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Empirically quantifying city-scale transportation system resilience to extreme events

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ABSTRACT

This article proposes a method to quantitatively measure the resilience of transportation systems using GPS data from probe vehicles such as taxis. The granularity of the GPS data necessary for the method is relatively coarse; it only requires coordinates for the beginning and end of trips, the metered distance, and the total travel time. The method works by computing the historical distribution of pace (normalized travel times) between various regions of a city and measuring the pace deviations during an unusual event. Periods of time containing extreme deviations are identified as events. The method is applied to a dataset of nearly 700 million taxi trips in New York City, which is used to analyze the city transportation infrastructure resilience to Hurricane Sandy. The analysis indicates that Hurricane Sandy impacted traffic conditions for more than five days, and caused a peak delay of two minutes per mile. Practically, it identifies that the evacuation announcements coincided with only minor disruptions, but significant delays were encountered during the post-disaster response period. Since the implementation of this method is very efficient, it could potentially be used as an online monitoring tool, representing a first step toward quantifying city scale resilience with coarse GPS data.

1. Introduction

1.1. Motivation

In recent years, many quantitative and qualitative methods have been proposed to determine resilience of transportation infrastructure (Matherly and Langdon, 2014; Faturechi and Miller-Hooks, 2014; Konstantinidou et al., 2014a,b). When disasters and other extreme events occur, critical infrastructure may fail, incurring large human, economic, and environmental costs. This is especially relevant for urban transportation infrastructure, since it is crucial for city evacuations and emergency services in post–disaster environments. Empirical methods are needed to quantitatively monitor the transportation infrastructure in terms of its ability to withstand and recover from such events.

The goal of this article is to develop and implement a method for measuring resilience of city-scale transportation networks using only publicly available GPS data (e.g., available from taxis). The technique is designed with the following characteristics. First, the method can be applied at the city-scale, or larger. Because extreme events such as hurricanes have the ability to affect an entire city, it is important to examine impacts at a high-level city view, rather than the level of individual

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vehicles or streets. Second, the method measures network performance quantitatively, in terms of recovery time and peak pace deviations. Recovery time and peak performance degradation are standard quantities of interest in the resilience literature (Aven, 2011; Haimes, 2009b). While travel times are a natural performance measure for transportation networks, we instead use *pace*, or travel time per mile. This normalization accommodates the varied length of taxi trips within a city. Third, the method accommodates inherent variability in traffic conditions and data. The estimate of the state of traffic in a city contains noise and errors due to data availability and many unmodeled human factors. As a result, the method evaluates events that cause statistically significant disruptions, in order to separate the signal from the noise. Finally, the method is computationally tractable. Since taxi trips occur very frequently in large cities, the amount of data available for analysis is large. In order to be tractable, the computation should be $O(N)$, where N is the number of taxi trips, and ideally require only one pass through the raw data. Of practical significance, these single-pass algorithms could also be used to process the data in a real-time stream.

1.2. Related work

In recent years, the study of resilience has gained popularity in the systems engineering community. Haimes (2009a,b, 2011) gives a framework for assessing resilience, which focuses on modeling a system and the possible outcomes of various events. He asserts that a resilient system should suffer only slight degradation during an event, then rapidly recover. Reed et al. (2009) note that the quality of service abruptly drops during an event, then exponentially decays back to typical values. They suggest that an appropriate resilience measure is the integral of this exponential curve. Authors in the related field of risk analysis emphasize the importance of unknown factors while assessing resilience (Aven, 2011; Kaplan and Garrick, 1981).

Though there is no precise consensus on the definition of resilience, *peak disruption* and *recovery time* are consistently discussed quantities. In other words, peak disruption measures how far the quantity of interest deviates from typical values, and recovery time measures how long it takes to return to typical values. Most of these works also emphasize that resilience must be measured with respect to a given event and quantity of interest. For example, one case study used the number of functioning nodes in a power grid as the quantity of interest, assessing resilience against hurricanes and minor events (Ouyang et al., 2012).

Several authors have proposed quantities of interest for transportation systems. Omer et al. (2013) proposed a method which measures the resilience of a road-based transportation network in terms of travel times between cities. Chang and Nojima (2001) evaluated a post-earthquake transportation network in terms of accessibility and coverage. This is partly based on an accessibility metric devised by Allen et al. (1993), which considers travel times between various regions of a city. Thus, travel time is a standard quantity on which to measure resilience. This article will use the related quantity of pace, or travel time per mile. A comprehensive set of measures for transportation system resilience can be found in the review by Faturechi and Miller-Hooks (2014). The interested reader is directed to the related reviews on evacuation modeling (Murray-Tuite and Wolshon, 2013) and post disaster planning and management (Konstantinidou et al., 2014a,b) for a more complete picture of transportation system resilience, evacuation, and post-disaster response.

A distinct set of studies use large amounts of data to extract useful information about urban systems. The works most closely related to resilience are the studies by He and Liu (2012) and Zhu et al. (2010), which measure the effect of the I-35 W bridge collapse in Minneapolis in 2007. Geroliminis and Daganzo (2008) use loop detector data, combined with 500 GPS vehicles to extract macroscopic traffic properties from an urban-scale transportation network. Other works use GPS traces of mobile devices to analyze movement patterns of crowds during typical days and atypical events (Calabrese et al., 2010, 2011). Castro et al. (2012) present a method for inferring current and future traffic states from taxi GPS data. Zheng et al. (2011) propose a method that tracks taxi trips between various regions of a city and identifies flawed urban planning, while Zhan et al. (2016a) empirically measure the (in)efficiency current taxi systems. Another study measures temporal patterns in the density of taxi pickups and dropoffs to identify the social function of various city regions (Qi et al., 2011). They point out that unusual output can be used to detect events like holidays. Chen et al. (2012) specifically focuses on identifying anomalous taxi trajectories, in order to detect fraud or special events. Ferreira et al. (2013) created a graphical querying tool which can be used to count taxi trips between arbitrary geometrical regions as a function of time. They noted the drop in the frequency of taxi trips during Hurricane Sandy and Hurricane Irene, pointing out that the Irene-related drop was more significant, but the Sandy-related drop was longer lasting. By examining pace, we confirm that Hurricane Sandy had a longer recovery time, but find the contrasting result that Hurricane Sandy also has a more significant peak disruption.

1.3. Outline and contributions

The contributions of this work are as follows. In Section 2, a method is proposed to use taxis as pervasive city-scale resilience sensors. This method detects unusual events and measures them in terms of peak disruption and recovery time. It introduces paces between regions of the city as the key performance measure, and it uses the historical pace distribution to detect and measure extreme events. In Section 3, the method is applied to a four-year dataset from New York City to identify and compare properties of events such as Hurricane Sandy. Of practical significance, the analysis identifies minor atypical traffic is observed pre-Sandy, contrasted with the extreme conditions observed post-Sandy. Conclusions and future work