Commuting efficiency in the Beijing metropolitan area: an exploration combining smartcard and travel survey data

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ABSTRACT

Using Beijing as an example, this research demonstrates that smartcard data can be used to (a) assemble the required data for excess commuting studies, and (b) visualise related results. Based on both smartcard and household travel survey data, we find that the theoretical minimum commute is considerably lower for bus users than for car users in Beijing. This suggests that there is a greater inter-mixing of jobs–housing functions (i.e., a better jobs–housing balance) associated with users of that mode compared to the corresponding land-use arrangement for car users, who locate further from the central area (Tian'anmen) than bus users. The commuting range for car users is 9.4 km greater than for bus users. Excess commuting is slightly higher for bus users (69.5%) than for car users (68.8%). Commuting capacity values are slightly lower for car users than for bus users, implying that car users consume less of their available commuting resources overall than bus users, albeit only marginally.

1. Introduction

Car dependency, traffic congestion, long commutes, sprawl, and associated air and noise pollution characterise many contemporary cities. They are all challenges that are central to achieving the goal of environmentally sustainable cities (Scott et al., 1997; Marcotullio and Lee, 2003; Black, 1997; Litman and Burwell, 2006). Planners, policy makers, and public agencies have advocated, and even incentivised, jobs–housing balance policies as one way to reduce travel demand, increase the efficiency of commuting patterns, and improve overall quality of life (Boarnet et al., 2011; Cervero, 1989, 1991). This is largely because research has shown that there is potential for commuting to be reduced if jobs and housing are carefully arranged to assist with minimisation of actual commuting patterns (Murphy, 2012). Indeed, it has also been shown through simulation that an improved jobs–housing balance has the potential to provide for significant reductions in congestion and associated environmental emissions (Scott et al., 1997).

Unsurprisingly, different factors contribute to the ratio of a jobs–housing balance among different social groups and in different locales. In the United States (U.S.), for example, suburbanisation of employment, housing segregation, inefficient public transportation services, and race may all (more or less) contribute to a jobs–housing balance or otherwise (Bauder, 2000; Horner and Mefford, 2007; Preston and McLafferty, 1999). In the Chinese context, the idea of the work unit (*Danwei*) in cities represents a very top-down and urban village-like arrangement of jobs, housing, and social services that contributes to a better jobs–housing balance and shorter commutes (Wang and Chai, 2009). During the socialist period, people residing in a *Danwei* did not even need to exit the compound to meet their daily needs, with schools, shops, and hospitals located therein (Walder, 1986). The basic planning idea of *Danwei* was adopted from the former Soviet Union, which had a close political relationship with the People's Republic of China (PRC) during the 1950s. *Danwei* was designed as a compound that contained both jobs and housing as well as other facilities, and was widely adopted as a planning principle across Chinese cities during the first five years of the establishment of the PRC government in 1949 (Li, 1993). One of the advantages of the *Danwei* planning approach was the belief that it facilitated short commutes and a reduction in travel demand generally (Zhang and Chai, 2009). In the post-socialist period, the dismantling of *Danwei*, accompanied by the suburbanisation of more housing than jobs, has contributed to a widening jobs–housing imbalance and is thought to have contributed to the lengthening of commutes (Yang, 2006; Wang and Chai, 2009). However, despite significant transformations of the built environment in China, the positive impact of *Danwei* on urban

commuting patterns is thought to persist, albeit in a more subtle way, as evidenced in the case of the city of Xi'an (Zhou et al., 2014).

Our research furthers the work of Long et al. (2012), who describe how to derive home and workplace locations from smart-card data and quantify and visualise the existing bus commuting trips in Beijing based on the derived location information. However, Long et al. (2012) do not investigate how existing bus commuting trips might be optimised, how those trips compare with car commuting trips, or how Beijing's bus/car commuting efficiency compares to that of other cities. This paper, therefore, examines all of these issues and is organised as follows. The next section discusses the excess commuting framework and associated literature that are central to the overall research objectives (described in the next section). The paper is set within associated research in the Chinese context before the methodology is outlined, including the study area, provenance of the smartcard and car data and associated assumptions, as well as the formulations utilised for calculating the theoretical minimum and maximum commutes. The results are then outlined and analysed before some broad-ranging discussion and conclusions are offered.

