

# Vulnerability Analysis of Transportation Network under Scenarios of Sea-level Rise

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**ABSTRACT**

Climate change is increasingly attracting attention from transportation planners, engineers and decision makers. As a result of climate change, sea-level rise is rapidly becoming a major concern, especially for coastal regions. This paper develops an accessibility-based transportation network vulnerability analysis process which is used to quantify network-wide vulnerability and identify the most vulnerable regions under different sea-level rise scenarios. The accessibility reduction rate before and after inundation is calculated to measure the potential consequences. The probability of different sea-level rise scenarios together with the overall accessibility reduction contributes to the overall transportation network vulnerability. Most notably, the traffic analysis zones with the most accessibility reduction are considered the most vulnerable areas. This methodology is applied to south Miami road network under two different sea-level rise scenarios for the year 2060. We estimated the extent of road network vulnerability and accessibility reduction of individual traffic analysis zones for two scenarios. The results show that there is almost 100 percent accessibility reduction for traffic analysis zones with all roads inundated and as high as 30 percent accessibility reduction in zones with some or no road directly affected. This information can help local transportation planners, engineers and decision makers identify the most vulnerable areas and transportation facilities as a result of sea-level rise, in order to make better and more informed decisions about adaptation planning and retrofitting.

**KEYWORDS:** Transportation network, Vulnerability analysis, Accessibility, Sea-level rise, Climate change

## 1. INTRODUCTION

Climate change appears to negatively affect sustainable development, with adverse effects tending to increase with higher levels of Greenhouse Gases (GHGs) concentrations (1). The Transportation Research Board (TRB) recently released a special report discussing the impacts of climate change on the United States (US) Transportation network (2). In the report, five climate changes are discussed as particularly important to transportation in the US, including rising sea levels. Sea levels will continue to rise in the 21st century with an occurrence probability of greater than 99 percent (2). As transportation planners and engineers, it is important to understand what the impacts of climate change on transportation network are and know how to quantify these impacts, so as to make better decisions in the transportation planning and engineering processes.

Transportation network vulnerability analysis measures the impacts of disasters on the transportation network system and identifies the most vulnerable areas and important links. Through network vulnerability analysis, the most vulnerable regions and road segments can be ascertained under several scenarios. Then, proactive transportation planning and engineering measures can be taken to address issues in the most vulnerable areas and road segments as precautionary measures. As climate change become a more important issue in the transportation world, transportation network vulnerability analysis can be incorporated into transportation planning and engineering processes to make more accurate adaptations to climate changes and improve the network performance.

A related concept with network vulnerability is network reliability. Transportation network reliability addresses the probability of the network fulfilling its normal functions. Network vulnerability is a combination of probability and consequence that is closely related to both risk and reliability. The vulnerability of a network can be a more important indicator than reliability, because of the potentially severe adverse consequences of network degradation (3). However, as the Transportation Research Board (TRB) Special Report 290 states, “the vulnerability of the transportation sector to climate change impacts has not been thoroughly studied, nor has it been widely considered by transportation planners and decision makers in planning, designing, constructing, retrofitting, and operating the transportation infrastructure” (2). To date, no consensus has been reached as to the definition of transportation system vulnerability, nor with the methodologies that address it.

This paper proposes a methodology to measure transportation network vulnerability and uses the highway network in the south Miami as a study area. This study seeks to quantify the extent of transportation system vulnerability and ascertain which areas of south Miami are most threatened by sea-level rise (SLR). The paper will start with a comprehensive literature review to understand the state of art of the transportation network vulnerability study.

## 2. LITERATURE REVIEW

The concept of transportation network vulnerability entered the research field more than a decade ago, following the Kobe earthquake in 1995 (4). Transportation network vulnerability studies have been the focus of increased attention (3, 5, 6, 7, and 8) sparked by the events of September 11, 2001. However, there is no commonly accepted definition of transportation

network vulnerability, and methodologies adopted by researchers can fall into several kinds. This section presents studies on the definition of transportation network vulnerability, methodologies, and applications.

## 2.1 Definition of Transportation Network Vulnerability

There are many possible definitions of what vulnerability could and does mean. The most cited definition of transportation network vulnerability is given by Berdica, who describes vulnerability in the road transportation system as susceptibility to incidents that can result in considerable reductions in road network serviceability (3). Berdica argues that by studying transportation network vulnerability from an accessibility point of view, the emphasis should be put on the function of the whole system, rather than the physical network itself. This addresses concerns regarding the perspective of probability and the consequence of risks. Berdica also demonstrates that events with low levels of probability but high levels of consequence are often omitted by previous studies, and a very important aspect of vulnerability study is to minimize the consequence of a risk since the probability is not always suitable to address. Therefore, vulnerability involves events that have a low probability of occurrence, but high consequences.

