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Spatiotemporal analysis of critical transportation links based on time geographic concepts: a case study of critical bridges in Wuhan, China

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ABSTRACT

Critical transportation infrastructure has been studied extensively in recent years. This paper presents a spatiotemporal analysis of critical transportation links based on time geographic concepts. With widespread adoption of information and communication technologies (ICT) and location-aware mobile devices, large tracking datasets have become readily available. This study uses a tracking dataset of approximately 12,000 taxis in Wuhan, China over 1 week to analyze spatiotemporal origin–destination (O–D) patterns of trips that use three critical bridges connecting the three districts of Wuchang, Hankou, and Hanyang separated by the Yangtze River and the Han River. We use the space–time prism concept to identify alternative space–time paths passing through different bridges that observe the spatial and temporal constraints between each O–D pair derived from the taxi trajectory data. This case study illustrates the feasibility and benefits of using the proposed time geographic approach to analyze spatiotemporal patterns of travel demands on the critical links and their alternative paths in a transportation system.

1. Introduction

Most transportation networks have critical links that are essential to the functioning of a society, its economy, and daily life (Tolone, 2009). Critical transportation links sometimes could be partially disrupted or completely disabled due to excessive traffic volume, traffic accident, adverse weather, or technical failure. Previous studies of critical infrastructure have focused on assessing network vulnerability (Hellström, 2007; Taylor and D'Este, 2007; Jenelius, 2009; Eusgeld et al., 2011), analyzing critical infrastructure interdependence (Rinaldi et al., 2001; Setola et al., 2009; Zhang and Peeta, 2011), assigning remedial responsibility to critical infrastructure (van der Bruggen, 2008), evaluating risk levels of critical infrastructure (Guikema, 2009), and reviewing spatial equity and efficiency of critical infrastructure (Bröcker et al., 2010). This study differs from previous research by taking a time geographic approach of exploring spatiotemporal patterns of using critical links in a transportation network. Specifically, we first identify spatiotemporal origin–destination (O–D) patterns of trips that use the critical links in a transportation network. We then use the space–time prism concept in time geography to find alternative space–time paths of each O–D pair that can meet the original spatial and temporal constraints (i.e., being able to travel between the same origin–destination pair within the same time window) by taking different critical links in the transportation network. Spatial distribution patterns of alternative space–time paths are expected to vary with time of day and day of week. These patterns can help transportation planners gain insight on how people could take different critical links in a network to fulfill their travel needs without violating their spatial and temporal constraints.

Hägerstrand's (1970) time geography examines human activities under various constraints (i.e., authority, capability, and coupling constraints) in a space–time context. The concept of space–time prism offers an approach of modeling the spatiotemporal extent that an individual could reach between an O–D pair under a given time window and an average travel speed. A space–time prism can find all potential travel paths that meet the given constraints for an individual. Researchers (e.g., Miller, 1991; Kwan and Hong, 1998; Wu and Miller, 2001; Yu and Shaw, 2008; Neutens et al., 2008; Kuijpers and Othman, 2009; Miller and Bridwell, 2009; Shaw and Yu, 2009; Fang et al., 2011; Chen et al., 2011) have developed geographical information system (GIS)-based approaches of implementing time geographic concepts and spatiotemporal analysis functions. This study builds on the previous research to develop a time-dependent approach of computing space–time prism and alternative space–time paths using travel speeds derived from a GPS-based tracking dataset of approximately 12,000 taxis in Wuhan, China. We take an

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exploratory data analysis (EDA) approach of examining the spatiotemporal patterns of O–D flows, alternative space–time paths of traveling through different critical transportation links (i.e., three main bridges in Wuhan), and the implications of time-dependent travel demand to different critical links in the network. The analysis results illustrate the feasibility and benefits of assessing spatiotemporal interdependency between different critical transportation links in a network based on the proposed time geographic approach.

This paper is organized into five sections. Following this introduction section, Section 2 discusses the literature related to network-based space–time prism, critical transportation infrastructure, origin–destination estimation, and spatiotemporal analysis of activity-travel patterns. In Section 3, an exploratory analysis approach is presented for studying spatiotemporal patterns of O–D distributions and alternative travel paths that use different critical transportation links. Section 4 presents a case study of three critical bridges in Wuhan, China to demonstrate the feasibility and benefits of the proposed approach. The final section draws conclusions and discusses future research directions.

