Identification and Prioritization of Critical Transportation Infrastructure: Case Study of Coastal Flooding

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Abstract: In order to better inform transportation decision makers of the criticality of transportation infrastructure, this paper explores an accessibility-based criticality prioritization methodology to identify and prioritize critical transportation infrastructure. In particular, the methodology evaluates the network-wide impacts of infrastructure degradation based on the increase in travel cost taking origin importance, destination attractiveness, and traffic congestion into account. The methodology is applied to the road network of Hillsborough County, Florida, threatened by flood risk from storm surge, sea-level rise, and intense precipitation. Light detection and ranging digital elevation data, transportation infrastructure and network data, and zone-based population data of the county are processed for analysis. The approach yields results of not only the criticality of transportation infrastructure under flooding impact but also the most vulnerable zones as a result of infrastructure inundation. The results show that some infrastructure is critical to adjacent areas, while some becomes important to a much broader region. The results further demonstrate that the infrastructure is more critical if it serves more people. **DOI: 10.1061/(ASCE)TE.1943-5436.0000743.** *© 2014 American Society of Civil Engineers.*

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Introduction

Identified as one of 17 critical infrastructure sectors in the national strategy for homeland security [U.S. Department of Homeland Security (USDHS) 2007], transportation infrastructure is exposed to hazards as a result of global climate change. The Transportation Research Board (TRB) identifies five climate change factors of particular importance to the transportation system in the United States, three of which are (1) rising sea levels, (2) increases in intense precipitation, and (3) increases in hurricane intensity (TRB 2008). All of them could pose flood risk on the transportation sector especially in coastal areas resulting in infrastructure disruption, network interdiction, traffic congestion, and serious economic costs. In the future, flooding caused by extreme events might even beyond the current planning and engineering regime [Federal Highway Administration (FHWA) 2010; Rosenzweig 2011; Lu and Peng 2012]. Although little can be done about the scales, frequencies, or predictability of these risks, it is possible to develop protection and adaptation measures to minimize the negative impacts caused by such attacks (Lou and Zhang 2011). In order to mitigate the potential impacts of flood risk, protection strategies are preferred to be developed in advance, as previous experience has shown that it is almost impossible to develop countermeasures waiting until a disaster occurs (National Consortium on Remote Sensing in Transportation 2002).

However, it is virtually impossible to protect or fortify all the affected infrastructure components. Therefore, the infrastructure at risk must be prioritized and protected in a way that minimizes the potential impacts within a limited budget. Infrastructure prioritization is one of the important steps of a critical infrastructure protection plan, as suggested by USDHS (2009). Current works emphasize more on issues of transportation system resilience, robustness, and critical infrastructure protection plan than criticality infrastructure prioritization (Wardekker et al. 2010; Croope and McNeil 2011; Farhan and Fwa 2011). The identification and prioritization of critical transportation infrastructure can be as or even more important than the resilience and protection plan of the transportation network, as the former provides basic information to the infrastructure protection and resilient analyses. Moreover, literature addressing transportation infrastructure criticality prioritization usually deals with daily maintenance and terrorist attacks following the events of September 11, 2001 (Science 2002; Powell 2007; Seyedshohadaie et al. 2010; Lou and Zhang 2011; Farhan and Fwa 2011). The criticality prioritization under flood risk is different from that of daily maintenance and terrorist attack, which emphasize the daily deterioration of transportation infrastructure and smart and targeted infrastructure disruption.

To address the previously mentioned issues, a road segment criticality prioritization methodology is proposed based on a location-based accessibility index. The accessibility index measures the network-wide performance before and after transportation network interdiction and quantifies the degree of network degradation. The criticality of road segments is then prioritized based on the network-wide accessibility reduction. In case of road segment failure, the most vulnerable regions that rely on the failed segment can also be identified with the proposed methodology. Finally, the methodology is applied to the road network of Hillsborough County, Florida, under flooding impact. The remainder of the paper starts with a review of current literature.

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Literature Review

It is commonly agreed that a segment is more critical if its removal results in a relatively high increase in the overall network-wide travel time compared to the removal of a less critical segment which results in a relatively low network-wide travel time increase (Sullivan et al. 2010). Transportation network analyses based on the previously mentioned definition lead to the criticality prioritization of transportation infrastructure. Previous efforts addressing critical transportation infrastructure adopt localized level-of-service (LOS) measures such as the volume/capacity (V/C) ratio (Bremmer et al. 2004; Dheenadayalu et al. 2004). If a segment has a higher V/C ratio, this segment is more important, and improvements and investments are suggested to mitigate the congestion on this particular segment. As a result, the investments of road retrofit and maintenance are actually made based on the susceptibility to congestion instead of the criticality of a link. However, the protection of less exposed segments might result in more network-wide travel time saving as opposed to the protection of these more exposed ones. The transportation infrastructure should be protected in a way that improves the network-wide performance as measured by travel time instead of exposure or susceptibility to risk.

