Transportation Research Part B 114 (2018) 68–85

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

Transportation network redundancy: Complementary measures and computational methods[☆]

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ARTICLE INFO

Article history:
Received 5 August 2017
Revised 28 March 2018
Accepted 23 May 2018

Keywords:
Redundancy
Travel alternative diversity
Network spare capacity

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 normal or disruptive event*?" 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.

1. Introduction

1.1. Research subject and motivation

Transportation networks are not only vital in providing accessibility and promoting the safe and efficient movement of people and goods, but also central to the functioning of modern society to support our daily activities and maintain relations in business, social, and family settings. Yet they are vulnerable to disruptions whether planned or unplanned. Recent natural and man-made events such as earthquakes in China, Japan, New Zealand, Nepal, and Afghanistan/Pakistan,

☆ An earlier version of this paper was presented at the 21st International Symposium of Transportation and Traffic Theory, Kobe, Japan, and included in the Proceedings (Transportation Research Procedia, 2015, 9, 283–302).

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https://doi.org/10.1016/j.trb.2018.05.014

hurricanes/typhoons in the United States, Philippines, and Hong Kong have repeatedly emphasized the importance of transportation networks, and the need for government agencies and communities to strengthen transportation networks more *resilient* to planned and unplanned disruptions. 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 an airport's runway and taxiway network, and Faturechi and Miller-Hooks (2014,2015) for a general civil/transportation infrastructure system). Faturechi and Miller-Hooks (2015) provided a comprehensive review on seven common performance measures of transportation infrastructure systems in disasters, including risk, vulnerability, reliability, robustness, flexibility, survivability, and *resiliency*.

The Multidisciplinary Center for Earthquake Engineering (MCEER) provided the four "Rs" concept to characterize *resiliency*: robustness, redundancy, resourcefulness, and rapidity (Bruneau et al., 2003). The first two Rs (robustness and redundancy) are mainly related to the pre-disaster planning state, while the last two Rs (resourcefulness and rapidity) are related to the post-disaster recovery and mitigation. The former two Rs apply directly to the transportation infrastructure, network design, and mode options, while the latter two Rs pertain to the transportation system's operating entities. *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 (2014) 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. In the event of disasters, redundancy not only provides alternatives to travelers to minimize the impacts of disruptions, but also improves recovery and redesign strategies by making transportation networks more resilient against disruptions. The Federal Highway Administration (FHWA, 2006) defined redundancy as the ability to utilize backup systems for critical parts of the system that fail. To improve network resiliency, 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 concept of resiliency. Along a different line, Jenelius (2010) proposed the concept of redundancy importance and two measures (i.e., flow-based and impact-based) by considering the importance of links as backup alternative when other links in the network are disrupted. The flow-based measure considers a net traffic flow that is redirected to the backup link and the impact-based measure considers an increased travel time (cost) due to the rerouting effect. However, these two measures only quantify the localized redundancy importance of a transportation network. In other words, they are unable to capture the diversity of alternatives, which is an important property in measuring network redundancy. The diversity of available routes when the primary choice is inoperative needs to be explicitly considered in the redundancy characterization. In summary, despite that there is a growing body of research on *resiliency and also redundancy has been listed as one of the important concepts in characterizing resiliency, it is the least study in the context of transportation networks according to the above comprehensive review by* Faturechi and Miller-Hooks (2015) *on the transportation infrastructure system performance in disasters. Few research studies have provided concrete definitions of trans-*