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Enhancing Resilience of Transportation Networks: A Topological Analysis of Extreme Climatic Events

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ABSTRACT

In light of the escalating frequency and intensity of extreme climatic events, evaluating and improving the resilience of transportation networks has become paramount for sustainable infrastructure development. This investigation presents a comprehensive methodology to assess network resilience and compare measures across different systems, considering both existing and upgraded infrastructure. The current prevailing uncertainty surrounding extreme climatic events often compels transportation agencies to resort to over-engineered designs or, regrettably, to disregard necessary preparations due to the exorbitant costs associated with potential hazards. However, armed with pertinent data derived from this study, decision-makers and legislators can make informed choices in allocating resources efficiently to critical locations, thereby enabling a more feasible and well-considered response to climatic hazards. By leveraging hurricane storm surge simulation results, transportation agencies can accurately identify the most critical network components responsible for maintaining seamless network flow. Rather than undertaking a complete and expensive system overhaul, agencies can now prioritize targeted replacements and structural updates with ease. Furthermore, this approach facilitates the identification of network nodes that are most vulnerable to specific hazards, enabling planners to incorporate these vulnerabilities into long-term planning strategies. The research underscores the effectiveness of utilizing topological graph properties to track network response, making it a valuable tool for investigations into the resilience of transportation networks. By examining the nodes most impacted by the envelope simulation, planners can develop strategies that integrate and mitigate these vulnerabilities, thereby enhancing the overall resilience of the transportation system.

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I. INTRODUCTION

Resilience is an indicator of the preparedness and adaptability of a civil infrastructure system; itis useful to a range of management teams such as policy makers, engineers and emergency service workers. Civil infrastructure systems, such as transportation networks, power transmission systems and water distribution networks, constitute the backbone of a functioning society and affect entire populations if disrupted. The importance of resilience in networks has grown parallel to the increasing traffic volumes traveling highways and roads, and the continued construction of urban and suburban areas, trends that will continue well into the future. Additionally, there is a lack of long-term investment to elongate, if not simply guarantee, the lifespan of current infrastructure systems. With more vehicles on the roads, and the increase of truck loads, the consequences and delays resulting from a seemingly minor accident or failure can propagate through the system over a wide radius (FHWA, 2010); a developed area will suffer greater economic damage from an extreme event than a more rural region. Infrastructure resilience can be improved after assessing its current state, thereby reducing the vulnerability of civil infrastructure networks to disruptions and extreme events, allowing plans for possible failures, flexibility during probable disruptions, and post-event response and eventual repairs. These components correspond to the preparedness, absorptiveness, adaptation, and recovery of a resilient infrastructure system. This can be done by analyzing the resilience of the infrastructure system, allowing a holistic approach that takes into account several different aspects to improve the network's overall performance against disturbances.

II. Literature Review

Holme et al. (2002) brought about an important point regarding network topology that challenged the accepted significance of node degree with respect to resilience measurement. While nodes with the highest degrees are vital, nodes with small degrees may connect two important clusters of a network, acting as bridges. These should not be overlooked in evaluating resilience and how node removal will affect the average shortest path value. Especially relevant for targeted attacks, node betweenness provides a measurement on which nodes can be ranked by importance in the network. From this logic, the relevance of measures of betweenness centrality has evolved. Betweenness centrality, like degree, is specific to each node and depends on the number of shortest paths within the network which travel through the considered node. Goh et al.(2002) showed that the distribution of betweenness centrality in scale-free networks follows a power law. One would expect that the nodes with the most degrees have the highest betweenness. Zio and Sansavini (2011b) employ betweenness measures to the maximum load which can be distributed by a node in a power network, constantly comparing the value to the component capacity. Although, in every network, there is a correlation between node degree and betweenness centrality, there are sometimes low-degree nodes which have the largest betweenness centrality. This is proven by plotting the correlation between degree and betweenness across several network models.

Scott et al. (2005) found the same pattern from another similar measure, network robustness index. The greatest difference between network robustness index and capacity is in networks with low connectivity. The difference in ranking nodes based on degree and ranking based on betweenness may explain the difference in response to targeted and random attacks. Initial betweenness-based removal of nodes is IB removal and the recalculated removal is RB removal. Generally, Scott et al. (2005) found attacks based on the nodal degree are local while those based on betweenness are global, resulting in more inefficient algorithms.