There are other discussions about the definition of transportation network vulnerability. Taylor and D'Este divide network vulnerability into two types: network node and network link vulnerability (9). As measured by a standard accessibility index, a network node is vulnerable if loss of a small number of links significantly diminishes the accessibility of the node, and a network link is critical if loss of the link significantly diminishes the accessibility of the network or of particular nodes (10). Jenelius et al. argue that vulnerability is related to the concept of risk and could be treated in the same way as risk consisting of two aspects: probability and consequence (7). They do not provide a specific definition of road network vulnerability, but the concept used in the study is a combination of both the probability of occurrence and potential consequences. Husdal defines vulnerability as the non-operability of the network under certain circumstances and reliability as the operability of the network under varying strenuous conditions (11). Erath and Axhausen introduce the definition of vulnerability as the probability of inadequate performance and the related consequences: direct consequence and indirect consequence (12). These discussions also indicate that the probability and consequence are commonly considered in the definition of transportation network vulnerability.

Vulnerability relates to the susceptibility of transportation system and consequences of events. This is something most scholars agree upon. Many definitions of vulnerability focus on the consequences and identifying the criticality of different road sections. As of yet, there is also no quantitative explanation defining network vulnerability. Consequently, the definition of transportation network vulnerability has not yet been well addressed or interpreted.

## 2.2 Methodologies for Transportation Network Vulnerability Analysis

Road network vulnerability definitions are often discussed from the perspective of accessibility, as the basic purpose of building a highway network is to improve accessibility and mobility to travelers. Accessibility is a fundamental concept in transportation analysis

and planning (13). It is already used as a system performance measure in the disaster content (14). Taylor and D'Este state that for the case of large scale networks, such as regional or national highway networks, relatively simple indices are appropriate (4). Many other accessibility indices are used in previous studies as a basis of transportation network vulnerability measurement (6, 14, and 15). Taylor et al. compare three different accessibility measures which are generalized travel cost utility function, the Hansen integral accessibility index, and the accessibility/remoteness index of Australia (ARIA) developed by Australian Department of Health and Aged Cared (16). These three indices are used to study the network vulnerability at the Australian national highway network level and identify the critical links of the network. There are also new indices created for vulnerability analysis. Sohn develops an accessibility approach evaluating the significance of highway network links under flood risk (14). The accessibility index is composed of a population weighted travel distance and traffic volume. The importance of links is prioritized based on changes of the accessibility value. Chang and Nojima propose three performances measuring transportation networks in reaction to the 1995 Kobe earthquake: total length of network open (measure L), total distance-based accessibility (measure D), and areal distance-based accessibility (measure Ds) (17). The purpose of using this method is to measure the shortest travel distance reduction rate before and after the earthquake for all the OD pairs at the whole transportation network level. An accessibility-based method takes population, distance, and traffic volumes into account and is therefore capable of capturing the regional and traffic characteristics in the analysis.

Yet another type of transportation network vulnerability analysis is the importance-exposure method. Based on Nicholson and Du, who describe link weak and importance concepts (18), Jenelius et al. introduce the concepts of link importance, site exposure and criticality (7). If a link is both weak and important, it becomes a critical link in the greater system. The link's importance and site exposure indices are derived based on generalized travel cost, which serves as a measure of the consequence of failure. However, in their study, much attention is paid to the consequence of link failure, and the susceptibility of the network is not addressed. Jenelius proposes aggregate supply-side and demand-side indicators and incorporates them into a statistical regression model (19). The supply-side variables are link redundancy, network scale, road density, and population density, while the demand-side variables are user travel time and traffic flow. As a similar study, Scott et al. also present a link importance measurement with the name of network robustness index and test the methodology using traffic equilibrium assignment (20). The concept of link importance and exposure is good but the probability of network failure has not been made clear in the corresponding methodologies.

These are only some of the methodologies that have been used in transportation network vulnerability analyses. Others include game theory, used by Bell et al. (8) and so on.

