Journal of Transport Geography 51 (2016) 158–169

Contents lists available at ScienceDirect

Journal of Transport Geography

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

Systematic comparison of trip distribution laws and models

Maxime Lenormand *, Aleix Bassolas, José J. Ramasco

Instituto de Física Interdisciplinar y Sistemas Complejos IFISC (CSIC-UIB), Campus UIB, 07122 Palma de Mallorca, Spain

ARTICLE INFO

Article history:
Received 6 July 2015
Received in revised form 16 December 2015
Accepted 26 December 2015
Available online xxxx

Keywords:
Trip distribution
Gravity law
Intervening opportunities law
Radiation law
Commuting networks

ABSTRACT

Trip distribution laws are basic for the travel demand characterization needed in transport and urban planning. Several approaches have been considered in the last years. One of them is the so-called gravity law, in which the number of trips is assumed to be related to the population at origin and destination and to decrease with the distance. The mathematical expression of this law resembles Newton's law of gravity, which explains its name. Another popular approach is inspired by the theory of intervening opportunities which argues that the distance has no effect on the destination choice, playing only the role of a surrogate for the number of intervening opportunities between them. In this paper, we perform a thorough comparison between these two approaches in their ability at estimating commuting flows by testing them against empirical trip data at different scales and coming from different countries. Different versions of the gravity and the intervening opportunities laws, including the recently proposed radiation law, are used to estimate the probability that an individual has to commute from one unit to another, called trip distribution law. Based on these probability distribution laws, the commuting networks are simulated with different trip distribution models. We show that the gravity law performs better than the intervening opportunities laws to estimate the commuting flows, to preserve the structure of the network and to fit the commuting distance distribution although it fails at predicting commuting flows at large distances. Finally, we show that the different approaches can be used in the absence of detailed data for calibration since their only parameter depends only on the scale of the geographic unit.

1. Introduction

Everyday, billions of individuals around the world travel. These movements form a socio-economic complex network, backbone for the transport of people, goods, money, information or even diseases at different spatial scales. The study of such spatial networks is consequently the subject of an intensive scientific activity (Barthelemy, 2011). Some examples include the estimation of population flows (Murat, 2010; Gargiulo et al., 2012; Simini et al., 2012; Lenormand et al., 2012; Thomas and Tutert, 2013; Lenormand et al., 2014; Yang et al., 2014; Sagarra et al., 2015), transport planning and modeling (Rouwendal and Nijkamp, 2004; Ortúzar and Willumsen, 2011), spatial network analysis (De Montis et al., 2007, 2010), study of urban traffic (De Montis et al., 2007) and modeling of the spreading of infectious diseases (Viboud et al., 2006; Balcan et al., 2009; Tizzoni et al., 2014).

Trip distribution modeling is thus crucial for the prediction of population movements, but also for an explanatory purpose, in order to better understand the mechanisms of human mobility. There are two major approaches for the estimation of trip distribution at an aggregate level. The traditional gravity approach, in analogy with the Newton's law of gravitation, is based on the assumption that the amount of trips between two locations is related to their populations and decays with a function of the distance (Carey, 1858; Zipf, 1946; Wilson, 1970; Erlander and Stewart, 1990). In contrast to the gravity law, the Stouffer's law of intervening opportunities (Stouffer, 1940) hinges on the assumption that the number of opportunities plays a more important role in the location choices than the distance, particularly in the case of migration choices. The original law proposed by Stouffer has been reformulated by Schneider (1959) and extensively studied since then (Heanus and Pyers, 1966; Ruiter, 1967; Wilson, 1970; Haynes et al., 1973; Fik and Mulligan, 1990; Akwawua and Poller, 2001). The two approaches have been widely compared during the second half of the twentieth century (David, 1961; Pyers, 1966; Lawson and Dearinger, 1967; Zhao et al., 2001) showing that generally both approaches performed comparably. However, the simplicity of the mathematical form of the gravity approach appears to have weighted in its favor (Ortúzar and Willumsen, 2011). Indeed, the gravity approach has been extensively used in the past few decades to model, for instance, flows of population (Viboud et al., 2006; Griffith, 2009; Balcan et al., 2009; Murat, 2010; Gargiulo et al., 2012; Lenormand et al., 2012; Thomas and Tutert, 2013; Masucci et al., 2013; Liang et al., 2013; Lenormand et al., 2014; Tizzoni et al., 2014; Liu et al., 2014), spatial accessibility to health services (Luo and Wang, 2003), volume of international trade (Anderson, 1979; Bergstrand, 1985), traffic in transport networks (Jung et al., 2008; Kaluza et al., 2010) and phone communications (Krings et al., 2009).

* Corresponding author.
E-mail address: maxime@ifisc.uib-csic.es (M. Lenormand).

