Computers, Environment and Urban Systems 45 (2014) 78–88

Contents lists available at ScienceDirect

Computers, Environment and Urban Systems

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

Synthesising carbon emission for mega-cities: A static spatial microsimulation of transport CO_2 from urban travel in Beijing

Jing Ma *, Alison Heppenstall, Kirk Harland, Gordon Mitchell

School of Geography, University of Leeds, Woodhouse Lane, Leeds LS2 9JT, UK

ARTICLE INFO

Article history:
Received 8 November 2013
Received in revised form 12 February 2014
Accepted 13 February 2014
Available online 12 March 2014

Keywords:
Spatial microsimulation
Simulated annealing
Travel behaviour
Transport CO_2 emission
Beijing

ABSTRACT

Developing low carbon cities is a key goal of 21st century planning, and one that can be supported by a better understanding of the factors that shape travel behaviour, and resulting carbon emissions. Understanding travel based carbon emissions in mega-cities is vital, but city size and often a lack of required data, limits the ability to apply linked land use, transport and tactical transport models to investigate the impact of policy and planning interventions on travel and emissions. Here, we adopt an alternative approach, through the development of a static spatial microsimulation of people's daily travel behaviour. Using Beijing as a case study, we first derive complete activity-travel records for 1026 residents from an activity diary survey. Then, using the 2000 population census data at the sub-district level, we apply a simulated annealing algorithm to create a synthetic population at fine spatial scale for Beijing and spatially simulate the population's daily travel, including trip distance and mode choice at the sub-district scale. Finally, we estimate transport CO_2 emission from daily urban travel at the disaggregate level in urban Beijing.

1. Introduction

1.1. Contextual background

The transport sector is a major source of greenhouse gases, and has the fastest growth in CO_2 emission of any sector (Yan & Crookes, 2009). It is estimated that transport produced the largest increase in global CO_2 emissions from 1970 to 2004 and was responsible for 23% of all energy-related CO_2 emissions in 2005 (IPCC., 2007). With increasing travel demand and car usage, it is projected that transport CO_2 emissions globally will grow by nearly 50% to 2030, and by more than 80% by 2050 (IEA., 2009). Clearly, the transport sector has a key role to play in achieving the energy saving, energy diversification and carbon emission reduction goals of the international community (e.g. Kyoto protocol) and national governments (e.g. China's current Five-Year Plan).

Accurately estimating transport CO_2 emission is an important task, which can be tackled using one of two main approaches. The first is to estimate CO_2 emissions using aggregate data on total energy consumed or the size of vehicle fleet and average vehicles kilometres travelled (VKT) per vehicle. This 'top-down' approach is straightforward and has been widely used (Dhakal, 2009; Hu, Chang, Li, & Qin, 2010), including in China, where on the basis of fuel consumption Cai et al. (2012) estimated CO_2 emissions from transport at national and regional levels for 2007. However, application of this approach at the urban scale is often constrained by poor data, particularly a lack of reliable data on the vehicles fleet in the city, its city-wide energy use, and the average distance travelled per vehicle (He et al., 2013). Furthermore, this approach is unable to directly link travel behaviour with land use patterns or urban development policies. For example, it is known that a city's physical form (urban form features) influence the distance people travel each day, their choice of mode, and resulting CO_2 emission (Grazi, van den Bergh, & van Ommeren, 2008).

In contrast, the second approach is to estimate emissions from less aggregate travel attributes, including trip frequency, mode choice and vehicle kilometres travelled for each trip (e.g. He et al., 2013). This 'bottom-up' method can not only differentiate CO_2 emission from different types of vehicles, but also help to understand the influence that other factors (e.g. socio-demographic or urban form characteristics) have on carbon emissions, and hence is useful for examining how much emissions may respond to development scenarios or strategic policy and plan interventions (noting that factors such as fuel type, speed, and road condition are also influential; Cai et al., 2012). This approach is prevalent in urban air quality (and CO_2 emission) analyses but such studies rarely address people's travel behaviour at the individual

* Corresponding author. Tel.: +44 7741151376.
E-mail address: gyjm@leeds.ac.uk (J. Ma).

http://dx.doi.org/10.1016/j.compenvurbsys.2014.02.006
0198-9715/

level or account for urban form. This is likely due to the large amount of detailed data required on travel behaviour for large populations, which is not usually available, particularly in the case of fast growing mega cities in developing economies such as China.

Here, we present a new 'bottom-up' methodology to provide improved transport CO_2 emissions based on individuals' observed daily travel behaviour. We employ static spatial microsimulation, and generate a realistic synthetic population at fine geographical resolution as a basis from which to model the entire population's daily travel and subsequently their CO_2 emission. The method provides an alternative means to estimate transport CO_2 emissions, and provides a means to gain greater insight into the spatial variability of the emission at micro-scale than has previously been possible. Following a brief review on spatial microsimulation, we present the case study and its data sources, and then detail how the microsimulation model is developed within the Flexible Modelling Framework using a simulated annealing technique. Constraint specification and model validation is then discussed. Finally, we present and discuss results of the population synthesis and spatial simulation of urban travel and CO_2 emission.

