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On Criticality Assessment Based Evacuation Modeling: Empirical Findings

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***Abstract*—In this paper, criticality assessment is introduced as an intermediate step in evacuation modeling, in order to identify the optimal allocation of measures for the development of evacuation traffic management strategies. The criticality assessment of network components is reviewed and analyzed concerning its sensitivity in demand and supply variations. It is proposed that when highlighting the most critical component(s) of a network under evacuation conditions, one could either intervene to the component(s) itself, assuring the preservation of its operation and enhancement of functionality or intervene to alternative component(s) of the network that could offer attractive alternatives to the critical one. The two intervention approaches are presented in detail and evaluated in terms of minimizing travel times of evacuees in the Sioux Falls test network.**

***Index Terms*—Criticality assessment, evacuation modeling, sensitivity analysis**

I. INTRODUCTION

Disruptions in the transport system often result in undesirable impacts for the road users. The importance of this fact is best reflected in cases of emergency, when people need to travel facing the least possible degradations of the system. Especially during evacuation instances, the components of a network gain additional importance, due to rising safety issues. It is therefore crucial for authorities to identify where the most vulnerable components of a network are, in order to protect or enhance their operation.

When developing evacuation strategies authorities have to decide where to orient their plans in order to assure the safest (and in this context fastest) transport of evacuees. This paper proposes the inclusion of a methodology to identify highly important links during evacuation modeling and suggests using its outcomes as an indicator in order to optimally allocate measures and actions. The paper's objective is to provide a means for answering the "where-to" intervene question, instead of evaluating "what-if" scenarios. Its contribution lies in the proposed framework, according to which critical components of the network are highlighted and the possible approaches to use this criticality assessment are evaluated and discussed.

The remainder of the paper is organized as follows. Section 2 reviews the pertinent literature on criticality assessment (CA) of network components and outlines rising issues concerning its outcomes. Section 3 describes the introduction of CA as an intermediate step in evacuation modeling and outlines various approaches on its usage. Test results from the comparison of these approaches against each other are given in Section 4. Finally, Section 5 discusses the advantages of the introduced methodology.

II. CRITICALITY ASSESSMENT

A. Literature Review

Various definitions of vulnerability and criticality can be found [1-14] in the literature. This paper adopts the definition of Knoop et al. [1], where vulnerability describes the weakness of a network and criticality stands for the importance of its components. The performance of transport networks and the criticality of network components have been studied by several researchers. Taylor and D'Este [2] propose a methodology for obtaining the vulnerability of each component of the network. The methodology is applicable on the level of national networks. In their model, nodes are vulnerable and links have criticality values. Jenelius, and Knoop et al. [3, 4] approach deals with blocking every component of a network for determining their vulnerability. Kim and Lee [5] identify the crucial infrastructure from national economic functional view point, reflecting the spatio-temporal characteristics of the economy. In their model, criticality of each link is analyzed for earthquakes, defining zones and using the national highway network and economic data for calculating criticality values. Nagurney and Qiang [6] propose a methodology for calculating criticality of network links, using the total

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demand of the network and the difference in the travel time as consequence of the closure of a link.

B. *Criticality Assessment of Network Components*

There are two different criticality assessment approaches in relation to transport infrastructures [6]; the link and the node approach, each one associated with a specific transport infrastructure. It must be underlined though, that these two approaches are based on the same technique; the removal of links in the first case and the removal of nodes (that leads to the removal of the respective links) in the second case. The link criticality assessment methodology, described below, is applicable to road transport networks, in order to determine the most important links related to the efficiency of the transport network. The resulting importance - in the form of an index - for all network links is considered in the computation of the costs (travel time delays).

The steps of the respective method proposed to be used are presented next.

