Computers, Environment and Urban Systems 64 (2017) 332–343

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

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

Scaling laws of spatial visitation frequency: Applications for trip frequency prediction

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ARTICLE INFO

Article history:
Received 12 July 2016
Received in revised form 10 April 2017
Accepted 11 April 2017
Available online xxxx

Keywords:
Human mobility
Scaling laws
Urban dynamic
Transport prediction
Built environment

ABSTRACT

The relationship of the built environment to human travel is one of the mainstream themes in urban studies. It provides a foundation for transport prediction. The existing literature is limited in accuracy when predicting spatial temporal travels from built environment. Understanding the scaling laws of spatial visitation frequency sheds new light on the issue. The scaling laws connect travel and the built environment by ordered-rankings, which make it possible to predict the number of arrivals from environmental variables. This research analyses the scaling laws of dynamic spatial visitation frequency using taxis' global positioning system (GPS) records, and proposes a model to predict spatial temporal arrivals from points of interest (POIs). The results show that: (i) the scaling law of spatial visitation frequency is exponential; (ii) the exponential scaling law is explained by the linear preferential attachment effect and a logarithmic travel growth process; (iii) the exponential scaling law is not sensitive to time; (iv) the proposed model predicts spatial temporal arrivals with high accuracy (R^2>0.6).

1. Introduction

Uncovering the relationship between the built environment and human travel is of research interest in urban studies. Understanding the influence of the built environment has the potential to provide guidance for transport prediction. Travel is generally defined as the displacement of individuals and measured by frequency, length, modes and purposes (Handy, Boarnet, Ewing, & Killingsworth, 2002). The built environment is measured by environmental variables such as density, diversity, design, destination accessibility, distance to transit (Ewing & Cervero, 2010), and land-use (Crane, 2012). The analysis of the built environment and travel relationship can be in the aggregate level of traffic zones or in the disaggregate level of the individual/household (Handy, 1996). Examining the influence of the built environment on travel is a long research tradition in both aggregate analysis (Aljoufie, Zuidgeest, Brussel, van Vliet, & van Maarseveen, 2013; Ewing, Hamidi, Gallivan, Nelson, & Grace, 2014; Holtzclaw, Clear, Dittmar, Goldstein, & Haas, 2002) and disaggregate analysis (Cervero & Kockelman, 1997; Chao & Qing, 2011; Crane & Crepeau, 1998; Dieleman, Dijst, & Burghouwt, 2002; Ewing & Cervero, 2001; Fan & Khattak, 2009; Meurs & Haaijer, 2001; Zhang, 2005). Despite the appeal of this fruitful research, there are still challenges in predicting travel frequency with high accuracy because of the limit of predictability in human mobility (Lu, Wetter, Bharti, Tatem, & Bengtsson, 2013; Song, Qu, Blumm, & Barabási, 2010). Generally, spatial travel frequency is assumed to be a function of environmental variables, and a rigorous mathematical relationship is required. However, it is not fully clear which particular mathematical form (linear, power, exponential, polynomial, etc.) is the most appropriate for the prediction function. Predicting travel frequency from environmental variables is also highly dependent on the spatial context. As geographical heterogeneity varies in different spatial contexts, it is challenging to summarise a universal regularity of the built environment and travel frequency relationship.

Scaling laws of human mobility in complex systems may shed light on this issue. The scaling laws uncover statistical patterns of human mobility by finding probabilistic distributions of mobility variables. The main research interests in the scaling laws of mobility are spatial density (Makse, Havlin, & Stanley, 1995; Rozenfeld, Rybski, Andrade, Batty, Stanley et al., 2008; Yuan, Raubal, & Liu, 2012) and movement displacement (Calabrese, Di Lorenzo, & Ratti, 2010; Jiang, Yin, & Zhao, 2009; Krings, Calabrese, Ratti, & Blondel, 2009; Liang, Zheng, Lv, Zhu, & Xu, 2012; Liu, Kang, Gao, Xiao, & Tian, 2012; Yan, Han, Wang, & Zhou, 2013; Zheng, Rasouli, & Timmermans, 2016). Visitation frequency, or spatial travel density (see Liu, Gong, Gong, & Liu, 2015), reveals the probability of an individual's arrival at a specific location. The higher visitation frequency a location has, the more likely it is to attract visitors. The frequency-ranking law defines a relationship between visitation frequency and an ordered-ranking of a location. As the mathematical

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http://dx.doi.org/10.1016/j.compenvurbsys.2017.04.004
0198-9715/

relationship in scaling laws is rigorous, visitation frequency can be estimated from the given ordered-ranking of a location. At the same time the rankings can be empirically estimated from built environment variables. Two relationships are accordingly built: visitation frequency and locational ranking, locational ranking and the built environment. Therefore, a transport prediction model can be hopefully built using the scaling laws.

There is great value for doing so. Theoretically, this approach is advantageous for traditional models as it introduces locational rankings. First, a rigorous mathematical relationship can be defined. Travel frequency is seen as a function of ordered-ranking, rather than environmental variables. It is easier to find and explain the mathematical regularity of the frequency-ranking law. Second, the relationship of locational ranking and the built environment is more relaxed. It is not necessary to apply a mathematical relationship to rankings and environmental variables. All locations are ranked via criteria of environmental variables. If the environmental criteria of location A are greater than location B, the ranking of A is then superior to B. Rankings provide relative comparisons among locations. For A to be superior to B only requires greater environmental criteria for A, regardless of how much greater A is. Such a relaxed relationship adapts to geographical heterogeneity: locational rankings, which are estimated from environmental variables, may differ in different spatial contexts. The geographical heterogeneity effect is reduced as long as locational rankings are properly estimated. Practically, predicting visitation frequency from spatial facilities, improves adjusting planning and transportation policies for urban planners. Cities in developing countries are experiencing fast changes in land uses and spatial facilities, thus raising great challenges in transportation planning and management. New town construction and city regeneration generate great traffic volumes. The prediction model can provide support in forecasting traffic volumes from land-use changes and newly constructed facilities.