Redundancy, a critical part of network resiliency, depends on the availability of alternative paths to traverse from one node to another. Duenas-Osorio et al. (2005) uses the number of paths between a node and the neighborhood of its neighborhood to calculate the node's redundancy within a graph:

$$R_{Rv} = \frac{1}{(|S|-1)^2} \sum_{j \in (\Gamma v 2)} I(v,\ j) \qquad (1)$$

Determined by a fairly complex equation, the *redundancy ratio* is specific to one node. I(i,*j*) is the number of paths between nodes *i* and *j* which share only *i* and *j* as nodes. I(v,*j*) is thus the number of node-independent paths between nodes *v* and *j*. Γ^2 is the neighborhood of all of the nodes in the neighborhood of *v*. So the number of node-independent paths is taken between the node under consideration and each node in the neighborhood of neighbors. This sum is then divided by the number of independent paths between *v* and the complete graph connecting *v*, Γ_v and Γ^2. To achieve one redundancy ratio representative of the entire network, the collective set of redundancy ratios for all nodes are ordered and the median is taken as the redundancy ratio for the network.

Ortiz et al. (2009) explored the resiliency of the freight transportation network. The freight transportation network is made not only of highways, roads, ports and railway infrastructure but also the carriers and shippers that transport goods. Although notably larger and more inclusive than the highway and roadway system, the fundamentals of analyzing resilience are common. Resilience here is defined as the ability to absorb smaller disturbances as well as the ability to quickly return to full functionality after large disasters. The benefits of experiencing small disruptions in a real network are found in identifying where the critical network components seem to be post-event. In this way, DOTs can be better prepared against larger disruptions. Ortiz et al. (2009) first proved the costly nature of both small and large disruptions, which cost not to just directly repair routes and reroute traffic but also ripple through the economy in more subtle ways. The economic importance of the transportation and freight systemis undeniable as almost all sectors of the economy depend on it in some way. Resilience of the network is also highly dependent on its redundancy and the availability of alternative paths in the event of a component failure or close. The distinguishing factor in the logical use of alternative paths is their relative capacity to that of the main road; in most cases, in fact, their capacity is quite limited.

Of the expected extreme events, the urban networks located on the northeastern coast of the US are most

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susceptible to hurricanes, their hazardous wind speeds and storm surges.Hurricanes are so deadly because of their combination of destructive forces; namely, high wind speeds, powerful storm surges and the resulting flooding. As a result of climate change, the intensity of hurricanes and extreme climatic events is expected to worsen (IPCC, 2014). Storm surges will be the concentration of this investigation and the Sea, Lake, Overland Surges from Hurricanes (SLOSH) program by NOAA will be used to develop storm surge projections. Simultaneously, the predictions for sea level rise released in the 2014 IPCC report were more severe than those in previous reports. The Atlantic coast of North America is expected toexperience accelerated sea level rise because of regional factors increasing the effects of global sea level rise. These include the spatial distribution of Earth's gravitational mass, the climate of the Atlantic coast and geological processes along the shore. The northeastern coast of the US willthus be one of the most affected regions in the world, necessitating improvements and preparations for worsened conditions.

To effectively and efficiently manage the planning and finances of these improvements, decision makers need to know where vulnerable areas and the most important links of the transportation network are located. In a dense highway network, this often translates to identifying the roads and intersections which are highly vital to the adequate connectivity of a transportation network. This can be done using network performance indicators such as topological properties that describe, quantitatively, the connectivity and redundancy present inthe system. Topological graph theory is the study of the physical layout and structure of a network; this is especially relevant to transportation networks, which are entirely physical systems. The New York City metropolitan transportation network is chosen as a case study with which to illustrate the measured performance and resilience of a major urban transportation network. Modeling the region's highways and roads as a simple network made of links andnodes allows the mathematical determination of network properties. With these measurements, the resiliency of the current transportation network can be quantified.

After reviewing resilience and its many definitions as an academic term, a form specific to thisstudy was outlined. This definition is that of engineering resilience, comprised of aspects of robustness, resourcefulness, redundancy, and rapidity. Although it can be measured in differentways, in this thesis research, resilience was quantified by topological graph properties of thenetwork under consideration. The hazards most relevant to coastal urban networks were then examined, and hurricanes, specifically storm surges, were identified as the focus of this study.

Before modeling hazard scenarios, the original network was investigated and general graph properties were determined. Of these characteristics, the most significant one was finding the degree distribution, which is closest to a Poisson distribution, or the distribution of a random graph. Interestingly, random graphs are less robust to failures of a random nature, and more robust to targeted attacks, providing some insight to the results of the failure simulations of the New York City network. These failure simulations were random, and the failures subjected to thenetwork occurred at increasing fractions of node failures to observe how the network behaved during random node removal. Topological graph properties were then used to illustrate this behavior of system resilience, specifically degree correlation, local and global connectivity, and redundancy. The evaluated graph properties evaluated showed varying trends reflecting overall degradations in network performance and connectivity.

