MPC-464
April 1, 2014- July 31, 2017

Project Title:
Development of Network-Based Measures and Computational Methods for Evaluating the Redundancy of Transportation Networks

University:
Utah State University

Principal Investigator:
Anthony Chen, Ph.D. (PI)
Professor (Utah State University)
anthony.chen@usu.edu
4110 Old Main Hill
Logan UT 84322-4110
(435) 797-7109

Research Needs:
Natural and man-made disasters encountered in the past decade (e.g., the 9/11 terrorist attacks in 2001, the London Bombing in 2005, Hurricanes Katrina and Rita in 2005, Minneapolis' 35W bridge collapse in 2007, Christchurch, New Zealand's earthquake in February 2011, Japan's devastating earthquake/tsunami in March 2011, and the Superstorm Sandy in 2012) have repeatedly emphasized the importance of transportation networks and the need for government agencies and communities to make this system more *resilient*. Recently, various conceptual and/or computational frameworks have been proposed to analyze *resiliency* (e.g., Chang and Nojima (2001), Victoria Transport Policy Institute (2005), Tierney and Bruneau (2007), Heaslip *et al*. (2010), and Croope and McNeil (2011) for a general transportation network resiliency evaluation framework, Caplice *et al*. (2008), Adams and Toledo-Durán (2011), and Miller-Hooks et al. (2012) for a freight system resiliency evaluation framework, and Faturechi and Miller-Hooks (2013) for a general civil infrastructure system).

The Multidisciplinary Center for Earthquake Engineering (MCEER) provided the four "Rs" concept to characterize *resiliency*: robustness, redundancy, resourcefulness, and rapidity (Bruneau *et al*., 2003). In their definitions, **robustness** refers to "*strength, or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function*"; **redundancy** refers to "*the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of function*"; **resourcefulness** refers to "*the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis*"; and **rapidity** refers to "*the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption*".

The Federal Highway Administration (FHWA, 2006) defined *redundancy* as the ability to utilize backup systems for critical parts of the system that fail. They emphasized that it is extremely important to consider redundancy in the development of a process or plan for emergency response and recovery. One of the pre-disaster planning strategies is to improve network resiliency by adding redundancy to create more alternatives for travelers or by hardening the existing infrastructures to withstand disruptions. Despite a growing body of research on *resiliency, there is no formal mathematical definition of transportation network redundancy, and few researchers have concretely developed quantitative network-based measures and computation methods to assess the redundancy of real transportation networks*.

The objectives of this research proposal are twofold: (1) to develop network-based measures for systematically characterizing the redundancy of transportation networks, and (2) to develop computational methods for evaluating the network-based redundancy measures. The proposed research on network redundancy can be considered as a critical component in assessing network resiliency and also designing a more resilient transportation network against disruptions.

Research Objectives:
Redundancy is vital for transportation networks to provide options to users and planners during disastrous events. This research proposal will develop network-based redundancy measures and computation methods for evaluating the redundancy of transportation networks. Specifically, the objectives include the followings:

1. Develop network-based measures for characterizing the redundancy of transportation networks.
2. Develop computational methods for evaluating the network-based redundancy measures.
3. Collect data from different sources to develop a case study for evaluating the redundancy of a real transportation network.

Research Methods:
This research proposal will develop a network-based methodology for evaluating the redundancy of transportation networks. It consists of: (1) developing network-based measures for systematically characterizing the redundancy of transportation networks, and (2) developing computational methods for evaluating the network-based redundancy measures.

Network-based Redundancy Measures
Two network-based measures will be developed to characterize the redundancy of transportation networks: route diversity and network spare capacity. Specifically, the *route diversity dimension* is to evaluate the existence of multiple effective routes available for *travelers* or the degree of connections between a specific origin-destination (O-D) pair. An effective route has two requirements: (1) a less detoured route with an acceptable travel cost is more likely to be considered by travelers as a reasonable substitution when the primary or secondary route is not available, and (2) a less overlapping route is a more meaningful alternative under disruptions. On the other hand, the *network spare capacity dimension* is to quantify the *network-wide* reserve capacity with an explicit consideration of congestion effect and travelers' route choice behavior. These two measures complement each other by providing a two-dimensional characterization of network redundancy from the perspective of both travelers and planners. They can address two fundamental questions in the pre-disaster transportation system evaluation and planning, i.e., "*how*

many redundant effective routes are there for travelers' evacuation use?" and "*how much redundant capacity does the network have*?"

<u>Computational Methods</u>
Two computational methods will be developed to evaluate the two network-based redundancy measures discussed above. To the *route diversity dimension*, a definition of a route (e.g., simple route, efficient route, distinct route, etc.) is needed. In this research proposal, the efficient routes (also called reasonable routes) will be adopted and is defined as follows:

Definition. *Efficient Routes*: if a route includes only links that make the travelers further away from the origin, it is an efficient route.