The purpose of this research is to find the dynamic scaling laws in spatial visitation frequency, and to propose a transport prediction model. Human travel in this research is represented by arrival behaviour, and arrivals are identified by drop-off points from taxis' global positioning system (GPS) records. Generally, transport can be predicted from trip generation (Moreira-Matias, Gama, Ferreira, Mendes-Moreira, & Damas, 2013), trip attraction (Giannotti et al., 2011), or both (Black, 2003). The ability to attract travellers directly reflects the influence of the built environment on travel. The number of spatial arrivals, or spatial visitation frequency, is a straightforward measurement of the attractiveness of the built environment. This research uses points of interest (POIs) to represent the built environment. Spatial density of POIs reflects spatial attractiveness, and types of POIs reflect spatial function. Moreover, accessibility of POIs is sensitive to time of day, such that different POIs types have different opening time windows and temporal attractiveness (Gong, Liu, Wu, & Liu, 2015). Therefore, using POIs as a representation of the built environment, means the prediction model is sensitive to dynamic daily travels. The contribution of this work is accordingly twofold. First, the scaling law of spatial visitation frequency and its underlying mechanism is uncovered. The key to understanding the scaling laws lies in the preferential attachment mechanism and travel growth process. Second, a transport demand prediction model is built. Spatial arrivals depend on locational rankings, and locational rankings depend on POIs density. The innovation is in the simplicity of the model: it predicts dynamic spatial arrivals from POIs density.

2. Related works

2.1. Built environment and human travel

The relationship of the built environment and human travel has a long research tradition in transportation and urban studies. A review of relevant works can be found in Handy (1996) for early studies and Ewing and Cervero (2010) for recent studies. This section briefly introduces new research trends since 2010.

With the development of information and communication technology (ICT), collecting large volume data becomes an alternative approach to studying human travel. Various data sources (floating car data, mobile phones, transit check-ins, social media, etc.) provide new insights into human travel. There are two aspects to innovations from the usage of big data. First, it is possible to discover spatial distribution of daily travels. Traditional travel diary surveys use random sampling to represent the whole population. However a small sample cannot fully represent the spatial travel patterns of the whole population. Alternatively big data are good representatives of spatial travel patterns. Second, points of interest (POIs) have the potential to be new measurements of the built environment. Traditionally, the built environment is characterised by variables beginning with 'D', the original 'three Ds' of density, diversity and design (Cervero & Kockelman, 1997), and later 'six Ds' of additional destination accessibility, distance to transit and demand management (Ewing & Cervero, 2010). The function of the built environment is important. Residential and work function can be measured by population density and job density, but commercial, recreational, public service, etc. functions are less discussed. POIs data of spatial facilities are good supplements for the functions of the built environment.

Veloso, Phithakkitnukoon, and Bento (2011) formulated a taxi trip prediction model based on POIs. Given the drop-off area type (identified by POIs), temporal variables and weather condition, the probability of pick-up area type can be predicted with an accuracy of 54%. Huang, Li, and Yue (2010) identified POIs temporal attractiveness from GPS traced data. It contributes to a shortcoming of environmental variables - not sensitive to time. Thus it is possible to predict temporal trips from POIs. Several works examined the qualitative relationship of travel and the built environment. For example, Liu, Kang, et al. (2012) compared the spatial density of taxi trips and population density. They found taxi trip distribution is more concentrated in the city centre rather than according to population distribution. Using mobile phone massive data, Kang, Ma, Tong, and Liu (2012) examined how urban morphology influences human travels. Large or less compact cities have larger numbers of trips, and an irregular shape of a city constrains local movements but brings more long trips. Peng, Jin, Wong, Shi, and Lio (2011) identified taxi trips purposes as commuting, business and other, and examined the interaction with locational function. Pan, Qi, Wu, Zhang, and Li (2013) found taxi travel dynamics exhibited clear patterns corresponding to land-use classes. Liu, Wang, Xiao, and Gao (2012) examined how land-use types affected daily trip generation using taxi GPS traces.

Rich literature examined the influence of the built environment on travel, while the usage of big data makes it possible to discover the reverse relationship - identifying environmental information from travel. Four types of land-use (residential, commercial, recreational and industrial) were successfully identified from the spatial and temporal distribution of taxi trips (Liu, Wang, et al. 2012). In other research (Pan et al., 2013) land-use classes were identified from taxi pick-up points (PUPs) and drop-off points (DOPs) with an accuracy of 95%. Yuan, Zheng, and Xie (2012) used 2-year POIs datasets and 3-month taxi GPS trajectory datasets and formulated a topic-based inference model. The result showed a region is represented by a distribution of human mobility patterns. Using London subway 'Oyster' card data, Roth, Kang, Batty, and Barthélemy (2011) found a poly-centric structure for large flows, and a mixed hierarchy structure for small flows. Taxi trips well reflect urban space function and temporal variation.

From the above brief review, it can be seen that the quantitative relationship of trip frequency (from big data) and the built environment is less discussed. Our research contributes to current studies by formulating a quantitative model linking trip frequency and POIs density.

2.2. Scaling laws in urban studies

Spatial visitation frequency can be measured by two approaches: frequency-ranking laws or frequency probability distributions. The