Vulnerability assessment and quantitative risk analysis of road infrastructure

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The complex system of road infrastructures of a country plays a fundamental role both on the economy and on the development of the territory and on the management of accident scenarios that occur as a result of natural disasters.
It is therefore essential to assess the vulnerability of the infrastructural network to natural and man-made risk factors in order to identify any critical issues and plan improvements and upgrades to the infrastructure.
This article examines some of the approaches used to assess the vulnerability of complex systems and the methodologies used in the field of road infrastructure. From the analysis of the developed methodologies it emerges that to date there is not a shared definition of road infrastructure vulnerabilities nor a shared methodology of vulnerability assessment. The Quantitative Risk Analysis seems to be the tool that allows to approach in an integrated way the issue of road infrastructure vulnerability, as it allows to relate natural or anthropic events that can occur on the territory and which can interact with the infrastructure, with the characteristics and functional levels in degraded conditions of the infrastructure itself.
Keywords: *Vulnerability, Quantitative risk analysis, road infrastructure, hazard, earthquake.*

La valutazione della vulnerabilità e Analisi di Rischio Quantitativa delle infrastrutture stradali. *Il complesso sistema di infrastrutture viarie di un paese assolve un ruolo fondamentale sia sull'economia e sullo sviluppo del territorio sia rispetto alla gestione di scenari incidentali che si verificano a seguito di calamita naturali.*
Risulta pertanto fondamentale valutare la vulnerabilità della rete infrastrutturale ai fattori di rischio naturale ed antropici al fine di individuare eventuali criticità e programmare interventi di miglioramento e potenziamento dell'infrastruttura.
In questo articolo vengono esaminati alcuni degli approcci utilizzati per la valutazione della vulnerabilità di sistemi complessi e le metodologie utilizzate nel campo delle infrastrutture stradali. Dall'analisi delle metodologie sviluppate scaturisce che ad oggi non si dispone di una definizione condivisa di vulnerabilità delle infrastrutture stradali né tantomeno di una metodologia condivisa di valutazione della vulnerabilità. La Quantitative Risk Analysis sembra essere lo strumento che consente di approcciare in maniera integrata il tema della vulnerabilità delle infrastrutture stradali, in quanto consente di mettere in relazione eventi naturali o antropici che possono verificarsi sul territorio e che possono interagire con l'infrastruttura, con le caratteristiche e i livelli funzionali in condizioni degradate dell'infrastruttura stessa.

Parole Chiave: *Vulnerabilità, Analisi quantitativa del rischio, infrastrutture stradali, pericoli, sisma.*

1. Introduction

The functions of modern society depend on the complex system of infrastructure and services networks commonly included in the vast concept of lifelines. Among the lifeline systems, road transport infrastructure plays a key and strategic role in the economic and social development of a country. The efficiency and effectiveness, reliability and availability of the road transport system is a determining factor for the development of the economy of a territory. The transport system and interconnections with international networks must ensure the accessibility and "mobility" of people and goods safely and efficiently.

Despite the awareness of the importance of land transport infrastructure, there is no shared methodology for evaluating the safety level of such infrastructures: Kaundinya *et al.* (2016) highlight how the theme is addressed with sectoral approaches, definitions and variable concepts and partial methods. In addition to the theme of the best ordinary functionality and the methods required for its design, the availability of the road system is a precondition for the application of emergency measures in the event of natural disasters. This was evident in the recent earthquakes and phenomena of hydrogeological disruption in Italy. Indeed, only the guarantee of a sufficient level of infrastructure efficiency can help to reach areas hit by a catastrophic event in a short time and therefore mitigate the consequences. The need to ensure the functionality of the transport network during seismic events or other natural disasters, therefore requires an analysis of the vulnerability of transport infrastructures and planning of recovery and rescue measures aimed at ensuring their usability in order to support the management of post incidental event. After the occurrence of widespread catastrophic events such as earthquakes or floods, it is essential that the transport network remains operational or that its functionality is restored as soon as possible. It is necessary that the system be sufficiently resilient, with reference to the network in its entirety or to parts of it which are considered indispensable. Proper design of network resiliency also favors the economic recovery of the affected area.

For this purpose, it is essential to have analytical tools assessing the local and systemic effects of earthquakes or other calamitous events in advance. The availability of a unitary global method for assessing the resilience of the network would also enable rational investment of resources and would make it possible to reduce the risk of unavailability of the infrastructure.

2. Definition of vulnerability and resilience of disaster societies

The concept of vulnerability [lat. Vulnerabĭlis, der. di *vulnerare* To "hurt"] is used in a number of areas where risks and dangers are assessed but to date there's no shared definition.