In order to address the previously mentioned research gap, several works develop methodologies evaluating the network-wide impacts to identify critical transportation links. Ukkusuri and Yushimito (2009) propose a heuristic transportation infrastructure criticality assessment procedure by using a network-wide travel time performance, and find a big criticality difference between the proposed measure and the volume/capacity ratio method. Considering the uncertainties in daily maintenance and rehabilitation, Seyedshohadaie et al. (2010) develop a risk-based methodology for the maintenance of transportation infrastructure as well as the network-level resource allocation. After a review of pervious works, Scott et al. (2006) call for a comprehensive system-wide approach to identify critical infrastructure and evaluate network performance, and develop a new index known as the network robustness index to evaluate the network performance and identify critical transportation infrastructure. While other studies focus on the infrastructure criticality under natural or artificial disasters. Sohn (2006) derives an accessibility index to assess the network-wide significance of highway links under flood damage and finds that the criterion for the significance evaluation may depend on the philosophy of the policy to be introduced. Based on the consequences resulted from multiple intentional and unintentional hazards, Science Applications International Corporation (SAIC) and Parsons Brinckerhoff Consult (Science 2009) develop a costing asset protection, an all hazards guide for transportation agencies methodology to provide decision makers with critical asset protection information. Based on several climate change scenarios, Lambert et al. (2013) adopt multicriteria analysis to prioritize the allocation of transportation assets. Trucco et al. (2012) address the interdependency of critical infrastructure in physical and functional sectors, and develop a model to assess the propagation of impacts due to single and coupled threats. In general, most of the studies evaluate the transportation network performance and find out the most critical links without giving the quantified criticality and prioritization of the links. The methodologies in the literature are different from each other based on different purposes and targets. Recently, more and more attention is being paid to natural disasters, especially risks posed by climate change. While the critical transportation infrastructure analysis under natural disaster is different from those of daily maintenance, traffic accidents, and terrorist attacks. Furthermore, if a critical link is failed, it is better to find out the areas that are seriously affected so that additional measures can be taken to mitigate the impacts in these vulnerable regions.

In case of natural disaster, it is important to guarantee the connectivity and accessibility of the transportation network. Accessibility is especially becoming an important indicator measuring transportation system performance in the disaster content (Chang and Nojima 2001). Taylor (2008) presents an accessibility-based transportation network vulnerability framework to evaluate the network-wide impacts of traffic incidents. Based on the combination of the shortest distance and travel time weighted by population, Sohn (2006) develops an accessibility index to find out the priority of retrofit among transportation links against flood damage. Several recent studies also address the natural disaster issue with accessibility method (Lu and Peng 2011; Shiomi et al. 2011; Taylor and Susilawati 2012), among which the location-based accessibility index dominates. Other accessibility methods are also reported in the literature. For example, Chen et al. (2011) make efforts on the development of an opportunity-based accessibility index incorporating both spatial and temporal dimensions. After elaborating the concept of accessibility and factors affecting accessibility, as concluded by Litman (2012) that no single method can evaluate all accessibility factors and practitioners are still figuring out how to apply accessibility techniques to specific decisions. Based on the writers' research efforts, an accessibility-based methodology is proposed for road segment criticality prioritization which is elaborated as described next.

Transportation Infrastructure Criticality Prioritization

In order to make critical infrastructure more resilient, function-based priorities may more effectively ensure the continuity of operations in the event of a terrorist attack or natural disaster (USDHS 2009). Accessibility is a fundamental concept addressing system performance and function in transportation analysis. An accessibility indicator suitable for use by transportation planners should be technically feasible and simple, and include an element of spatial separation (Morris et al. 1979). This paper proposes an improved accessibility index for road segment criticality prioritization. The accessibility index is formulated as

$$A_i = w_i^d \sum_{j=1}^{n-1} w_j^o [f(t_{ij})/f^0(t_{ij})]^{-\alpha} \qquad (i \neq j) \tag{1}$$

where A_i = accessibility of zone i; w_i^d = destination trip weight of zone i which equals to $D_i/\sum_{k=1}^{n} D_k$; D_k = trip attraction of zone k, and k = all the zones; w_j^o = origin trip weight of zone j which equals to the $O_j/\sum_{m=1}^{n} O_m (m \neq i)$; O_m = trip generation of zone m, and m = all the zones; $f^0(t_{ij})$ = original travel cost between region i and j without network degradation; $f(t_{ij})$ = travel cost between region i and j after network degradation; D_i = total trip attraction of zone i; O_j = total trip generation of zone j; α is the travel cost decay parameter ($\alpha > 0$); and n = number of zones in the study area.

