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2015 IOP Conf. Ser.: Mater. Sci. Eng. 95 012080

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The influence of transport network vulnerability for maritime ports

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Abstract. The concepts of reliability and vulnerability are quite important in assessing the ability of transport networks from land to provide continuity in operation tacking in consideration the relation with seaports. Transport infrastructure modernizing and extension according to land use and sustainable development requirements still represents a challenging issue among policy makers, regional/local communities and scientists. The interest for the researches reliability and vulnerability for transport networks who connect maritime ports with interior city's is generate by the natural disasters, the terrorist acts, unconventional war, etc.. Transport network modelling enable the development of mathematical models used in evaluating the reliability and vulnerability. Nodes or link disruption could have an important impact over transport network users. In our paper we investigates the Romanian road network vulnerability related to Danube crossing versus maritime ports (Constanța and Mangalia) and its mitigation by improving network topology. We use Visum software to promote a methodology to assess road transport network vulnerability versus Romanian seaports and we propose some solutions to reduce probability of road transport network to fail.

1. Introduction

Seaports are important nodes in the supply chains, joining high capacity transport modes: rail, auto and maritime transport. Transport infrastructure modernizing and extension according to land and maritime use, respectively sustainable development requirements still represents a challenging issue among policy makers, regional/local communities and scientists. Due to the importance of the transport networks for logistics production the reliability and vulnerability of transport networks are key factors in network management, prioritization of investments, maintenance and repair, emergency planning, evaluation of regional disparities and collateral effects [1]. The current literature defines reliability and vulnerability as two related, but different concepts. Transport network reliability has mainly a system engineering approach. Reliability is perceived as an expression of the probability of links functioning and thus as the stability of the service provided. Bell and Iida [2] analyze the network reliability as connectivity and travel time reliability. Nicholson et al. [3] introduce capacity reliability and flow decrement as measures for reliability. Husdal [4] states that a reliable network exhibits a high degree of operability as expressed by its serviceability, accessibility and non-variability under any circumstances, due to the presence of redundancy, robustness and resilience in the network. Chen &all [5] have a series of study about transport network capacity reliability. Mathematically it is defined as being equal to the probability that the maximum capacity of the network to be greater than or equal to the demand when capacity values of arcs may have some random variations. While



probability is a major concern in transport network reliability, the consequences of links failure is the main focus of vulnerability [1]. Berdica [6] define in her paper a new concept: vulnerability of transport networks. This new network attribute is defined as “a susceptibility to incidents that can result in considerable reduction in network serviceability, namely the operability of the link/route or network during a given period”. Also Taylor and D’Este [7] have made some research about how accessibility of nodes is correlated to notion of vulnerability .

The interest for the researches reliability and vulnerability for transport networks who connect maritime ports with interior city’s is generate by the natural disasters, the terrorist acts, unconventional war, etc.. Also it is a EU demand to connect seaports to TEN-T network. Romania has 2 Core Network Corridors crossing its country. One is The Orient/East-Med Corridor who connects the German ports Bremen, Hamburg and Rostock via Czech Republic and Slovakia, with a branch through Austria, further via Hungary to the Romanian port of Constanta [8]. So it is important to determinate influence of vulnerability for maritime ports of land transport network.

2. Method

A method to evaluate transport network vulnerability is proposed by Jenelius et al. [9] who use, as a measure of reduced performance of the network, the increase in the generalized cost of travel (time, distance, money) for the users. When a link k is closed, the network may be divided into several disconnected parts, so that a number of trips from origin i are not able to reach the destination j . Thus results an unsatisfied demand.

$$u_{ij}^{(k)} = \begin{cases} \varphi_{ij} & \text{if } c_{ij}^{(k)} = \infty \\ 0 & \text{if } c_{ij}^{(k)} \neq \infty \end{cases}, \quad (1)$$

where φ_{ij} represents the travel demand from node i to node j and $c_{ij}^{(k)}$ is the generalized cost of travel from node i to j when link k is closed.

Therefore, there is a dichotomy of the link importance according to travel cost increasing and unsatisfied demand into the network. If the link k belongs to the set of non-cut links, the importance of the link k for the whole network is

$$\Omega(k) = \frac{\sum_i \sum_{j \neq i} \varphi_{ij} (c_{ij}^{(k)} - c_{ij}^{(0)})}{\sum_i \sum_{j \neq i} \varphi_{ij} c_{ij}^{(0)}} \quad (2)$$

where $c_{ij}^{(0)}$ is the generalized cost of travel from node i to node j in the undamaged network.