2. The excess commuting framework

2.1. The Western context

In the literature, there have been significant attempts over the last two decades to establish a framework for analysing the efficiency of regional commuting patterns. Central to this has been the notion of a jobs–housing balance, which has most frequently been studied via the excess commuting framework (Horner, 2004). In existing studies, a jobs–housing balance concerns "the spatial relation between the number of jobs and housing units within a given geographical area" (Peng, 1997: 1216), and this is normally represented as a ratio at the level of a zonal unit such as a census tract or Traffic Analysis Zone (TAZ) or at the aggregate regional level within the excess commuting framework.

As mentioned already, the excess commuting framework has often been utilised to provide insights into the nature of the jobs–housing balance in cities, as well as the overall efficiency of trip-making therein. Excess commuting is defined as "the nonoptimal or surplus work travel occurring in cities because people do not minimise their journeys to work" (Horner, 2002: 543). Thus, non-excessive commuting is where the average actual commute (T_{act}) is equivalent to the theoretical average minimum commute (T_{min}) in a city, where individuals travel to the closest possible workplace on average in terms of some measure of zonal separation (e.g., time, distance). In other words, commuting above what is necessary given the distribution of existing jobs and housing is considered excessive. It is expressed as a percentage of the actual commute as follows:

$$EC = \left(\frac{T_{act} - T_{min}}{T_{act}} \right) * 100 \tag{1}$$

This relationship implies that careful (re)organisation of jobs and housing in a city-region has the potential to produce more efficient commuting patterns. Under this framework, the minimum commute can be thought of as an indicator of the mean distance or time separation between jobs and housing (i.e., the jobs–housing balance) across a city-region. Lower relative average minimum commutes represent a higher degree of a jobs–housing balance, while higher average minimum commutes represent the opposite.

At the opposite end of the scale, Horner (2002) introduced the notion of an average maximum commute (T_{max}). It represents a theoretical situation where individuals, on average, commute to the furthest possible workplace destination in a city-region.

Together T_{min} and T_{max} represent the lower and upper limit of the theoretical extent to which individuals can minimise or maximise commuting costs within the context of the existing distribution of home-work land-use arrangements. Horner (2002) used the addition of T_{max} to develop a measure for, what he refers to as, capacity utilisation (C_u) – the percentage travel cost capacity of a city-region being consumed by daily commuting:

$$C_u = \left(\frac{T_{act} - T_{min}}{T_{max} - T_{min}} \right) * 100 \tag{2}$$

Recent extensions to the framework have been added, including the introduction of the notion of random commuting (T_{rand}) (Charron, 2007; Murphy and Killen, 2011). This metric has led to the development of additional measures of commuting efficiency, such as commuting economy (C_e) and normalised commuting economy (NC_e) where the average random commute (T_{rand}) is considered to be the more realistic upper bound of commuting capacity (Murphy and Killen, 2011). Indeed, Niedzielski et al. (2013) have pointed out that C_e and NC_e are influenced to a much lesser extent by MAUP effects than either the EC or C_u measure. However, neither C_e nor NC_e are the focus of the current research. It is also the case that few studies have assessed trip efficiency by mode within the excess commuting framework, which is likely to be related to the difficulty of acquiring data disaggregated by mode in most city regions. Nevertheless, some studies have undertaken modal choice analysis within the framework, including, for instance, Horner and Mefford (2007), Murphy (2009, 2012) and Murphy and Killen (2011).

