Identification of Critical Locations in Road Networks due to Disasters

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Abstract: Disasters have occurred in various patterns from both natural and man-made causes and tend to increase in the future. Disaster preparedness is necessary for concerned authorities to cope with disasters and prevent critical situations from getting worse. This paper presents the application of vulnerability analysis to identify the critical locations that adversely affect the performance of road network most when the network is degraded or failed by any disaster. Destination accessibility index is proposed to measure the ability of evacuees to access the destinations (e.g. assembly points or evacuation centers). If the failure or capacity degradation of a road section affects maximum reduction in the accessibility index, that road is identified as the critical location. The road network of Hat Yai city is used to illustrate the applicability of the proposed index. The results can be further applied as part of evacuation route planning.

Keywords: Vulnerability Analysis, Critical Locations, Accessibility, Road Network, Disasters

1. INTRODUCTION

Disasters have occurred in various patterns from both natural and man-made causes. The trend of disasters are more likely to increase in the future. In Thailand, several disasters, e.g. floods, earthquakes, demonstrations, and catastrophic accidents, have profoundly affected to the city in terms of people's livelihood and economy. Consequently, people and concerned authorities need to adapt and prepare for disasters that may occur in the future.

Previous approaches for road network planning and management seems to be reactive. In some disasters, even if the probability of network failure may be small, the socio-economic impacts on particular areas of the community may be large and need some remedial actions (Taylor, 2008). On the other hand, vulnerability analysis, as a proactive approach, aims to evaluate the weakness (vulnerability) and consequences of network failure, irrespective of the failure probability. This approach can anticipate structural weaknesses of the network and help to avoid or at least relief potential adverse effects, rather than to react to them afterwards.

This paper presents the application of vulnerability analysis to identify the critical locations that adversely affect the performance of road network most when the network is degraded or failed by a disaster. Based on the accessibility index (Hansen, 1959), destination accessibility index is proposed to evaluate the network performances during normal period and critical situations. The index represents the degree to which a destination, e.g. assembly point or evacuation center, is accessible by as many people or evacuees as possible. If the failure or capacity degradation of such a road section affects the most reduction in the proposed index, that road is identified as the critical location.

To obviously illustrate the applicability of the proposed index, the road network of Hat Yai city, Songkhla province, Thailand; where is the center of commerce, business and tourism in the southern Thailand, is selected as a case study based on the urgent needs of the local concerned authorities for disaster preparedness planning. The city is recurrently affected by floods, especially the big floods in 2000 and 2010, and possibly encounters with terrorist attacks.

The paper consists of the following five sections. Section 2 presents the literature review. The methodology is described in Section 3. Section 4 shows and discusses the results. Finally, Section 5 concludes the paper and give some recommendations for future research.

2. LITERATURE REVIEW

In general, vulnerability analysis is a process of identifying, quantifying, and ranking the vulnerabilities (weaknesses) of individual members or elements in a specific system or network that internal and/or external factors can cause the vulnerabilities (U.S. Department of Energy, 2002). The analysis results can be used as part of risk assessment process to answer the following questions: what is the likelihood that the system will fail; what are the consequences (cost and lives) of such failure; are these consequences acceptable (Baker, 2005).

Vulnerability analysis has been applied extensively in various infrastructure systems, e.g. electric powers (U.S. Department of Energy, 2002), water utilities (KDHE, 2003), telecommunication systems (Danfeng and Fangchun, 2009), and transportation networks (Berdica, 2002; Berdica and Mattsson, 2007; D'Este and Taylor, 2003; Jenelus, 2010; Taylor, 2008; Taylor and D'Este, 2007; Taylor *et al*., 2006).

In the fields of transportation, Berdica (2002) initially defined the road network vulnerability that is "a susceptibility to incidents that can result in considerable reductions in road network serviceability". Later, Taylor (2008) described the concept of vulnerability analysis that is related to the consequences of failure of any network components (e.g. links or nodes), irrespective of the probability of failure.

Several causes affect to the failure of a road network. During normal period, the road capacity can be reduced or the road segments (or intersections) can be interrupted by e.g. traffic congestion, road accident, or road maintenance. During critical situations, the same road network may be exposed to non-recurrent natural and man-made disasters, e.g. floods, earthquakes, or demonstrations.

Several researchers have devised or improved the definition and the measure of network vulnerability extensively. Some commonly used indices for vulnerability analysis of road networks can be summarized in Table 1.

The indices presented in Table 1 have been used for different purposes in network vulnerability analysis. In addition, different indices require various factors and techniques in the analysis. This paper focuses on the evaluation of network vulnerability in terms of the ability of evacuees or people to access the assembly points or evacuation centers (desire destinations) during critical situations caused by disasters. As mentioned earlier, the road network of Hat Yai city is selected as a case study. However, based on the limitation of existing transport models and data availability in Hat Yai, the potential accessibility, proposed by Hansen (1959), is applied to propose the destination accessibility index in this paper. The details and formulation are explained in Section 3.3.