http://dx.doi.org/10.1016/j.jtrangeo.2015.12.008

However, the concept of intervening opportunities has recently regained in popularity thanks to the recently proposed radiation approach (Simini et al., 2012, 2013; Ren et al., 2014; Yang et al., 2014). This approach is inspired by a simple diffusion model where the amount of trips between two locations depends on their populations and the number of opportunities between them. The gravity law and the radiation law have been compared several times during the last years giving the superiority to either of the approaches depending on the study (Simini et al., 2012; Lenormand et al., 2012; Masucci et al., 2013; Liang et al., 2013; Yang et al., 2014). Two main issues can be identified in these comparisons. First, the inputs used to simulate the flows are not always identical. For example, in the comparison proposed in Masucci et al. (2013), the gravity law tested takes as input the population, whereas the radiation law is based on the number of jobs. Second, in all these studies, the models used to generate the trips from the radiation and the gravity laws are not constrained in the same way. The radiation models are always production constrained, this means that the number of trips, or at least an estimation of the number of trips generated by census unit, is preserved. The models used to generate the trips with the gravity laws can be either, unconstrained (Simini et al., 2012; Masucci et al., 2013), only the total number of trips is preserved or doubly constrained (Lenormand et al., 2012; Yang et al., 2014), both the trips produced and attracted by a census unit are preserved. Therefore, to fairly compare different approaches the same input data must be used and, most importantly, we need to differentiate the law, gravity or intervening opportunities, and the modeling framework used to generate the trips from this law. Indeed, both the gravity laws and the intervening opportunities laws can be expressed as a probability to move from one place to another, called trip distribution law, and based on these probability distributions, the total number of trips can then be simulated using different trip distribution models including different level of constraints.

In this work, we test and compare, in a systematic and rigorous way, gravity and intervening opportunities laws against commuting census data coming from six different countries using four different constrained models to generate the networks: unconstrained model, single constrained models (production or attraction) and the well-known doubly constrained model. For the gravity law, since the form of the distance decay functions may vary from one study to another (Fotheringham, 1981; Viboud et al., 2006; de Vries et al., 2009; Balcan et al., 2009; Barthelemy, 2011; Lenormand et al., 2014; Chen, 2015) both the power and the exponential forms are tested to model the impact of the distance. The intervening opportunities law is given by the Schneider's version of the Stouffer's original law as it is usually the case. We also considered two versions of the radiation law, the original free-parameter model (Simini et al., 2012) and the extended version proposed in Yang et al. (2014). The simulated networks are compared with the observed ones on different aspects showing that, globally, the gravity law with an exponential distance decay function outperforms the other laws in the estimation of commuting flows, the conservation of the commuting network structure and the fit of the commuting distance distribution even if it fails at predicting commuting flows at large distances. Finally, we show that the different laws can be used in absence of detailed data for calibration since their only parameter depends only on the scale of the geographic census unit.

2. Data

In this study, the trip distribution laws and models are tested against census commuting data of six countries: England and Wales, France, Italy, Mexico, Spain and the United States of America (hereafter called E&W, FRA, ITA, MEX, SPA and USA, respectively) and two cities: London and Paris (hereafter called LON and PAR, respectively).

- The England & Wales dataset comes from the 2001 Census in England and Wales made available by the Office for National Statistics (data available online at https://www.nomisweb.co.uk/query/construct/summary.asp?mode=construct&version=0&dataset=124).
- The French dataset was measured for the 1999 French Census by the French Statistical Institute (data available upon request at http://www.cmh.ens.fr/greco/adisp_eng.php).
- The Italian's commuting network was extracted from the 2001 Italian Census by the National Institute for Statistics (data available upon request at http://www.istat.it/it/archivio/139381).
- Data on commuting trips between Mexican's municipalities in 2011 are based on a microdata sample coming from the Mexican National Institute for Statistics (data available online at http://www3.inegi.org.mx/sistemas/microdatos/default2010.aspx).
- The Spanish dataset comes from the 2001 Spanish Census made available by the Spanish National Statistics Institute (data available upon request at http://www.ine.es/en/censo2001/index_en.html).
- Data on commuting trips between United States counties in 2000 comes from the United State Census Bureau (data available online at https://www.census.gov/population/www/cen2000/commuting/index.html).

Table 1
Presentation of the datasets.

Case study	Number of units	Number of links	Number of Commuters
England & Wales	8846 wards	1,269,396	18,374,407
France	3645 cantons	462,838	12,193,058
Italy	7319 municipalities	419,556	8,973,671
Mexico	2456 municipalities	60,049	603,688
Spain	7950 municipalities	261,084	5,102,359
United State	3108 counties	161,522	34,097,929
London	4664 output areas	750,943	4,373,442
Paris	3185 municipalities	277,252	3,789,487

Each case study is divided into n census units of different spatial scale: from the Output Area in London with an average surface of 1.68 km^2 to the counties in the United States with an average surface of 2596.8 km^2. See Table 1 for a detailed description of the datasets.

Figs. 1 and 2 display the centroids of the census units for the eight case studies. For each unit, the statistical offices provide the following information:

- T_{ij}, the number of trips between the census units i and j (i.e. number of individuals living in i and working in j);
- d_{ij}, the great-circle distance between the unit i and the unit j computed with the Haversine formula;
- m_i, the number of inhabitants in unit i.

In this work we consider only inter-unit flows (i.e. $T_{ii}=0$), mainly because it is not possible to estimate intra-units flows with the radiation laws.[1] We note $N=\sum_{i,j=1}^{n}T_{ij}$ the total number of commuters, $O_i=\sum_{j=1}^{n}T_{ij}$ the number of out-commuters (i.e. number of individuals living in i and working in another census unit) and $D_j=\sum_{i=1}^{n}T_{ij}$ the number of in-commuters (i.e. number of individuals working in j and living in another census unit).

3. Comparison of trip distribution laws and models

The purpose of the trip distribution models is to split the total number of trips N in order to generate a trip table $\tilde{T}=(\tilde{T}_{ij})_{1\le i,j\le n}$ of the estimated number of trips form each census area to every other. Note that

[1] Note that it is possible to estimate intra-unit flows with the gravity laws by approximating intra-unit distances with, for example, half the square root of the unit's area or half the average distance to the nearest neighbors.