Introduction and Problem Statement: The threats accompanying a highly advanced and interdependent society are increasing in complexity [1]. The interconnected sectors that backbone our modern society and economy are expanding, interconnecting and adapting to our progressing civilization. However, in doing so they become more vulnerable to perturbations [1]. Events such as the Northeast Blackout of 2003, Hurricanes Katrina, Rita and Sandy and the Tohoku earthquake and tsunami have demonstrated the potential for widespread and cascading failures amongst interdependent infrastructures. The U.S. Department of Homeland Security identified sixteen critical infrastructure sectors as vital to the wellbeing of our nation's economy and security. Furthermore, recent U.S. Presidential Policy Directive (PPD 21) on Critical Infrastructure Security and Resilience addresses the resilience of such infrastructures and their ability to maintain their structure and functionality in light of disruptions or attacks as a national imperative [2]. Subsequently, examining the resilience of these expanding, large-scale and interconnected systems has become an emerging area of study and research.

As one of such critical infrastructures, the transportation sector is vital to the development of secure, sustainable and appealing urban areas. Rapid urbanization, new cultural and social trends and urban planning strategies cause changes in the topological structure of metropolitan areas. It is therefore necessary that the resilience of public transportation systems be holistically understood. The purpose of this proposal is to use recent breakthroughs in the fields of resilience and network theory to equip urban planners and disaster response professionals with quantitative methods, tools and metrics that will aid in designing, retrofitting and maintaining resilient transportation networks.

Hypothesis: By combining network and statistical theory analytics with an interdisciplinary understanding of predicted and hypothetical changes in urban transportation systems, large-scale transportation infrastructures can be evaluated for implications regarding resilience. This will supplement developing smart, sustainable and fault-tolerant U.S. cities.

Methodology to test hypothesis: Analysis of urban transportation systems begins by accepting network theory as the optimal method to organize and quantify topological and functional aspects of public transportation. Light rail, bus or subway systems are understood as a network by regarding transfer stations or stops as the nodes of the network, while passenger flows and connections between stations become the edges connecting those nodes [3]. Under this system of analysis, world transit systems can be described according to their network properties. These properties compute from a series of metrics imparted on the network's adjacency matrix; a matrix fully describing the connections or flows between the nodes of the network [3].

Network theory is applicable to a diverse set of disciplines including biological sciences, economics, agriculture, power grids and social networks [3]. Additionally, past work demonstrates that network theory metrics are an ideal platform for novel evaluations on the robustness, resilience and efficiency of public transit systems [4]. However, our lab at the University of Pittsburgh was the first to target specific vulnerabilities and locations of interdependence within a weighted public transit network, publishing a multifaceted investigation of the London Underground in terms of resilience [4]. While receiving many positive reviews, a consistent critique of our analysis is its applicability: Can our findings be used to make an immediate difference in the transportation sector? Resolving the shortcomings of our work requires a more interdisciplinary approach for our model.

Studying the sequential organization of the network in question and using passenger data available through collaboration with the local government body responsible for public transit activity allows for construction of a computational model of the network. My model includes both a weighted and unweighted representation of the network, whereby the weighted network represents the amount of passenger flow between nodes, while the unweighted network represents a physical bus or rail between nodes.

Using my undergraduate research training, coursework background and technical skill in network theory analytics and visualizations; I will develop a quantitative understanding of the network's fault-tolerance. For example, applying metrics like clustering coefficient, shortest path length and local and global efficiency, we can achieve a basic understanding of the system's robustness [3, 4]. More powerful computational methods, like power law distribution testing, targeted and random node removal or pattern recognition techniques, identify specific areas of vulnerability and patterns of interdependence within the network [4]. While these analytics are both novel and critical to the proceeding challenges facing the field of resilience and transportation, they are further elucidated in our London Underground publication [4].

The missing component from past work is the ability to apply the analysis and make an immediate impact within urban boundaries. To achieve this, I will take interdisciplinary coursework, including economics, urban planning and sociology, to bring a broad and pragmatic perspective to my computational model. I will then expand the scope of my research, including transit management professionals and researchers in the process, to discuss ongoing and future strategic initiatives pertinent to public transportation. Working with these professionals, I will adjust the computational model, matching hypothetical, proposed or ongoing changes to the network under study. I will then compare the adjusted and unadjusted models, applying network theory analytics to both models, allowing for quantitative understanding of how any proposed change in the network—expected or unexpected—will impact the system's resilience.

Expected Significance and Broader Impact: This method will immediately aid urban planning decisions and policies, allowing urban transit and planning professionals to predict implications for resilience caused by both strategic initiatives and perturbations. This effort will not only result in the development of smarter U.S. cities, but will also contribute to our national endeavor to build secure, sustainable and resilient critical infrastructures. The results of this study will be shared with similar stakeholders and can be disseminated widely to other urban areas.

Further, this work will contribute heavily to the scientific community by attacking the next unanswered question in the emerging fields of resilience and network theory analysis. The procedures and insights provided from this work are applicable to other infrastructure systems. In turn, my work will break ground on the creation of new network theory methods that are capable of helping scientists understand resilience over a broad spectrum of engineered networks.

Citations:

1. Helbing, D., *Globally Networked Risks and How to Respond.* Nature, 2013. **497**(7447).
2. Obama, B., *Presidential Policy Directive 21: Critical Infrastructure Security and Resilience.* Washington, DC, 2013.
3. Newman, M., *Networks: An Introduction*. 2010: Oxford University Press.
4. Dillon, T., S. Chopra, M. Bilec, and V. Khanna, *Understanding the Network Structure and Resilience of London Metro System.* Journal of the Royal Society Interface, 2015 (Under Review).