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Exploring the spatiotemporal structure of dynamic urban space using metro smart card records

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ABSTRACT

The wide application of pervasive computing technology has allowed for the emergence of big data on spatial behavior and therefore provides an opportunity to explore dynamic urban space. In this paper, an eigendecomposition method is proposed to capture the common patterns of passengers' variation over time among all metro stations as well as to explore the spatial heterogeneity of the dynamic space around the metro stations based on the common patterns with low dimensional structures. Using Shenzhen as a case study, four datasets for check-in/check-out and weekday/weekend are decomposed to obtain the principal components (PCs) and eigenvectors. The first several PCs are the most common patterns of passengers' variation over time among all metro stations, while the corresponding elements in the eigenvectors, referred to as EigenStation in this paper, can describe the characteristics of the metro station. The decomposition result is evaluated at both the aggregation and individual station levels, and the result demonstrates that the first two elements of the EigenStation can approximate the original dataset. The EigenStation vector angle, i.e., ω, is used to represent the structure of the EigenStation, and its value is highly related to the land use structure around the metro stations. The proposed method can provide deep insight into static and dynamic urban spaces, which can help improve urban planning around metro stations.

1. Introduction

With wide applications of wireless communication, global position system (GPS), pervasive computing technology, and WEB 2.0, big data on spatial behavior can reveal human mobility patterns at very refined temporal and spatial resolutions and thus sense the socioeconomic environments in an urban system (Liu et al., 2015a). Passively acquired spatial behavior data such as mobile telephone data (Bagrow & Lin, 2012; Onnela et al., 2007; Phithakkitnukoon, Smoreda, & Olivier, 2012; Nobis & Lenz, 2009), the trajectories of floating cars (Liao, Patterson, Fox, & Kautz, 2007; Rhee et al., 2011; Scholza & Lu, 2014; Wang, Pan, Yuan, Zhang, & Liu, 2015), smart card data (Gong et al., 2012; Morency, Trépanier, & Agard, 2006; Tao, Rohde, & Corcoran, 2014), Wi-Fi and Bluetooth data (Calabrese, Reades, & Ratti, 2010; Eagle & Pentland, 2006, 2009; Perttunen, Kostakos, Riekki, & Ojala, 2014), and actively acquired data such as social media check-in data (Noulas, Scellato, Lambiotte, Pontil, & Mascolo, 2012) can reveal the spatial and temporal patterns of individual behaviors. Using the circulation of bank notes, Brockmann, Hufnage, and Geise (2006) reported the scale-free laws and fat tail distribution of travel distance with a two-parameter random walk model. González, Hidalgo, and Barabási (2008) studied the trajectory of 100,000 anonymous mobile telephone users over 6 months to characterize the high regularity of spatial and temporal behavior and the significant probability of visiting a few places. Their data indicated predictable and reproducible spatial patterns within the diversity of individual spatial behavior (González et al., 2008). Despite studies from the physics and complex networks communities, much effort has been made to explore the spatiotemporal pattern under a specific context and its relationship with the built environment or the social context from the geographic aspect. With the use of taxi trajectories (Liu, Wang, Xiao, & Gao, 2012) and metro smart card data (Gong et al., 2012), it was reported that human activity is highly related to land use in urban space at the neighborhood scale. For example, the spatial concentration of human activity is highly related to the intensity of land use development, and the temporal variation of human activity is highly related to the distribution of different land use types. Kang, Ma, Tong, and Liu (2012) identified the exponential law of human mobility distance inside urban spaces using mobile telephone data from eight cities in northeast China and revealed the variation of the exponents among the cities related to their compactness, shapes, and sizes. Other