Within this context, the current research investigates the trip efficiency of commuters in Beijing, China, within the context of the excess commuting framework. The paper contributes to existing studies in three ways. First, it outlines the potential role of, and utilises, a new data source, namely smartcard data, for outlining patterns of public transport commuting efficiency within the excess commuting framework. The future role of such datasets is important because they are updated daily and, therefore, have the potential to contribute to more dynamic excess commuting analysis. Thus, they have clear advantages over census data that have tended to comprise the dataset of choice for excess commuting studies to date. Second, it utilises innovative approaches for mapping not only actual commuting patterns but also minimum commuting patterns within the excess commuting framework. This provides an intuitive way in which to explore the geography of flows visually under the perfect efficiency assumptions of the minimum commute. Finally, the research offers the only analysis to date of commuting efficiency in Beijing within the context of the excess commuting framework. Given the size of Beijing and its role in the Chinese economy, applying the excess commuting framework here and within other Chinese cities is important comparatively, given their altogether different historical development outside the typical market-led framework that is seen in many Western cities.

2.2. The Chinese context

In recent years Chinese cities have undergone significant spatial and social transformation and this has had a considerable impact on land use arrangements (including the jobs–housing balance) and commuting patterns. There has been large-scale urban expansion accompanied by the suburbanisation of affordable housing opportunities. This has resulted in an increase in average commuting distances across the city, but especially among Beijing's suburban residents who have been forced outwards due to a lack of affordable housing closer to employment centres (Li and Li, 2007; Liu et al., 2009; Meng, 2009; Meng et al., 2011); similar

trends also are seen in cities such as Guangzhou (Zhou and Liu, 2010; Liu et al., 2008).

However, few Chinese studies have analysed commuting patterns within the context of the excess commuting framework. The only two exceptions are the work of Liu et al. (2008) and Liu and Wang (2013). Liu et al. (2008) estimated excess commuting in Guangzhou for 2001 and 2005 and found that it had decreased from 58% to 44% over that period. However, they used a small sample of commuters (*n* = 1500) and a relatively large unit of analysis (zonal units with an average size of 12.5 square kilometres), which tends to underestimate real excess commuting because of a greater MAUP effect at larger units of analysis (see Niedzielski et al., 2013). Moreover, Liu et al.'s (2008) study did not differentiate between modes of transport in determining measures of excess commuting. Elsewhere, Liu and Wang (2013) calculated excess commuting for the city of Mianyang, China. Compared to existing studies, Liu and Wang's (2013) contribution is that they assumed that the number of workers/jobs in each TAZ could grow by up to 30%. The purpose here was to find the number of extra workers and jobs by TAZ where the resultant T_{min} is optimised. Using this model, they found that T_{min} tends to follow a "U" shape as the total number of workers/jobs increases. Despite these exceptions, there remains a considerable gap in our knowledge of commuting patterns across Chinese cities, especially when leading Chinese cities are compared with their European and U.S. counterparts.

There has also been some research that has examined the related issue of the jobs–housing balance. The most notable studies are those undertaken by Wang and Chai (2009) and Zhao et al. (2011). Based on a sample of data (*n* ⩽ 750) from the Beijing household travel survey, Wang and Chai (2009) found that *Danwei* contribute to a better jobs–housing balance and ultimately shorter commutes for Beijing residents. They also found that the relatively recent free-market approach adopted in the housing sector has led to a decline in the jobs–housing balance and longer distance commutes on average. Rather importantly, these studies and findings indicate that the mechanisms associated with the jobs–housing balance and resulting commuting patterns in China are considerably different from those found in the Western context. In addition, recent research by Li and Li (2007) investigated the jobs–housing balance and commuting patterns in two new suburban affordable housing communities in Beijing. They found that the journey times of bus commuters are significantly longer than that of commuters by automobile.

In 2008, there existed in Beijing 184 km of commuter subways (excluding the airport express rail, which extended 28.1 km and only served the airport and two stations in the inner city). Recent investment has led to an expansion of the subway network, such that subway trips have gradually increased as a proportion of overall trip making. Beijing Metro manages and maintains the subways, which were built and financed by the Beijing Municipal Government and Beijing Public Transportation Company, a state-owned company providing public bus services in the Beijing metropolitan area. As of 2011, the company operated 28,343 buses on 948 bus routes over a network length of 187,500 km. In 2011 alone, these buses produced 1.7 billion vehicle kilometres travelled and transported of 4.9 billion passengers.[1] These figures indicate that Beijing has one of the most extensive public transportation systems in the world that is heavily bus-based. Indeed, bus trips account for a significant share of total public transportation trips.