- Step 1: The Origin-Destination demand matrices are assigned on the road network, using given network data (O-Ds, centroids, connectors, links, nodes). For each O-D, demand is assigned on the network according to a user equilibrium criterion.
- Step 2: Network efficiency is computed based on Nagurney's Unified Network Performance Measure (UNPM) [6]:

$$\varepsilon = \varepsilon(G,d) = \frac{\sum_{w \in W} \frac{d_w}{\lambda_w}}{n_W} \qquad (1)$$

where ε denotes unified network performance measure, G denotes the network topology (links, nodes), d denotes the demand vector (O-D pairs), W denotes the set of O-D pairs, dw denotes the demand of O-D pair w, λw denotes the disutility of O-D pair w (travel time) and nW denotes the number of O-D pairs for G

- Step 3: One link of the network is removed and ε is computed again. Iteratively, this process is repeated for each link of the network in order to compute ε for each removed link. If the removal results in no path connecting an O-D pair, the demand for that O-D pair is assigned to an abstract path with a cost of infinity.
- Step 4: The importance of each network component (link) is computed, based on Nagurney's Network Component Importance [6]:

$$I(g) = \frac{\Delta\varepsilon}{\varepsilon} = \frac{\varepsilon(G,d) - \varepsilon(G-g,d)}{\varepsilon(G,d)} \qquad (2)$$

where G - g is the resulting network after component g (link) is removed from network G.

This criticality index for each link (I) represents the difference of the network's efficiency after the link(s) removal in relation to the initial (normal) condition of the network. It can be assumed that the higher the I(g) indicator is (values near one), the more important is the removed link(s) and the lower the I(g) is (values near zero), the less important is the link(s) removed.

C. *Criticality Assessment Sensitivity Analyses*

1) *Demand and supply*

This section aims to determine whether the CA of a network's components depends on demand and supply variations and to what extent. It is important to identify whether criticality is demand and supply sensitive during emergency situations (for instance evacuation conditions), where such disruptions are often observed. For this reason, a sensitivity analysis in the Sioux Falls test network is conducted, as this was initially presented in [7] and adapted in [8], assuming stepped variations of demand and capacity. Demand variations have been chosen so that the sum of trips is always equal to that of the initial O-D matrix and individual matrix values are allowed to vary from ±10% to ±90% from the initial value. On the contrary, capacity values are examined at stepped fractions of the initial ones. Demand values are also tested in fixed proportions of the random/initial ones, from 0.1 to 2. Fig. 1-3 depict the findings of this analysis.

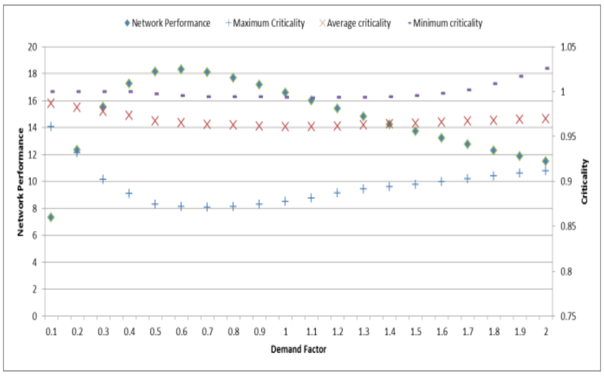

Figure 1. Network performance and criticality sensitivity analyses for different demand factors applied to the same demand profile

The results obtained from the demand sensitivity analysis show that the network performance appears to be sensitive to demand variations. The obtained curve is smooth, proving the relation between the network performance and the total number of trips for the same O-D profile. The maximum, average and minimum values of the criticality also change smoothly given the demand factor, presenting the maximum criticality value when the network performance is maximum. This is a rather expected result, since when the network is working at its full capacity, any disruption may have a higher impact due to the non-extra capacity remaining for allocating the affected trips.

Fig. 2 shows the results of the analysis concerning the sensitivity of the network performance and criticality both in relation to the demand profile and the total number of trips, as well as the network performance for different demand profiles with the same total trips. It is noted that network performance has low sensitivity in regard to the demand profile, while the most important factor is the total number of trips. Based on this result, it is obtained that when searching for the network performance, the demand profile is not crucial compared to the total number of trips. This result can be useful in evacuation situations since the demand profile is unknown most of the times, but the total number of evacuees can be easily extracted.