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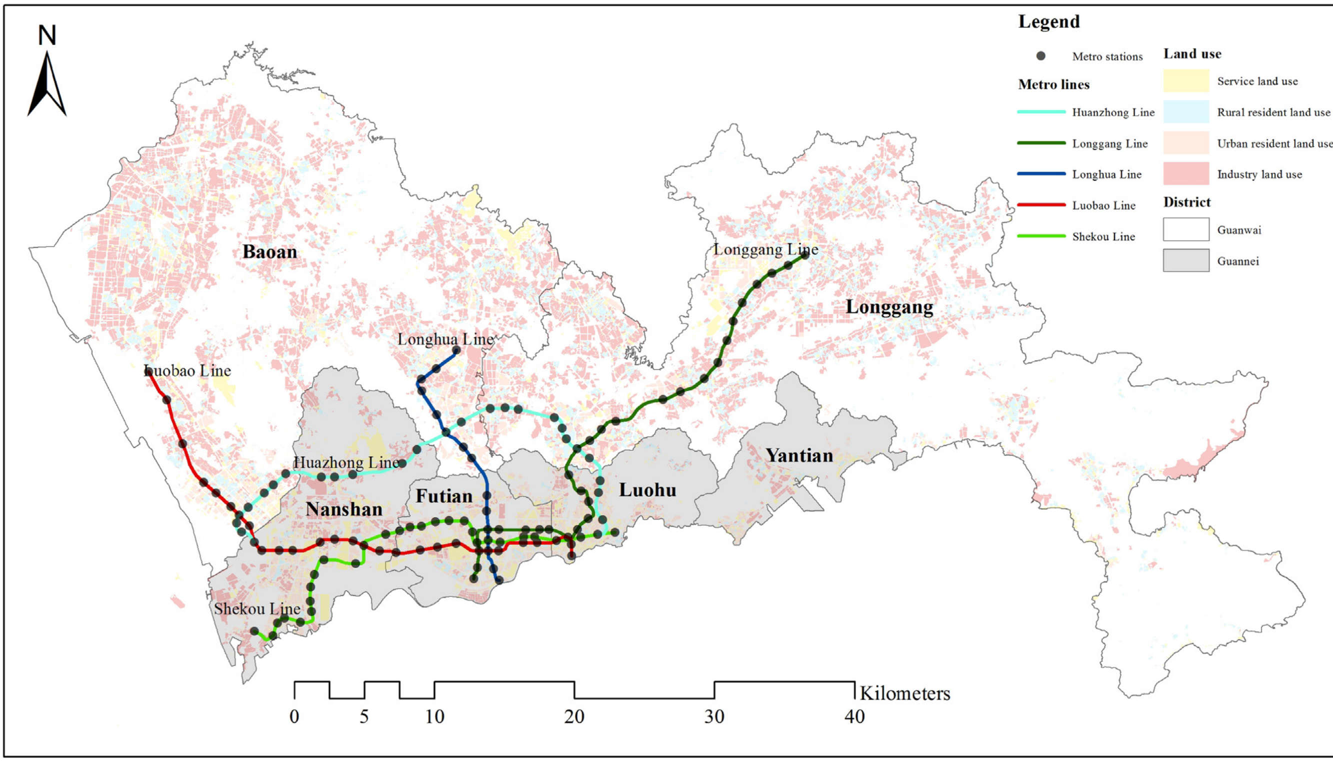

Fig. 1. Metro lines in Shenzhen.

studies have focused on the detection of the urban polycentric and layered concentric structures using taxi trajectory data (Liu, Gong, Gong, & Liu, 2015). The increasing amount of big data on spatial behavior provides a very promising source with which to identify human mobility patterns.

Among all types of spatial behavior big data, continuously observed smart card data from automated transit fare collection systems have received much attention because public transit plays an important role in the urban system. The smart card data from public transit can reveal the usage of public transit in urban space and therefore can be utilized to improve the transit service at operational, tactical, or strategic levels (Pelletier, Trépanier, & Morency, 2011). One of the most important applications of smart cards in urban planning was to facilitate the collection of an origin–destination matrix (Munizaga & Palma, 2012; Nassir, Hickman, & Ma, 2015; Tamblay, Galilea, Iglesias, Raveau, & Muñoz, 2016), which was a critical but costly task in the traditional household travel survey. The smart card data were also exploited to combine with household travel survey data to estimate the behavioral attributes of trips (Kusakabe & Asakura, 2014) or to evaluate jobs–housing relationships in urban spaces (Long & Thill, 2015). Because smart card data were very refined in spatial and temporal granularity, these data can be used to explore the spatiotemporal patterns of public transit passengers (Tao et al., 2014) or to measure the variability of human mobility (Zhong, Manley, Arisona, Batty, & Schmitt, 2015).

Big data can record continuous spatial behavior varying over time and space, which is much different from traditional household travel survey data. Several studies have attempted to uncover the spatiotemporal structure of urban space using eigendecomposition methods. Eagle and Pentland (2009) used eigenbehavior to identify the daily behavior structure at an individual level and to detect communities in the social network of a population with the use of integrated mobile telephone data. An eigen-based method, eigenplace, was adopted to capture the common patterns of several days' spatial behavior over hours for each place using mobile telephone data as well as to identify the characteristics of each place by comparing both the common patterns and the loadings of different days in different places (Reades, Calabrese, & Ratti, 2009). This study, however, found it difficult to characterize each place when there were a large number of places because the pattern is only applicable to each place. Another eigen-based study decomposed aggregated Wi-Fi access records from more than 3000 access points over time on campus to capture many eigenvector and coefficient pairs (Calabrese et al., 2010). As the eigenvectors were common for all places, each place could be identified by seven coefficients, but the characteristics of the places could not be clearly compared when there were a large number of places.

In this study, an eigendecomposition method is adopted to capture the spatiotemporal structure of travel behavior in an urban space using metro smart card datasets. The proposed eigendecomposition method computes the principal components (PCs) and the corresponding loadings for all metro stations to 1) capture the common underlying patterns of urban dynamics among all metro stations in the urban space; 2) characterize the dynamic space around the metro stations with low dimensional structures; and 3) analyze the relationship between urban dynamic space and static space (i.e., land use) around the metro stations. The contributions of our work involve two main areas. First, we capture the most common patterns of passengers' variation over time among all metro stations and examine the spatial heterogeneity of the dynamic space of metro stations based on the common patterns. Passengers checking in or checking out of metro stations over time can be decomposed into PCs as the variation patterns. The first few PCs imply the most common patterns of passengers' variation among all metro stations. We take the first two elements of eigenvector as coordinate x and coordinate y to construct a vector, named the EigenStation in this paper, and plot the vector to clearly compare the characteristics of the metro stations using low dimension structures in a unified manner. The second contribution is that we uncover the relationship between the structure of the EigenStation and the structure of the land use around the metro stations. The relationship between the