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Evaluation of transportation network reliability during unexpected events with multiple uncertainties

Ali Soltani-Sobh [a,*], Kevin Heaslip [b], Aleksandar Stevanovic [a], John El Khoury [c], Ziqi Song [d]

[a] *Department of Civil, Environmental and Geomatics Engineering, Florida Atlantic University, United States*
[b] *Department of Civil & Environmental Engineering, Virginia Polytechnic State Institute, United States*
[c] *Lebanese American University, Lebanon*
[d] *Utah State University, United States*

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ABSTRACT

Measuring transportation network reliability in destabilizing events is a complex task because an accurate modeling requires the inclusion of uncertainty in both the infrastructure and the users' behavior. This paper presents an approach for evaluating the performance reliability, considering the uncertainty in both demand and supply sides of the road network due to an unexpected event. These uncertainties are likely due to the effect of natural disasters on road networks. On the supply side, in addition to link capacity, environment parameters of roads, which indirectly influence parameters of link travel time, are degraded after disasters. Road environment parameters, such as visibility, geometric, pavement condition, and safety elements, impact road capacity by a perceived increased cost or inability to travel. A generalized link travel cost is suggested to capture these effects. On the demand side, elastic demand is modeled with lognormal distribution and a logit-based stochastic user equilibrium is formulated to presents the traveler's uncertain behavior in route choice. In this study, the first order second moment reliability method is used to evaluate network reliability. This paper presents a numerical example that shows the result of ignoring uncertainties after a disaster is overestimated. Also, it was observed that increasing variation of demand and supply decreases the network performance and network reliability, and the increasing knowledge of the user in route choice behavior increases the network efficiency.

1. Introduction

Concept of resilience focuses on the quality of life of people at risk and to develop opportunities to enhance a better outcome [1]. Resilience is used to present the capability to sustain a level of functionality or performance for a given facility such as transportation, lifeline network, and hospital over a time period [1,2]. Resiliency of a system is defined as the capacity of tolerating external disturbances to remain in the current state, possibly by restoration [3]. Transportation network resiliency is defined as the ability of transportation systems to retain performance during and after disasters undergoing little to no loss, and their ability to return to the normal state of operation quickly after disasters. Reliability can be defined as the probability that the transportation network will meet an acceptable level of service after an event. The effect of network disruption degrades the network performance; the probability that the network can gain an acceptable level of performance in new equilibrium point after an unproductive event demonstrates system reliability in response to unexpected events [4].

As local, regional, national and international societal interaction and economic activities become more fully integrated and interdependent; the dependence on reliable transportation systems and facilities grows. Disruptions can have substantial uncertain and unpredictable effects on both infrastructure and human behavior. Ignoring these uncertainties results in inaccurate estimation of disruption outcomes. For this reason, considering uncertainties to increase the accuracy of system reliability assessment is of great benefit to transportation professionals in planning for destabilizing events.

Traditionally, estimation of transportation network performance is conducted by assuming a deterministic approach for both supply and demand; however, both supply and demand are subject to stochastic variation in reality. When disruptions occur, the capacity of road networks is degraded. Disasters might also change the road environment and travel time parameters of intact parts of capacity which are still under operation. The capacity reduction and road environment degradation both increase travel cost; consequently, the behavior of people in trip making and route

* Corresponding author.
E-mail addresses: asoltanisobh@fau.edu (A. Soltani-Sobh), kheaslip@vt.edu (K. Heaslip), astevano@fau.edu (A. Stevanovic), john.khoury@lau.edu.lb (J.E. Khoury), ziqi.song@usu.edu (Z. Song).

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choice decisions are influenced.

In this study, these types of uncertainty are captured in order to better estimate network reliability. This paper aims to propose a model of network reliability that focuses on the impact of unexpected events on road performance and the accuracy of modeling travel behavior under times of great uncertainty. The emphasis of this study is to model network reliability considering uncertainty on road capacity, and road environment issues that decrease operational link capacity, travel demand, and route choice behavior.

Capacity uncertainty, as the main outcome of disaster, is modeled using probability distribution to give a range of possible outcomes. Disasters and unexpected events might degrade the road environment and driving condition which cause a reduction in speed that increases free-flow travel time and cost of traveling the link. The user's perception of travel time on the affected roadway, which is influenced by driving conditions, is considered by adding the risk associated with traveling to the link as an additional cost, thereby modifying the link cost function. Under normal conditions, travel demands between a specific origin-destination pair varies according to the time of day, day of the week, and month of the year. However, the variation that occurs in a disaster situation is caused by the event's impact and users' reactions to the event. The modeling of demand uncertainty is achieved by using a lognormal distribution. To model the user's decision making while taking into consideration of potential knowledge imperfection during route choice, stochastic user equilibrium is used for network assignment.