Table 1 shows the modal share breakdown of trips for 2008 and 2010, highlighting the car as the most dominant mode of travel, with its share on the increase. On the other hand, the bus is the

Table 1
Mode share percent of Beijing residents. *Source:* BTRC (2011).

Mode	2008 Share (%)	2010 Share (%)
Bus	28.8	28.9
Subway	8.0	10.0
Taxi	7.4	7.1
Car	33.6	34.0
Bike and walking	20.3	18.1
Company shuttle	1.9	1.9
Total	100	100

most dominant form of public transport and its share has remained more or less constant over the period, with a large increase seen in the use of the subway. It is notable also that, contrary to many world cities where the share of biking (see Murphy and Usher, 2015) and walking is increasing, the trend in Beijing is for a decline in the role of these modes.

3. Methodology

3.1. Data origins and zonal system

As the capital of China, Beijing has over 20 million residents and is one of the most populous cities in the world. Metropolitan Beijing's land area is c. 16,410 km². The Beijing Transport Public Transportation Company (BTRC) is the local transportation planning agency and is charged with collecting local travel survey data, as well as developing and maintaining local travel demand models. Unlike its U.S. counterpart, the BTRC does not integrate data from the China Census Transportation Planning Packages into its models but, instead, assembles its travel demand model from data collected through separate surveys. Indeed, it is not easy to gain access to transportation data in China, and acquiring data for research purposes requires special permission granted only at the discretion of the BTRC. Often, data that are acquired for research purposes stem from personal connections to high-level individuals within these organisations, as is the case with the data utilised for this research. The 2008 smartcard data and the 2010 Beijing Household Survey data are the primary data used for this paper and have been provided by the Beijing Institute of City Planning (BICP). These data have not been utilised previously in other studies of Beijing's transportation patterns.

In excess commuting studies, interzonal flow (in terms of trip volumes) and cost matrix data (in terms of some measure of zonal separation such as distance and time) are required for the calculation of T_{min} and T_{max}. In the case of our study, we were able to acquire comparable data only for bus and car modes for 2008 and 2010 respectively. Due to institutional constraints, data hoarding and the difficulty of acquiring data for research purposes in China, it was not possible to get a complete public transport flow matrix broken down by bus and rail modes (c.f., Zhou, 2012).