The importance regarding the unsatisfied demand of a link k is

$$\Omega_{\text{uns}}(k) = \frac{\sum_i \sum_{j \neq i} u_{ij}^{(k)}}{\sum_i \sum_{j \neq i} \varphi_{ij}} \quad (3)$$

In addition, the link disruption is translated into nodes exposure. The demand weighted exposure of node i is the maximum value over all non-cut links:

$$\Phi(i) = \max_{k \in L^{n-c}} \frac{\sum_{j \neq i} \varphi_{ij} (c_{ij}^{(k)} - c_{ij}^{(0)})}{\sum_{j \neq i} \varphi_{ij} c_{ij}^{(0)}}. \quad (4)$$

The exposure regarding the unsatisfied demand for the node i is

$$\Phi(i) = \max_k \frac{\sum_{j \neq i} u_{ij}^{(k)}}{\sum_{j \neq i} \Phi_{ij}}. \quad (5)$$

3. Experimental procedure

The variation of the travel time of the users due to the inoperability of the critical road links influences their perception on network performance. The identification of the threshold values above which the travel times lead to the journey refuse is one of the main concerns of engineers in the transport sector [10]. The following methodology assesses the transport network vulnerability according to the travel time.

Due to the complexity of modelling the land transport network which normally have thousands of nodes and links, it is necessary to use a specialized software (e.g. VISUM, TransCad) with user's friendly graphical interface and allowing accurate network representation [10].

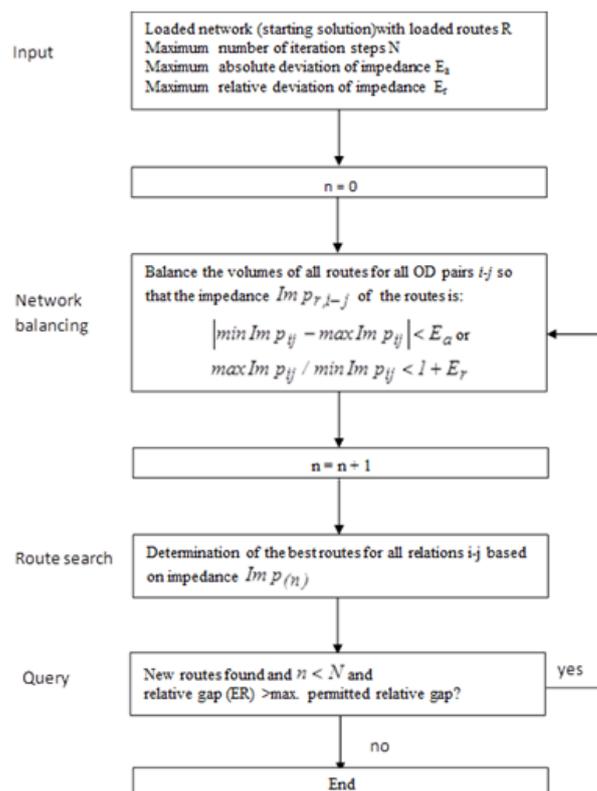


Figure 1. Equilibrium Assignment Algorithm [11].

In our model the generalized cost of travel from node i to node j is calculate as travel time. To determinate the initial value for travel time in model is used *Equilibrium Assignment Algorithm* (figure 1). This procedure distributes demand according to Wardrop's first principle: "Every individual road user chooses his route in such a way that his trip takes the same time on all alternative routes and that switching routes would only increase personal journey time." The state of equilibrium is reached by multi-successive iteration based on an incremental assignment as a starting solution. In the inner iteration step, two routes of a relation are brought into a state of equilibrium by shifting vehicles. The

outer iteration step checks if new routes with lower impedance can be found as a result of the current network state [11].

Travel times for motorised transport are determined by the saturation of links and intersections which result from the traffic volume and the capacity of these network objects. Also is necessary to know travel time at free traffic flow determined from the link length and the free-flow speed v_0 . The impedance of a route results from the sum of the link impedances of the route. It is assumed that impedance is equal to the current travel time and that the current travel time is calculated using a travel time volume delay functions. Because the procedure only terminates when all routes of any Origin-Destination relation are in the equilibrium state, the procedure provides realistic results

In table 1 are presented relation used to calculate travel time on a single network link:

Table 1 Travel time volume-delay functions (after [12]).