The vulnerability definition is therefore dependent on the analyst's sectoral viewpoint and its analysis purposes: who plans the transport system, associates the concept of vulnerability to system functionality in case of local disturbances or failures – typically of endogenous origin (incidents). In the field of structural engineering, the concept of vulnerability is usually used to indicate the propensity to damage of a particular structure (eg a bridge, a tunnel, etc.) when it is stressed by a particular event (eg, earthquake). In this case, the vulnerability of the system as a whole is not considered. In addition, the concept of vulnerability often includes exposure to danger, resulting in contamination of concepts. In order to approach the theme of vulnerability of road infrastructure, it is therefore necessary to analyze the different uses and definitions of the vulnerability term and related terms such as danger and exposure, risk, resilience and robustness, reliability and availability.

In the context of the assessment of the vulnerability and resilience of companies to natural disasters, Birkmann, (2006) finds that in literature there are over 25 different definitions and methods for assessing vulnerability.

Birkmann identifies different conceptual and analytical approaches to systematic assessment of the vulnerability among which:

1. The school of the double structure of vulnerability;
2. The theory of disaster risk;
3. The School of Climate Change;
4. The holistic approach.

1. The "double vulnerability structure" school considers vulnerability as the mediator between prevention, reaction and recovery capabilities following a perturbation (the response of a system) and exposure at danger factors (the solicitation at the system). However, the model presents ambiguity because it attempts to include the mediated concepts in the concept of vulnerability.
2. Within the theory of disaster risk, the vulnerability is separate from the concepts of exposure and reaction capacity. Vulnerability is considered as a risk component: For Bollin et al. (2003) the concept of risk is defined by four components: hazard, exposure, vulnerability and capacity and measures (fig. 2).

Villagràn de Leon (2004) resumes the "Risk Triangle" (fig. 3) and proposes a risk quantification model that includes vulnerability, hazard and deficiencies in preparedness (of a company, system or single

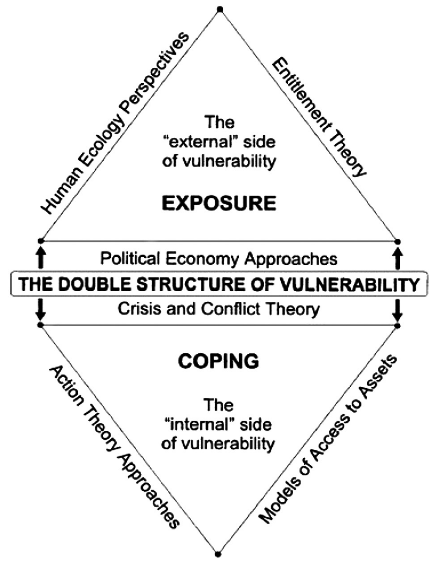

Fig. 1 Bohle's conceptual framework for vulnerability analysis.
La struttura concettuale della vulnerabilità secondo Bohle (2001).

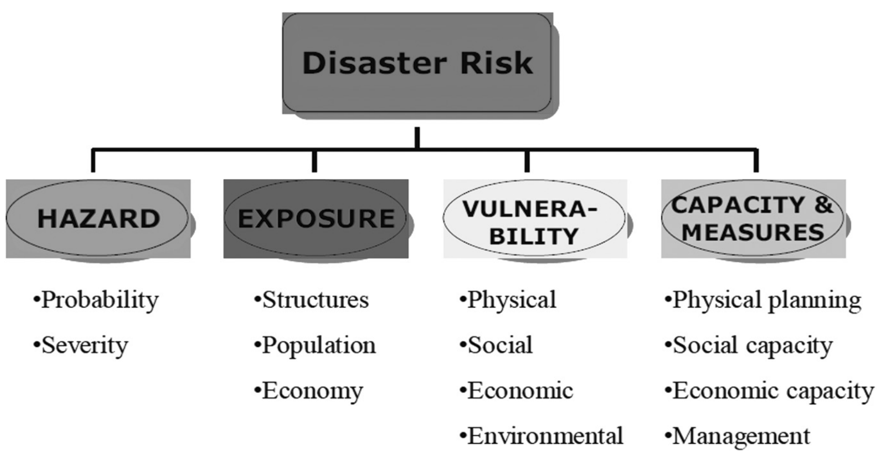

Fig. 2. The conceptual framework to identify disaster risk.
La struttura concettuale per identificare il rischio di catastrofi (Bollin et al., 2003).

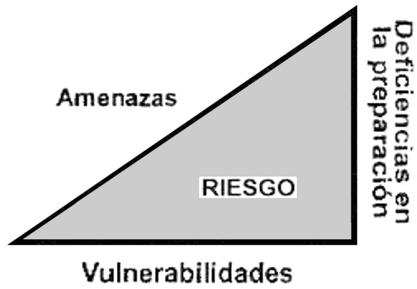

Fig. 3. Risk as a result of vulnerability, hazard and deficiencies in preparedness .
Rischio come risultato di vulnerabilità, rischio e carenze nella capacità di reazione (Villagràn de Leon, 2004).