While we had bus data for 2008, we acquired car commuter data from the 2010 Beijing Household Travel Survey (BHTS) because these data were the closest available in chronology to the 2008 bus data. The reason for this is due to the fact that the Beijing authorities only conduct large-scale Household Travel Surveys in years ending with "0" or "5." To protect personal privacy, the data were aggregated on the basis of the local TAZs for 2010. However, there are 1911 TAZs for 2010 but only 1118 for 2008 (see Fig. 1). On average, each TAZ in 2008 was about 14 square kilometres, but TAZs tend to decline in size from the periphery to the core of the city. The average size of TAZs in Beijing's core is comparable to or even smaller than that of the TAZs or sub-divisions used in existing studies. For instance, in Small and Song (1992), the 3341-square-kilometre Southern California Region was divided
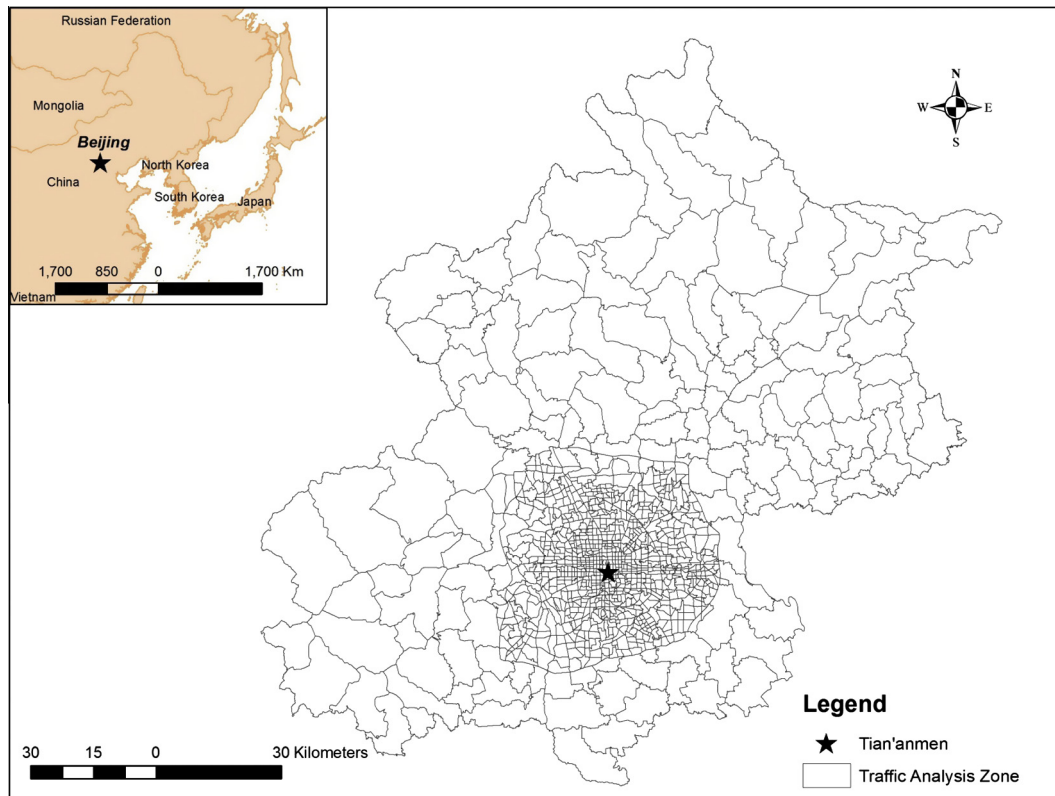
Fig. 1. 1118 TAZs in the 2008 Beijing zonal system.

into 706 TAZs. In Murphy (2009) and Murphy and Killen (2011), the Great Dublin Region consisted of 463 sub-divisions and covered 6982 square kilometres.

Tian'anmen Square is shown in Fig. 1. Geometrically speaking, the Square is not the centroid of Beijing, but is widely thought of as the centre of the city. Venues of national significance such as Zhong Nan Hai, the National Historical Museum, the Forbidden City, the State Council, and The People's Great Hall are all within walking distance of the Square and, therefore, our analysis considers this to be the city centre.

3.2. Allocating individuals to TAZs

In order to make useful comparisons between car and bus commuting trips, we needed to convert either the car data to the 2008 TAZs or the bus data to the 2010 TAZs. Given that we had a much large sample of bus commuters for 2008, we decided to do the former. When making the conversion, we assumed the following. First, at the TAZ level, we assumed that car commuters were evenly distributed across space. Because we knew the area of each TAZ and a subarea of the same TAZ, we were able to use a percentage of the subarea to determine the number of car commuters in that subarea. Second, we assumed that the ratio of the sample of car commuters to all car commuters in different TAZs was a constant (7%). Actually, this is similar to what the BHTS expects to achieve: a 5% response rate across TAZs. Third, we assumed that the underlying mechanism (e.g., the gravity model) governing the spatial distribution of car commuters was unchanged between 2008 and 2010. Fourth, we assumed that the jobs–housing distribution of the car commuter sample was representative of the broader population of car commuters. Using these assumptions, we were able to upscale the 2010 car commuter sample (N = 37,837) to 532,722 car commuters (approximately 7% of daily car commuters).

More specifically, the procedures for the translation were as follows. First, we performed an overlay analysis of the 2010 and 2008 TAZs in *TransCAD*, which generates 6757 distinct smaller TAZs. These TAZs have a one-to-one or one-to-many relation to the 2010 and 2008 TAZs. *TransCAD* automatically produces a relationship table of three sets of TAZs: their TAZ IDs and the respective percentage of the 2010 and 2008 TAZ areas that fall into the smaller one. Second, using the relation table, we disaggregated the 2010 sample into the smaller TAZs with the known area percentage and then aggregated the samples of the smaller TAZs into the 2008 sample. Third, we scaled up the 2008 sample to represent the larger sample of daily car commuters for the same year.