Table 1. Commonly used indices for vulnerability analysis of road networks

Name	Type	Description	Typical formulation
Topological	Supply	Proximity of geographic locations in a network	$A_{ij} = \min \sum_{a} \delta_{aij} c_a$, where c_a is the travel time or cost on link *a*; $\delta_{aij} = 1$ if a is on the minimum path from *i* to *j*; $\delta_{aij} = 0$ otherwise.
Space-time	Supply	Accounts for the constraints of time with space in defining the travel behavior possibilities of an individual	$A_{ij}^{t} = A_{ij}$ *if* $T \geq t_{ij} + t_j$, $A_{ij}^{t} = 0$ otherwise, where d_{ij} is the distance and v_{ij} is the mean travel speed between *i* and *j*, $t_{ij} = d_{ij} / v_{ij}$ is the travel time from *i* to *j*, *T* is the total time available, and t_j is the time required at the destination.
Potential accessibility	Supply	All possible opportunities that exist weighted by a cost function	$A_{ij} = O_j f\left(C_{ij}\right)$, where O_j is the number of opportunities available at *j* and C_{ij} is the travel time or cost between *i* and *j*.
Behavioral utility	Demand/ supply	The derived benefit for an individual from the available alternatives, given the preferences of the individual	$I_n = \ln \sum_{r \in R_n} e^{V_m}$, where I_n is the deterministic component of the utility function, and V_m is the deterministic component of each secondary choice *r* in the set of choices R_n.
Economic	Demand/ supply	The change in benefit $\left(\Delta E\left(CS\right)\right)$ attributed to a change in the urban system	$\left(\Delta E\left(CS\right)\right) = \frac{1}{\alpha}\left[\ln\left(\sum_{j=1}^{J^1} e^{I_j^1}\right) - \ln\left(\sum_{j=1}^{J^0} e^{I_j^0}\right)\right]$, where $\Delta E\left(CS\right)$ is the expected change in consumer surplus between the two scenarios “1” and “0”, the two logsums represent the inclusive values derived from the behavioral models under the two scenarios, and α is the negative of the coefficient of travel time or cost in the utility function

Source: Taylor (2008)

3. METHODOLOGY

3.1 Study Area

Hat Yai is a district of Songkhla province located in the southern Thailand. As shown in Figure 1, the city covers about 853 km^2 including 14 sub-districts with a total registered population about 378,000 (Hat Yai District Office, 2012). The city is not only attractive to the commerce and business during weekdays but also popular for Malaysian and Singaporean tourists during weekends. However, the city is located on the area downstream of U-Tapao canal basin, which is occasionally severely flooded as reported in 2000 and 2010. Unrest in the southern Thailand is the other social issue for the local concerned authorities to monitor and prevent unexpected terrorist attacks especially on the road network in the city. For these reasons, the road network in Hat Yai is selected as a case study to illustrate the applicability of the vulnerability analysis in this paper.