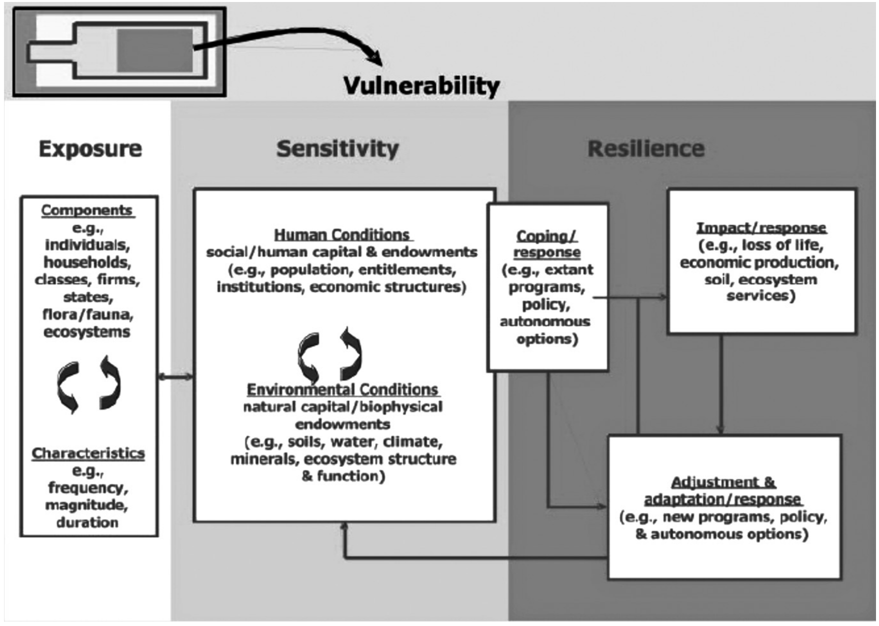

Fig. 4. Details of the exposure, sensitivity, and resilience components of the vulnerability framework.
Dettagli sui componenti della vulnerabilità: esposizione, sensibilità e resilienza (Turner et al., 2003).

element system). Vulnerability is seen as the precondition for making infrastructures, processes, services, and productivity more prone to being hit by an external danger. The limitation of this approach is in the formalization of the concept of deficiency, which should be understood, by definition, within the concept of vulnerability. Implicitly the model proposes a definition of vulnerability as damage that occurs when the hazard materializes. The United Nations Office for Disaster Risk Reduction (UNISDR) considers the vulnerability (social economic physical and environmental components) a risk factor.

3. Within the environmental change, Turner et al. (2003) in contrast to the disaster risk community consider vulnerability as a function of exposure coping response, impact response, and adaptation response to a dangerous event (fig. 4).
4. In the holistic approach, vulnerability is assessed globally and multidisciplinary. According to this approach for Carreño et al. (2007) the vulnerability depends on several factors divided into three categories: exposure and susceptibility to physical elements; system fragility and resilience. (fig. 5) These three categories of factors determine the direct, indirect and immaterial impacts of a dangerous event.

The approach defines exposure and susceptibility as necessary conditions for the existence of physical damage. While the socio-economic fragility and lack of resilience are vulnerability conditions for indirect impacts.

While recognizing in a variety of approaches a similar conceptual structure, it is evident that the definition of vulnerability is conditioned by the scope in which the concept is applied and by the model author's purpose, without a definite definition in the broader conceptualization of the theory of risk.

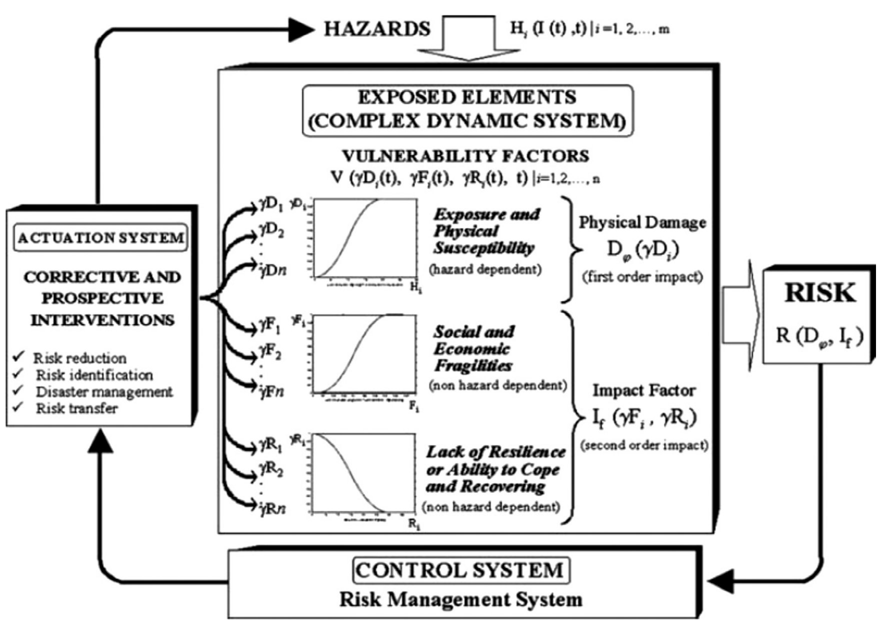

Fig. 5. Model for holistic approach of disaster risk.
Modello di rischio di catastrofi nell'approccio olistico (Carreño et al., 2007).