Eq. (1) shows a location-based accessibility index and is calculated based on location or traffic analysis zone (TAZ). The destination trip weight of the equation is used to describe the attractiveness of the destination zone. If the weight is very high for a destination zone, i.e., there are more people attracted to this zone, and then more travels are generated between this zone and other zones, and vice versa. The more weight of a zone, the more attractive it becomes. This is assuming that the attracted traffic volume is from all the other zones outside of this zone. A zone importance factor is also assigned to each origin zone, which equals to the ratio of the trips generated in this zone over all the trips of other origin zones. The more travels generated by the origin zone, the bigger of this factor, and thus the more important this zone becomes. Finally, the ratio of travel cost before and after the network degradation is employed to duplicate the spatial and temporal separation between the destination and origin zones. The travel cost after network degradation incorporates the increased costs as a result of rerouting and congestion when roads are destroyed. This process must also include a travel cost decay factor α which adjusts the sensitivity of travel cost ratio to the accessibility value. The travel cost decay factor is calibrated from the traditional trip distribution model such as the gravity model based on traffic flow and origin destination (OD) data. If there is a travel cost increase between two zones, the ratio will be less than 1, and therefore the accessibility will decrease. The ratio becomes zero on condition that there is no route connecting all the other zones. The TAZ attractiveness and importance weight factors could end up the overall accessibility of all the zones with 1 if the transportation network is not degraded and 0 if the network is totally inaccessible, and the lower the index the more degraded of the network. In this way, the methodology provides a way to better understand the accessibility reduction comparing to the original accessibility value of 1.

Different from previous indices, the advantages of the proposed accessibility index are that it includes origin importance in addition to the destination attractiveness and normalizes the network-wide accessibility value between 0 and 1. It not only shows the quantitative impact of segment failure on the network-wide accessibility but also identifies the most vulnerable zones. The network topology as well as rerouting and congestion on road segments under link failure are also captured in the travel cost update. Besides, this accessibility index is not complicated to understand and use.

The accessibility index measures the accessibility of individual zones and the accessibility summation of all the zones represents the network-wide accessibility provided by the transportation network. If there is accessibility reduction from any zone of the study area, the transportation network should have been degraded either by link failure or congestion as measured by the proposed accessibility index. This methodology captures transportation system performance indirectly from the accessibility of all the zones served by the transportation network. The criticality of the transportation links is then prioritized based on the network-wide accessibility reduction as a result of link failure.

Based on the accessibility index of Eq. (1), the accessibility reduction for each zone can be calculated before and after the failure of link (or link set) l. As a result, the accessibility reduction rate of zone i could be calculated as

$$\mathrm{ARR}_i^l = (A_i^0 - A_i^l)/A_i^0 \tag{2}$$

where ARR_i^l = accessibility reduction ratio of zone i with the failure of link (or link set) l; A_i^0 = original accessibility of zone i without network degradation; and A_i^l = accessibility of zone i after link (or link set) l failure.

The accessibility reduction for individual zone is captured by Eq. (2). This allows for the identification of the most vulnerable zones.

Overview of Data

The previously mentioned accessibility-based transportation infrastructure criticality prioritization methodology is applied to the road network of the coastal area of Hillsborough County, Florida. Hillsborough County lies in the coast of Florida, and is being challenged by flood risk from storm surge, sea-level rise, and river flooding. The county has the fourth largest population in the state, and ranks the first in population and land area in the Tampa Bay region. There are three interstate expressways, three U.S. national highways, and four state highways in the area. Airports, military base, and other critical infrastructure are all located in the coastal area of the county. These make the coastal area even more vulnerable to flood risk.

In case of disaster, road networks are more important than other transportation networks such as rail network because of their extensive coverage and strong role in maintaining the connectivity of urban systems (Shiomi et al. 2011). As a result, this paper focuses on the criticality prioritization of road network. The highway and major urban roads in the coastal area of Hillsborough County are addressed. In order to compare the criticality of affected road segments and bridges, it is assumed that the affected infrastructure is closed after flood. The road network data are from the Florida Standard Urban and Transportation Model Structure (FSUTMS) model, which is developed by the Florida DOT and customized for Florida application. The OD data of the study area are also derived from the FSUTMS model. The data of FSUTMS model are collected from the Florida Transportation Survey and regional and local metropolitan planning organizations. The model data have been checked with the census data and population data from the Florida Bureau of Economic and Business Research by the Florida DOT. There are totally 758 TAZs for Hillsborough County in the FSUTMS model. The transportation network in the model consists of highways, interstate expressways, and major roads. The FSUTMS model produces TAZ-based trip and shortest travel time data which is updated based on different infrastructure damage scenarios. This paper only considers trips within the county. The shortest travel time between TAZs also change the trip distribution results through a friction factor and the model split between auto and transit through a nesting coefficient in a nest logit model structure.

The flooding area is identified based on the land elevation data. Light detection and ranging (lidar) elevation data of Hillsborough County collected from National Oceanic and Atmospheric Administration (NOAA) coastal service center are processed in *ArcGIS* and used to generate the flooding map. The lidar data are collected from years 2004–2008 and has an elevation resolution of better than 30 cm at the 95% confidence level.

