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Role of road network features in the evaluation of incident impacts on urban traffic mobility

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ABSTRACT

In this paper, we seek to investigate the spatiotemporal impacts of traffic incident on urban road networks. The theoretical lens of a complex network leads us to expect that incident impacts are associated with the functionality that an intersection acts in a network, and also, the location of incident sites. Incident impacts are measured in both temporal and spatial dimension through mining the large-scale traffic flow data in conjunction with the incident record. In the complex network context, the urban road network can be converted into a weighted direct graph with intersections as nodes and road segments as edges with their geographic information. Four network features, i.e., Betweenness Centrality, weighted PageRank, Hub, and K-shell are assigned to each intersection to measure its functionality. Temporally, we find out significant correlations between incident delay and two network features by applying hazard-based models. Spatially, the micro impact and the macro impact are found to be strongly associated with three network features through estimating a Bayesian Negative-binomial Conditional Autoregressive model and a generalized linear model, respectively. Our study provides the basis of leveraging urban road network context to evaluate incident impacts, with some explanations, insights and possible extensions that would assist traffic administrations to guide the post-incident resilience and emergency management.

1. Introduction

Intersections are the busiest but dangerous locations in road networks due to the number of turning movements and the resultant conflict points (Chen & Xie, 2016). The hazards at intersections not only prompt more injuries and property losses, as showcased by previous studies (Barua et al., 2010; Chandler, 2013), they also lead to a decline in traffic efficiency, i.e., incidents at or near intersections induce traffic congestion and thus reduce the connectivity of the road network. To improve the reliability of road networks and facilitate emergency rescue, traffic management agencies need to acquire the incident impacts on road networks (Konduri et al., 2003; Weng et al., 2015). Specifically, if drivers can be informed in advance via online systems of potential congestion, they may actively change their routes; if management authorities are able to grasp an incident's spatiotemporal impact, they can mitigate traffic congestion more efficiently.

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Previous research on the estimation and evaluation of the spatiotemporal impacts mainly focused on road segments of freeways. Deterministic queuing diagrams (Erera and Garrick, 1998) and shock waves (Wirasinghe, 1978; Wang et al., 2016) are the conventional methods adopted by these studies. Sheu et al. (2001) developed a stochastic estimation approach to real-time prediction of incident congestions. Recently, Chung (2010), Chung and Recker (2012, 2015) developed a binary integer programming method to estimate the spatiotemporal impacts of freeway incidents. Unlike freeway segments, urban road networks are interconnected and interdependent, and thus accord with complex networks. However, the impact of incidents on traffic mobility in urban areas, specifically the role of road network features at an incident location in the impact analysis, has not been carefully examined.

Road network features have been drawing increasing attention in urban transport studies, especially, usually involved as risk factors in road safety analysis. Marshall et al. (2011) and Rifaat et al. (2011) found that road network structure has a significant impact on traffic safety. Wang et al. (2013) used Closeness Centrality, Betweenness Centrality, and Meshedness coefficients to measure road network properties within traffic analysis zones (TAZs) and found they are closely related to crash frequencies. Analogously, Zhang et al. (2015), adopted Betweenness Centrality and overall clustering coefficients to quantify road network structures, and proved that they are associated with the frequency of non-motorist accidents. In most studies, road network features have been used to represent the general profile and properties of the road network in an entire zone or area. The role of local network features, nevertheless, in the evaluation of incident impact on road networks has not been fully considered in previous analyses.

As a typical kind of incidents with significant negative impacts on mobility, traffic accidents have always been analyzed by previous research in terms of accident frequency (Lord & Mannering, 2010; Abdel-Aty & Radwan, 2000) and injury severity (Savolainen et al., 2011). These studies investigated the roles of different risk factors in road safety, but rarely considered the accident impacts on the reliability of road networks. Accidents, in fact, not only cause injuries that lower the safety performance of roads, but also give rise to congestion that deteriorates the mobility of the nerighour and even the whole road networks through the malfunction of those key road segments and intersections (Li et al., 2015). Hence, it is promising to analyze the spatiotemporal impacts of accidents in mitigating the negative influence of accidents, thus providing useful information for incident management. Moreover, the understanding of incident impacts on road network reliability would be beneficial in improving network design and developing incident management strategies (Lo & Tung, 2003).

In this paper, we seek to explore the impact of incidents, especially, injury accidents, on an urban road network in both temporal and spatial dimensions. Primarily, road network features are extracted in terms of Betweenness Centrality, weighted PageRank, Hub, and K-shell, which constitute the key independent variable set to tap into the incident impacts analysis. Next, we proceed to examine the incident impacts on traffic mobility from three perspectives: one in the time dimension and two in the spatial dimension. Specifically, our paper explores three concrete topics: temporally, as incident can lead to delay, we explore the association between the incident-induced delay at nearby intersections with the network features; spatially, at micro or local level, an intersection's mobility is affected by incidents, and this local impact should be associated with the network features of its location, as different intersections have disparate roles within a road network; at macro or global level, the connectivity or mobility of the entire road network would also be affected by an incident, and the reduction in network mobility should also be related to the incident site and its network features. This study contributes to the literature streams by innovatively combining complex network theory with incident impact analysis, that is, the proposed framework and inference approach can be applied to study the impacts of non-recurrent traffic events, with the purpose of identifying the network features that contribute to these impacts. Also, our data driven approach can be implemented practically and could yield managerial implications for post-event response actions and incident management.

The rest of this paper is organized as follows. Section 2 provides an overview of the contextual setting and data preparation, and Section 3 describes the empirical models used in our research. Section 4 presents and discusses the findings. Finally, conclusion and managerial implications for traffic safety and mobility are outlined in Section 5.

2. Data preparation

2.1. Data overview

Our data are collected in a medium-sized city in northern China, where 69 major urban intersections (denoted as V, $|V| = 69$) are laid out on a chessboard-style network (Fig. 1 small panel). Three datasets are organized to extract the accident impacts as dependent variables and network features as key independent variables.

(1) The traffic flow dataset is used to derive the benchmark of traffic flow. It contains 584 million records, each of which represents a vehicle passing a given intersection at a certain timestamp.
(2) The accident information dataset accounts for 299 injury-causing accidents that happened in this region (denoted as ACC, $|ACC| = 299$) and includes the accident type, severity, property loss, illumination conditions, and truck involvement.
(3) The geographic information dataset contains the longitude and latitude of the intersections. Road information is harnessed to build the graph model, from which the network features are extracted.

The following two subsections first consider the network features according to the complex network theory with the road network geographic information. Accident impacts are then measured by incorporating the traffic flow and accident information datasets.