3. Road Infrastructures vulnerability

As already introduced, the assessment of the efficiency and availability of the infrastructure under emergency conditions have to consider the vulnerability of the infrastructure itself to natural and man-made events that can limit its use.

Although this is evident, even in the study and design of road systems, there is no univocal definition of vulnerability in the proposed different approaches.

In literature, vulnerability has a different meaning if we focus on the functionality of a road network or if we focus on road infrastructure by considering its features and the different components.

Husdal (2004) Identifies three types of vulnerabilities in a road network (fig. 6):

1. Structural vulnerability, which refers to the road itself, and therefore to its constructive features: for instance, width, geometric and design features, presence and characteristics of structural elements (bridges, tunnels, underpass, Etc)
2. Natural vulnerability which refers to the characteristics and risks of the territory facing the road;
3. Traffic vulnerability, which refers to the characteristics that describe the flow of traffic and its variations (peak hours, particular days of the week, maintenance operations, etc).

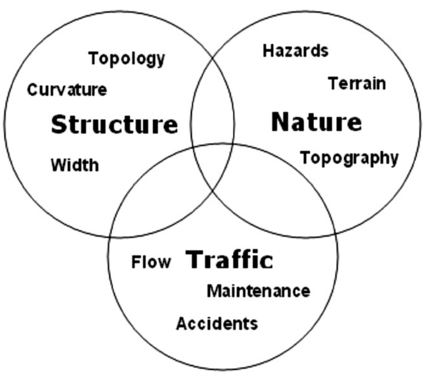

Fig. 6. Road networks are vulnerable to 3 influences: structure-related, nature-related and traffic-related.
Le 3 componenti della vulnerabilità delle reti stradali: struttura, territorio e traffico (Husdal, 2004).

Husdal also discriminates the concept of vulnerability and reliability: the vulnerability measures the consequences of a network malfunction, while the reliability is a measure of the degree of stability of the network

Berdica (2002) proposes an unified approach to both concepts of reliability and vulnerability: the vulnerability is the susceptibility to accidents that produce a reduction in network functionality that is the network's ability to perform its tasks over a given range of time (serviceability).

Taylor and D'Este address the issue of vulnerability by distinguishing it from the concept of reliability. The vulnerability is linked to the consequences of the event and depends on the weakness of the network, while reliability is linked to the likelihood of an event occurring and is therefore dependent on network connectivity. In this case, the concept of vulnerability is related to the concept of accessibility understood as the ease to access into the area (Taylor *et al.* 2006). In this case vulnerability measures the loss of accessibility of a community by assessing the variation of the general cost of transport.

Jenelius and Mattsson (2006) link the concept of vulnerability to the concept of criticality of the various components of the network. The criticality of an element of the network depends on its weakness or the probability of being affected by the failure and its importance, or the consequence that results from the failure of the element. Jenelius *et al.* (2006) define the importance of strings and the display of network nodes. Jenelius (2007) pose the problem of the end of closing arc (dynamic vulnerability). In addition, Jenelius (2010), in later studies, introduces the concept of inequality for the users. Jenelius defines inequality by introducing two concepts: efficiency and equity. Also, Jenelius and Mattsson (2012, 2015) analyze the vulnerability of a road network undergoing a disastrous space entity event by introducing the concepts of the importance of a grid and exposure to users in a region.

D'Andrea and Cafiso (2005) define vulnerability such as the propensity of goods, people or businesses to suffer damage or change as a result of the occurrence of the event. In particular it can be interpreted as a loss of efficiency of the territorial system and residual capacity to further elaborate the system's own functions. The vulnerability is therefore the propensity of elements or complex systems to suffer damage in according to their intrinsic characteristics. The authors introduce the concepts of direct vulnerability and indirect vulnerability: direct vulnerability is the propensity of a single element to suffer; indirect vulnerability refers to the impact on the organization of the territory resulting from the collapse of one or more elements that constitute it. The authors concentrate mainly on seismic risk by evaluating a structural vulnerability linked to the structural and geometrical characteristics of the road trunk and the surrounding structures.

From this concise overview we can see that the concept of vulnerability is particularly varied and applicable to different fields. Depending on the observation point, we can talk about a region's vulnerability, network vulnerability, network element vulnerabilities (strings, links, nodes), vulnerabilities to a particular trunk of the road network, or a network vulnerability particular structure (bridges, tunnels, excavated, etc.).