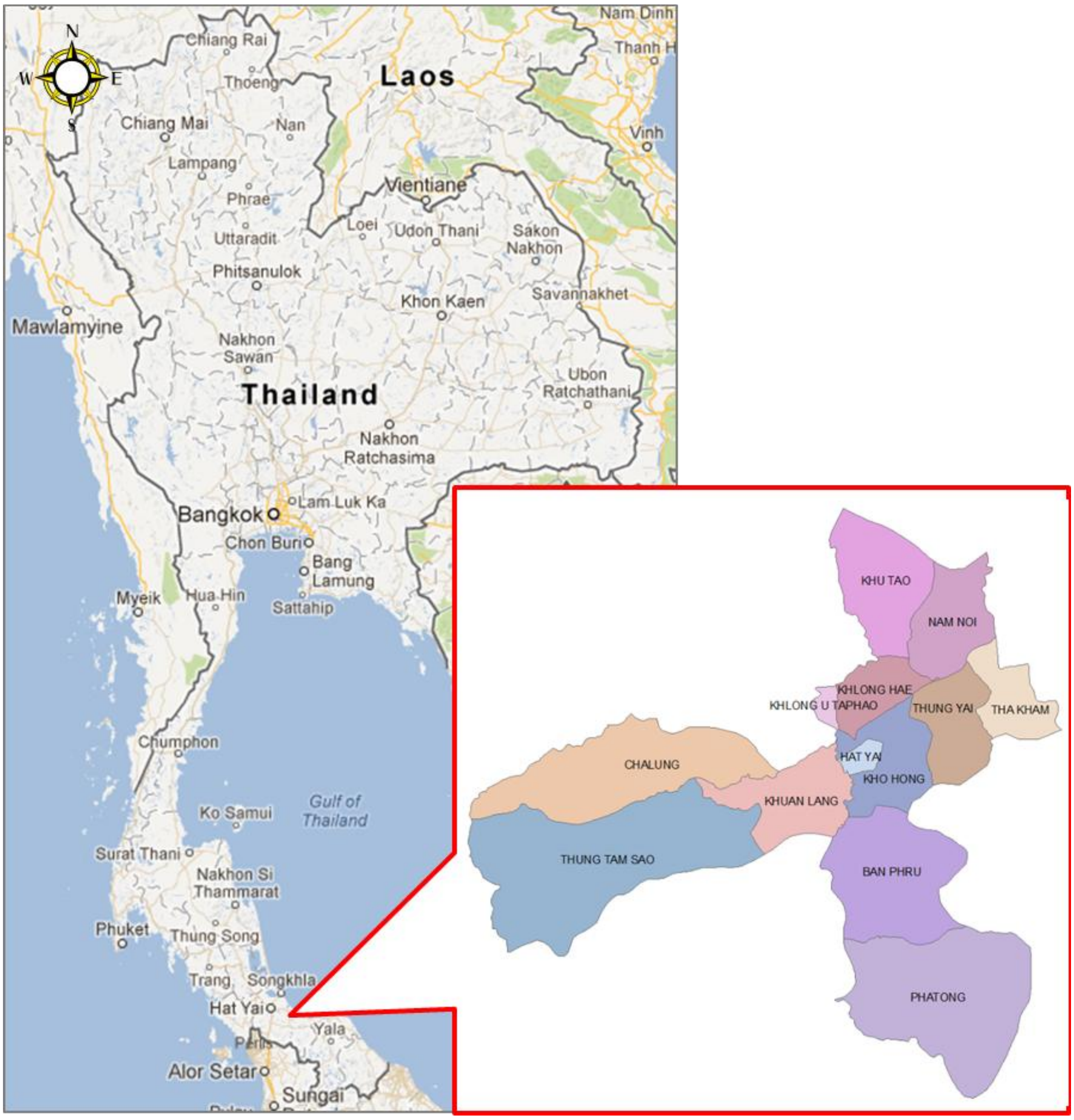


Figure 1. The study area

3.2 Development of Travel Demand Model

Prior to performing the vulnerability analysis, the travel demand model of Hat Yai city was developed to determine the number of people and vehicles traveling in the road network during normal and critical situations. The questionnaire survey was conducted to investigate the travel behaviors during both situations. 2,000 samples were randomly selected in the study area. One of the interesting results reveals that about 86% of the travelers prefer to use private vehicles, including motorcycles, private cars, and pickup cars. Only 14% travel by public transports (taxi motorcycles, tuk tuk, vans and buses). Thus, in this study we develop a simple four-stage travel demand model for private vehicles only.

Other related information such as link length, road type, and lane width were collected to develop the road network model using Emme 4.0.3 (INRO, 2013). The road network in the model is presented in Figure 2. The network consists of 4,659 directional links and 1,482 regular nodes, and has 211 zone centroids. The model was calibrated using the traffic volume count and speed data observed on 250 selected major links (about 5% of the total links). The result of model calibration presented in Figure 3 shows that the value of R^2 between the observed and model flows is 0.964, which is desirable.

Note that the developed model may not exactly represent the behaviors of the travelers and evacuees during the critical situation. However, based on the available data, the developed model can represent the likelihood of the travel patterns during the situation.

Figure 2. Road network model of the study area

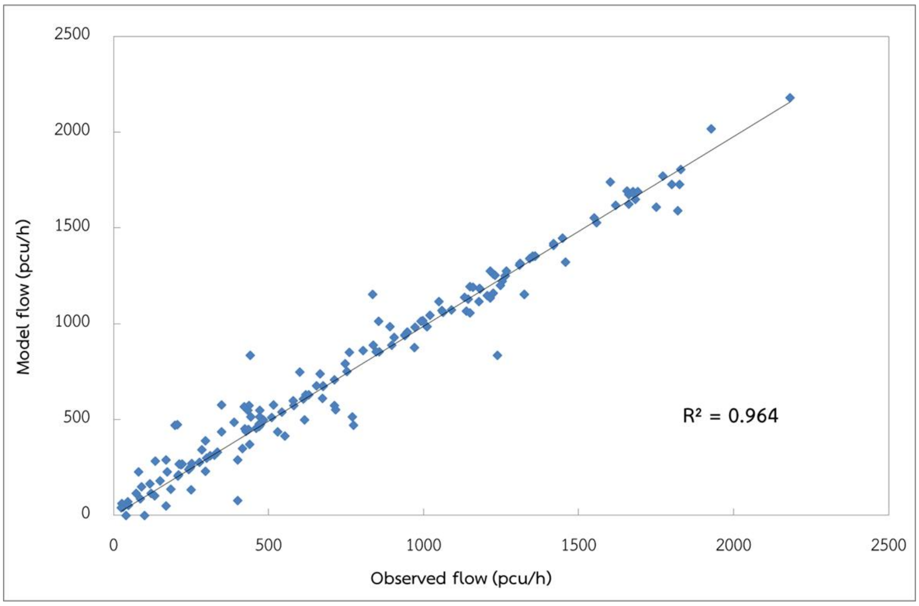


Figure 3. The result of model calibration

3.3 Vulnerability Analysis

As mention earlier, the potential accessibility is applied to measure the impacts of a disaster on the accessibility from surrounding locations (some origins) to a specific assembly point or evacuation center (one destination) in the study area. However, the potential accessibility measure presented in Table 1 generally evaluates the easiness in accessing between two locations (or zones) *i* and *j*, respectively. As explained in D'Este and Taylor (2003), the interconnections between the origin *i* and all destinations $j \in J$, where *J* is the set of all destinations, can be determined using the integral accessibility index. The index, which is a summation of the potential accessibility measure, is expressed as

$$AI_i = \frac{\sum_j O_j f\left(C_{ij}\right)}{\sum_j O_j}. \tag{1}$$

Following equation (1), the destination accessibility index (AI_j) can be formulated as

$$\begin{aligned} AI_j &= \frac{\sum_i q_{ij} f\left(C_{ij}\right)}{\sum_i q_{ij}} \\ &= \frac{\sum_i q_{ij} \Big/ \sum_{k \in K_{ij}} f_{ij}^k c_{ij}^k}{\sum_i q_{ij}} \end{aligned} \tag{2}$$

where,

q_{ij} : travel demand from zone *i* to *j*,

f_{ij}^k, c_{ij}^k : travel flow and cost, respectively, on path *k* in the path set K_{ij} connecting between zones *i* and *j*.