### 2.3 Applications of Transportation Network Vulnerability Analysis

As a proactive method of transportation systems analysis, transportation vulnerability analysis is used to evaluate performance changes in the network before and after network degradation. The impacts on the network can then be quantified. Network performance changes with the failure of each link. For example, if one link fails and leads to the greatest

reduction in network performance, the link is considered the most important link. Taylor and D'Este conducted a network vulnerability analysis on the Australian national highway network, and four vulnerable highway links are indentified as critical road sections which caused significant percent of accessibility decreases for big cities of Australia (4). Sohn develops an accessibility-based highway network vulnerability analysis method evaluating the significance of highway network links under flooding risk (14). He not only finds out the accessibility reduction rate of each link of the Maryland highway network, but also gives the accessibility decrease of each county in the study area. Chen et al. incorporate vulnerability analysis into the traditional four-step transportation planning process in order to find the quantitative impacts of abrupt events and the most vulnerable part of the network (6). They also make comparisons between including the vulnerability analysis in the four-step travel decision making process, and in just one step of the process. They suggest that applying vulnerability analysis in all the four steps makes more sense than just in only one of the steps. Based on an importance-exposure based network vulnerability analysis method, Jenelius et al. determine the importance of each link on the Swedish highway network, and the exposure of each region in Sweden. Bell et al. use an attacker-defender game theory model to find out critical links based on the distance of detours made if one link is disrupted (8). So, network vulnerability analysis is usually used to identify critical road segments under disasters.

With so many applications, transportation network vulnerability plays an important role in network evaluation especially threatened by global climate change. However, the network vulnerability is neither well defined nor studied in the literatures. The methodologies used are not particularly developed for network vulnerability study. Based on current studies, the paper starts discussion with the proposed definition of transportation network vulnerability followed by a vulnerability index-based network vulnerability analysis methodology in the next section.

### 3. TRANSPORTATION NETWORK VULNERABILITY ANALYSIS

#### 3.1 Definition of Transportation Network Vulnerability

There are a few ways in which transportation network vulnerability can be understood (3, 5, and 7). Most agree that a vulnerability study includes analyzing the consequences of an event on the entire transportation system. Both natural and manmade events are considered. A concept of system inability is proposed serving as a measurement of consequence on system. Meanwhile, the occurrence probability of such kind of consequence should also be included in the study, as there is no incident occurring for sure in the future especially for events as a result of climate change. Therefore, transportation network vulnerability involves a combination of both the probability and consequence of an event occurring.

Based on the literature review and discussion above, for the purposes of this study, transportation system vulnerability is defined as *the susceptibility and degree of inability of transportation systems to resist to natural or manmade incidents*. There are two aspects of to this definition: susceptibility to incidents and degree of inability caused to the transportation system. The susceptibility of transportation systems to a certain event refers to the probability of a certain consequence resulted from this event. For example, the susceptibility of transportation systems to a storm surge involves the probability the storm surge, along with

the probability of the consequences of a storm surge. Here, the consequences on the transportation systems vary by the land fall location and direction of a storm surge. If there is only one possible consequence, the susceptibility should be equal to the probability of the event, such as sea-level rise. When there are several possible consequences of a storm surge, the probability of one consequence equals to the product of probability of storm surge and probability of the consequence among all the possible consequences. The other constitution of vulnerability definition is the system inability. The definition should be a quantitative measurement of the degree of inability of transportation system to resist to natural or manmade events, which is discussed in more detail as follows.

### 3.2 Accessibility-based Transportation Vulnerability Analysis Method

Accessibility is already used as a system performance measurement in natural disaster analysis. Because of the strong role accessibility plays in transportation, it has been the subject of many studies. However, previous accessibility indices, such as Hansen integral accessibility index (4), only consider location attractiveness, and the accessibility value cannot deliver better information to readers. Rather, it considers only the attractiveness of other cities, and people have no idea about the accessibility changes without comparison. Additionally, when using different units of travel cost such as hours, minutes, or dollars, the value of accessibility is different. In order to improve the accessibility index, this study proposes an accessibility index for network vulnerability analysis.

$$A_i = w_i^p \sum_{j=1}^{n-1} w_j^r \left( \frac{f(t_{ij})}{f^0(t_{ij})} \right)^{-\alpha} \quad (i \neq j) \quad (1)$$

where,

$A_i$  accessibility of zone  $i$ ;

$w_i^p$  population weight of zone  $i$  which equals to the ratio of population in zone  $i$  over all the population in the study area;

$w_j^r$  weight of residence in zone  $j$  which equals to the ratio of residence in zone  $j$  over all the residence in the study area except for residence in zone  $i$ ;

$f^0(t_{ij})$  original travel cost between region  $i$  and  $j$  without network degradation;

$f(t_{ij})$  travel cost between region  $i$  and  $j$  after network degradation;

$\alpha$  travel cost decay parameter ( $\alpha > 0$ );

$n$  number of zones in the study area.