The models adopted in the literature for quantifying the vulnerability of road infrastructure depend, therefore, on the field of study and by the object of study.

Mattsson and Jenelius (2015) share the methodologies for assessing vulnerability in road transport systems in two different conceptual approaches: the first refers to an analysis of the topological vulnerability of the transport network, the second is based on the analysis of the systemic vulnerability of transport networks.

Topological vulnerability can be determined based on network configuration and is an inherent feature independent of the critical events to which it is subject and the traffic that circulates. Topological vulnerability therefore depends on the characteristics of the graph and, in particular, on the degree of its connection.

The system vulnerability is linked to the network's functionality and depends on both the spatial configuration of the network (therefore it is connected to the topology vulnerability) and the flows that circulate. However, system vulnerability refers to the effects that occur globally on a network as a result of a disruption regardless of the event that generated it. The system vulnerability study allows to evaluate which strings are most important for maintaining the overall network functionality.

4. Methodologies for assessing the vulnerability of a road system

Several indexes have been introduced in the literature for assessing the vulnerability of road transport infrastructure. These indices allow to evaluate the impact of interruptions on the transport system in terms of increased transport times or travel distances or in terms of accessibility to a particular area.

A review of the vulnerability assessment methodologies in literature is proposed by Mattsson and Jenelius (2015).

For example, Taylor *et al.* (2006) measure the vulnerability by assessing the increase in the cost of transport that arises following a network interruption or the assessment of the loss of accessibility of a given area. The loss of accessibility of a community is assessed by the following formula $V_{rs} = \Sigma_i \Sigma_j d_{ij} v_{ijrs}$ where v_{ijrs} is the difference of the general cost of transport from node i to node j when network link e_{rs} is interrupted and d_{ij} is a measure of the quantity of movement from i to j.

Similarly, the problem is addressed by Jenelius (Jenelius and Mattsson, 2006; Jenelius *et al.*, 2006). They evaluate the importance of a network link and the exposure of a node by estimating travel cost increases from a node i to a node j following a interruption of a network element. The importance of a link can be calculated with respect to a single demand node, a group of demand nodes or the whole network.

The authors distinguish between the case where the interruption separates the network into two parts (the set of cut link is denoted E^c) and the case where the interruption does not separate the network into two part (the set of non cut link is denoted E^{nc}). In the case of a no-cut link type interruption and of the whole network, the importance is determined through the following formula:

$$Importance\ (k)_{net} = \frac{\sum_i \sum_{j \neq i} w_{ij} \left(c_{ij}^{(k)} - c_{ij}^{(0)} \right)}{\sum_i \sum_{j \neq i} w_{ij}}, k \in E^{nc}$$

where k is the link of which the importance is calculated, w_{ij} represent a weight that reflects its significance in relation to the other pairs origin-destination (OD) and c_{ij} represents the cost of transport from node i to node j in case of working network (0) and in case of network with interrupted link k. In the case of a cut link type interruption the [$Importance\ (k)$]$_{net} = \infty$, $k \in E^c$. In the case of a cut link type interruption the autors introduce the concept of *unsatisfied demand* that represents the number of trips from i that are unable to reach j due to the closed element k. Similarly the exposure can be calculated with respect to a single demand node, a group of demand nodes or the whole network. When measuring the exposure for a municipality m, the $\Delta c_{ij}^{(k)} = c_{ij}^{(k)} - c_{ij}^{(0)}$ is aggregated over all origins i in the municipality and all destinations j in the entire network. The exposure measure the expected increase in travel cost. For the interruption of a random link

$$Exposure_{rand}(m) = \frac{\sum_{k \in E^{nc}} \sum_{i \in V_m^d} \sum_{j \neq i} w_{ij} \left(c_{ij}^{(k)} - c_{ij}^{(0)} \right)}{L^{nc} \sum_{i \in V_m^d} \sum_{j \neq i} w_{ij}}$$

where L^{nc} is the number of non-cut links and V_m^d is the set of demand nodes located in municipality m. The exposure of municipality m is then the maximum value over all non cut links.

