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Modeling Transportation Network Redundancy

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Abstract

Redundancy is vital for transportation networks to provide utility to users during disastrous events. In this paper, we develop two network-based measures for systematically characterizing the redundancy of transportation networks: travel alternative diversity and network spare capacity. Specifically, the *travel alternative diversity dimension* is to evaluate the existence of multiple modes and effective routes available for *travelers* or the number of effective connections between a specific origin-destination pair. The *network spare capacity dimension* is to quantify the *network-wide* residual capacity with an explicit consideration of travelers' mode and route choice behaviors as well as congestion effect. They can address two fundamental questions in the pre-disaster transportation system evaluation and planning, i.e., "*how many effective redundant alternatives are there for travelers in the event of a disruption*?" and "*how much redundant capacity does the network have*?" To implement the two measures in practice, computational methods are provided to evaluate the network redundancy. Numerical examples are also presented to demonstrate the features of the two redundancy measures as well as the applicability of the computational methods. The analysis results reveal that the two measures have different characterizations on network redundancy from different perspectives, and they can complement each other by providing meaningful information to both travelers and planners.

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Keywords: redundancy; travel alternative diversity; network spare capacity

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1. Introduction

1.1. Research subject and motivation

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' I-35W bridge collapse in 2007, New Zealand's earthquake in 2011, Japan's devastating earthquake/tsunami in 2011, the Superstorm Sandy in 2012, typhoon and earthquake in Philippines in 2013) have repeatedly emphasized the importance of transportation networks and the need for government agencies and communities to make this system more *resilient*. For example, the United States Department of Transportation (USDOT) has considered resiliency into the National Transportation Recovery Strategy (USDOT, 2009). The overall goal of this strategy is to enhance the recovery process of transportation networks under disruptions and to increase the resiliency of various infrastructures in the community. 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), Croope and McNeil (2011), Urena *et al*. (2011), and Omer *et al*. (2013) for a general transportation network resiliency evaluation framework, Caplice *et al*. (2008), Ortiz *et al*. (2009), Ta *et al*. (2009), Adams and Toledo-Durán (2011) and Miller-Hooks *et al*. (2012) for a freight system resiliency evaluation framework, Faturechi *et al*. (2014) for a airport's runway and taxiway network, and Faturechi and Miller-Hooks (2014a,b) for a general civil/transportation 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). *Redundancy* was defined as "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". The Webster/Merriam Dictionary (2012) gives a general definition of redundancy (or state of redundant) as: i) *exceeding what is necessary or normal,* or ii) *serving as a duplicate for preventing failure of an entire system upon failure of a single component*. Faturechi and Miller-Hooks (2014a) provided an infrastructure protection framework based on concepts used in describing a system's innate capability (i.e., coping capacity) to endure disruptions, and considering pre- and post-event actions to mitigate the impact of disaster events and increase inherent system qualities of resistance and excess (including expansion, retrofit, resource availability and response activities). Among others, the coping capacity characteristics include the ability to withstand stress, i.e., resistance, and/or excess in terms of redundancies and underutilized capacity; expansion includes pre-event actions to enhance network performance by increasing connectivity (e.g., adding redundancy) or capacity. Also, redundancy has been widely studied and applied in many domains, such as reliability engineering (O'Connor, 2010), communication (Wheeler and O'Kelly, 1999), water distribution system (Kalungi and Tanyimboh, 2003), and supply chain and logistics (Sheffi and Rice, 2005), etc.

In transportation, some researchers have introduced various measures for assessing the resiliency of transportation networks, and redundancy is one of those measures. For example, Berdica (2002) developed a qualitative framework and basic concepts for vulnerability as well as many neighboring concepts such as resiliency and redundancy. According to Berdica (2002), redundancy is the existence of numerous optional routes/means of transport between origins and destinations that can result in less serious consequences in case of a disturbance in some part of the system. 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. Godschalk (2003) and Murray-Tuite (2006) defined redundancy as the number of functionally similar components that can serve the same purpose, thus the system does not fail when one component fails. Also, Goodchild *et al.* (2009) and Transystems (2011) introduced redundancy as one of the properties of freight transportation resiliency, and defined redundancy as the availability of alternative freight routes and/or modes. In Miller-Hooks *et al*. (2012) and Faturechi *et al*. (2014), the innate capability to resist and absorb disruption impacts through redundancies and underutilized capacity, the effects of adaptive post-event actions, and the preparedness decisions of supporting these actions were integrated into the