SLOSH software was employed to simulate enveloped hurricane scenarios of different categories, wind speeds, tide levels, and directions. The storm surge heights were combined with elevation data of the nodes to simulate the results of a real hurricane. The SLOSH results were then used to determine which nodes were effectively removed from the network in scenario based node removals. By using results from SLOSH investigations, nodes can be more accurately identified as disrupted and then removed. Similar to the method applied in the randomremoval scenarios, topological graph properties were measured in each hurricane scenario. Thesewere grouped with respect to surge height at Battery Park, Manhattan, and then compared among each other and to the random removal results.

III. Methodology

The aim of the Paper is to highlight the sensitivity of the network to different levels of node removal and highlight its impact on different aspects of the network characteristics. Furthermore, the probable storm surge heights under specific scenarios have been evaluated and the performance of the network under these conditions is measured using graph theory.

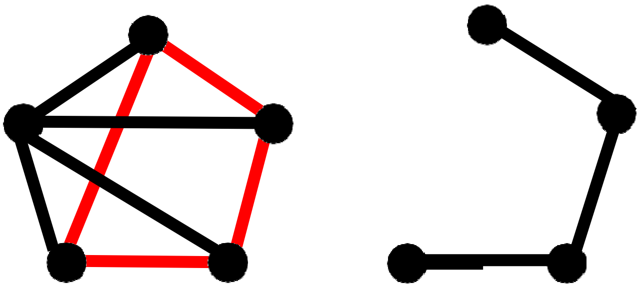

Figure 1 A graph and one possible subgraph (right).

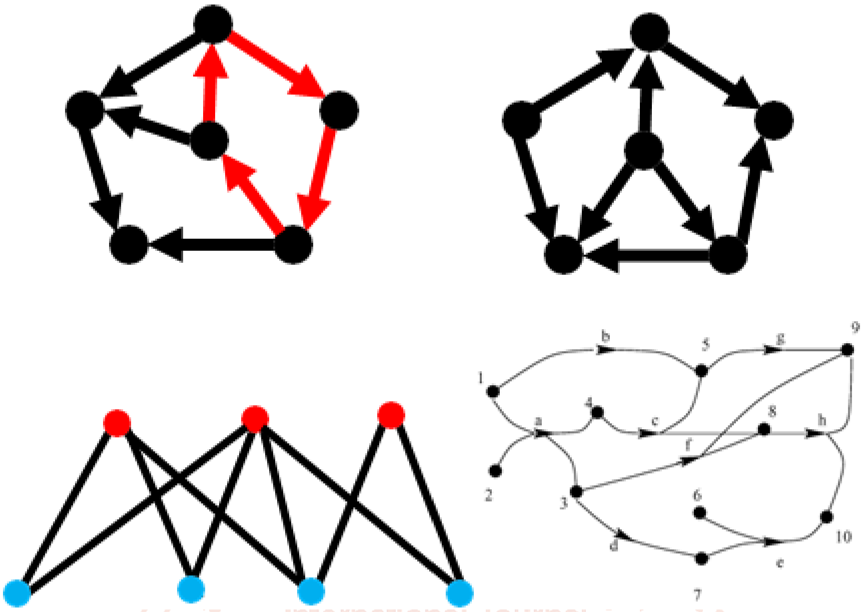

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Figure 2 Clockwise from top-left: A cyclic directed graph, acyclic directed graph,bipartite graph, hypergraph

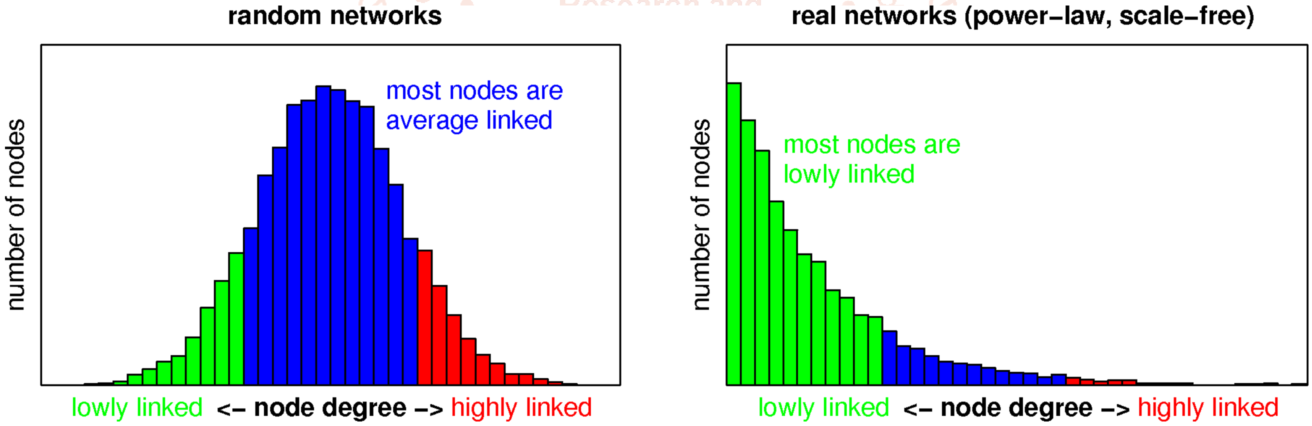

Figure 3 Degree distribution histograms of a random (left) and a real network (right)

