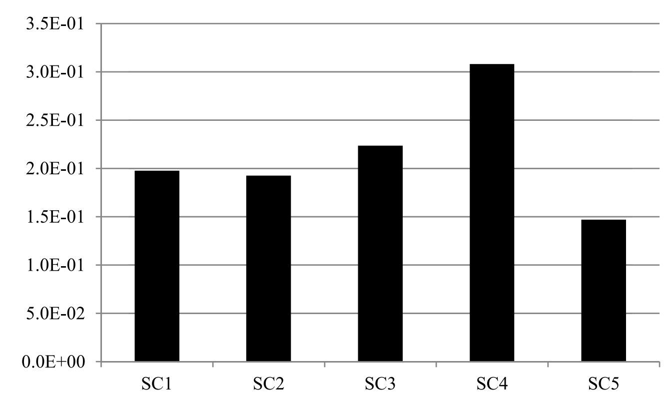

Fig. 16. Average risk $\overline{R_{6,1}}$ of $L_{6,1}$ after the accident.

substance and for each sublink. In particular, the diagrams show that the highest risk value is obtained for substance $h = 7$. This result can be justified by the data reported in Table II where the substances indicated by $h = 7$ exhibit the highest probability to be carried out.

Moreover, it is important to point out that the risk changes in each sub-link in function of the applied procedure. In particular, the risk is very high in link $L_{6,2}$ if procedures P1 or P3 are applied since such procedures increase the vehicle congestion in the links upstream the accident. On the other hand, if P4 is applied, the vehicles are redirected in the opposite direction of link $L_{6,3}$ that becomes congested and the risk increases. Moreover, if procedure P2 is performed, then links $L_{6,2}$ and $L_{6,3}$ exhibit a similar risk level since the number of vehicles increases upstream and downstream the blocked lane.

Furthermore, in order to help the decision maker in the choice of the restoration procedure after the accident, the DSS can report the average value of the risk indices $\overline{R_5}$, $\overline{R_7}$, and $\overline{R_{6,j}}$ with $j = 1, \ldots, 4$ as shown in Figs. 15–20, respectively. As expected, the average risk is higher in links $L_{6,1}$ and $L_{6,3}$ that are the nearest links to the blocked lane. It is apparent that considering different sub-links, suitable restoration strategies can be selected to reduce the risk. For example, if we consider link L_5, then P1 is the best strategy: it is preferred waiting that the vehicles leave the highway. On the contrary, if we consider the sub-links $L_{6,1}$, $L_{6,2}$, and $L_{6,4}$ the best policy to be applied is P4 (scenario SC5). Finally, considering link $L_{6,3}$ and L_7 it is convenient to apply policy P3 to reduce the risk (scenario SC4).

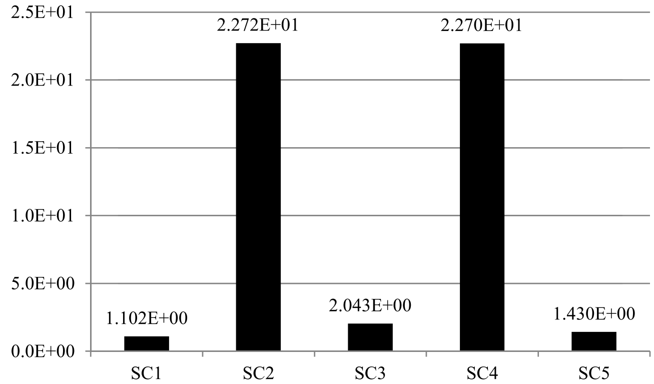

Fig. 17. Average risk $\overline{R_{6,2}}$ of $L_{6,2}$ after the accident.

