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Resilience-based risk mitigation for road networks

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ABSTRACT

Transportation infrastructure has been identified by the US Department of Homeland Security as one of sixteen critical infrastructure systems essential to the well-being of modern societies. In this study, we propose a resilience-based framework for mitigating risk to surface road transportation networks. We utilize recent developments in modern network theory to introduce a novel metric based on system reliability and network connectivity to measure resilience-based performance of a road transportation network. The formulation of this resilience-based performance metric (referred in the paper as WIPW), systematically integrates the network topology, redundancy level, traffic patterns, structural reliability of network components (i.e. roads and bridge) and functionality of the network during community's post-disaster recovery, and permits risk mitigation alternatives for improving transportation network resilience to be compared on a common basis. Using the WIPW as a network performance metric, we propose a project ranking mechanism for identifying and prioritizing transportation network retrofit projects that are critical for effective pre-disaster risk mitigation and resilience planning. We further present a decision methodology to select optimal solutions among possible alternatives of new construction, which offer opportunities to improve the resilience of the network by altering its existing topology. Finally, we conclude with an illustration that uses the WIPW as the performance metric to support risk-based mitigation decisions using a hypothetical bridge network susceptible to seismic hazards.

1. Introduction

The resilience of robust, large-scale, interdependent civil infrastructure networks, including transportation systems, utilities, telecommunication facilities, and social networks, individually and collectively play a major role in determining the resilience of a community as a whole. The performance of transportation networks, in particular, is critical because post-disaster restoration of virtually all other facilities and lifelines in a community depends on people and equipment being able to move to the sites where damage has occurred. Highway bridges typically are the vulnerable links in road transportation systems and require especially effective risk mitigation strategies aimed at improving the overall resilience of transportation systems against future natural disasters.

The resilience of a system is its ability to withstand or adapt to external shocks and to recover from such shocks efficiently and effectively [44,33]. In the case of civil infrastructure, resilience is often associated with four attributes [6,8]: *robustness* – the ability to withstand an extreme event and deliver a certain level of service even after the occurrence of that event; *rapidity* – to recover the desired functionality as quickly as possible; *redundancy* – the extent to which elements and components of a system can be substituted for one another; and *resourcefulness* – the capacity to identify problems, establish priorities, and mobilize personnel and financial resources after an extreme event. These attributes are illustrated in Fig. 1a; all are characterized by considerable uncertainties. Many research studies have discussed the resilience of systems other than civil infrastructure, including ecosystems [19,46,25], computer networks [40], communication networks [43,35], and socio-economic systems [37,26].

Strategic investments and mitigation strategies can gradually improve the resilience of a system against future disasters, as indicated in Fig. 1b. For road transportation systems, such risk mitigation strategies often involve rehabilitation or retrofit of network bridges. However, the engineering processes of retrofitting can be very costly and time consuming, and retrofit decisions are often constrained by limited financial and human resources. Consequently, systematic retrofit prioritization is a critical element for an effective risk mitigation framework. Such a framework requires *not only* a consideration of the physical condition and structural vulnerability of each individual bridge in the network (e.g. [38,30]) *but also* a system perspective that takes into account the

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overall pre- and post- disaster operation and functionality of the network as a whole (e.g. [42,29,31]). As examples, Shiraki et al. [39] combined bridge fragility curves with network user-equilibrium functions to estimate the total road network delay due to earthquake-introduced damages; Bocchini and Frangopol [3] proposed a bridge network maintenance scheduling approach that incorporated both individual bridge reliabilities and the network connectivity into a decision optimization formulation. Ghosh et al. [16] presented a two-stage reliability assessment framework for aging bridge networks, including seismic fragilities of individual bridges and correlations among them, and further estimated the network reliability by a revised Markov Chain Monte Carlo simulation. The proposed method is illustrated on part of the highway bridge network in South California, USA [36].