Mathematically, a route (composed of a sequence of nodes) $r \rightarrow n_1 \rightarrow n_2 \rightarrow \cdots \rightarrow n_K$ is an efficient route, if and only if

$$l_r\left(n_{i+1}\right) > l_r\left(n_i\right),\ i = 1, 2, \cdots, K-1,$$

where $l_r(n_i)$ is the shortest route cost from origin r to node n_i. Accordingly, we use the number of efficient routes to measure the route diversity of a specific O-D pair. A combinatorial algorithm with polynomial-time complexity based on Meng et al. (2005) for counting the different efficient routes between an O-D pair will be implemented to evaluate the route diversity dimension. This algorithm consists of two parts: (1) constructing a sub-network for each origin r, G_r=(N_r, A_r), and (2) counting the number of efficient routes from origin r to all nodes in the sub-network G_r=(N_r, A_r). The sub-network G_r=(N_r, A_r) is a connected and acyclic network. The concept of efficient routes is used in the sub-network construction. In other words, the sub-network only includes the links that are on the efficient routes from this origin. Counting the number of efficient routes from origin r to all nodes in the sub-network is essentially based on the node adjacent matrix operation. A network-based procedure will be implemented for counting the different efficient routes for each origin r. It is worth noting that the above definition of *route diversity dimension* is at an O-D pair level. However, we can aggregate it to different spatial levels (e.g., zonal and network levels) according to planners' different evaluation and comparison purposes. This aggregation explicitly considers the effect of travel demand on route diversity, which is different from a simple arithmetic average.

As to the *network spare capacity dimension*, an optimization-based approach will be developed to explicitly determine the maximum throughput considering both congestion effect and route choice behavior (see Sheffi, 1985; Yang and Bell, 1998; and Chen et al., 2011 for the detailed algorithmic procedures for solving the traffic equilibrium problem and bi-level mathematical programming formulations used to model the network design problem), while the weighted link spare capacity measure developed by Santos *et al*. (2010) can only provide a localized (or an approximate) network-wide spare capacity. Advanced path-based traffic assignment algorithms (see Jayakrishnan et al., 1994; Chen et al., 2002, 2012, 2014; Xu et al., 2012; Zhou et al., 2012) will be considered as part of the computational methods for solving the network capacity models used to evaluate the *network spare capacity* dimension. The optimization-based approach in determining network capacity enables planners to have a systematic assessment of system-wide network spare capacity.

Expected Outcomes:
The proposed research develops a network-based methodology for evaluating the redundancy of transportation networks. Specifically, route diversity and network spare capacity measures are used to systematically characterize the redundancy of transportation networks. These two measures complement each other by providing a two-dimensional characterization of network redundancy from the perspective of both travelers and planners. The proposed research on network redundancy can be considered as a critical component in assessing network resiliency and also designing a more resilient transportation network against disruptions. We believe that the network-based redundancy methodology developed in this research project will be useful to the State Department of Transportation (DOT) in making the transportation systems more robust and resilient to withstand the anticipated and unanticipated disruptions.

Relevance to Strategic Goals:
As mentioned above, the network-based methodology for evaluating the redundancy of transportation networks will assist state DOT to better plan, design, and manage the impacts of disruptions. These results aim to improve mobility of truck traffics along state and interstate highway systems, and hence have the potential to support regional and national economic developments. The results of this research project contribute to the following goals: (1) state of good repair and (2) economic competitiveness.

Educational Benefits:
Redundancy is vital for transportation networks to provide options to users during disastrous events. This research project will provide useful information and real-world data to develop a transportation network redundancy evaluation module for the Transportation Network Analysis course (CEE 6290) taught by the PI at Utah State University (USU). Our students will have the opportunity to learn how to evaluate the redundancy of transportation networks.

Work Plan:
To meet the objectives set out above, we propose to undertake the following tasks in 18 months. Specifically, these tasks are to:

1. Conduct a literature review on redundancy measures (2 months)
2. Collect and process the data to construct a transportation network and origin-destination demand for the case study (4 months)
3. Develop network-based redundancy measures and optimization procedures (4 months)
4. Develop computation methods for calculating the network-based redundancy measures (4 months)
5. Conduct a case study using the data collected in Task 2 (2 months)
6. Document findings and prepare final report (2 month).

Project Cost:
Total Project Costs: $103,557
MPC Funds Requested: $50,000
Matching Funds: $50,667.00

Source of Matching Funds: Faculty Salary, Tuition & Fees award for a Ph.D. student, Fellowship for a visiting Ph.D. Student from China (See Budget for breakdown

TRB Keywords:
Transportation networks; redundancy; resiliency; route diversity; network spare capacity.

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