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THE VULNERABILITY OF TRANSPORT CRITICAL INFRASTRUCTURES

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Rezumat. *Infrastructurile de transport fac parte din categoria infrastructurilor critice ale societăţii alături de infrastructurile energetice, informatice, de alimentare cu apă, gaze etc., ale căror disfuncţionalităţi pot genera efecte adverse în plan economic, social sau natural. Vulnerabilitatea reprezintă un concept important în analiza capacităţii reţelelor de transport de a asigura continuitate în operare, respectiv de a menţine nivelul serviciului în limite acceptabile. Vulnerabilitatea infrastructurilor critice de transport este analizată prin intermediul consecinţelor indisponibilităţii arcelor reţelei asupra indicelui de accesibilitate Hansen şi al costului total de deplasare. Studiul de caz realizat cu ajutorul pachetului software TransCad prezintă efectele întreruperii legăturilor pe reţeaua rutieră română, rezultând o clasificare a importanţei unor legături în condiţiile fluxurilor actuale de trafic.*

Abstract. *Transport infrastructures belong to critical social infrastructures beside power, informational, water, gas supply infrastructures etc., whose malfunctioning could generate adverse economic, social or environmental effects. The concept vulnerability is important when investigating the ability of transport networks to provide continuity in operation and maintaining the level of service between acceptable bounds. Vulnerability of critical transport infrastructures is analyzed through the consequences of links or nodes failure to Hansen index of accessibility and users total cost. The case study realized with TransCad software investigates the Romanian road network vulnerability due to links failure, resulting in a classification of links importance for the present transport flows.*

Key words: critical infrastructures, transport networks, vulnerability, accessibility

1. Introduction

According to the European Council strategy for the identification and designation of critical infrastructures and the need for improving their protection [1], critical infrastructures represents «*those assets or parts thereof which are essential for the maintenance of critical societal functions, including the supply chain, health, safety, security, economic or social well-being of people*».

Among critical infrastructures, the EU acquis encompasses:

- Energy – Oil and gas production, refining, treatment, storage and distribution by pipelines, electricity generation and transmission;

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- Nuclear industry – Production and storage/processing of nuclear substances;
- Information, Communication Technologies, ICT – Information system and network protection, instrumentation automation and control systems (SCADA etc.), internet, provision of fixed telecommunications, provision of mobile telecommunications, radio communication and navigation, satellite communication, broadcasting;
- Water – Provision of drinking water, control of water quality, stemming and control of water quantity;
- Food – Provision of food and safeguarding food safety and security;
- Health – Medical and hospital care, medicines, serums, vaccines and pharmaceuticals, bio-laboratories and bio-agents;
- Financial – Payment and securities clearing and settlement infrastructures and systems, regulated markets;
- Transport – Road transport, rail transport, air transport, inland waterways transport, ocean and short-sea shipping;
- Chemical industry – Production and storage/processing of chemical substances, pipelines of dangerous goods (chemical substances);
- Space and research activities.

The designation of an infrastructure as critical stands on three criteria:

- The geographical area – the effects of disruption are spread on an extended area (local, regional or even international area);
- The amplitude of the effects – these could be cumulated, providing economic, social, environmental or political incidence;
- Time persistence – the consequences due to the infrastructure disruption may last from a couple of ours till months or years, disturbing the activity of others social systems.

The interdependencies among critical infrastructures represent an important issue for the associated risks management, taking into consideration that the society and the economy rely on interconnected systems and networks whose unavailability generates a „domino effect”.

The risk management helps local and central authorities to identify the vulnerable points of the infrastructures and to assess strategies and priorities for eliminating or alleviating the effects [2].

2. Reliability versus vulnerability of transport networks

The concepts of reliability and vulnerability are extremely important in evaluating the transport networks ability in providing continuity in operation. The natural disasters (e.g. earthquakes, flood, fire, frosting, snow fall), the malevolence (terrorism, sabotage, war), and the human habitat and mainly the urban areas spread generate a special focus among scientists on reliability and vulnerability of critical transport infrastructures. Policy makers, local authorities, urbanists, and traffic engineers seek for methods and tools to investigate transport network reliability and to assess the consequences of the interruption of different critical elements. The ability to evaluate, to manage and to minimize the results of networks failure generates economic, social and environmental benefits. These are translated into travel costs reduction, cutting off the negative externalities, continuity in social and trade activities.

The reliability of a transport network element is associated with the probability that it will perform its intended function during a specified period of time under stated conditions. If some facilities of the transport networks become unavailable, the network as a whole could still operate, even with less performances and reallocation of the traffic on routes. The scientific literature differentiates among three forms of transport network reliability [3, 4]:

- *Connectivity reliability* – the probability that a pair of nodes in a network remains connected when one or more links have been cut;
- *Travel time reliability* – the probability that a trip between an OD pair could be completed within a given time interval despite the links failure;
- *Capacity reliability* – the probability that a network can still accommodate a given level of travel demand when one or more links are unavailable.