Equation (1) is a location-based accessibility index, calculated based on each location or traffic analysis zone (TAZ). The ratio of population including residence and employment in a destination zone over all the population in the study area is used to reflect the destination attractiveness of this zone. If the ratio is very high for the destination zone, i.e. there are more people in this zone, and then communications between this zone and others is greater; if it has

a low ratio, then the interactions between this zone and others will be less. The larger the ratio of a zone is, 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 assigned to each origin zone, which is the ratio of the residence in this zone over all the residences of the origin zones, except the destination zone. The more residence in the origin zone, the more communications made by this zone with attracting zones. Finally, the ratio of travel cost before and after the degradation is used to modify the zone importance factor.

This process must also include a travel cost decay factor,  $\alpha$ , which adjusts the travel cost ratio. The travel cost decay factor is calibrated from a simple gravity model based on traffic flow data. If there is a travel cost increase between the two zones, the ratio will be less than one, and therefore the accessibility results will fall. The ratio becomes zero on condition that there is no route connecting all the other zones. The reason using population and residence ratio as attractiveness and importance weight factors is that it can end up the overall accessibility of all the zones with one. If there is degradation to the network, the overall accessibility will be less than one. This methodology provides a way to better understand the accessibility reduction comparing to the original accessibility of one.

The advantage of the proposed accessibility index is that it incorporates the origin importance and destination attractiveness, and makes the overall accessibility equal to one. It can show not only the quantitative impact of segment failure on the network, but also find the most vulnerable areas. Besides, it captures the congestion on road segments as a result of link failures.

The degree of transportation network degradation is formulated based on the accessibility reduction before and after network degradation.

$$DD^l = \sum_{i=1}^n A_i^0 - \sum_{i=1}^n A_i^l \quad (2)$$

where,

$DD^l$  degree of network degradation if link (or link set)  $l$  is failed;

$A_i^0$  accessibility of zone  $i$  without network degradation; and

$A_i^l$  accessibility of zone  $i$  if link  $l$  is failed.

The accessibility index measures the accessibility of an individual zone within the study area. If there is a reduction in accessibility for any zone in the study area, the transportation network will be degraded either by link failure or congestion, measured by the proposed accessibility index. This methodology is able to measure transportation system performance indirectly from the accessibility of the zones served by the transportation network.

As a result of this process, special attention can be paid to the individual zones which have the greatest accessibility reductions. The accessibility reduction ratio for each zone is calculated based on the accessibility index in equation (1), for both before and after the failure of link (or link set)  $l$ .

$$ARR_i^l = \frac{A_i^0 - A_i^l}{A_i^0} \quad (3)$$

where,

$ARR_i^l$  accessibility reduction ratio of zone  $i$  with the failure of link (or link set)  $l$ .

The accessibility reduction for individual zones is captured by equation (3). This allows for those zones that are most vulnerable to network degradation to be identified.

As discussed above, transportation network vulnerability includes the susceptibility and consequences of both natural and manmade events. Here, the susceptibility is the production of the probability of the events and the probability of consequences. Consequences are calculated by the system accessibility reduction. Then, the transportation system vulnerability index is formulated as below.

$$V_d = prob_d \times DD^l \quad (4)$$

where,

$V_d$  vulnerability of the network with the network degradation probability  $d$ ; and

$prob_d$  probability of network degradation  $d$ .

In order to apply the above vulnerability analysis process, links directly affected by an event should be identified first, a process known as impact analysis. The impact analysis for sea-level rise is conducted in Section 4.