In equation (2), AI_j represents the ability of the travelers or evacuees from all origins $i \in I$, where I is the set of all origins, to access the desire destination j (i.e. assembly point or evacuation center). The authors take the destination choices of the travelers into account by setting the impedance function $f\left(C_{ij}\right)$ as the function of the travel cost (or time) c_{ij}^k weighted by the travel flow f_{ij}^k of the individuals on all paths $k \in K_{ij}$. In addition, the travel demand q_{ij} is used in the equation, instead of the number of available opportunities O_j, to consider the impact of travel demand on the degree of destination accessibility. Consequently, the term $q_{ij} \big/ \sum_{k \in K_{ij}} f_{ij}^k c_{ij}^k$, which is the reciprocal of the average travel cost between zones i and j (i.e. $\sum_{k \in K_{ij}} f_{ij}^k c_{ij}^k \big/ q_{ij}$), can be implied that the higher increase in the average travel cost, the lower destination accessibility.

The procedure for road network vulnerability analysis in this paper follows a traditional approach. The steps can be summarized in Figure 4. The step starts from the calculation of the normal network, called full network. Next, the links in the network are partially (or fully) selected, called candidate links. Later, each candidate link is partially degraded (or completely closed) in turn. The network is called degraded network. This step is based on the assumption that the probabilities of the failure of all links are the same. Then, the accessibility index of the degraded network from the failure of link a, denoted by AI_j^a, can be determined using equation (2) whereas f_{ij}^k and c_{ij}^k can be obtained by solving a static traffic assignment problem in EMME. Following the steps, let AI_j^0 and AI_j^1 be the destination accessibility indices of the full network and the network degraded by a link $a \in A'$, where A' is the set of all possibly degraded links (candidate links). The absolute and relative changes in the accessibility index can be calculated from $\Delta AI = AI_j^0 - AI_j^1$ and $\Delta RAI = 1 - AI_j^1 \big/ AI_j^0$, respectively. As noted in Taylor (2008), the absolute change may be suspect because it has no specific scale. On the other hand, the relative change, which represents a proportional or percentage change, may be more intelligible. Thus, the authors use the relative change in this paper. The link is considered as the critical location if the road is cut off (or degraded) by a disaster and, consequently, the destination accessibility index is reduced significantly.

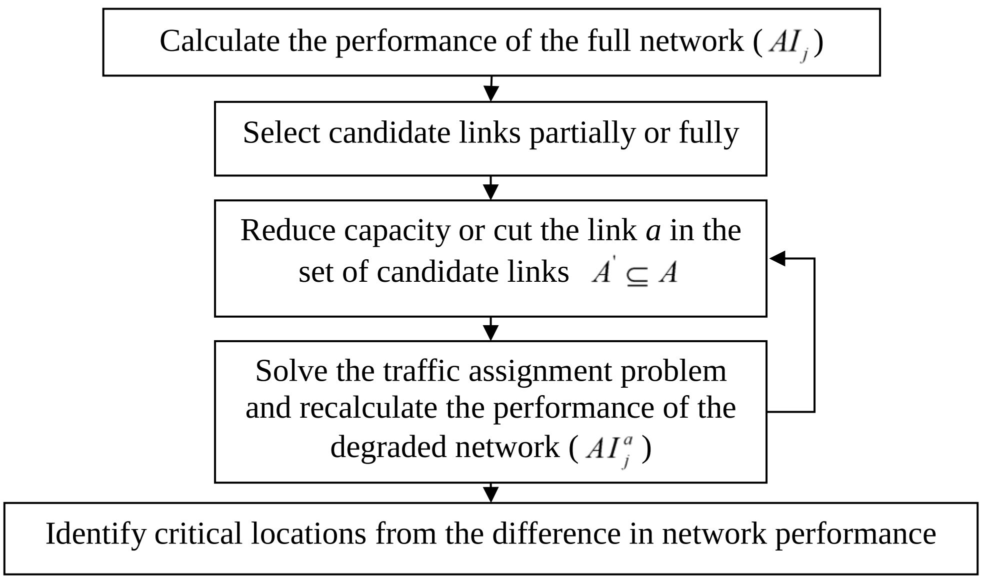


Figure 4. Steps of network vulnerability analysis

4. STUDY RESULTS

In this section, the results of three different tests, focusing mainly on the major urban area of Hat Yai city, are presented in the following subsections.

4.1 Impacts of Disruption to Major Bridges, Tunnel, and Intersection

The first test is to apply the destination accessibility index proposed in equation (2) to evaluate the impacts of five potential critical locations (as shown in Figure 5), including three overpass bridges (B1, B2, and B3), one tunnel (T), and one major intersection (I), on the migration of evacuees to the five main evacuation centers (D1 to D5) provided by Hat Yai municipality. The centers cover four zone groups (ZG1 to ZG4) in the urban area.