The study area is very vulnerable to sea-level rise. Based on a nonlinear forecasting approach, Walton (2006) collects historical sea-level rise data from NOAA tide gage station and estimates the sea-level rise in St Petersburg, Florida, at the year 2080. However, as a result of the combination effects of global temperature increase and land subsidence, FHWA (2010) projects a sea-level rise of 61–122 cm over next 50–100 years. The two estimations of sea-level rise rate correspond to sea-level rises of 0.3 and 0.6 m in the year 2060 which is also the year of the long-range Florida transportation plan (Florida 2011). In order to prepare for the worst-case scenario, 0.6-m sea-level rise scenario is used in this paper.

The previously mentioned data are collected and processed to evaluate the inundation impact on the road network of Hillsborough County. The affected road segments are identified and then interdicted in the transportation model. The accessibility-based road network criticality prioritization methodology is applied to the study area incorporating output from the transportation model. The results are presented and discussed in the next section.

Results and Discussion

The lidar elevation data are processed in *ArcGIS* using the spatial analyst function and land with elevation lower than

0.6 m is identified. Transportation network from FSUTMS model is then overlaid with the land elevation data and as a result transportation infrastructure in vulnerable areas is identified. There are 87 road segments with a total length of 40.83 km are vulnerable to coastal and river flooding (Fig. 1). The infrastructure types at risk include road segments, intersections, and bridge. In this paper, 14 facilities including nine road segments, one intersection, and four bridges are selected for transportation infrastructure criticality prioritization, as they are either located at important places such as airports and bridges or segments of major arterials of the study area.

Based on Eq. (1) and the previously mentioned flooding impact analysis and transportation model results, the network-wide accessibility, i.e., the overall accessibility value of all the 758 TAZs, is calculated before and after the flooding impact. The failure of each infrastructure is considered as one scenario, and there are totally 14 scenarios. The travel cost between TAZs in Eq. (1) is the shortest travel time. The accessibility score is calculated with different values of α between 0 and 1, and the criticality prioritization results are the same for different α values; as a result it is only reported when α is 0.5 and 1 (Tables 1 and 2). The FSUTMS transportation model generates OD and shortest travel time results, and outputs different origin and destination trips for each scenario. Each scenario is set up in the FSUTMS model, the model is then run in *Cube* software for 14 scenarios. The model outputs the updated shortest travel time among all the 758 TAZs as well as the origin and destination trips for each TAZ. The shortest travel time among TAZs is updated based on the Bureau of Public Roads (BPR) function for each scenario. The proposed accessibility index is coded in *Matlab*, and then the system-wide accessibility is calculated in *Matlab* software. The criticality of transportation infrastructure is then prioritized based on the value of network-wide accessibility reduction, i.e., the lower of the network-wide accessibility value, the more critical of the infrastructure. In order to find out the most vulnerable zones in each scenario, the accessibility reduction rate for each TAZ is also calculated in *Matlab* based on Eq. (2). In this context, the most vulnerable zones are those which have great (i.e., 80–100%) accessibility reduction or among the top of accessibility reduction as measured by Eq. (2). The selected 14 infrastructure and the calculation results are shown (Table 1).

In Table 1, the network-wide accessibility under each scenario is listed, and the criticality of each facility is prioritized based on the network-wide accessibility reduction. Among the affected