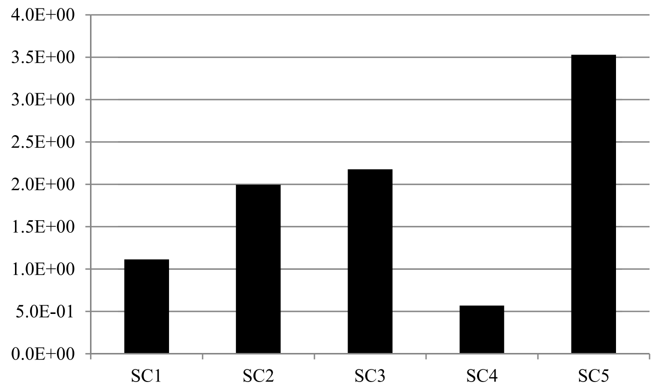

Fig. 18. Average risk $\overline{R_{6,3}}$ of $L_{6,3}$ after the accident.

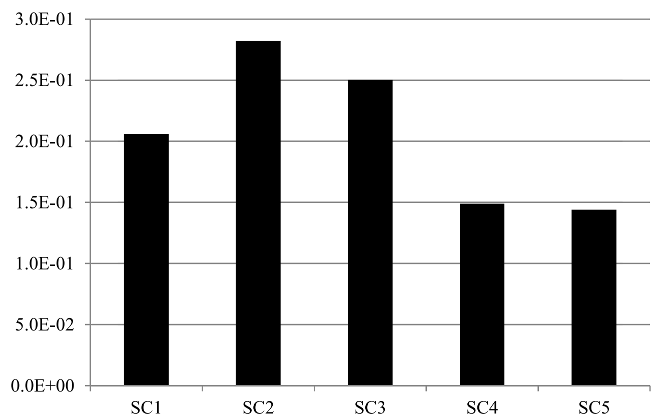

Fig. 19. Average risk $\overline{R_{6,4}}$ of $L_{6,4}$ after the accident.

Hence, the results show how the proposed DSS can help the decision makers to take the suitable decisions in function of the zone in which the hazmat vehicle is traveling. Such a result not only qualitatively confirms the evident basic importance of the application of the right rescue and restoring policy in order to reduce the risk after an accident involving hazmat, but also provides a sound quantification of it.

VI. Conclusion

This paper presents a DSS devoted to solve two problems: 1) assessing the risk induced on the population by vehicles transporting hazmat and traveling in the highways and

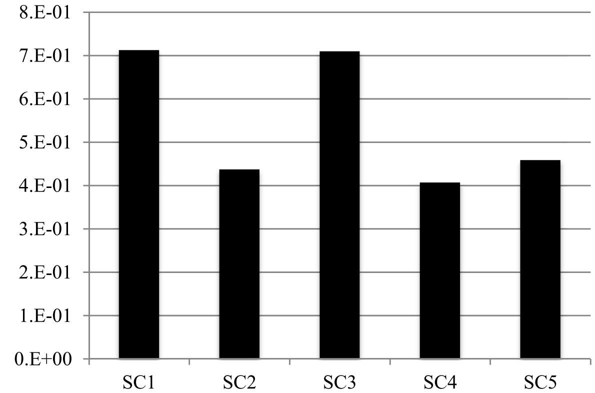

Fig. 20. Average risk $\overline{R_7}$ of L_7 after the accident.

2) selecting the optimal strategy to face critical situations such as accidents involving hazmat vehicles. Two basic modules of the DSS MC are specified: the RAM and the SM. In particular, the RAM assesses the risk of transporting hazmat and evaluates the number of people that can be involved in an accident. Moreover, the SM is based on a modular CTPN model that describes the highway network dynamics and the restoration procedure after the accident. In order to show the effectiveness and the applicability of the DSS, we describe a DSS prototype implementation devoted to evaluate the risk related to the transit of hazmat in a stretch of the A4 highway in the North-east of Italy. The simulation results give an example of the DSS application to manage the actions to be applied to solve blocking and restoration procedures involving hazmat vehicles.

Further research will deal with the detailed specification of the different modules of the DSS, such as the optimal routing of hazmat vehicles.

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