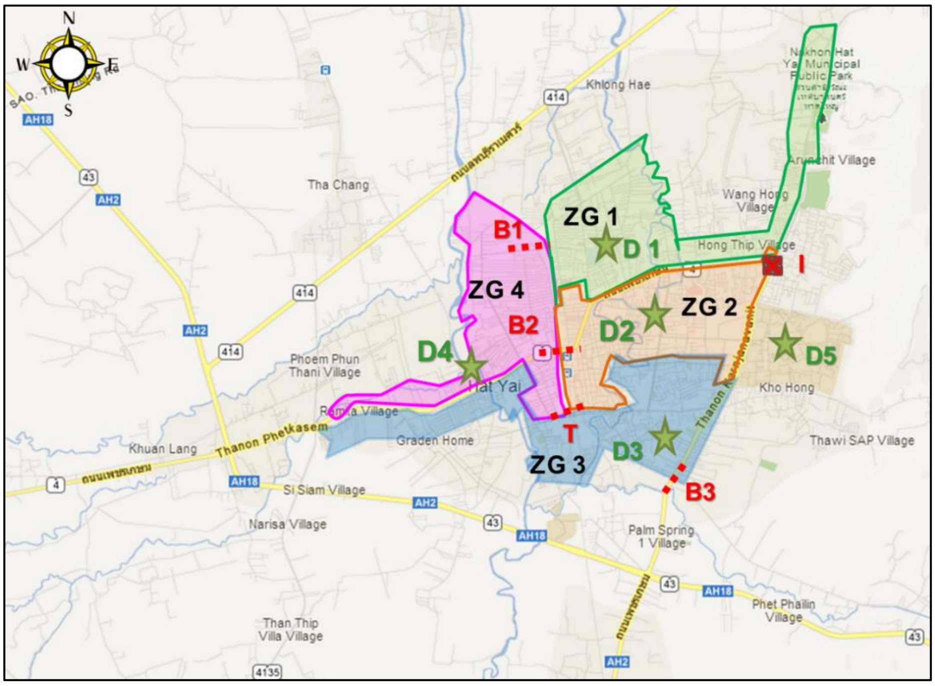


Figure 5. Possible critical locations and evacuation centers in Hat Yai municipality area

The test is conducted by individually disrupting the potential critical location and evaluating the accessibility measures of the full and degraded networks, respectively. The radar plots of the relative reduction of the measures at different locations are presented in Figure 6. The results vary by different locations. The disruption of the overpass bridge B1 causes relatively small impacts on the accessibility to all evacuation centers because it serves low travel demands and has high reserve capacity. On the other hand, the disruption of the overpass bridge B3, which is the major bridge carrying high volumes of traffic from the south bound to the city, causes high reduction of the accessibility, especially to the center D5. Moreover, the failure of the overpass bridge B2 contributes to large impacts of the accessibility to the centers D2, D3, and D1, respectively. Among the five locations, the intersection I and the tunnel T can be considered as the top two critical locations that adversely affect the accessibility to all centers. The reasons are that these two locations handle high travel demands, whereas their reserve capacities are quite low. From the results, it can be implied that the reduction of destination accessibility relies mainly on the levels of travel demand and the reserve capacity of link.