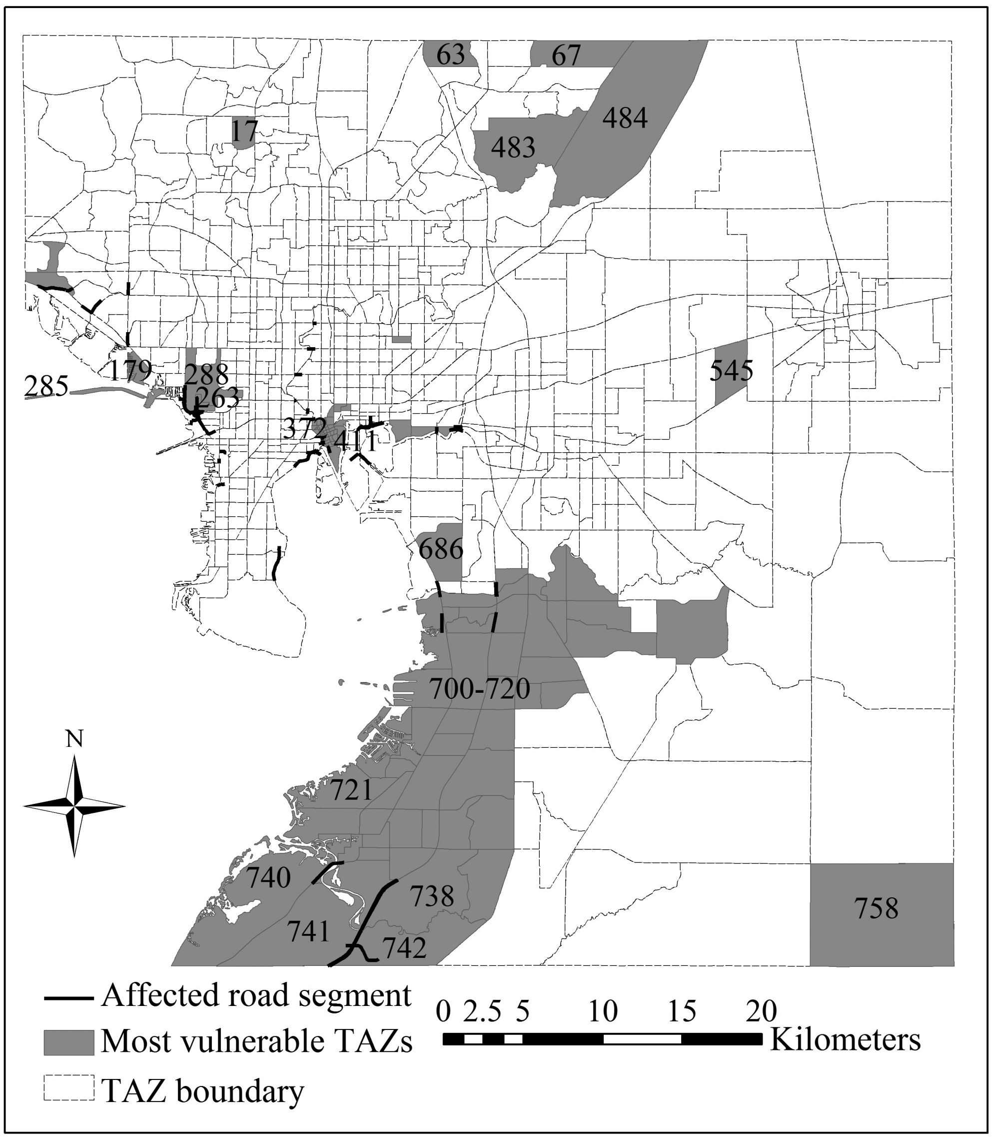

Fig. 1. Road segments affected and most vulnerable TAZs

Table 1. Transportation Infrastructure Prioritization and the Most Vulnerable Zones

Infrastructure name	Criticality prioritization	Network-wide accessibility		Hansen accessibility reduction	Most vulnerable TAZs
		$\alpha = 0.5$	$\alpha = 1$		
International airport intersection	1	0.9581	0.9265	0.1	288, 263, 285, and 286
I-75 freeway bridge	2	0.9632	0.9359	2.456	695–741, 686, and 670
Lee Roy Selmon Expressway segment	3	0.9747	0.9508	0.2071	245 and 370–415
Lee Roy Selmon Expressway bridge	4	0.9785	0.9583	0.3395	758 and 17
W. Hillsborough Ave. bridge	5	0.9963	0.9927	0.0008	67, 63, and 37
S. Tamiami Trail bridge	6	0.9964	0.9929	0.1940	700, 694, and 484
S. I-75 Freeway segment	7	0.9983	0.9969	0.5682	739, 740, 736, 742, and 285
N. Bayshore Blvd. segment	8	0.9986	0.9972	0.0251	285, 245, 484, and 545
S. Westshore Blvd. segment	9	0.9990	0.9980	0.0092	285, 483, and 63
S. Tamiami Trail segment	10	0.9996	0.9993	0.0041	740, 67, 741, and 285
S. Bayshore Blvd. segment	11	0.9998	0.9997	0.0005	67, 285, and 85
Forest Lakes Blvd. segment	12	0.9999	0.9998	−0.0072	285, 67, and 135
Shelton Rd. segment	13	1.0000	1.0000	−0.0061	37, 67, and 179
N. Ashley Dr. segment	14	1.0000	1.0000	−0.0075	758, 67, 285, and 393

infrastructure, the international airport intersection is the most critical whose failure results in the most network-wide accessibility reduction. The intersection connects several urban and regional arterials, and the failure of the intersection interdicts several segments which makes the intersection most critical. Another reason is that it is close to the Tampa International Airport, and the special location also makes it critical. The I-75 Freeway bridge is the second critical infrastructure among 14 facilities. The bridge is critical connecting the northern and southern parts of the study area as well as the whole state. Generally speaking, bridges are more critical than segments. This is because, unlike road segment, there may be less alternatives for people to choose when a bridge fails, so the failure of a bridge will cause more network-wide accessibility reduction than the failure of a road segment. Expressway is more important than local roads. However, some local arterial road bridges play a more important role than interstate highway segments. This is because that the accessibility index considers the number of people that a facility serves, and if a facility serves more people it is more critical. Road segments such as Shelton Rd. and N. Ashley Dr. have little impact on the network-wide accessibility (Table 1), although either road segment serves residential area or in the urban core area. The Shelton Rd. is a local road located in the southern suburban area, and the N. Ashley Dr. is located in the downtown area with many alternatives. So, the two segments are the least critical among the 14 infrastructure, and a conclusion can be drawn that they are not critical links. From the network-wide accessibility results, people will also have an idea of the degree of accessibility reduction under each scenario, as the original accessibility of the network is normalized to 1.