Chang (Chang and Nojima, 2001; Chang, 2003) evaluates the perturbation effects on the network through the measurement of network performance in terms of accessibility. In the formulation of Chang, the measure of accessibility variation is performed by measuring the increase of distance between the nodes. In this case, the author does not assess the vulnerability or importance of a network element but of a region following a catastrophic event by examining the network following the 1995 Kobe earthquake in Japan. Accessibility is assessed through the following formula

$$D_s(t) = \frac{f - A_s(t)}{f - 1}$$

where s represents the spatial unit on which the accessibility difference is measured, f is a constant and $A_s(t)$ is the ratio of accessibility to time t. The accessibility measure proposed by Chang does not assess the vulnerability or importance of a particular element of the network, but concerns an area and is therefore geared towards establishing the impact on the network of a catastrophic event such as the Kobe earthquake. Accessibility measures of an area have been proposed by other authors: Sohn (2006) links the accessibility index to distance and traffic volumes, Jenelius and Mattsson (2012, 2015) introducing the importance of a cell and a region's exposure to assessing the vulnerability of the transport system to natural or man-made calamitous events that may involve a large area and therefore multiple elements of the system infrastructure. In such cases the interruption may cover more than one element of the network and therefore any redundancy of the links may not be sufficient to ensure mobility after a catastrophic event. The importance of a cell and the exposure of a region is calculated using the following formulas.

The vulnerability assessments described above (Taylor and D'Este, Chang, Sohn and Jenelius and Mattsson) analyze systemic vulnerability of network and assess the consequences of interruption or disturbance on one or more elements of the network without assessing the probability of such a interruption

With particular reference to unintended natural and man-made events to which transport infrastructures are exposed there are no consolidated methodologies in literature that allow an assessment of the probability of interruption of network elements from the hazard analysis and its consequences.

An approach in this direction we find in the studies of Cafiso and D'Andrea (Cafiso *et al.* 2004; Cafiso *et al.* 2005; D'Andrea *et al.* 2005; D'Andrea and Condorelli 2006) which propose an assessment of the structural vulnerability of the transport infrastructure with reference to seismic risk. Seismic events can have catastrophic consequences both directly on populations and indirectly through damaging the lifelines systems that are the basis of modern societies. There are more or less consolidated methodologies for the assessment of the seismic risk of buildings in the literature but, as the authors point out, a seismic risk assessment can not ignore the analysis of the conditions of transport infrastructures (highways, roads, railways, etc.) for both 'Direct exposure of the population that uses these structures on a day-to-day basis and with regard to post-earthquake emergency management. The methodology proposed by the authors for assessing the seismic risk of road infrastructure is structured according to the following points:

- Study of the seismic hazard of the site related to the events occurring and the geological and tectonic characteristics of the territory
- Direct exposure analysis related to the likelihood of road users in the various parts of the network directly exposed to the seismic event
- Analysis of indirect exposure to population distribution served by infrastructures to which post-earthquake accessibility needs to be guaranteed
- Evaluation of functional vulnerability with respect to the potential substitution of damaged tracts considering network configuration and geometric characteristics
- The structural vulnerability assessment of the trait related to the characteristics (structural, mechanical, technological, etc.) of the various elements that constitute it (bridges, basins, trenches, galleries).

The total vulnerability for each stroke is calculated using the following formula $V_t = V_s \times (G \times R_e)$

where V_s represents the Structural Vulnerability of the infrastructure section in question, while G is a functional factor that takes into account the geometry of the road, R_e is a functional factor that takes into account the possible alternatives offered by the network. The seismic risk of the subject in question can therefore be expressed by the formula $R = H \times (E \times V_t)$ where H is the indicator of the earthquake hazard and E is the indicator of exposure. The methodology was implemented through a GIS Geographic Information System application in the case of extraurban network (Cafiso *et al.* 2004) and urban area (Cafiso *et al.* 2005) and the results obtained are represented by appropriate indicators.

Cirianni (Cirianni and Leonardi 2012; Cirianni *et al.* 2012) also study the vulnerability of road infrastructure to natural hazards by focusing on the characteristics of the infrastructure and surrounding environment. Authors adopt a fuzzy methodology to assess the infrastructure vulnerability of a landslide risk.

El-Rashidy and Grant Muller (2014) extending the work of Tampère *et al.* introduced a new vulnerability Index calculated by considering some vulnerability attributes of a link. The authors noted that most of the research on vulnerability assessment focused on assessing the impact of link closure without referring to the characteristics of the link that lead to vulnerability and they propose a methodology for measuring the impact of disruptive events (eg human events such as accidents or natural events such as adverse weather conditions) and the functionality of the road transport network. In agreement with Srinivasan, they identify different types of attributes that can have a significant effect on the vulnerability of the links, which categorize into four main categories; Network Features, Traffic Flows, Threats and the Environment.

As part of projects funded by the European Commission, the authors of the All TraIn project (Kaundinya *et al.* 2016) have developed a guideline to the dangers of transport infrastructure. The main objective of the AllTraIn project was to develop a practical and easy-to-use guide to all the dangers that could interfere with land transport infrastructures to use for infrastructure security management according to a holistic risk assessment approach. The guide analyzes the dangers of both intentional nature and nature-related events and the elements that make up the transport infrastructure (bridges, tunnels, embankment, trenches and centralized systems).

A methodological approach has been developed for the assessment of impacts on structures that combines information on the dangers and characteristics of the infrastructure Figure 9.