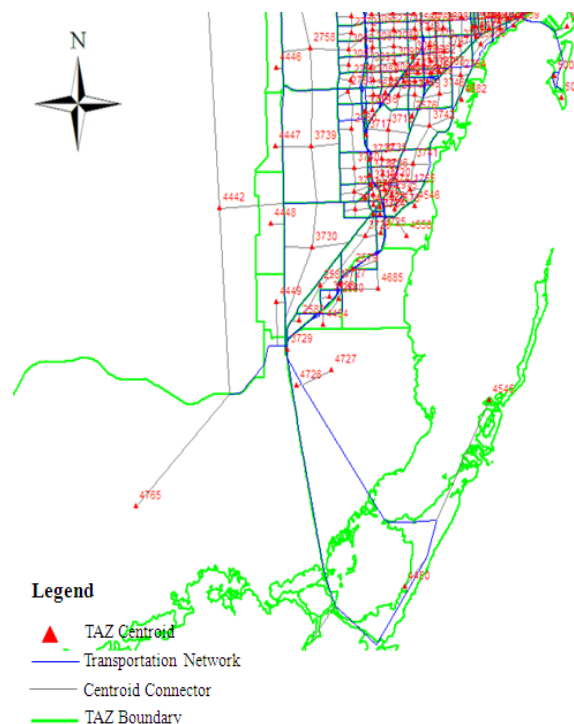
#### 4. SEA-LEVEL RISE IMPACT ANALYSIS

The south Miami area, illustrated in Figure 1, is the study area for this work. Miami is among the world's top ten most vulnerable coastal cities (21). Miami is on a low-lying area, and south Miami has a relatively low elevation and sparse road network, making the transportation system especially vulnerable. This area experienced an average sea-level rise rate of about 1.5 inches per century over the past 2,500 years, but about a one foot rise per century since 1932 (22). The Intergovernmental Panel on Climate Change (IPCC) estimates a somewhat low range of 7-23 inches global sea-level rise by the end of this century (1). With global climate change, the sea-level rise rate either observed or projected is accelerating in the study area and as a result it becomes much more vulnerable than ever before.

As a result, many sea-level rise projections are made related to this area. The Miami-Dade County Climate Change Task Force projects an additional three to five feet of global sea-level rise over this century (22). In a study conducted by the Federal Highway Administration (FHWA), sea-level rise increases of two to four feet over the next 50 to 100 years is projected for Gulf of Mexico as a result of global temperature increase and land subsidence (23, 24). A conservative projection of the rates of sea-level rise in Florida indicates the increases in sea level between the years 2006 and 2080 range from 0.25 meters to 0.35 meters (25). A United States Global Climate Research Program study suggests that by 2100, there will be a 0.5 meter increase in sea level at Miami Beach (26). The target year for this impact analysis is 2060, which coincides with the 2060 Florida Transportation Plan.

Average sea-level rise rates of each year suggested by Federal Highway Administration and US Global Change Research Program are used to calculate for the year 2060, as these two projections are especially for Miami Beach and transportation use. As a result, the sea-level rise information for the two projections is shown in Table 1.

In order to analyze the potential impacts of sea-level rise in this area, the data has been collected as follows. The transportation network information for south Miami was obtained from the Florida Statewide Model (FLSWM) of the Florida Standard Urban and Transportation Model Structure (FSUTMS). The model provides detailed information about each link of the transportation network in the FSUTMS model, including length of the segment, number of lanes, and the capacity of the link. As shown in Figure 1, there are a total of 130 TAZs for the study region in the FSUTMS model, including four island TAZs. Light Detection and Ranging (LiDAR) data for the Miami coastal region was collected from the National Oceanic and Atmospheric Administration (NOAA). This has been used to generate sea-level rise inundation maps. The LiDAR data has an elevation accuracy of better than 30 centimeters at a 95 percent confidence level.