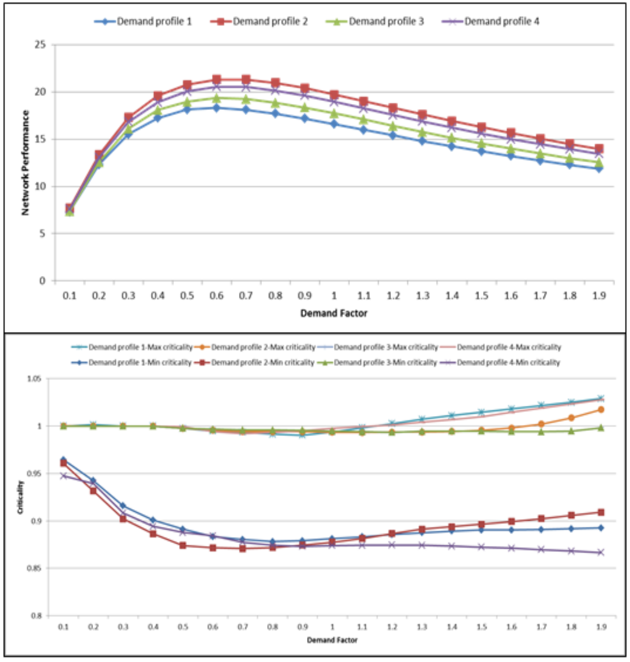

Figure 2. Network performance (a) and criticality sensitivity (b) analyses for different demand profiles and demand factors

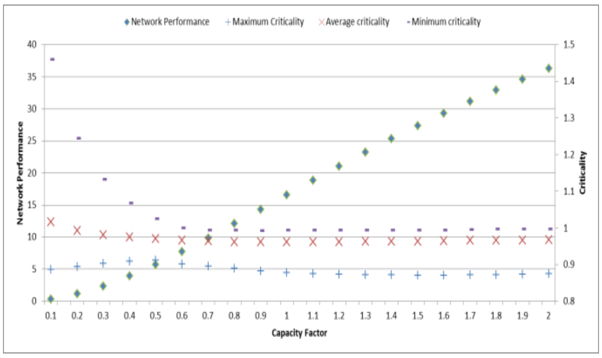

Figure 3. Network performance and criticality sensitivity analyses for different capacity factors

The same analysis on the maximum and minimum criticality values shows that the critical values are related more to the total number of trips rather than the demand profile itself, as it can be concluded from Fig. 2. It can be concluded that the criticality value of the links depends on the total number of trips, and their order depends more in the characteristics of the links rather than in the demand profiles.

As shown in Fig. 3, the relationship between capacity and network performance appears to be linear. Maximum, average and minimum criticality of the network's components appears to be insensitive to capacity variations (besides very small capacity factors). Concerning network performance, based on variations of the capacity factors along with random demand profiles, as depicted in Fig. 4, this appears to be insensitive to the latter. The same conclusion is drawn for the maximum and minimum criticality values of the components.

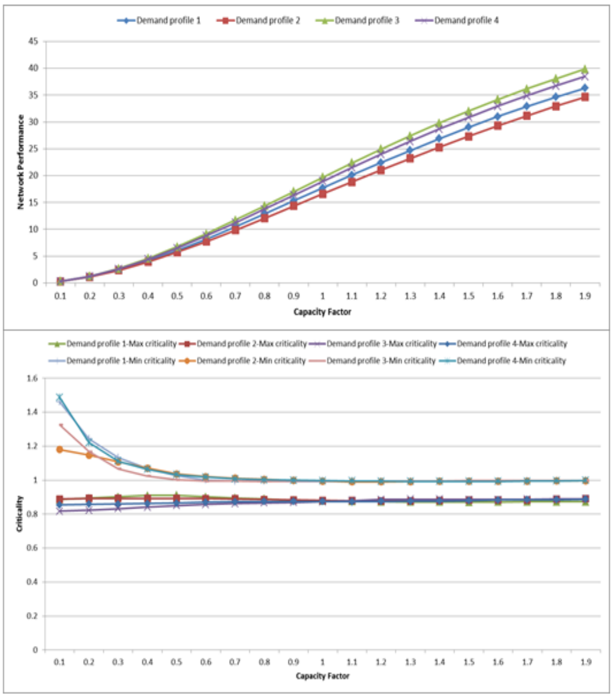

Figure 4. Network performance (a) and criticality sensitivity (b) analyses for different demand profiles and capacity factors