Within the project, a qualitative assessment procedure was developed for the vulnerability of the various transport infrastructure elements over a number of dangers implemented through a tool represented in the Figure 7.

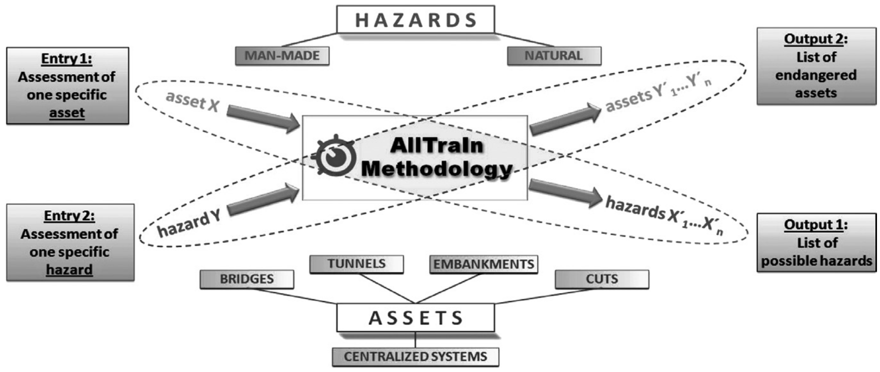

Fig. 7. Qualitative assessment vulnerability procedure in Alltrain project.
Procedura di valutazione qualitativa della vulnerabilità nel progetto All train (Kaundinya et al., 2016).

5. Considerations and assumptions for developing an integrated model for assessing the vulnerability of transport infrastructures

The above bibliographic analysis shows that in the field of transport infrastructures the scientific research on the vulnerability has focused mainly on assessing the systemic vulnerability of the network. The most of methodologies evaluate the impact of closing a network's arc in terms of increasing travel times or distances to travel to reach a destination from a source. Some approaches, however, assess the vulnerability of some infrastructure elements to specific hazards such as earthquake or landslides. There seems to be no integrated approach that takes into account the various hazards to which the infrastructure is exposed and that by defining a risk model can correlate the probability of closing a network's arcs and its consequences.

The risk analysis approach as a global risk assessment tool has

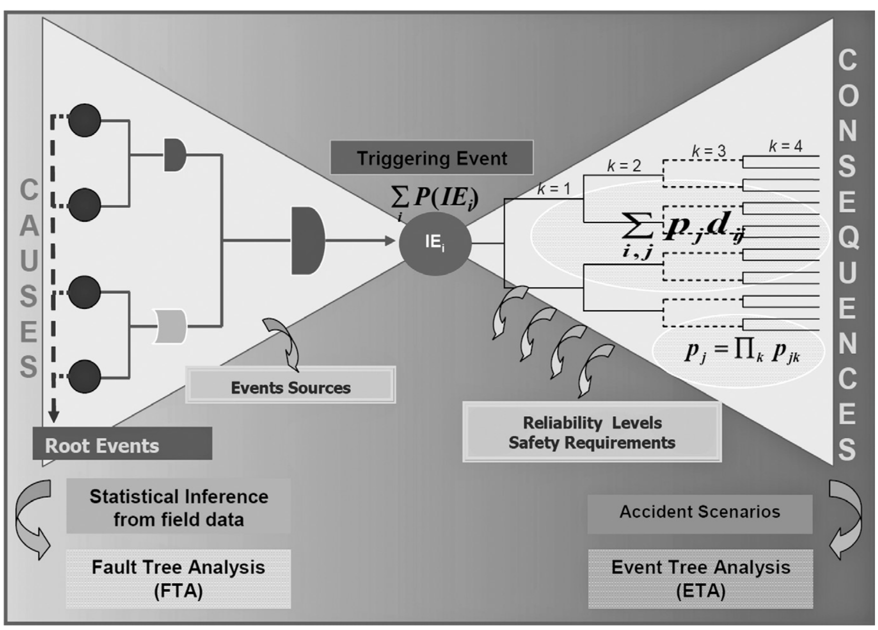

Fig. 8. Bow-Tie model logical and sequential structure of events in quantitative risk analysis.
Modello Bow Tie struttura logica e sequenziale degli eventi nell'analisi di rischio quantitativa (Guarascio et al., 2007).

been initially developed to study the safety of potentially dangerous industrial processes (eg in the chemical industry) or potentially hazardous industrial plants (such as nuclear power plants). Today quantitative analysis of probabilistic risk is a powerful common tool in many engineering and civil engineering sectors Guarascio *et al.* (2007).

Quantitative analysis of probabilistic risk responds to the fundamental question: "What could happen and what are the consequences?" Hazardous conditions may develop from evolving events and generate an initial critical event from which several incident scenarios may result depending on the characteristics of the system being analyzed. The logical and sequential structure of events is graphically represented by the graph shown in the figure 8 usually referred to as the Bow-Tie model. The model considers the initial critical event as a "nodal point" separating root events ("causes") and events as a consequence ("effects").