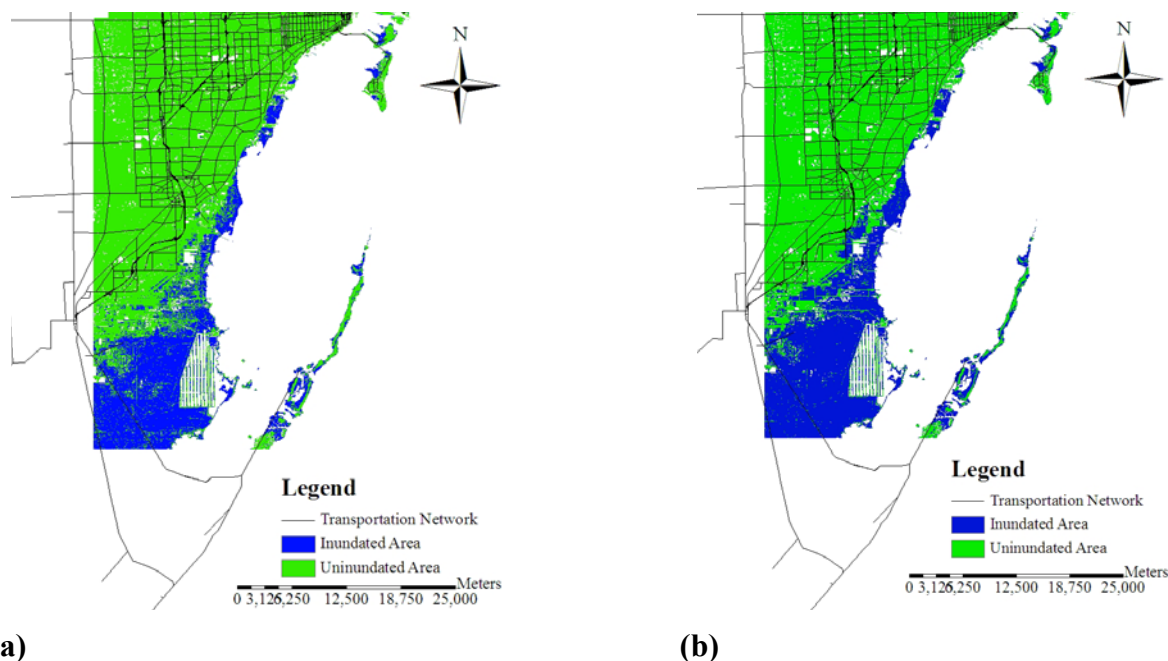


**FIGURE 1 TAZ distribution of south Miami area.**

Based on the two sea-level rise scenarios found in Table 1, the sea-level rise impact analysis is processed in ArcGIS. Within the software, inundation maps are generated using LiDAR data. Then, the transportation network is overlaid with the inundation maps. Road links in the inundation area are indentified. For the sake of simplicity, only road segments in the inundation area are considered for failure, although more segments will be affected because of shore recession, storm surge, and erosion. The inundation areas and affected road segments in the two sea-level rise scenarios are shown in Figure 2 (a) and (b).

As shown in Figure 2, the south-most area of south Miami has relatively low elevation, which will be inundated either by scenario 0.3 or 0.6 meter sea-level rise. The coastal area and the islands in the Miami area are particularly susceptible to sea-level rise. So

the vulnerable road segments lies in the south part, coastal area, and the three islands of the study area, and there are more segments affected by the 0.6 meter sea-level rise in the south-middle part of the area.



**FIGURE 2 Inundation maps of two sea-level rise scenarios.**

**(a) Inundation map of 0.3m meter SLR.**

**(b) Inundation map of 0.6m meter SLR.**

## 5. RESULTS AND DISCUSSION

The transportation network vulnerability methodology has been tested in the south Miami area. As there is no actual road network representation but centroid connectors in the FSUTMS model in Cube software, the travel within each TAZ is not considered. The travel cost in equation (1) is set to be the shortest travel time between TAZs, which are computed from the FSUTMS model. The shortest travel time is considered to be the shortest driving time, and other traffic modes are not taken into account, because of the limitation of the FSUTMS model. Based on a shortest routes finding algorithm, the alternative shortest paths are found after the degradation of the transportation network. The degraded shortest travel time is then calculated based on the alternative shortest paths and traffic volumes on that path. The travel cost decay factor  $\alpha$  is assumed to be one, which means that the travel time has a direct relationship with the accessibility. The FSUTMS model was run with its original data to find the base shortest travel time between TAZs. Afterwards, the model with the two sets of sea-level rise inundation scenarios is run. The calculation methodology of the overall accessibility and accessibility of each TAZ is coded in Matlab, which outputs the vulnerability analysis results. The results for transportation network vulnerability for the south Miami area under two sea-level rise scenarios are shown in Table 1.

The results of the study show that there is little difference between the road segments affected in the two scenarios. This is largely because the south part of the study area has a relative low elevation, and can be easily inundated by 0.3 meter sea-level rise, but would not be affected that much by 0.6 meter sea-level rise. There is a little increase in the total travel

time increase on unaffected segments in 0.6 meter sea-level rise scenario, as three segments of major arterials and one centroid connector are inundated by this scenario. The Hansen accessibility is higher than the original case without degradation, which does not logically follow predictions. The number is huge for Hansen accessibility changes, and people have no idea of the actual meaning of the number.

