Transportation Research Part B 114 (2018) 147–170

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

A mobility network approach to identify and anticipate large crowd gatherings

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ARTICLE INFO

Article history:
Received 4 December 2017
Revised 23 May 2018
Accepted 24 May 2018

Keywords:
Human mobility
Large crowd gatherings
Complex networks
Collective behavior

ABSTRACT

The study of large crowd gatherings combines aspects of longer-range human mobility with site-specific pedestrian dynamics. Recently, substantial progress has been made in understanding the collective behaviors of crowds on the site-specific scale. Yet, the human mobility aspect remains vague in terms of how large crowds come together in the first place. Using high-resolution human mobility data in form of millions, potentially real-time, subway and taxi records, our approach uncovers the mobility patterns involved in large crowd gatherings. In addition, we discriminate anomalous mobility fluxes from ordinary mobility fluxes by introducing the concept of anomalous mobility networks, within which nodes are traffic zones and links are defined via the Jensen-Shannon divergence. Our approach allows for easy identification of occurrence, location and developing stages of crowd formation. Strikingly, within the anomalous mobility networks, we find high-stress crowd density to be preceded by a node in-degree k_{in} surpassing the critical threshold k_c, typically preceding the maximum crowd density by a couple of hours, enabling us to anticipate large crowd gatherings via a surprisingly simple approach based on the simple network index k_{in}.

1. Introduction

Many cities, especially in developing countries, are experiencing a serious imbalance between an explosively growing demand for space and limited resources of land (Makse et al., 1995; Bettencourt et al., 2007; Batty, 2008; Bettencourt, 2013). This imbalance is particularly exacerbated during large crowd gatherings, where an extraordinarily large number of people gather in confined areas. In the last five years, resulting crowd disasters have witnessed nearly 3000 fatalities all over the world (List of human stampedes, 2017). A variety of approaches, ranging from the social force model, fluid-dynamics, cellular automata to cognitive science approaches, animal experiments, and video analysis, have been proposed to study the collective behaviors of crowds. These approaches offer knowledge and rules for designing better space geometries and achieving better crowd organization or guidance. Yet, particularly in locations that are not subject to regular scheduled and well controlled occurrences of large crowds, such as public squares, or recreational parks, substantial difficulty remains

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https://doi.org/10.1016/j.trb.2018.05.016
0191-2615/

to evacuate people both safely and rapidly when partially unforeseen high-density crowds have already formed. So, while locally organizing overly crowded groups of people remains an important challenge, there can be no doubt that there is a desire for additional methods of anticipation to pre-emptively confine crowd density within a safe range. The present study employs long-period and high-resolution human mobility data obtained for Shenzhen, a major city in China. The aims are to estimate the crowd density and reveal the mobility patterns involved in large crowd gatherings, and thereby to provide valuable insight to anticipate and avoid dangerous crowding states.

Two research areas are related to our work: One research area is crowd dynamics, which studies the collective behaviors of crowds on the site-specific scale. The other research area is human mobility, which studies the laws of individual or collective human travels.

A variety of approaches have been proposed to study the collective behaviors of crowds on the site-specific scale (Haghani and Sarvi, 2018). A fluid-dynamics approach, in which crowd movement is seen analog to gas or liquid, was developed to measure the moving velocities of different types of crowds (Henderson, 1971). The social force model was proposed to model pedestrian flow and understand the mechanisms of escape panic (Helbing and Molnar, 1995; Helbing et al., 2000). Cellular automata were used to simulate crowd dynamics in the evacuations from a room (Kirchner et al., 2003) or a university building (Lu et al., 2016). Recently, mean field game theory was employed to model competitive and cooperative behaviors of crowds in crowded space (Cao et al., 2016), and the mixed walking behaviors of able and disabled people was studied (Sharifi et al., 2017). Some studies were performed based on empirical data. Animal experiments were conducted to understand the dynamics of crowding (Saloma et al., 2003; Shiwakoti et al., 2011). A cognitive science approach was used to understand how pedestrians adapt their walking speeds and directions in an indoor environment (Moussaïd et al., 2011). Using video surveillance data, researchers discovered the collective behavior of crowds and the rules for designing better space geometries and achieving better crowd organization (Helbing et al., 2005, 2007; Helbing and Mukerji, 2012; Batty et al., 2003; Pretorius et al., 2015; Haghani and Sarvi, 2017; Feng and Miller-Hooks, 2014).

The second research area is broken into individual and collective human mobility. Research into individual human mobility has experienced rapid developments in recent years. Brockmann et al. (2006) discovered the scaling laws of human travel using the trajectories of bank notes. González et al. (2008) studied the trajectories of 100,000 mobile phone users to uncover the universal laws of individual human travel. Individual human mobility was found to have a surprisingly high predictability that is independent of an individual's age, gender, and travel distance (Song et al., 2010a). Mobile phone data collected during and after the 2010 Haiti earthquake were analyzed to uncover individual human mobility patterns after a disaster (Lu et al., 2012). Based on individuals exploring new places and returning to familiar locations, the human mobility model of exploration & preferential return was proposed (Song et al., 2010b). Using a principal component analysis (PCA) approach, a high accuracy individual movement model was introduced (Eagle and Pentland, 2009). Recently, a stochastic model of randomly accelerated walkers was proposed based on an analysis of private vehicle trajectory data in Italy (Gallotti et al., 2016).

Research into collective human mobility has also experienced rapid developments. Sevtsuk and Ratti (2010) studied aggregate patterns of urban mobility in Rome. Giannotti et al. (2011) developed a knowledge discovery approach to transform raw GPS trajectory data into aggregate mobility patterns. Simini et al. (2012) proposed the radiation model that is parameter-free and was demonstrated to perform better than the well-known gravity models. The radiation model was further improved by incorporating travel cost information and used to predict traffic flows in US highways (Ren et al., 2014). The radiation model was furthermore improved by considering the opportunities of locations (Yan et al., 2014). A method to extract coarse-grained human mobility information from origin-destination (O-D) matrices was developed by Louail et al. (2015). Multi-mode human mobility was studied using the probabilistic tensor factorization (Sun and Axhausen, 2016). Recently, a universal model which simultaneously considered individual and population mobility on diverse spatial scales was proposed (Yan et al., 2017). Machine learning approaches, such as clustering (Dong et al., 2015; Fan et al., 2015), Gradient Boosting Decision Trees (Zhou et al., 2018) and deep learning (Zhang et al., 2017), were also employed to predict short-term crowd flows.

2. Data

2.1. Geographic information data on urban traffic zones

In this study, we obtained and employed long-period and high-resolution human mobility data for Shenzhen. To measure the mobility fluxes, the geographic area of Shenzhen is partitioned using the layout of traffic zones provided by the Shenzhen Transportation Authority (Fig. 1). One problem with the raw data was that subway stations are usually located at the intersection or boundary of several traffic zones rather than located at a central point of a zone that covers the area within walking distance from the station. To confine the region where a passenger resides after exiting a subway station, traffic zones around each subway station were divided into smaller regions comprising street blocks with higher spatial resolution. Street blocks within a Euclidean distance of 500 m of the station were reassembled to generate a new traffic zone. Street blocks not assigned to any subway station were also reassembled to generate new traffic zones based on spatial proximity. The adjusted traffic zones (996 in total) were maintained at a size that deviated only within an allowable range from the sizes of the original zones.