The QRA was adopted in Italy for the risk analysis of tunnels (Guarascio *et al.*, 2007) or for the evaluation of catastrophic events (Guarascio *et al.*, 2009; Cardarilli *et al.*, 2018). In the case of road infrastructures, a reflection is under way on risk analysis methods, acceptability criteria and safety practices, requested by PIARC and also conducted in the context of European research projects (including Ecoroads) (Rossi *et al.*, 2016; Rossi *et al.*, 2018). Also, today the use of open source tools and open data helps to determine some parameters useful for the assessment of vulnerability and risk (Baiocchi *et al.*, 2017).

The QRA seems to be the tool that allows to approach in an integrated way the issue of road infrastructure vulnerability. The definition of an integrated risk model in which the "vulnerability" is defined as a functional link between stress and response in terms of system availability, allows to relate natural or anthropic events interfering with the infrastructure, characteristics of the infrastructure and functional level infrastructure following a given event. We are therefore able to correlate the probability of closing the edges of a network and its consequences. A multidisciplinary and modular approach also makes it possible to integrate the methodologies already developed in the individual engineering sectors: structural, hydraulic, geotechnical, transport, etc. The implementation of the model requires:

- Analysis of the danger factors to which the infrastructure is exposed and quantifying the probability of occurrence of possible initiator events;
- The characterization of the infrastructure for the identification of sections and / or components with homogeneous behavior;
- The definition of damage functions of the infrastructure interfering with the danger factors that allow to classify increasing damage levels according to the magnitude of the solicitation;
- The implementation of analysis models of traffic flows in degraded conditions for the verification of post-disaster scenarios;
- The definition of infrastructure vulnerability and risk indicators;
- Representation of results through a GIS tool.

The logical scheme of the risk model is shown in the diagram shown in the Figure 9.

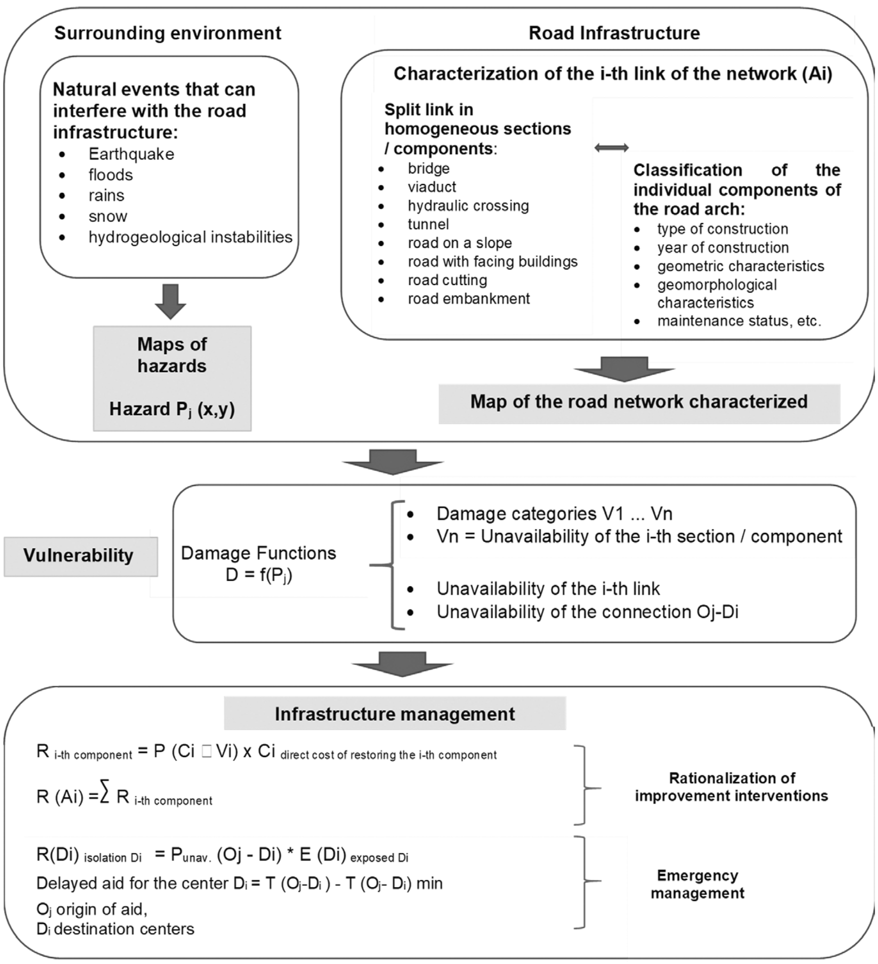

Fig. 9. Integrated Model Flowchart.
Schema a blocchi del modello integrato.

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