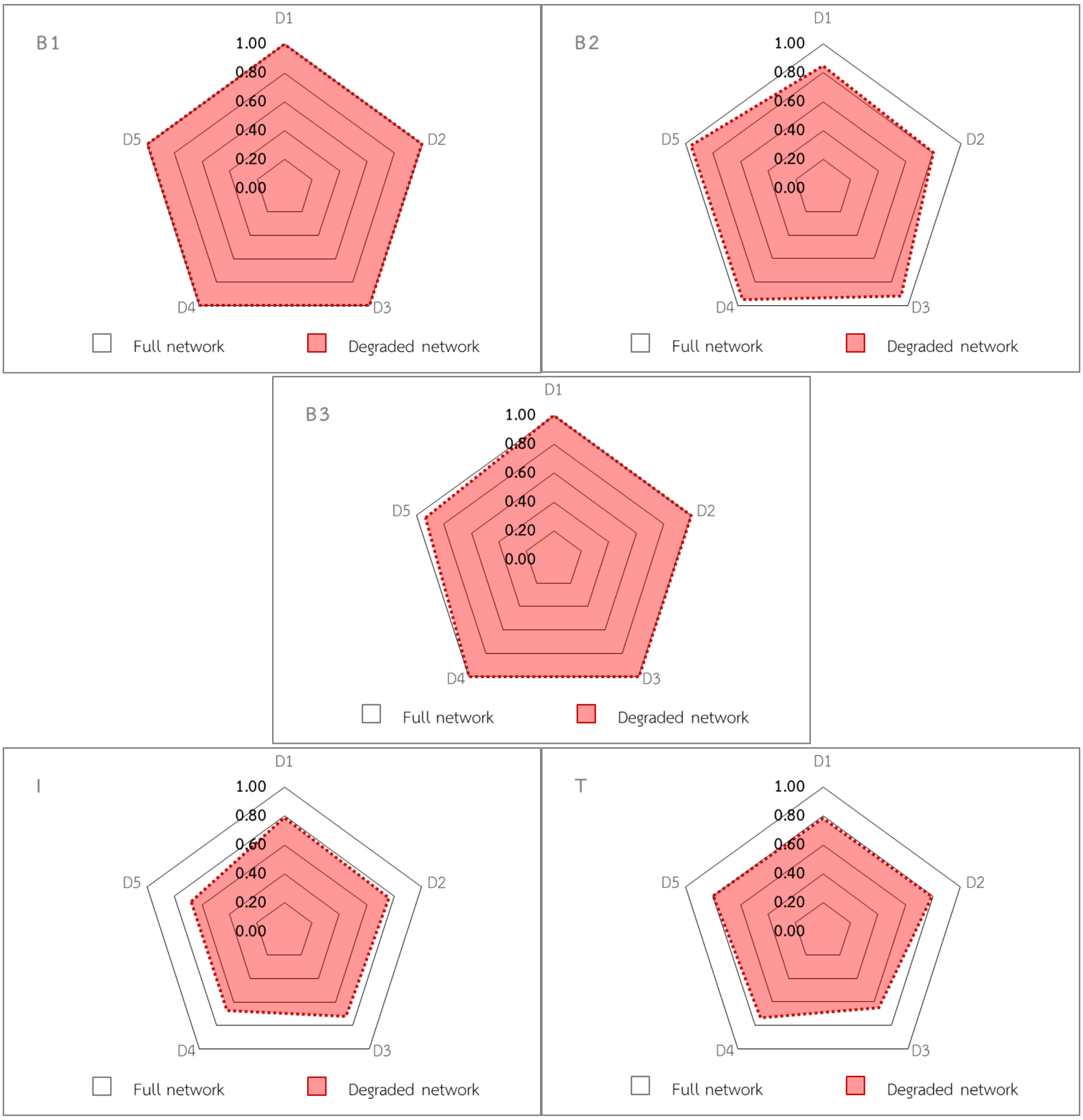
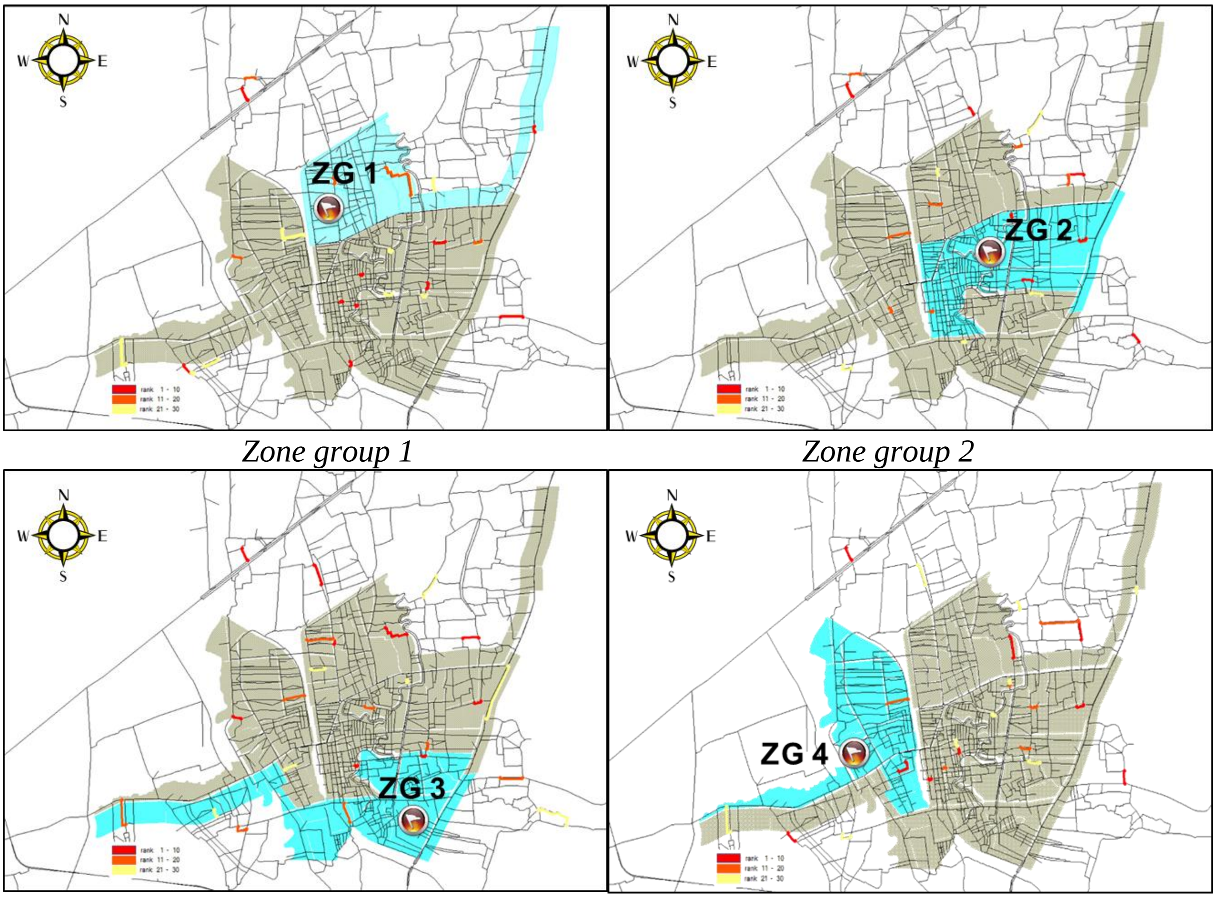


Figure 6. Relative reductions of destination accessibility from different locations

4.2 Critical Road Locations

The second test is to identify the critical road locations in the urban area using the steps presented in Figure 4. The accessibility to the center of each zone group shown in Figure 5 is evaluated and used to identify the critical road locations. The results of the top thirty critical road locations are presented in Figure 7. The results show that the locations of critical road for each zone group are different. From the investigation of the developed model, it was found that the top critical locations heavily depend on high travel demand and low reserve capacity, similarly to the findings from the previous test.