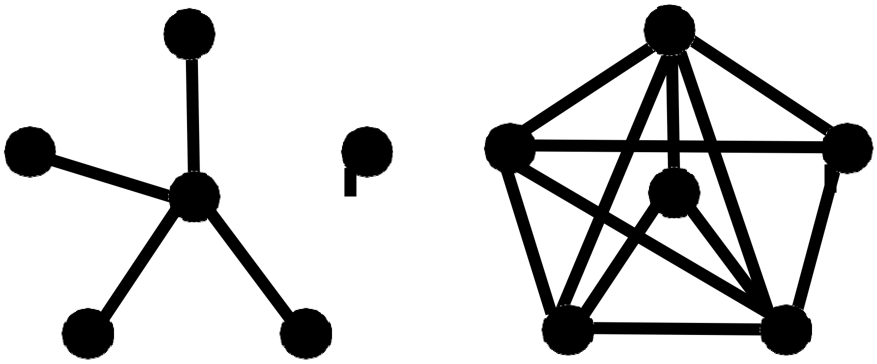

Figure 4 Clustering of zero (right) and high clustering (left).

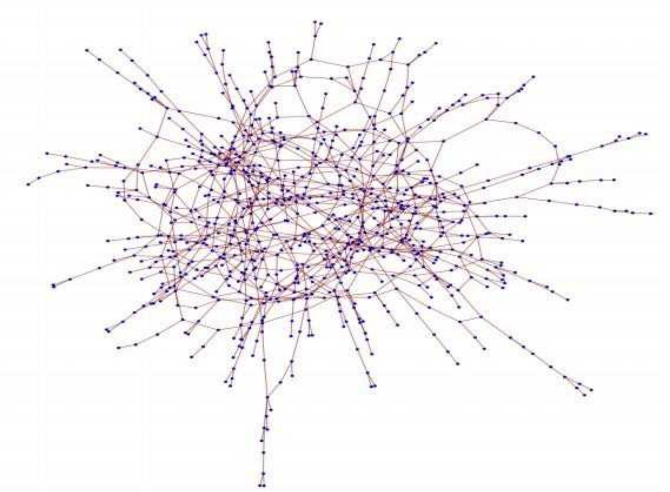

Figure 5 An Erdos-Renyi random graph (Barabasi et al., 2012).

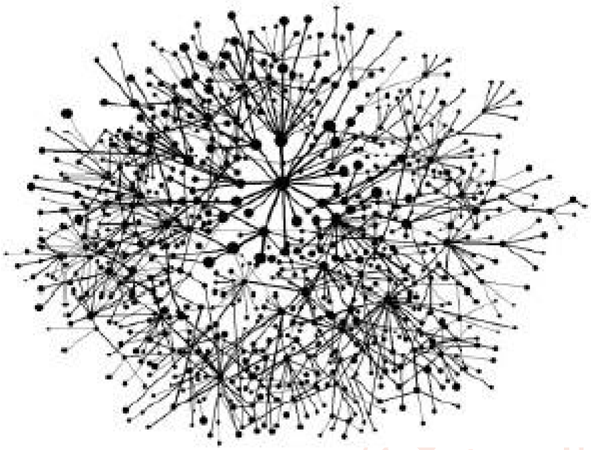

Figure 6 The Internet, an example of a complex network

IV. Conclusion

The results in this investigation can be replicated to evaluate and compare network resilience measures between different systems or after improvements and developments have been made to existing infrastructure. The large uncertainty associated with extreme climatic events forces transportation agencies to respond with over-engineered designs or in many cases, to not prepare at all because of the overwhelming and expensive nature of the potential hazards. Supplied with this type of data, however, decision-makers and legislators are better able to direct resources to the most vital locations, allowing a more reasonably budgeted response to climatic hazards. Transportation agencies can pinpoint the specific network components which are most critical to maintaining network flow. Instead of attempting a complete system overhaul, agencies can easily achieve prioritization of replacements and structural updates. The approach which references hurricane storm surge simulation results allows transportation agencies to identify not only the nodes which are most critical to network flow, but also those which are most vulnerable to a specific hazard. While a range of methods exist to measure the resilience of a network, the use of topological graph properties to track network response are shown to be useful in investigations of this transportation network. Examining the nodes most affected by the envelope simulation, planners can incorporate these vulnerabilities into long-term planning.

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