No.	Author	Year	Function
1.	Irwin&all	1961	$T_a(\varphi_a, C_a) = \begin{cases} t_a^0 + a_a \varphi_a & \varphi_a < C_a \\ t_a^0 + \beta_a \varphi_a + (\alpha_a - \beta_a) C_a & \varphi_a \geq C_a \end{cases}$
2.	Smock	1962	$T_a(\varphi_a, C_a) = t_a^0 \exp\left(\frac{\varphi_a}{C_a}\right)$
3.	Mosher (1)	1963	$T_a(\varphi_a, C_a) = t_a^0 + \ln(C_a) - \ln(C_a - \varphi_a)$
4.	Mosher (2)	1963	$T_a(\varphi_a, C_a) = \alpha_a - \frac{C_a(t_a^0 - \alpha_a)}{\varphi_a - C_a}$
5.	Soltman	1965	$T_a(\varphi_a, C_a) = t_a^0 2^{\frac{\varphi_a}{C_a}}$
6.	Davidson	1966	$T_a(\varphi_a, C_a) = t_a^0 \left(1 - \alpha_a \frac{\varphi_a / C_a}{1 - \varphi_a / C_a}\right)$
7.	Akcelik	1991	$T_a(\varphi_a, C_a) = \begin{cases} t_a^0 \left(1 + a_a \frac{\varphi_a / C_a}{1 - \varphi_a / C_a}\right) & \varphi_a < \rho C_a \\ t_a^0 \left(1 + a_a \frac{\rho}{1 - \rho}\right) + \frac{\alpha_a}{(1 - \rho)^2} \left(\frac{\varphi_a}{C_a} - \rho\right) & \varphi_a \geq \rho C_a \end{cases}$

where t_a^0 is travel time at free traffic flow, T_a travel time for traffic volume φ_a on link a, C_a is link capacity and calibration parameters. In our model we use a BPR function [13]

$$T_a = t_a^0 \left[1 + \left(\frac{\varphi_a}{C_a}\right)^4\right] \tag{6}$$

4. Results and discussion

In our study case we investigate the Romanian road network vulnerability related to Danube crossing versus maritime ports (Constanța and Mangalia). Using Visum software, we implement a methodology to assess road transport network vulnerability versus Romanian seaports. In our study case are studied some routes between Romanian Seaports (Constanta Port and Mangalia Port) and road border points (Albita, Bors, Nadlac, Calafat, Giurgiu, Moravita, Siret and Vama Veche).

The density and the poor connectivity of the road transport network are responsible for its vulnerability to structural, natural and traffic factors. The Danube Bridges represent critical

infrastructure elements. The disruption of their functionality generates increasing of travel times and induces network vulnerability.

The Romanian road network has a length of 82,386 km of which 15,396 km of national roads (6,188 Km of European roads), and 529 km highways. The modelled network used in the case study has a total length of 17,530 Km including national roads, highways and major county roads (figure 2). The network is separated by the Danube River in two sub-networks connected by two bridges (Cernavodă Bridges-in reality are two bridges connected by a land link on Balta Ialomitei Island, Giurgeni Bridge). The initial traffic flow on road transport network is presented in figure 3 and is obtained using Equilibrium Assignment Procedure [10].

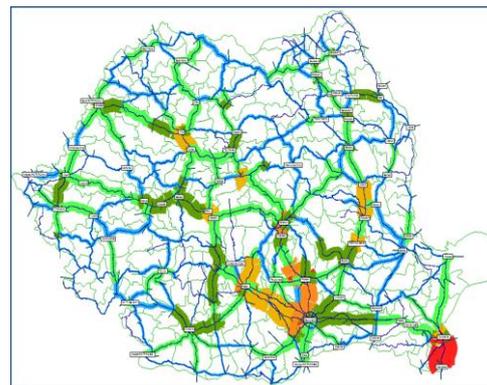
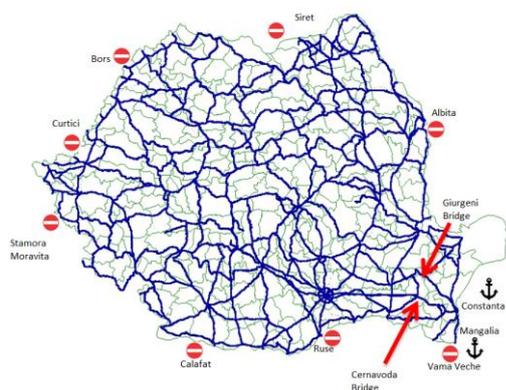


Figure 2. Road transport network with interest points. **Figure 3.** The initial road traffic flow.