The Hansen integral accessibility index (Taylor et al. 2006) is introduced to make a comparison with the results from the proposed accessibility-based infrastructure prioritization method. The Hansen accessibility index is formulated as

$$A_i = \left[\sum_j B_j f(c_{ij})\right] / \sum_j B_j \tag{3}$$

where A_i = accessibility of location (zone) i; B_j = attractiveness of a location (zone) j; and the impedance function $f(c_{ij})$ represents the separation between two locations, and is usually formulated as the inverse of travel time or cost.

Eq. (3) is used to calculate the network-wide accessibility of 14 scenarios. The results of Hansen accessibility reduction are shown (Table 1). According to the Hansen accessibility results, the most

Table 2. Transportation Infrastructure Prioritization under Multiple Infrastructure Failure or Capacity Reduction

Multiple infrastructure damage	Infrastructure name	Damage type	Criticality prioritization	Network-wide accessibility	
				$\alpha = 0.5$	$\alpha = 1$
A	Forest Lakes Blvd. segment	Failure	6	0.9999	0.9998
	Shelton Rd. segment	Capacity reduction			—
B	International airport intersection	Capacity reduction	4	0.9971	0.9943
	S. Westshore Blvd. segment	Failure			—
C	S. Bayshore Blvd. segment	Failure	5	0.9981	0.9962
	N. Bayshore Blvd. segment	Failure			—
	N. Ashley Dr. segment	Capacity reduction			—
D	W. Hillsborough Ave. bridge	Failure	3	0.9734	0.9483
	Lee Roy Selmon Expressway segment	Capacity reduction			—
	Lee Roy Selmon Expressway bridge	Failure			—
E	I-75 Freeway bridge	Failure	2	0.9464	0.9107
	S. Tamiami Trail bridge	Failure			—
F	S. I-75 Freeway segment	Capacity reduction	7	1.0000	1.0000
	S. Tamiami Trail segment	Failure			—
G	All the previously mentioned infrastructures	Failure	1	0.9194	0.8588

important infrastructure is the I-75 Freeway bridge whose failure results the most accessibility reduction, and the second important facility is the I-75 Freeway segment. However, the international airport intersection ranks the sixth among 14 facilities. The intersection is not only important to the international airport but also a critical node connecting the downtown area with the northern and southern parts of the county. The failure of the intersection disconnects several road segments, and the criticality of the intersection should be higher than a signal segment. Another difference is that W. Hillsborough Ave. bridge falls to the fifth in the Hansen accessibility calculation results. The bridge is an important facility of Hillsborough Ave. which connects the populated downtown area and the west northern coast region. The reason is that the Hansen accessibility does not consider the importance of the location, i.e., the number people in a zone; as a result the Hillsborough Ave. bridge is not critical although it serves populated residential areas. Generally, the results of the two indices are similar, but different in the prioritization of some infrastructure as discussed previously. A general conclusion drawn from the comparison is that the Hansen index shows that infrastructure is more important if its failure affects a larger area, while the proposed index indicates that a facility is more important if its failure affects more people. In the Hansen index, the population in a TAZ is used to define the attractiveness of a zone, and the index only has the attractiveness parameter without the origin importance factor, which thinks the importance of zones is the same although they have different area, population, and so on.

Vulnerable TAZs which receive the most accessibility reduction under each scenario are also shown (Table 1), and their locations in the study area can be found (Fig. 1). If the international airport intersection is failed, TAZs 288 and 263 will have a 100% accessibility reduction, and most of the TAZs between 1 and 185 in the west northern part of the study area will get accessibility reductions around 10%. Other parts of the study area such as the southern and eastern parts almost have no accessibility reduction. In the I-75 Freeway bridge scenario, the bridge plays an important role in the accessibility of the southern TAZs; for example, TAZs between 667 and 758 all have obvious accessibility reductions around 30%. However, the failure of Lee Roy Selmon Expressway bridge does not have much impact on the accessibility of most TAZs except for TAZs 758 and 17. Lee Roy Selmon Expressway segment is important for the downtown TAZs whose failure will cause about 10% accessibility reduction for most of the TAZs in the downtown area. The scenarios of S. I-75 Freeway segment and the S. Tamiami Trail segment have prominent impact on surrounding TAZs resulting in accessibility reductions between 20 and 30%. The N. Ashely Dr. doesn't have obvious impact on any TAZ which might because that the downtown area has a high road density and people can easily find an alternative road for their travel. In short, some transportation infrastructure plays important roles in the regional accessibility of the study area, while some infrastructure only has impacts on the accessibility of surrounding zones. The accessibility changes bigger in rural areas with low road density than in the downtown area which has high road density.