In the following section, a brief literature review is provided to give insight on traditional modeling of network performance. After literature review, Section 3 discusses the sources of unreliability and various uncertainties in transportation networks. In Section 4, the methodological framework for the modeling is presented. The methodology provides a quantitative structure models the effect of link travel time parameters and demand uncertainty on link cost. The procedure to model stochastic user equilibrium under elastic demand is presented to complete the modeling methodology. The performance measure definition and methodology to estimate reliability of the system are then explained. The illustrative example is provided to demonstrate the application of the methodology. A five-node test network is used to provide an application of the analysis framework. The paper concludes with a summary, and concluding remarks.

2. Literature review

Traditionally, modeling transportation network performance is done considering both the transportation supply and demand as deterministic parameters. In reality, based on the nature of the stochastic world, both supply and demand are subject to variations. The previously performed reliability analysis has been limited to connectivity reliability, travel time reliability, and capacity reliability. Connectivity reliability is defined as the probability that the nodes of the network remain connected. Iida defines connectivity by assigning each link a binary statement of 0 or 1, corresponding to a failed and operating link respectively. Each origin-destination (O/D) pair is deemed reliable if at least one path linking the two is functioning [5]. A common example of travel-time reliability is Asakura's work, in which network reliability is calculated as a function of O/D travel time before and after a disturbance [6]. He considers two states for all components of the network: failed or not failed. Accordingly, capacity reliability compares and evaluates network capacity before and after an event. Determining the range of O/D requires the network to function within its capacity. This range is used to estimate the probability with which the network can accommodate a given traffic demand at a required service level [7].

In this study, supply uncertainty is a result of a relatively minor or major event, which affects the physical road capacity and driving conditions. Driving conditions are affected by road safety parameters, road geometrics, road pavement, etc., and are reduced as a minor result of an event. Based on the type of event, road conditions such as visibility, lightning, and pavement friction are reduced and cause a reduction in free-flow speed and capacity. Prior studies focus on physical capacity reduction as a cause for performance decline. On physical capacity reduction, Chen et al. [7] modeled the concept of capacity reliability considering the stochastic characteristics of the link capacities. Lo et al. [8] and Soltani Sobh et al. [4] used the road capacity as a uniform distributed random variable to model the effect of the events.

On the demand side, the level of demand variation is significant during disaster situation, therefore using demand as a deterministic variable is not realistic. Walting [9] and Clark and Walting [10] used Poisson distributed O-D demand to model stochastic network. Origin-Destination was modeled as a Poisson distributed by Sumalee et al. [11] in the reliable network design problem, as well. Binomial distributed O-D demand was applied by Nakayama and Takayama in a similar stochastic network [12]. Soltani-Sobh et al [4] proposed normal distribution to model demand uncertainty. They imply uncertainty in demand by considering the sensitivity of users' behavior with respect to travel time as a random variable, which controls trip-making decisions. These studies have shown that there is not a consensus on the correct distribution to model O-D demand, especially under great uncertainty.

Based on the microeconomic theory, the focus of travel behavior analysis is on travel disutility, such as travel time and monetary cost [13]. However, some evidence shows that there are a number of variables that significantly impact travel choices, but are not included in the travel behavior model [14]. Focusing on mode choice behavior, DeDonnea measured three relevant attributes of each travel mode: travel time, travel cost, and comfort [15]. Liu proposed a conceptual framework that includes travel time, monetary cost, comfort, and safety/security in the travel choice model [16].

In transportation engineering and planning literature, there are few studies that incorporate the effect of road environment parameters and driving condition. However, the objective of this study is to present a methodology that considers the uncertainty capacity, road environment (which links to travel time parameters), demand, and route choice behavior in network performance reliability.

3. Source of unreliability

Unreliability in transportation network arises from two different sources: capacity variation and flow variation. Excess flow and degraded capacity both lead to higher travel time, which decreases transportation network reliability. In reality, these variations are uncertain and cannot be treated deterministically. In the study of transportation system reliability, uncertainty may be associated with system capacity variability or with knowledge deficiencies of system users. Usually, uncertainties occur on a daily basis in transportation systems, but are exaggerated greatly by destabilizing events. System capacity variability represents uncertainty inherent to the physical resiliency and design of the system. Uncertainty could potentially be reduced by changing the physical characteristics of the system, resulting in greater infrastructure resiliency to the event. Knowledge uncertainty deals with the users' lack of understanding of impact of the destabilizing event