Zone group 1 *Zone group 2*

Zone group 3 *Zone group 4*

Figure 7. Critical locations in the urban area

4.3 Sensitivity Analysis

The final test adopts sensitivity analysis to investigate the variability of the top critical locations from different degrees of network failure, resulting from different severities of a disaster, and different demands of evacuation. Two levels of disaster severity, causing 50% and 100% of road capacity reduction, are assumed, while three levels of evacuation demands, including low, medium, and high are considered. Note that the evacuation demands under low and high levels are assumed to be, respectively, 0.5 and 2 times of that under medium level. In addition, the medium evacuation demand is estimated based on the travel demand during normal condition. The results of the critical locations in accessing the city center from the whole network is presented in Figure 8, whereas Figure 9 shows the results of the top 30 critical locations in the urban area.

The results show that at the same level of evacuation demand the road becomes more critical when the degree of road capacity reduction increases. Similarly, the critical locations change at different conditions of network congestion. These results may be implied that the location of critical road is sensitive to the degree of disaster severity and evacuation demand. Therefore, critical road locations should be evaluate thoroughly before using as part of disaster preparedness planning, e.g. evacuation routing.

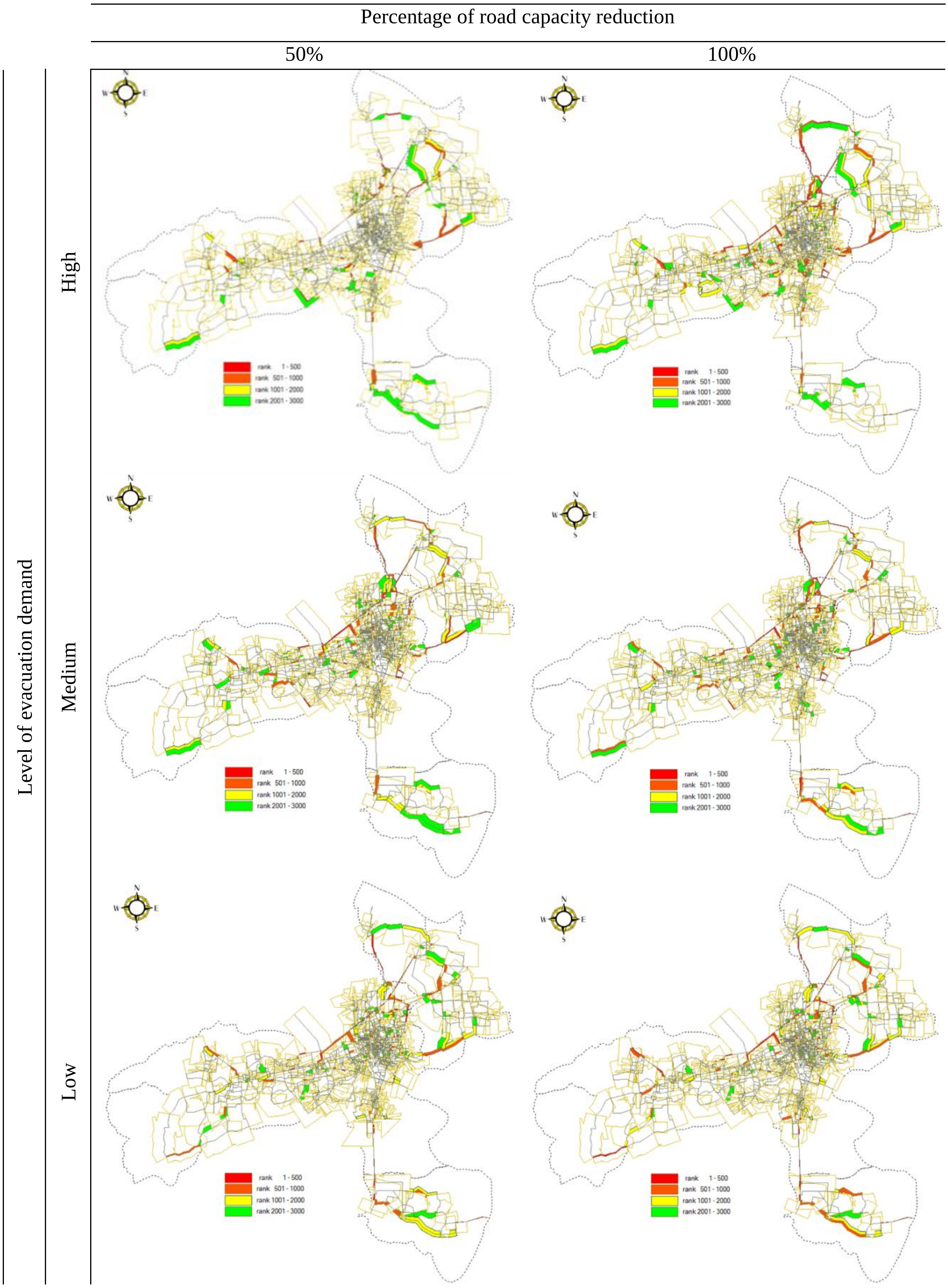


Figure 8. Sensitivity analysis of the critical locations in the whole network

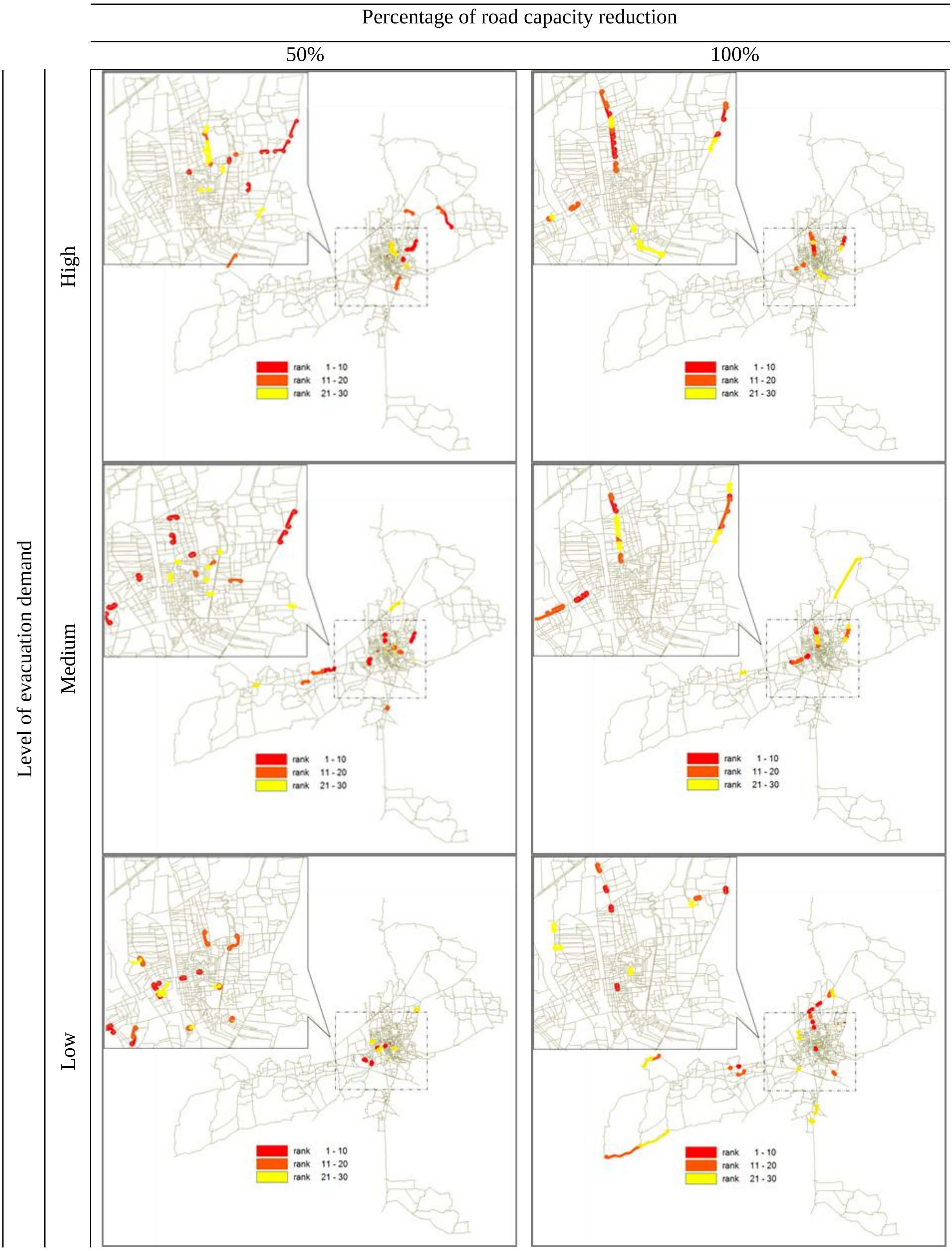


Figure 9. Sensitivity analysis of the critical locations in the urban area

5. CONCLUDING REMARKS

This paper applied the vulnerability analysis to identify the critical locations of road network. Based on potential accessibility index, the destination accessibility index was proposed to measure the ability of travelers or evacuees to access the assembly points (or evacuation centers) if a road link was failed by a disaster. A road was identified as the critical location if its failure or capacity degradation adversely affected the accessibility index most.