The transport networks vulnerability is related to the consequences of link failure, irrespective of the probability of failure [3]. The probability of link failure can be statistically insignificant, but if the event occurs, the social, economic and environmental adverse impacts are so intense to indicate a major issue. The analysis of transport networks vulnerability shows out the structural malfunctions in the networks topology [5-7]. One differentiates between two forms of transport network vulnerability:

- *Vulnerability with respect to the travel cost* – the disruption of one or more links generates a substantial increase in the travel generalized cost;
- *Vulnerability with respect to the accessibility* – the fail of one or more links significantly reduces the accessibility of a node or of the entire network.

3. Transport network vulnerability

3.1. Vulnerability with respect to accessibility

Taylor and D'Este [3] use the Hansen accessibility index in assessing the transport network vulnerability. The accessibility of a node *i* is:

$$A_i = \sum_{j \neq i} B_j f(c_{ij}), \tag{1}$$

where B_j represents the attractiveness of node *j*, c_{ij} – the generalized travel cost between the node *i* and *j*, and $f(c_{ij})$ – the transport deterrence function. Usually, the transport deterrence function is a negative power function or a negative exponential function.

The Hansen accessibility index for a node is:

$$HA_i = \frac{\sum_{j \neq i} B_j f(c_{ij})}{\sum_{j \neq i} B_j}, \tag{2}$$

and for the entire network is:

$$TA = \sum_i HA_i . \tag{3}$$

A disturbing event in the network, providing inoperable the link *k* generates the cut in the accessibility index:

$$\begin{aligned} \Delta HA_i &= HA_i^{(0)} - HA_i^{(k)}, \\ \Delta TA &= TA^{(0)} - TA^{(k)}. \end{aligned} \tag{4}$$

where $^{(0)}$ reflects the network initial state and $^{(k)}$ the network with link *k* disrupted.

3.2. Vulnerability with respect to travel cost

Jenelius et al. [8] use the generalized travel cost as a method to evaluate the loss of the transport network performances. If the link *k* belongs to a set of links whose fail does not isolate regions in the network, then the importance of the link is:

$$\Omega(k) = \frac{\sum_i \sum_{j \neq i} \varphi_{ij} (c_{ij}^{(k)} - c_{ij}^{(0)})}{\sum_i \sum_{j \neq i} \varphi_{ij} c_{ij}^{(0)}} \tag{5}$$

where $c_{ij}^{(0)}$ is the generalized travel cost between the nodes *i* and *j* in the initial network, and $c_{ij}^{(k)}$ the generalized travel cost between the same nodes when the link *k* is failed.

More, the link disruption is translated into nodes exposure. The vulnerability of a node *i* is:

$$\Phi(i) = \max_{k \in L^{n-c}} \frac{\sum_{j \neq i} \varphi_{ij} \left(c_{ij}^{(k)} - c_{ij}^{(0)} \right)}{\sum_{j \neq i} \varphi_{ij} c_{ij}^{(0)}}. \tag{6}$$

where L^{n-c} represents the set of links whose fail does not isolate regions in the network.

4. Case study. Romanian road network vulnerability

Regional and urban disparities in the Romanian socio-economic activities system lead to the isolation for a large amount of local communities and the increase in travel time access to jobs, medical services, social and cultural activities or for entertainment/tourist purpose [9].

Poor density and connectivity of the national transport networks generates the vulnerability with respect to the structural, natural and traffic factors. This aspect came into sight following the 2005 flood, which broke down the road and rail access between the regions in south and east of Romania. The direct consequences (the allocation of the traffic on diverted routes, the increase in travel times, the spatial isolation) last for at least one year. The Danube bridges and the trans-Carpathians routes are also critical points of the transport networks.

