Determination of Network Robustness with isolated Sub-Networks

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Modeling Complex Systems as Networks

Complex systems comprise many interacting parts; the interaction patterns can be represented as a network. As the number of interacting parts grows, predicting the interaction patterns becomes intractable. Network representation allows us to model these interactions mathematically, developing more accurate solutions to large-scale problems.

Network Disruption

The recent focus of network study has been steered toward disruption analysis by external events in the United States and around the world, like the 1995 earthquake in Kobe, Japan and the World Trade Center attacks of September 11, 2001. Major catastrophic events, both natural and anthropogenic, have proven to be numerous enough, in some cases, to warrant increased consideration in network optimization for critical infrastructures. For some of these networks, it has become more the norm than the exception to be experiencing some form of disorder, and attempting to recover from it or work around it. Networks studies that focus on disruption scenarios have blossomed to account for these demands.

Vulnerability, Reliability and Robustness

The goals of network disruption studies are:

1. to maximize the network’s robustness (capability of adapting to and recovering from disruption)
2. to maximize the network's reliability (resistance to disruption), OR
3. to minimize the network’s vulnerability (potential for disruption).

It is important to distinguish network vulnerability from susceptibility. Vulnerability in a network is typically taken to refer to the degree of inability of a system to function due to the effects of disruption, whereas susceptibility is often the link-specific measure of the likelihood of failure due to a disruptive event. Links that are well-protected are not susceptible to failure. Links that are critical to a network make the entire network vulnerable when they fail. Studies often involve traditional modeling techniques, applied before and after a disruption, to assess the relative impact.

Robustness and vulnerability of complex systems are ideas that span a wide variety of disciplines. For example, biologists are concerned about the fate of the African cheetah. Although its numbers have rebounded well from its endangerment, the species is not genetically robust. Its genetic makeup continues to show that it is extremely susceptible to sudden extinction, a scenario analogous to catastrophic, cascading failure in networks. Comparable studies are also done with social networks to identify critical links between social agents in a network.

The end results of these studies of robustness and vulnerability often fall into one of two general categories – those that seek to develop a network performance index (for potential inter-network comparisons) and those that seek to compare individual elements within a given network (intra-network comparisons).

The Network Robustness Index (NRI)

The focus of this project is a system-wide measure which considers, in turn, the effect that the removal of a given link has on the overall travel cost for users in a transportation network, after the traffic is re-routed. The significant aspect to this approach is that we consider each and every link in the network, in an effort to find those that are most/least critical, and then develop an index to quantify the overall robustness of the entire network in the face of a variety of disruptive scenarios.

The Network Robustness Index, or NRI, was developed in 2006 to provide these metrics. The NRI was proposed as an alternative to the link-based variable to capacity (VC) ratio for identifying critical links in a highway network and as an alternative to the network gamma index for measuring network robustness. The NRI represents, in both cases, a more comprehensive measure since it accounts for network-wide demand and traffic re-assignment. As currently formulated, calculation of the NRI requires sequential removal of individual network links and iterative application of a user equilibrium traffic assignment model (middle left).

Motivation

Transportation planning efforts, especially those involving highway capacity expansions, have traditionally relied on the VC ratio to identify “highly congested” or critical links, resulting in localized solutions that do not consider system-wide impacts related to congestion, security, and emergency response. The NRI is a new, comprehensive, system-wide approach to identifying critical links and evaluating network performance that relies on readily available sources of data from transportation demand planning models. The NRI measures overall network benefits rather than local benefits such as volume to capacity ratios. The research is based on the premise that a fundamental change in highway network design philosophy is needed. Instead of identifying individual congested or critical links based on localized measures, such as level of service, we argue that infrastructure management should focus on maximizing the robustness of the overall transportation system or on minimizing the system vulnerability.

Project Objective

The main research hypothesis associated with this project is that the impact of orphaned traffic associated with isolated sub-networks can be included in the NRI as a function of lost and replaced demand. Calculation of the NRI requires sequential removal of individual network links and iterative application of a user equilibrium traffic assignment model. One potential problem avoided during the application of the NRI to the hypothetical networks used previously (top left) was the creation of isolated nodes or isolated sub-networks by isolating links (bottom left, in red). In the preliminary research, we do not directly address situations where a section of the network is effectively cut off from the rest of the network. It is clear that, in a real-world application, the NRI must account for trips that either start or end within a sub-network that has been disconnected from the body of the network by the removal of an isolating link. As it is currently formulated, though, the effects of the removal of an isolating link on the network are ignored, since flow into or out of the isolated sub-network can not be re-routed. In this study, we attempt to solve this problem so that the NRI can be calculated.

Proposed Solution Methods

Method 1: Capacity Disruptions

The first method will use capacity disruptions of the network links, instead of complete link-removals, to find an NRI that is useful and consistent for both inter- and intra-network comparisons. Two approaches will be applied in the first method. A variety of reduced-capacity scenarios (e.g., 95%, 90%, 80%) will be used and the resulting data studied for relationships which indicate consistency across a variety of networks.

Method 2: Formulation of the Network Delay Index (NDI)

The second method will use an alternate formulation for the calculation of robustness, where the travel time variable is placed in the denominator. The key to this approach will be to allow the link-specific cost to go to “0” when the travel time across that link approaches infinity, as is the case when an isolating link is cut and flow is re-assigned across that link. The resulting index for this formulation will be known as the Network Delay Index (NDI).

Method Selection and Application

Each of the methods implemented will have been evaluated according to its usefulness and consistency for intra-network and inter-network comparisons. The method that is most consistent and that adequately accounts for isolated sub-networks will be selected for an application to the Chittenden County highway network (below).

As part of Signature Project #1, Land-use, Transportation, and Environmental Complex Modeling Frameworks: Evaluation, Calibration, Sensitivity, Refinement and Applications, we propose to utilize the detailed road networks and origin / destination (O/D) flow matrix for Chittenden County, Vermont as input data to assess which network links are considered the most critical in Chittenden County. The input data are provided by the integrated land-use and transportation planning micro simulation team members. Using the NRI, we will identify specific road links that are the most critical or valuable with respect to maintaining the robustness of the overall road network within Chittenden County. These results can be used by planners throughout the county for capacity improvement planning and to investigate sustainable land-use development strategies.