As illustrated in Fig. 1, any resilience-based analysis and decision require a quantitative measure of the system performance and condition (i.e. the vertical coordinates in Fig. 1). While structural reliability (failure probability) is a well-accepted performance measure for individual roads and bridges to natural hazards, the performance of a transportation network must be measured by different metrics. Many researchers have quantified network performance based on network service functions, e.g., flow capacity [29,24], connectivity [9,11,18,3,22], and travel time [2,10,47]. However, these metrics are mainly used to measure network performance under normal service conditions and are not effective in reflecting the network susceptibility to disruptive, low-probability high-consequence natural and man-made hazards or its resilience (earthquakes, floods, terrorist attacks, etc.). More recently, Peeta et al. [31] used post-disaster connectivity and traversal cost between multiple origin-destination pairs in a network as the basis for pre-disaster investment decisions. Morlok and Chang [28] proposed capacity flexibility to reflect a transportation system's ability to adapt to changes in traffic patterns caused by natural disasters. Chang and Nojima [7] introduced the notion of network coverage and transport accessibility as the performance measures for post-disaster network recovery. Ip and Wang [20] suggested that pathway redundancy between all origin-destination pairs be used as a resilience measure for transportation networks. These performance metrics all have their merits in quantifying the network performance under hazardous conditions. However, none of them individually can reflect the network resilience-based performance in terms of its ability to provide functionality to community following a disaster and to support community recovery decisions from hazard-induced interruptions. Furthermore, none of these studies has attempted to quantify the uncertainties associated with these performance metrics. Different metrics might be appropriate for different decisions (e.g. retrofit, repair, new construction, etc.) at different stages (e.g., pre-event, immediately following event, and long-term recovery) of network resilience planning. Uncertainties must be quantified to ensure these decisions are risk-informed.

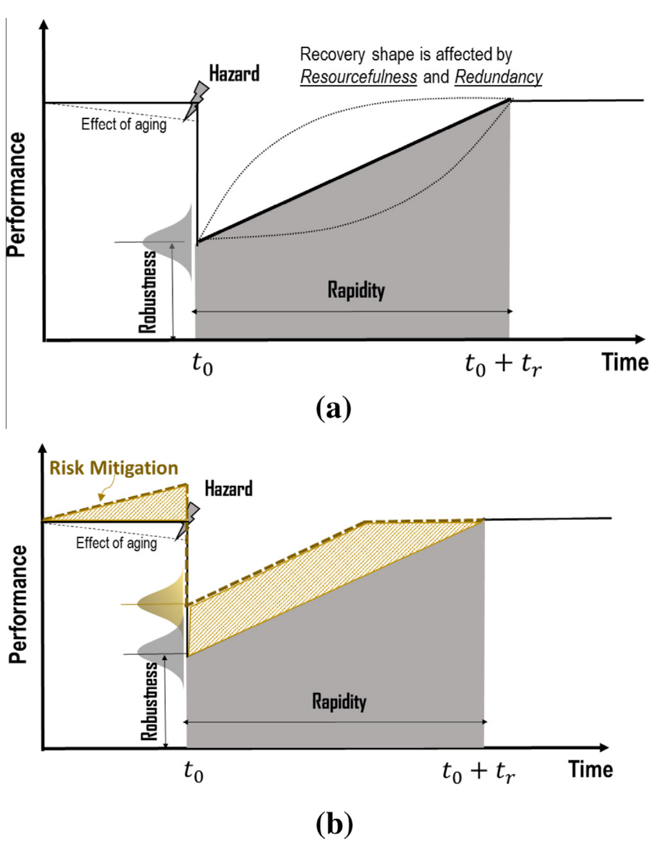

Fig. 1. Illustration of (a) the concept of resilience and (b) the effect of risk mitigation plan.

2. Organization and highlights of the paper

In this paper, we propose a novel resilience-based performance metric for road transportation networks, which allows resilience-based risk mitigation alternatives to be measured and compared on a common basis. The performance metric is based on graph theory, in a formulation which systematically integrates the network topology, system redundancy, traffic patterns, reliability (failure probability) of network components (i.e. bridges and roads) and the network functionality in a community's immediate post-disaster recovery period. Based on this resilience-based performance metric, we next introduce a project ranking mechanism for identifying and prioritizing bridge retrofit projects that are critical for effective pre-disaster risk mitigation of road transportation networks. We provide a decision methodology to select optimal solutions among possible alternatives of new construction which offer opportunities to improve network resilience by altering its existing topology. We conclude with an illustration of a risk-based mitigation framework, considering a hypothetical networked system of 37 bridges that are susceptible to seismic hazard.

3. Resilience-based network performance metric, WIPW

The fundamental purpose of a transportation system is to carry traffic from origins to destinations. The resilience of such a system is reflected in its ability to continue to fulfill this purpose in the event of natural or man-made disasters. Extreme hazard events can damage many bridges and roads simultaneously in a local transportation network, and financial and human resources required to restore the network function often are not immediately available following the disaster. Thus, the existence of redundant alternative paths between network origin–destination (O–D) pairs is crucial for the continued function of the transportation system during the period of emergency response immediately following the disaster as well as the long-term recovery of the community, and is an essential characteristic of a resilient transportation network.

Accordingly, by extending the concept suggested by Ip and Wang [20], we define a resilience-based performance metric of a transportation system as the weighted average number of reliable independent pathways between any network O–D pairs. A pathway between an O–D pair usually consists of several links that represent roads, with or without a bridge, which are connected in series. Two pathways between the same O–D pair are considered