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Identifying critical road segments and measuring system-wide robustness in transportation networks with isolating links: A link-based capacity-reduction approach

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ABSTRACT

A wide range of relatively short-term disruptive events such as partial flooding, visibility reductions, traction hazards due to weather, and pavement deterioration occur on transportation networks on a daily basis. Despite being relatively minor when compared to catastrophes, these events still have profound impacts on traffic flow. To date there has been very little distinction drawn between different types of network-disruption studies and how the methodological approaches used in those studies differ depending on the specific research objectives and on the disruption scenarios being modeled.

In this paper, we advance a methodological approach that employs different link-based capacity-disruption values for identifying and ranking the most critical links and quantifying network robustness in a transportation network. We demonstrate how an ideal capacity-disruption range can be objectively determined for a particular network and introduce a scalable system-wide performance measure, called the Network Trip Robustness (NTR) that can be used to directly compare networks of different sizes, topologies, and connectivity levels.

Our approach yields results that are independent of the degree of connectivity and can be used to evaluate robustness on networks with isolating links. We show that system-wide travel-times and the rank-ordering of the most critical links in a network can vary dramatically based on both the capacity-disruption level and on the overall connectivity of the network. We further show that the relationships between network robustness, the capacity-disruption level used for modeling, and network connectivity are non-linear and not necessarily intuitive. We discuss our findings with respect to Braess' Paradox.

1. Introduction

Over the past decade there has been a noticeable increase in research related to the disruption of transportation networks which has been largely motivated by major catastrophic events. Investigating the impact of transportation network-disruptions should not be limited to natural and anthropogenic catastrophes, emergency response scenarios, and evacuation

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planning; however, as these types of events are relatively infrequent and are not part of the day-to-day transportation planning process. A wide range of less severe and relatively short-term disruptive events occur on transportation networks on a daily basis. Despite being relatively "minor" when compared to catastrophes, these events still have profound impacts on traffic flow. Stormwater ponding, partial flooding, visibility reductions, traction hazards due to weather, pavement deterioration, debris on the road, and a wide variety of traffic accidents are all examples of disruptive events that are likely to result in only a short-term, partial reduction of capacity on a given link; while catastrophic events like the collapse of a bridge, a chemical spill, or major accident are likely to be long-term and reduce the capacity of the affected links to zero.

Network-disruption analysis is a methodological approach that has been successfully applied to transportation maintenance and planning problems to identify and rank the most critical links in a network and to evaluate the robustness of the network as a whole (Sullivan et al., 2009; Scott et al., 2006; Jenelius et al., 2006; Poorzahedy and Bushehri, 2005; Myung and Kim, 2004; Chen, 2000). Network *robustness* is defined as the degree to which the transportation network can function in the presence of various capacity disruptions on component links. A "robust" network can compensate for disruptions on network links with relative ease and with only slight increases in overall system-wide travel times. A "non-robust" network does not adjust well to disruptions on network links and is subject to substantial increases in system-wide travel times. In network-robustness analysis, the sequential disruption of the component network links is part of the solution procedure. The link disruption modeling approach is employed to capture the relative importance of the disrupted link to the other links in the network and to evaluate the overall robustness of the network as a whole; it is not used to investigate the impact of a specific disruption, to capture the potential chaining of disruption events, to try and map a particular capacity-reduction value to a particular disruptive event, or to estimate the probability a certain type of disruptive event will occur.

Existing research has shown that the performance metrics, terminology, methodologies, and even the underlying modeling assumptions used in network-disruption studies can vary dramatically depending on the application, problem domain, and the specific goals of the research (Sullivan et al., 2009). When modeling transportation network-disruptions the traffic flow regimen and the assumptions related to the disruptive event are important. Traffic flows can vary dramatically on a particular link depending on whether a disruption is modeled as a complete or partial reduction in the capacity on that link and on the actual duration of the disruption. It is also the case that traffic that re-routes as a result of the disruption may choose from many different alternative paths or even cancel certain trips altogether. To date there has been very little distinction drawn between different types of network-disruption studies and how the methodological approaches used in those studies differ depending on the specific research objectives and on the types of disruption events being modeled.

We argue that it is important to carefully consider how network-disruptions are modeled within the context of a particular research problem, as different approaches and assumptions yield disparate results. It is equally important to have a sound methodological foundation for the assumptions used in the model and to define exactly what performance measures are used and how they are derived. Given the potential for substantially different performance outcomes, the selection of a specific capacity-disruption level to model network robustness and to identify the most critical links on a network is imperative. For example, the arbitrary but common use of a 100% capacity-disruption level (complete link removal) is not inexorably sound methodologically, nor is it necessarily realistic with respect to modeling the affects of common, every day disruptions that occur most frequently on transportation networks. The *capacity-disruption level* is defined as the reduction in the capacity on a given link due to some type of disruption expressed as a percentage. Using a 100% capacity-disruption level effectively removes the link from the network (either physically or functionally) and reduces the capacity on a given link to zero.

In this paper, we advance our Network Robustness Index (NRI) methodology for evaluating network robustness and identifying and ranking the most critical or important links in a transportation network. We show that the rank-ordering of the most critical links in a network can vary dramatically based on both the capacity-disruption level and on the overall connectivity of the network. We further show that the relationships between network robustness, the capacity-disruption level, and network connectivity are non-linear and are not necessarily intuitive. *Network connectivity* refers to how well connected the network is with respect to redundancy (alternative routes) and the number of links connecting the component nodes. It is important to consider the type of disruption (infrequent, catastrophic –versus – common, day-to-day) and the connectivity of the network being modeled prior to selecting a capacity-disruption level.

There are four specific research objectives: (1) Introduce a methodology for measuring system-wide network performance using a link-based capacity-disruption level other than 100%; and evaluate the use of a variety of capacity-disruption levels on each link (for example, 100% capacity-reduction, 99% capacity-reduction, 95% capacity-reduction, etc.) to identify the most critical links in the network based on the overall travel time impacts on all users. We refer to this methodology as the modified NRI. The original NRI utilized complete link removal. The modified NRI produces results that are independent of the degree of network connectivity and can be used to evaluate networks with isolating links. An *isolating link* is one that completely cuts off a portion of the network if it is removed. (2) Introduce a scalable, system-wide network performance measure to quantify network robustness over all links in the network called the Network Trip Robustness (NTR). Existing network performance measures do not necessarily scale and cannot be used to compare disparate networks to one another – a characteristic that is very useful in evaluating alternative projects or options, comparing different sized networks with dissimilar levels of connectivity, allocating limiting infrastructure funding between regions and comparing the robustness of dynamic networks over time. The NTR can be used for inter-network comparisons. (3) Show how an ideal capacity-disruption range can be objectively determined for a particular network. (4) Demonstrate our methodology by