III. CRITICALITY ASSESSMENT AS AN INTERMEDIATE STEP IN EVACUATION MODELING

A. CA as an Intermediate Step

This paper examines the issue of evacuation in transportation networks and the methodological approach to evaluate emergency strategies at offline level. The main concept lies in the introduction of an intermediate step to the already well known evacuation modeling procedures, according to which evacuation measures and strategies are optimally allocated in the transportation network (e.g. route guidance, information dissemination, capacity reallocation through lane reversals or contra-flow lanes, etc.). Fig. 5 summarizes the flow of procedures when modeling evacuation.

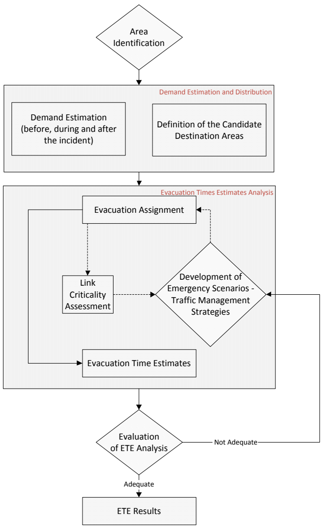

Figure 5. Flowchart of the proposed evacuation methodology

Initially, the region that will be evacuated is identified. The next step concerns the estimation of the demand over the evacuation area before, during and after the occurrence of the incident. The demand population is then distributed to the destination areas. The choice of these areas is based on a series of factors (accessibility, proximity, etc.) [9]. Subsequently, a traffic assignment and simulation model is applied, in order to compute the optimal routing of evacuation trips out of the area via the formerly specified destination nodes and simulate the movement of vehicles during the evacuation.

The model should be able to capture the variation of travel demand over time, both in and out of the evacuation area, the saturation of specified network's links and the created spillback phenomenon, the application of Traffic Management Strategies (TMS) and the reaction of potential drivers to it. The tool used for the purpose of this paper is DynusT, a simulation-based dynamic traffic assignment tool for regional operational planning analysis that has been used in several studies of mass evacuation applications [9, 10].

DynusT's ability to capture the complexity of the various road user classes existing in reality and their respective reaction to real time traffic conditions, traffic management and information provision is suitable for modeling adverse incidents, such as those presented in this paper. Based on the initial run of the assignment, the criticality index for each link is computed according to (2).

In an effort to evaluate alternative strategies that could minimize the evacuation travel time, it is proposed that the "where-to-intervene" identification is conducted through the criticality assessment of the links included in the paths that evacuees choose during the initial assignment. The output of the criticality assessment process is the identification of the critical links of the network, i.e. the links whose alternative options are costly. In the context of evacuation modeling, this can be interpreted in two ways, discussed in section III.B. After the critical links of the network have been highlighted, a series of traffic management strategies are developed in order to minimize evacuation travel times.

This paper only examines capacity allocation through partial or total lane reversals as a possible measure. The procedure culminates in the calculation of the ETE that stands for the elapsed time for the traffic originating within the evacuation area to leave the region. The ETE are then further evaluated, and if not found to be at acceptable levels, they are re-calculated after specified alterations at the scenario development step (for instance use of TMS). The link criticality assessment highlights the links of the paths that will need to have enhanced operation and functionality, and subsequently the links on which the evacuation measures or traffic management strategies should be targeted to. Instead of abstractly allocating, testing and implementing various emergency measures on the network, the proposed methodology aims to answer the "where-to" intervene question, enriching the "what-to" indications provided by supply design models [11].