1.2. Spatial microsimulation

Spatial microsimulation was developed in the field of economics (Orcutt, 1957), and has since been applied in the fields of geography (Ballas & Clarke, 2000; Birkin & Clarke, 1988; Wu, Birkin, & Rees, 2008) and social sciences (Brown & Harding, 2002; Rakowski, Gruziel, Krych, & Radomski, 2010). For example, using the 1991 UK Census Small Area Statistics (SAS) and British Household Panel Survey (BHPS), Ballas et al. (2005) applied the deterministic reweighting method to spatially and dynamically simulate the entire population of Britain to 2021 at the small area level. Such microsimulation can be performed for a range of heterogeneous subgroups at different spatial scales, and represents a useful tool for addressing policy-sensitive problems, generating long-term forecasts and evaluating government policies (Mannion, Lay-Yee, Wrapson, Davis, & Pearson, 2012; Miller, Douglas Hunt, Abraham, & Salvini, 2004).

In the transport field, problems of congestion, air pollution, and energy consumption have raised interest in the use of microsimulation of travel since the 1990s (Goulias, 1992; Kitamura, Chen, Pendyala, & Narayanan, 2000). Microsimulation modelling has been used to replicate the temporal, spatial and modal decisions of observed activity-travel patterns and predict the aggregate behaviour of a large numbers of individuals. Models include UrbanSim in the USA (Waddell, 2002), ILUTE (integrated land use, transportation, environment) in Canada (Miller et al., 2004), and RAMBLAS (regional planning model based on the micro-simulation of daily activity patterns) in Europe (Veldhuisen, Kapoen, & Timmermans, 2000). These microsimulators are developed as econometric models using multinomial logit or regression techniques, and aim to generate synthetic travel patterns using Monte Carlo simulation. However, these modelling systems require large samples of travel data to derive the required conditional or transition probabilities, and rarely account for transport CO_2 emissions in their framework.

Whilst transport problems are serious in transitional countries and in the developing world, microsimulation of travel has to date remained the preserve of developed economies (Yagi & Mohammadian, 2010). There are several possible reasons for this lack of microsimulation application to the transport problems of developing countries. First, there is a general lack of expertise in the technique, and model development is challenging requiring a high level of programming skills. Second, there is little publicly available software suited to transport microsimulation problems; those models that do exist have a rigid design and generally require large samples of very specific data (Geard, McCaw, Dorin, Korb, & McVernon, 2013).

A third explanation is a lack of data at an appropriate scale. Microsimulation addresses individuals, households, or firms as the basic analytical unit (Merz, 1991), and requires detailed information at the microscale. However, large micro scale datasets are generally lacking in many, and particularly developing, countries. In China, there is no national travel survey or published governmental large sample of detailed travel information (Long, Shen, & Mao, 2011; Pucher, Peng, Mittal, Zhu, & Korattyswaroopam, 2007). Even for the population census conducted every ten years, the Chinese government only publishes a selection of demographic tabulations at relatively coarse geography (i.e. the district or city level). Confidentiality issues also mean that at finer scales information that is collected is not disclosed, constraining the use of microsimulation techniques further.

Attempts have been made to get around this problem: for example, using the 1990 population census and the USA Public Use Microdata Sample, Beckman, Baggerly, and McKay (1996) applied iterative proportional fitting (IPF) to generate a synthetic baseline population of individuals and households so as to estimate future travel demand. Using the 1991 Sample of Anonymised Records and Small Area Statistics samples, Ballas and Clarke (2001) synthesised a household micropopulation of Leeds UK, using the IPF technique. They used this synthetic population to perform 'what-if?' economic policy analysis at small-area level, estimating the geographical impact on patterns of employment and income from major changes (jobs lost or created) in the local labour market. In a recent study, Lovelace, Ballas, and Watson (2014) also presented a spatial microsimulaiton to analyse people's daily commuting patterns at different levels in the UK, providing insight into spatial variability of commuting behaviour and its relationship with sociodemographic attributes (e.g. income, type of car, number of children). A critical review on current methods to generate synthetic spatial microdata using synthetic reconstruction or reweighting techniques can be found in Hermes and Poulsen (2012).

Microsimulation has been widely used in western countries to provide a better understanding and estimation of a large population's daily travel behaviour. However, there is little research on the spatial microsimulation of urban transport CO_2 emissions at a fine spatial scale for developing countries, where the dominant approach remains econometric modelling drawing on small sample surveys, and at an aggregate or a coarse scale for both past and prospective emission (Dhakal, 2009; Yan & Crookes, 2009). Long, Shen, and Mao (2011) and Long, Mao, Yang, and Wang (2011) developed a multi-agent model for the analysis of urban form, residential commuting energy consumption and environmental impact at the inner-city scale. They also proposed an Agenter (i.e. agent producer) approach to disaggregate lots of heterogeneous agents with non-spatial attributes and spatial locations using aggregate data and small-scale surveys, for future microsimulation or agent-based modelling analysis (Long & Shen, 2013). The daily travel behaviour and concomitant CO_2 emission of a large population has rarely been investigated by spatial simulation at the microscale. The aim of this paper is to develop a spatial microsimulation of daily travel behaviour and transport CO_2 emission in the Chinese context, and provide a basis for urban planning and transport policy evaluation.

2. Research area

2.1. Case-study: Urban Beijing

Beijing, China's capital city, was selected as our case study. It has undergone rapid urban expansion since the 1980s, and the