2. Related work

2.1. Network-based space–time prism

The space–time prism concept in Hägerstrand's (1970) time geography provides a simple, yet useful, framework for studying human spatial behavior under different types of constraints. With the advancements of GIS, researchers have developed computational representations and analytical functions for the space–time prism concept. For example, Miller (1991) developed a network-based algorithm for computing space–time prisms in a two-dimensional environment using the Arc/Info GIS software. Kwan and Hong (1998) implemented the space–time prism concept within a transportation network using the Arc macro language (AML) in the Arc/Info GIS. Wu and Miller (2001) proposed the concept of a dynamic network time prism to study time-dependent travel conditions within a transportation network, and Miller and Bridwell's (2009) field-based theory extended this idea by considering location-varying travel velocities. Yu and Shaw (2008) developed a spatiotemporal 3D GIS framework to examine activities in physical and virtual spaces using an adjusted network-based space–time prism concept. A 3D polygon representation of a space–time prism was introduced by Kuijpers and Othman (2009) to respond to alibi queries on road networks. This paper builds on and extends previous research to develop a time-dependent GIS approach that supports spatiotemporal analysis of travel demands on different critical links in a transportation network.

2.2. Critical transportation infrastructure

In recent years, critical transportation infrastructures (e.g., bridges, tunnels) have received increasing research attention in response to economic, security, and emergency planning needs. In general, the literature on critical infrastructure can be grouped into two categories. The first category is related to network structure. Much work has been conducted to identify critical transportation links and the interdependencies of transportation systems. For example, Taylor et al. (2006) used accessibility-based measures to analyze the vulnerability of strategic road networks. Scott et al. (2006) proposed a network robustness index to identify critical links and to evaluate network performance. Jenelius (2009) investigated the effects of network structure and travel pattern on the long-term vulnerability of a road network. Zhang and Peeta (2011) used a multilayer network concept to capture the interdependencies among various infrastructure systems with disparate physical and operational characteristics. Eusgeld et al. (2011) demonstrated the mechanisms leading to interdependencies in critical infrastructures.

The second category focuses on the society and economy. For example, van der Bruggen (2008) developed a concept of responsibility for critical infrastructure that deals with the responsibilities inherent in infrastructure operation and management. Guikema (2009) proposed an approach based on statistical learning theory to assess the impact of natural disasters on large-scale critical infrastructure systems such as electric power distribution, transportation, water supply, and natural-gas supply systems. Bröcker et al. (2010) presented a spatial computable general equilibrium (SCGE) model to estimate the spatial distribution of social well-being effects generated by investments in transport infrastructure. Cohen (2010) reviewed the importance and challenges of protecting critical infrastructure. We focus on spatiotemporal analysis of alternative travel paths between each O–D pair which pass through critical links.

2.3. Origin–destination estimation

Origin–destination (O–D) information is essential to traffic assignment models which aim at predicting traffic network flow patterns and generate traffic control strategies (Zhou and Mahmassani, 2006). O–D estimation methods can be classified into three general approaches. The first approach is based on data collected from travel diary surveys. Travel diary surveys usually use face-to-face interview (Brög et al., 1983), place-based trip diary (Harvey, 2003; Battellino and Peachman, 2003), or activity diary (Harvey, 2003) to estimate O–D information. Such surveys often are expensive and time-consuming to conduct and result in relatively small sample sizes (Stopher and Greaves, 2007).

The second approach uses traffic count data. Willumsen (1978) reviewed methods of estimating an O–D matrix based on traffic counts and discussed three types of models (calibrating gravity-based models with the observed counts, network equilibrium model, and entropy maximizing model) for O–D estimation. Yang et al. (1992) estimated O–D matrices from link traffic counts on congested networks to integrate the generalized least squares technique into an equilibrium traffic assignment. Zhou and Mahmassani (2006, 2007) proposed a dynamic O–D estimation method to derive day-to-day demands from automatic vehicle identification (AVI) counts, which sampled population OD split fractions from point-to-point AVI counts and extracted OD-demand distribution information. Lou and Yin (2010) presented a decomposition framework for estimating dynamic O–D flows on actuation-controlled signalized arterials from link counts. These studies offer different O–D estimation methods for dynamic traffic assignment models to predict traffic network flows (Zhou and Mahmassani, 2006). However, a major shortcoming of traffic count data is that the data do not indicate the O–D locations.

The third approach takes advantage of location-aware technologies such as global position system (GPS) and mobile phone tracking to collect details trip information (Wilson, 2004). This approach can record time and location associated with an individual's trajectory over an extended period of time at an affordable level. Wolf et al. (2007) used GPS tracking data of personal vehicles to derive information collected from a conventional travel diary survey such as O–D and trip purpose. Bohte and Maat (2009) estimated the travel mode, trip purpose, and the location of trip ends from GPS data. This study also uses GPS tracking data of almost all taxis in Wuhan, China. However, our objective is not on O–D estimation since our taxi tracking data include the time and location when passenger get on and off a taxi. We instead focus on spatiotemporal analysis