B. Interpreting CA in the Context of Evacuation Modeling

According to the definition of CA, a link is highlighted as critical when there are limited or no available options serving the O-D pairs using this link [6], which in turn means that the cost for choosing an alternative link (path) is associated with higher costs compared to the former choice. This can be interpreted as follows:

- Since a link is critical, strategies can aim at lowering its criticality by providing alternative "solutions" that are not costly. This concept evaluates the effectiveness of an evacuation strategy in terms of its impact on the evacuation travel time by orienting the strategies to alternative links rather than the critical one(s). The question that rises here is of a "where-to" intervene nature, i.e. how to determine which links can be characterized as alternative options. The answer can either be subject to the network manager/planner and based on his knowledge of the exact network's characteristics and conditions or can be conducted through a K-Shortest path search algorithm that would connect the nodes of the critical link(s). In this approach, the intervention does not occur in the critical link of the path itself, but in the links that would offer alternatives to this one.

Since a link is critical, strategies could aim at keeping it operational with any means. This interpretation of criticality orients any strategies towards assuring that the critical link(s) will remain open and continue serving the trips as before (or even enhance its operation) and will continue to do so under extreme conditions, i.e. change of driving behavior. In this approach, the intervention occurs to the critical link(s) itself, avoiding to deal with links that are not highlighted as critical in the introduced criticality assessment step and evaluate the effectiveness of the intervention through the evacuation travel time.

IV. CASE STUDY RESULTS

A. Modeling Assumptions

The outcomes of the proposed methodology are evaluated in the Sioux Falls test network. After the criticality assessment of all network's links is computed, it is assumed that the demand served from the most critical link corresponds to a hypothetical evacuation demand in the network. This assumption is made in order to assess the impact of the measures' allocation in the estimated evacuation time of a certain number of O-D pairs. Chapter IV.B presents a statistical analysis that aims to answer the "how-to" intervene in case of capacity reallocation. In the Sioux Falls network a series of static user equilibrium assignments using Linear User Cost Equilibrium [12] are conducted with stepped proportions of the initial demand and variant fractions of random demand in order to determine how capacity allocation influences the overall impedance of paths chosen by O-D pairs.

B. Results

Initially, the criticality index of all links is computed based on a UE static traffic assignment. Subsequently, the most critical link is identified and assuming it serves all evacuating O-D pairs, the "evacuation" travel time is computed using DynusT, by summing the travel time of all O-D pairs. The travel time of all O-D pairs, which use the critical link, is summed independent of whether only a certain number of trips are served by a path containing the critical link. After having identified the most critical component, the "where-to" intervene question is answered, in order to decrease the formerly computed evacuation travel time. Based on the interpretation of this answer, presented in III.B, following approaches are evaluated:

1) *Intervene in the most critical link*

This approach aims at preserving and/or enhancing the functionality of the most critical link. For this reason, the capacity of the opposite directed links is attributed to the critical ones, and the evacuation travel times are recomputed. In detail, link nr. 37 is identified as the most critical one. Thus, in this approach the capacity of link nr.38 is fully allocated to the opposing direction.

2) *Intervene in alternative links/paths*

a) Empirical knowledge: This approach is based on the manager's/planner's knowledge of the network's characteristics and conditions. In order to assess this, and based on the authors personal judgment, the whole capacity of links nr. 40 and 43 are attributed to links nr. 34 and 28 respectively.

b) Based on K-shortest paths: This approach is based on intervening in the links of the paths that are identified as shortest paths between the nodes of the critical link(s). In this case, the 1st shortest path between nodes 12 and 13 is highlighted through the path containing link nr. 36-34-42-73-74. Therefore the capacity of the links nr. 33-40-71-76-39 is allocated to the links with the opposite directions respectively.

Table 2 summarizes the findings of the analyses and the sum values are expressed in seconds. The results show that Approach 2a minimizes evacuation travel times. However, this approach is subject to a human empirical knowledge and judgment. Among the rest of the approaches, the one concerning an intervention in alternative links/paths, becomes more important, as it considerably lowers evacuation travel times.