With different values of α, Fig. 2 shows the infrastructure criticality prioritization as well as the network-wide accessibility reduction rate for each scenario. The prioritization results of the previously mentioned infrastructures are the same no matter what α value adopted (Fig. 2). As a result, the ranking on the horizontal axis (Fig. 2) is the same as that of Table 1. However, the network-wide accessibility reduction rates are different with different α values under the same scenario. When α is given a big value, the network-wide accessibility has a large reduction and the

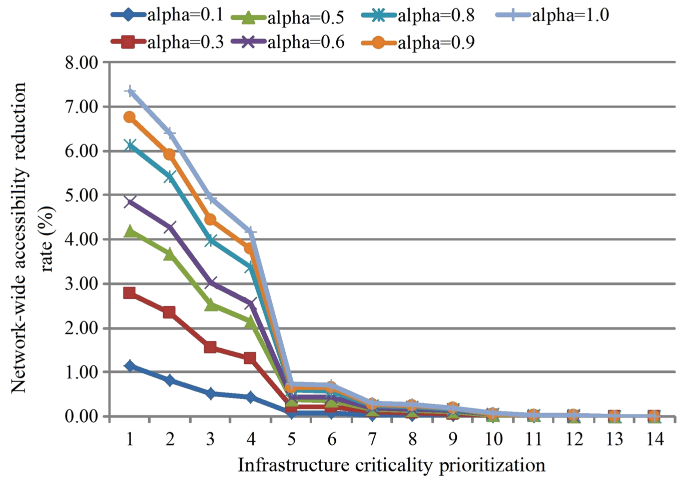

Fig. 2. Network-wide accessibility changes with alpha

difference between accessibility reduction rates becomes small with the increase of α value. As the most critical infrastructure, the international airport intersection receives the most accessibility reduction rate change when α increases from 0.1 to 1.0. The less critical of the infrastructure the less change of the network-wide accessibility reduction rate with the change of α value. As a result, the network-wide accessibility is sensitive to the travel decay factor α and the more important of an infrastructure the more sensitive of the accessibility reduction, but the results of the critical infrastructure prioritization keep the same whatever α values are used.

In order to look into the detailed impacts of infrastructure failure, Figs. 3(a and b) show the accessibility reduction rates of all the TAZs when the Tampa International Airport intersection and S. I-75 Freeway bridge, respectively are inundated. The accessibility reduction rates are calculated based on Eq. (2) and visualized in *ArcGIS* with TAZ data. Both the infrastructure failure scenarios cause great accessibility reduction to their surrounding TAZs, e.g., the Tampa International Airport intersection failure results in almost 100% accessibility reduction for TAZs 288 and 263, and the TAZs 702, 703, and 704 receive more than 40% accessibility reduction when the S. I-75 Freeway bridge fails. The failure of Tampa International Airport intersection also has obvious impacts on the west northern part TAZs of the study area and most of the southern TAZs have dramatic accessibility reductions in the S. I-75 Freeway bridge scenario. Although the S. I-75 Freeway bridge scenario results in more TAZs with obvious accessibility reduction and a larger affected area, the Tampa International Airport intersection is more critical than the S. I-75 Freeway bridge (Table 1). The reason is that the southern part of the study area is rural area with agriculture and grass land uses while the urban residence land is located in the west northern part, as a result the Tampa International Airport intersection serves more people than the S. I-75 freeway bridge. The accessibility index developed in this paper captures not only the shortest travel time changes among TAZs but also the population or travel trip weight of each TAZ, which better interprets the criticality of transportation infrastructure.

However, there would be multiple infrastructure failure under flood in the real world and some affected infrastructure may only have partial capacity reduction. To address this concern, scenarios of multiple infrastructure failure and capacity reduction at the same time are developed and shown (Table 2). The scenarios are generated based on the land elevation and location of the infrastructure, i.e., adjacent infrastructure with similar land elevation is included in one scenario. Two infrastructure damage types are defined to the