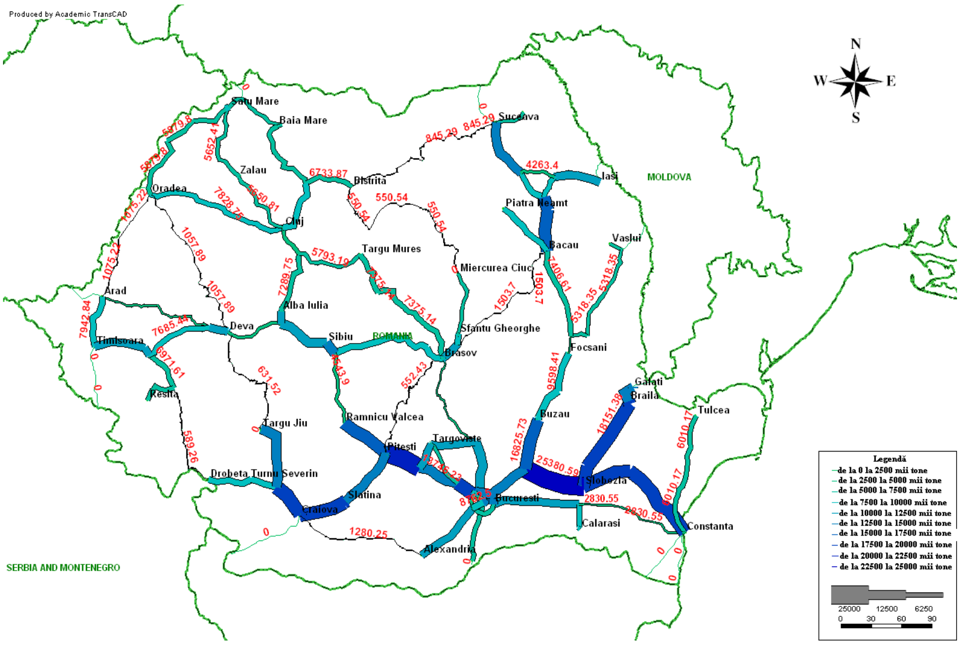

Fig. 1. Transport flows on Romanian road network.

Figure 1 shows the transport flows on the road network. The disruption of the road links generates the increase in travel cost in the entire network due to the traffic reallocation on longer routes. Using the TransCAD software and a GIS map of the Romanian road network, one computed the changes in travel cost at the whole network level. The traffic was reallocated between initial OD pairs using the Dijkstra's shortest path algorithm. The hierarchy of links importance for different trans-Carpathians routes, based on the variation in the travel cost is depicted in Figure 2.

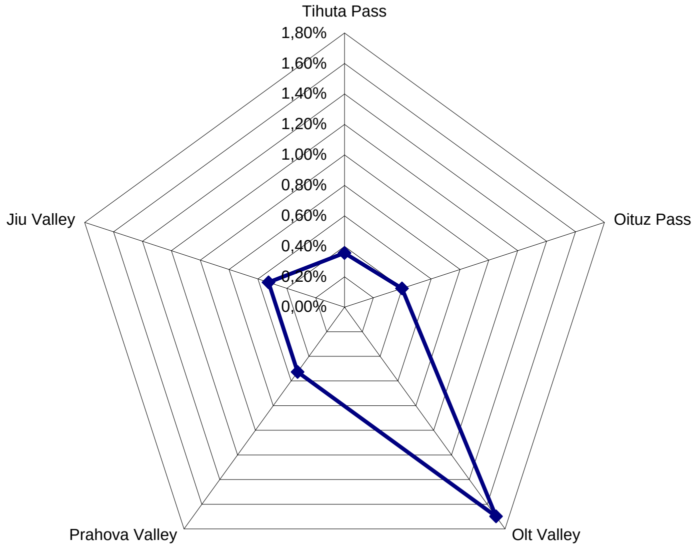

Fig. 2. Variation in the travel cost for the trans-Carpathians routes fail.

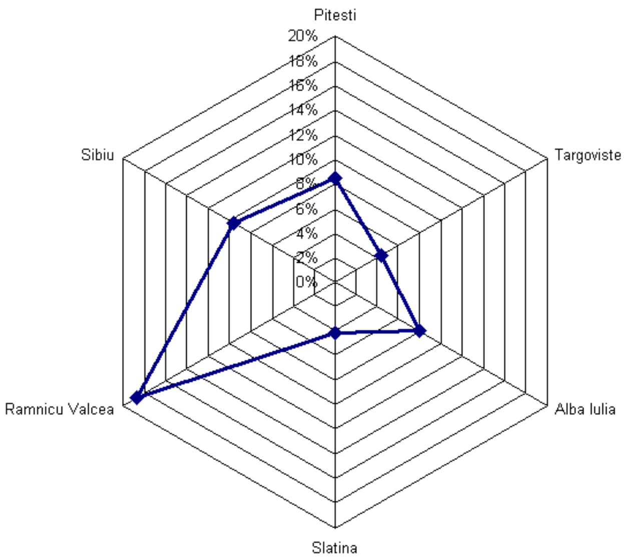

Fig. 3. Travel cost increase for nodes in proximity of the Olt Valley.

For the actual traffic flows, the traffic disruption on Olt Valley brings an increase for 1.8% of the travel cost for the entire network. Smaller variations are associated to the others trans-Carpathians routes. For the nodes located in the proximity of the Olt Valley, the fail of the route generates strong variations in travel costs (Figure 3).

Conclusion

Transport infrastructures belong to critical infrastructures, having connections and interdependencies with different infrastructures of the society.

Their well-functioning is responsible for the supplying without gaps of solid/liquid fuels for power plants, commodities distribution, supplying resources for industry, safe transport of dangerous goods, passengers transport, and accomplishing all administrative goals in emergency situation (e.g. population evacuation in case of disasters).

Also the well-functioning of the transport system is dependent of the power and fuel supply, of the information systems availability and of all economic activities served by the transport system.

The identification of critical points of the transport networks, the assessing of the reliability and vulnerability of the networks provide the local and central authorities with data for taking decision concerning investments for alleviating the infrastructure state and reducing the negative consequences due to fail of network elements.

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