TABLE II: TRAVEL TIME IN SECONDS FOR THE EVACUATION O-D PAIRS IN DIFFERENT APPROACHES

O-D-Pairs	**Base Case**	**App. 1**	**App. 2a**	**App. 2b(i)**	**App. 2b(ii)**
1_13	2587	1810	2146	2141	2287
1_20	18796	20832	17238	19761	17898
1_21	4698	4732	3832	4594	4398
1_22	10663	11576	8224	10932	10064
1_23	4404	4712	3196	4806	4104
1_24	3657	3260	2895	2815	3357
2_13	3258	2519	2839	2889	2958
2_21	5369	5442	4524	5342	5069
2_22	12004	12996	9608	12430	11404
2_23	5075	5422	3888	5554	4775
2_24	4327	3970	3587	3564	4028
3_13	2196	1431	1749	1720	1896
3_20	17623	19695	19155	18702	16725
3_21	4307	4354	3435	4173	4007
3_22	9881	10820	7428	10090	9282
3_23	4013	4334	2798	4385	3713
3_24	3265	2882	2497	2394	2966
4_13	2710	1973	2143	2197	2410
4_20	31939	34330	30525	30725	30440
4_21	4820	4896	3828	4650	4521
4_22	10908	11904	8216	9912	10308
4_23	9053	9750	6384	8094	8454
4_24	3779	3423	2891	2872	3479
5_13	5170	4479	4330	4597	4871
5_23	13975	14764	10758	12894	13376
5_24	6240	5930	5078	5271	5940
6_13	4291	3655	3924	4083	3991
6_21	6402	6578	5610	6536	6102
6_22	28141	29488	22028	27728	26940
6_23	6108	6558	4973	6748	5808
6_24	5360	5106	4672	4757	5061
7_13	7042	6779	6862	7196	6742
8_13	6104	5651	5689	6135	5804
8_23	7921	8554	6739	7844	7621
8_24	7173	7101	6438	6810	6873
9_13	6040	5373	5210	5508	5740
9_23	15713	16552	12518	14716	15114
9_24	7109	6823	5958	6183	6809
10_13	7158	7000	6384	7667	7158
11_13	4089	4039	2912	4272	3789
12_13	1422	679	1060	738	1123
12_14	6989	6446	7132	5746	6390
12_15	8773	9468	11264	8598	8174
12_20	15302	17439	17088	15759	14403
12_21	3533	3602	2746	3192	3234
12_22	8333	9316	6050	8128	7734
12_23	3239	3582	2110	3403	2940
12_24	2492	2129	1808	1413	2192
16_13	47899	46878	45744	50028	47898
Sum	**421350**	**431032**	**368111**	**410692**	**400370**

V. CONCLUSIONS

This paper introduces criticality assessment as an intermediate step to answer the "where-to" intervene question when developing evacuation traffic management strategies. Its sensitivity analyses concerning demand, supply and traffic assignment algorithm according to which it is computed show that network performance depends on the total demand expressed in number of trips rather than on the demand matrix profile and distribution. There appears to be linearity in the network performance and capacity relationship, while independent of the demand profile and factoring of the total amount of trips, the criticality categorization (hierarchy) of individual links appears to be related to its capacity. The criticality of links, observed as an absolute value, depends on the total demand expressed in number of trips rather than on the demand matrix profile and distribution.

Criticality assessment in the evacuation context can be interpreted either as identifying and intervening to the critical network components themselves or offering attractive (or less costly) alternatives. The evaluation of these approaches was conducted based on the impact they have on evacuation travel time. Results show that empirical knowledge of a network's characteristics and conditions is decisive when forming evacuation strategies or implementing measures. However, criticality assessment proves to be an effective tool for highlighting the location of intervention. In general, it is concluded that is more efficient to adopt the approach according to which interventions occur at alternative links/paths rather than the critical(s) one(s).

Further research is needed for testing the effectiveness of capacity allocation as a tool for allocating evacuation measures in more complex/realistic networks.

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