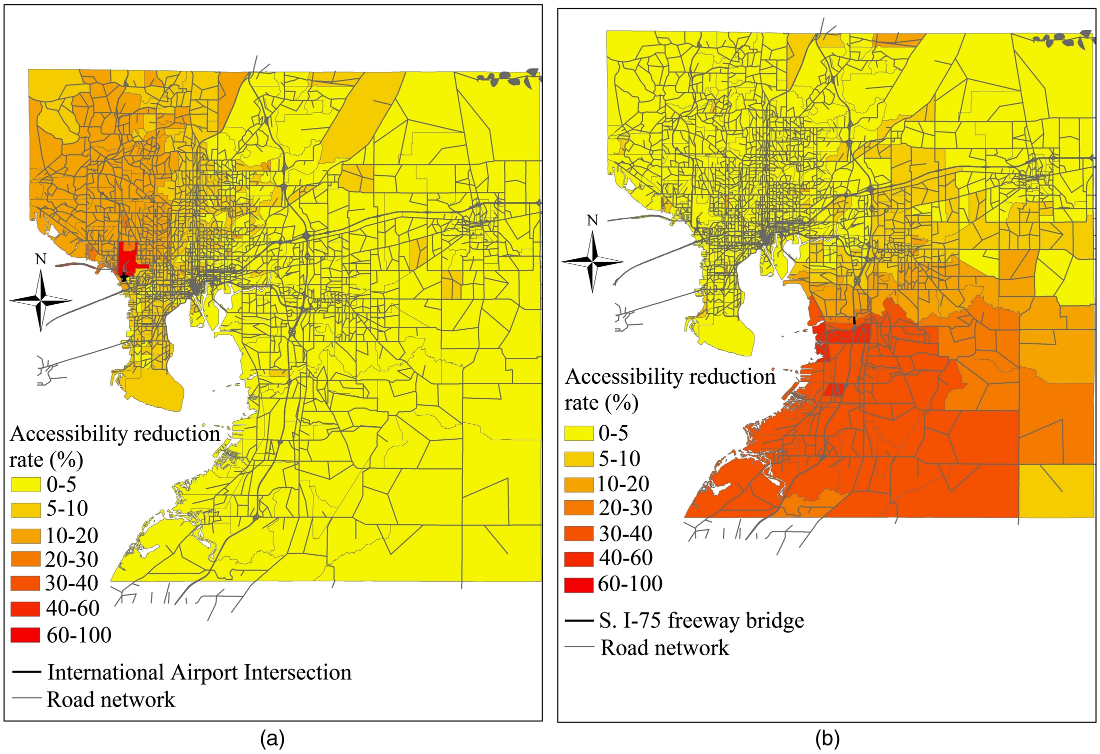

Fig. 3. Vulnerable TAZs in two infrastructure failure scenarios: (a) Tampa International Airport intersection failure scenario; (b) S. I-75 Freeway bridge failure scenario

affected infrastructure, which are (1) complete failure, and (2) partial capacity reduction, and infrastructure closer to the coast are more likely to be failed and otherwise is more likely to get a partial capacity reduction. For simplicity, half capacity is reduced if one infrastructure receives partial capacity reduction. In order to duplicate the worst-case scenario, a scenario with all the 14 infrastructure failure is also proposed. The transportation model is run for each scenario (Table 2), and origin importance and destination attractiveness factors as well as travel time are updated in the accessibility index. The accessibility value under each scenario is then calculated (Table 2). There is a great network-wide accessibility reduction if all the affected infrastructures are failed as demonstrated in Scenario G. Scenario E, including two bridge failures, is the second critical infrastructure scenario following Scenario G. Scenarios with bridge failure or important intersection capacity reduction such as Scenarios D or B also show great criticality. The prioritization of the criticality of the proposed scenarios is shown (Table 2). However, segment failure or capacity reduction becomes less important especially in the rural area as shown in Scenarios A and F. A general conclusion from these results is that bridge failure causes more network-wide accessibility reduction than capacity reduction of arterial road segment or major intersection and road segment failure or capacity reduction in the rural area is less critical than in the urban area. As a result, under the threat of flood risk bridges are more important than major road segments and road segments in the urban area are more critical than in the rural area.

Conclusions

It is important to understand the criticality of transportation infrastructure which will affect the investment decision making and infrastructure maintenance priority in the future. The criticality prioritization of transportation infrastructure in coastal areas can be more urgent because of the challenges posed by coastal flooding as a result of climate change. This paper provides a network-based methodology prioritizing the criticality of transportation infrastructure. Based on a location-based accessibility index, the methodology can capture the criticality of transportation infrastructure. Besides, the most vulnerable zones in a specific infrastructure failure scenario are also identified. Criticality prioritization of multiple infrastructure failure or capacity reduction at the same time is also demonstrated and discussed. The results of this paper can better inform decision makers in coastal areas of the transportation infrastructure maintenance and retrofitting plan especially for facilities vulnerable to flood risk. Better information will also be given to transportation planners and engineers about the most critical infrastructure and vulnerable zones so that more robust coastal transportation infrastructure and network are designed and constructed. The proposed accessibility index could also be applied to situations such as traffic congestion, traffic accident, and terrorist attack to evaluate the network-wide impacts and identify critical infrastructure.

This paper is not without its limitations. First, considering water intrusion, the impacts of coastal flooding will be broader and more transportation facilities will be affected in the flooding scenario proposed in the paper. Second, this paper addressed the worst-case scenario by assuming that once affected by flood the transportation infrastructure is completely inaccessible; however, in some cases the infrastructure can still be partially accessible. Based on the analyses of this paper, if the infrastructure is affected to the same degree, the criticality prioritization result should be the same as that of the completely inaccessible case. However, when the affected infrastructure is degraded to different degrees, for example, some is partially accessible and some is completely interdicted, the prioritization result might be different and should be reevaluated with the proposed methodology. Third, the research reported in this paper considers centroid connectors as the road network inside a TAZ and the roads inside a TAZ may serve as potential detours in case of flooding. Finally, if flood is caused by heavy precipitation, the duration of the flood should be addressed, as the infrastructure at risk and the criticality may change for different duration periods of the flood. These limitations should be addressed as extensions of this paper in the follow-up study.

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