In our study case is taken in consideration for the generalized cost of travel the duration of travel time on loaded road network and is examine the situation when Cernavoda Bridges (figure 4) or Giurgeni Bridge (figure 5) are closed.

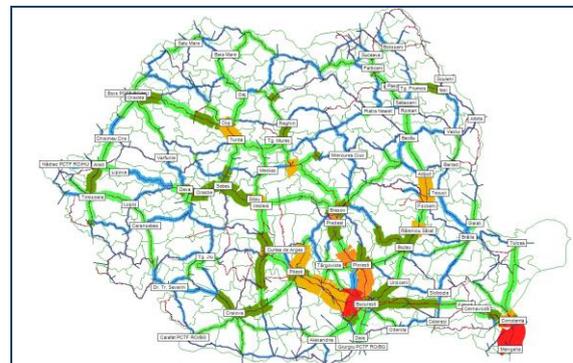
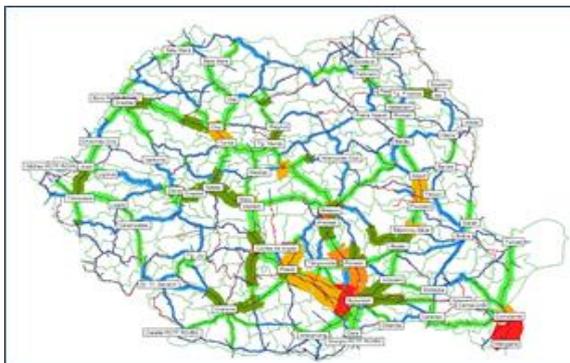


Figure 4. Road traffic flow –Cernavodă Bridges closed. **Figure 5.** Road traffic flow –Giurgeni Bridge closed.

Using equation (4) is calculate the exposure regarding the unsatisfied demand for the Romanian seaports (Constanta and Mangalia) for road border points induced by Danube Bridges. The result are presented in figure 6.

The fail of the present Danube crossing points generates important increasing in the vulnerability of the Romanian seaports versus road crossing border. The link containing the Cernavoda bridges is an important link of the network. Its fail results for the demand weighted exposure parameter big value for relation with Calafat, Moravita and Nadlac. When Giurgeni bridge is closed the routes from Romanian seaports to road border points (Albita, Bors, Nadlac, Calafat, Giurgiu, Moravita, Siret and Vama Veche) are not affected. Also in both case the route to Vama Veche is not affected.

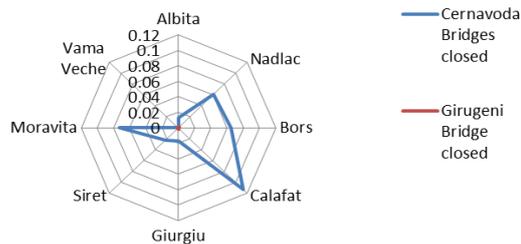


Figure 6. The demand weighted exposure.

5. Conclusions

Events like natural disasters, the terrorist acts, unconventional war generates from researcher a particular interest to evaluate transport network reliability and vulnerability. The developed procedure leads to some result which highlights the importance of Danube Bridge for Romanian seaports. If Cernavoda Bridges are closed for routes from maritime ports to road border points Calafat and Moravita we obtain a big value for the demand weighted exposure parameter. So it highlights the role of Danube Bridges in connection of maritime ports with European Inland Network. The opening of a new bridge near Brăila will also increase accessibility in the region and will reduce the vulnerability of the network versus Danube Bridges: Cernavoda and Giurgeni.

Acknowledgement

The work has been funded by the Sectoral Operational Programme Human Resources Development 2007-2013 of the Ministry of European Funds through the Financial Agreement POSDRU/159/1.5/S/132397

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