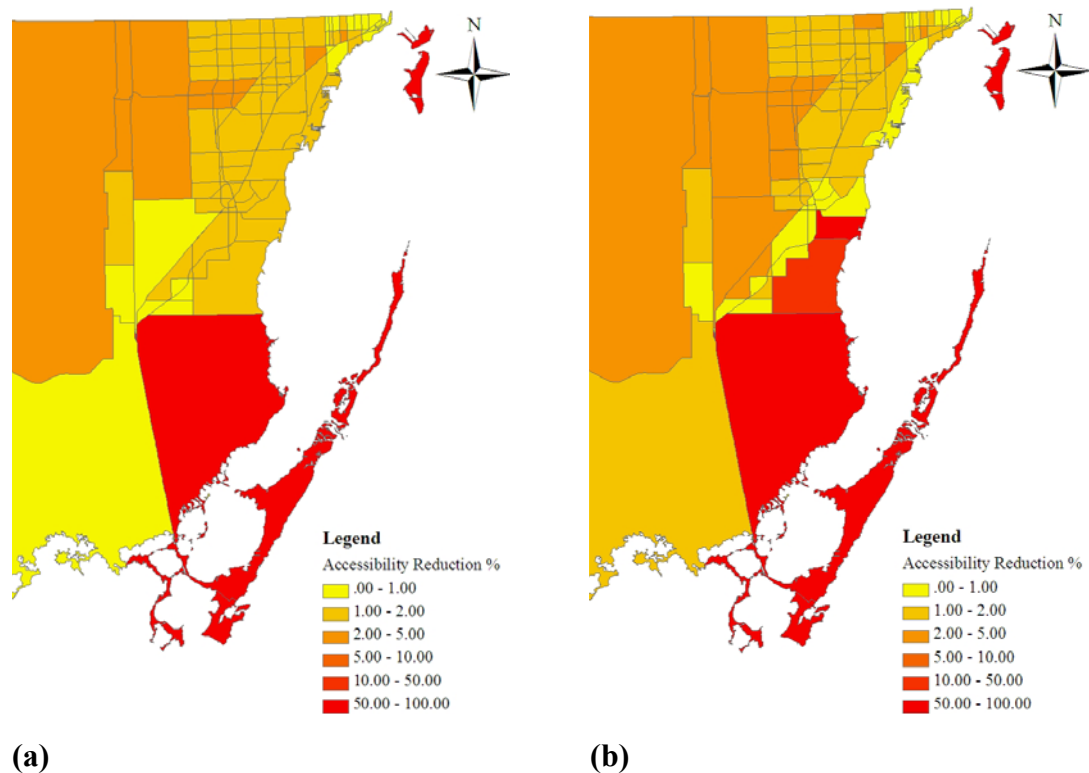
The susceptibility in this study is the probability of sea-level rise, and consequence is the overall reduction in accessibility to the region. However, there is no probability forecasted for the two sea-level rise scenarios in literatures which is usually the case for most of the sea-level rise projections. Although there is only one sea-level rise projection in each literature, it doesn't mean each of them has a 100 percent probability. Therefore, we assume two probability scenarios for each sea-level rise scenario. One probability scenario is 95 percent for each, which is the 95 percent confidence level like those often used statistical calculations. The other probability scenario is 95 percent for 0.3 meter sea-level rise and 50 percent for 0.6 meter sea-level rise. As shown in Table 1, the overall accessibility reduction of 0.6 meter sea-level rise is just a little higher than that of the 0.3 meter sea-level rise. The degree of network vulnerability in the first probability scenario follows this progression. But in the other probability scenario the 0.6 meter sea-level rise scenario gains much lower network vulnerability than 0.3 meter sea-level rise. So, as shown in Equation (4) the probability also plays an important role in the vulnerability value.

**TABLE1 Transportation Network Vulnerability of Two Scenarios**

SLR scenario (m)	SLR probability (%)	Number of road segments inundated	Increase in total travel time (h)	Hansen accessibility reduction	Overall accessibility reduction	Vulnerability (%)
0.3	95	13	147.31	-115403.74	0.0413	3.92
0.6	95	17	205.14	-253104.63	0.0453	4.30
0.3	95	13	147.31	-115403.74	0.0413	3.92
0.6	50	17	205.14	-253104.63	0.0453	2.27

Large areas of the south part of the region will be inundated under both scenarios, as shown in Figure 2, but the overall accessibility reduction is relatively low, as is the network vulnerability. This is because the most south part of Miami is located away from the main downtown area and also has a smaller population than the north part. This methodology favors areas of greater population over smaller ones. As described in the accessibility index, the focus of the index is people rather than the area of inundated land. The proposed methodology and data analysis results quantify the definition of transportation network vulnerability given in Section 3 and offer quantitative results of network vulnerability.

Following Equation (3), the accessibility reduction rate of each TAZ under the two sea-level rise scenarios is shown in Figure 3. The accessibility changing tendencies are similar for both sea-level rise scenarios. The TAZ-based accessibility reductions for the two scenarios show high values for the southeast part of the study area. When compared with the 0.3 meter sea-level rise scenario in Figure 3 (a), the 0.6 meter sea-level rise scenario in Figure 3 (b) shows more accessibility reductions in the inland middle and eastern sections of the area.