Three tests were performed using Hat Yai road network as a case study to demonstrate the applicability of the proposed index. The first test evaluated the impacts of the disruption to potential critical locations, including three major bridges, one tunnel, and one major intersection, on accessing four evacuation centers in the urban area. The second test applied the traditional approach to analyze the top vulnerable locations in the case that the evacuation center in each zone group can operate in turn. The results from both tests revealed that the reductions of the destination accessibility index depend mainly on the levels of traffic volumes and link reserve capacity. Using sensitivity analysis, the last test determine the variability of the critical locations from different degrees of network failure and evacuation demand. The results show that the critical locations are sensitive to both factors. Thus, the critical locations should be identified carefully before using them as part of a disaster preparedness planning.

The analysis results can be considered as a proactive approach that allow road system managers to anticipate the potential network vulnerabilities from several consequences of disasters in the future and to provide strategic plans for alternative evacuation routes during critical situations. By improving the performance of the critical roads, or by adding redundancy into the network capacity, e.g. by constructing new bypass roads or parallel paths, the overall vulnerability of the network can be reduced.

The process of vulnerability analysis used in this paper is a computationally intensive operation, which takes about 8 minutes for a full run of one link failure on the computer with Intel Core i5 CPU 1.6GHz, 4GB RAM, and 64-bit Windows 8 operating system. The larger network may require more computational time. Future research should develop efficient algorithms for evaluating network vulnerability. The transport model developed in this paper was restricted to private vehicles only. Multimodal transport modeling and the effects of saturated and oversaturated flow condition should be considered for future research.

ACKNOWLEDGEMENT

The first author would like to thank Prince of Songkla University for supporting the internal research fund project (ENG550148S). The authors also thank all respondents for valuable questionnaire information.

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