**FIGURE 3 Accessibility reduction rate of individual TAZ under two scenarios.**

**(a) Accessibility reduction rate under 0.3 meter SLR.**

**(b) Accessibility reduction rate under 0.6 meter SLR.**

**TABLE 2 Accessibility Changes of TAZs (Selected)**

TAZ number	Population	Accessibility reduction rate (%)		Change rate of the two scenarios (%)
		0.3 m SLR	0.6 m SLR	
2548	23456	1.86	1.94	0.08
2575	4997	2.18	2.40	0.22
2580	9	0.95	1.37	0.42
2581	23781	1.79	2.17	0.38
2760	38319	1.84	2.34	0.51
2765	15348	2.15	2.36	0.21
3444	18942	0.33	0.75	0.42
3689	12989	2.20	2.43	0.23
3715	2428	1.57	2.24	0.68
3716	8782	1.57	2.16	0.59
3717	1187	1.62	2.17	0.55
3721	8822	1.49	1.64	0.16
3739	115819	2.26	2.55	0.29
3740	10657	1.83	2.27	0.44
4450	3219	99.06	99.06	0
4451	4426	99.20	99.20	0
4545	70	98.92	98.92	0
4558	3389	1.42	99.63	98.21

<b>4606</b>	8	99.23	99.23	0
<b>4685</b>	4915	1.61	18.73	17.12
<b>4727</b>	11525	99.33	99.33	0
<b>5002</b>	16272	99.36	99.36	0
<b>5003</b>	862	99.47	99.47	0
<b>5006</b>	862	98.18	98.18	0

The TAZs that are of particular accessibility reduction rate are shown in Table 2. According to the results, TAZs such as 4545, 4606, 4727, 5002, 5003 and 5006 in the south part of the study area have the greatest accessibility reduction rate under both sea-level rise scenarios. Roads in these TAZs will be almost completely submerged under both scenarios, so the difference of the accessibility change for the two scenarios is zero for these TAZs. TAZs 4558 and 4685 have a little accessibility reduction under 0.3 meter sea-level rise, but a much greater accessibility reduction under the 0.6 meter sea-level rise scenario. The reason for the significant accessibility difference is that part or almost all the roads in these areas are inundated in the 0.6 meter sea-level rise but not in the 0.3 meter sea-level rise. Therefore, the accessibility index can capture road failure in the form of significant accessibility change. Those TAZs which are most inland have the least accessibility reduction. The shortest travel time increase in these areas also reduces their accessibility which is captured by the accessibility index. Besides, population plays an important role in the accessibility change. For example, inland TAZs 2548, 2581, 2760, 3444, 3689, 3739 and 3740 which have relatively large populations receive more accessibility reduction. Other TAZs such as 2580 also have some accessibility reduction although there is less population for them. This is because TAZ 2580 is partially affected by 0.6 meter sea-level rise. So, the accessibility index could tell different characteristics of TAZs which are indicated in the accessibility values.

The results of transportation network vulnerability analysis provide transportation planners and engineers a means by which to quantitatively analyze the impacts of 0.3 meter and 0.6 meter sea-level rise scenarios on the south Miami transportation network. Proper transportation adaptation strategies can then be implemented to individual TAZs, using the vulnerability analysis results. Shore protection or managed withdrawal measures could be taken to TAZs such as 4545, 4606, 4727, 5002, 5003, and 5006 which have almost 100 percent accessibility reduction. Transportation network retrofitting plans such as building redundancy roads and road protection may be made to TAZs 4558 and 4685 which would be partly inundated by 0.6 meter sea-level rise. Road widen and effective demand management could be applied in TAZs 2548, 2581, 2760, 3444, 3739 and 3740 which have large population and receive more affections from shortest travel time increase.

## 6. CONCLUSIONS

This work conducts a transportation network vulnerability analysis to quantify the impacts of sea-level rise on the road network, identifying the most vulnerable areas. A transportation network vulnerability index is proposed to evaluate the degree of network vulnerability. The methodology used in this study captures the influence of travel time increases as a result of inundated links. This work can also be used to prioritize critical road segment investments, by studying the rate of the overall accessibility reduction.

Following the proposed definition of transportation network vulnerability, the study

provides quantitative results to the degrees of network vulnerability and the prioritization of the vulnerability of traffic analysis zones, which have not yet been reported in other studies. These results can be used by transportation planners and engineers to identify the most vulnerable areas and network links, so that different adaptations strategies can be adopted in order to mitigate potential impacts of climate change and built a more robust transportation network.

There are some limitations in the analysis in this paper. First, only road segments in the inundation area are considered to be affected by sea-level rise. If storm surges, shore line recession, sea water soakage, or erosion were also considered, the impact of sea-level rise on road network would be even greater. Second, not all the transportation networks are considered in the analysis because of network limitations in the FSUTMS model. Local streets inside the TAZ which could be potential detours have been replaced by centroid connectors. Then, the resident and employment distribution and travel pattern will be different from what they are before sea-level rise inundation which is not considered in the case study. Finally, the accessibility index uses population as a key factor; therefore, if there are no people living or working in an area, the accessibility of this area is zero. This does not represent all places, including public parks, lakes, and so on. These limitations, as well as cost-benefit analysis of sea-level rise and adaptation strategies, should be developed in a follow-up study.

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