For the bus data, we utilised smartcard data for bus users. which is a potentially rich source of information; similar data have not been used previously in excess commuting studies. Since 2005, over 90% of bus riders in Beijing have swiped an anonymous smart card when boarding and alighting (for suburban routes) or when boarding (for inner-city routes) to pay for their fare. The high rate of smart-card usage among bus riders is due largely to a significant government subsidy for smartcard users. Those users benefit from a 60% discount on any route in the local bus system; the smartcards are also integrated with other services and can pay taxi, electricity, and sewage services that are offered by the BMG and associated companies. In this paper, we assume that the bus commuters identified through the smartcard data are representative of all bus commuters.

When cardholders use their smartcard to pay for bus services, the card reader installed on the bus automatically generates the following information:

(a) Bus trip origin and destination stop (if the cardholder is on a suburban route) or bus trip origin only (if the cardholder is on an inner-city route). For inner-city routes, the cardholder

only swipes the card when boarding the bus. In this case, we deduced the cardholder's trip origin and destination based on all swipes during five consecutive weekdays. An origin or destination and all bus stops within 500 m of them that are associated with recurring swipes were estimated as "home" and "workplace." This allowed home and workplace data to be differentiated using the local parcel-level land-use information. More technical details can be found in Long et al. (2012).

(b) Boarding and alighting time (if the holder is on a suburban route) or boarding time only (if the holder is on an inner-city route).

(c) Unique card number and card type (student card or regular card).

The above information is sent instantly to a central server where it is stored. For this study, we were granted access to a full week of historical data from the server administrator, containing 77,976,010 bus trips from 8,549,072 non-distinct cardholder records between April 7 and April 13, 2008. Given that over 90% of bus users are smartcard holders (Long et al., 2012), the one-week sample is representative of all bus users in Beijing. To identify a cardholder's workplace, we queried one-day data on an MS SQL Server and repeated the process for seven days based on the following rules:

(a) The card type is not a student card. Students were excluded on the basis that they are not commuters.

(b) $R_j \geqslant 6$ h, where R_j is the time that a cardholder stays at place j, which is associated with all bus stops within 500 m of one another.

(c) $j <> 1$, which means that j is not the first place in a weekday that the server records.

We also ensure that the land use associated with j is non-residential based on the local parcel-level land-use map.

Similarly, a cardholder's home (origin) was identified if it adhered to the following criteria:

(a) The cardholder already had an identified workplace.

(b) The card type is not a student card.

(c) $R_i \geqslant 6$ h, where R_i is the duration that a cardholder stays at place i, which is associated with all bus stops within 500 m of one another.

(d) $F_h \geqslant F_j$, where F_h is the first and the most frequent place a cardholder starts a bus trip of a day within the week; F_j is a cardholder's trip frequency to or from j.

In addition, to ensure that we singled out commuters solely by bus, we only selected cardholders that had continuous bus swipes. That is, our study excludes multimodal public transport users (i.e., bus and subway). It is possible to get a breakdown of the swipe-card data by mode (subway and bus) but, unfortunately, we were not permitted to access such information for this study. In total, we ended up with 216,844 distinct cardholders/workers commuting solely by bus within the study boundary (see Long et al. (2012) for more details). We then geocoded and aggregated each cardholders' home and workplace information by TAZ for 2008.

3.2.1. Inferring a cost matrix

As with numerous other studies (see Horner, 2002; O'Kelly and Lee, 2005), we used the Euclidean distance between zone centroids as a measure of inter-zonal cost for both bus and car. However, recent research by Shen et al. (2013) found that commuting routes between zonal units in Beijing deviated significantly from straight-line distances. Indeed, Shen et al.'s (2013) work questions the

conventional assumptions that commuting is relatively stable and fixed. Nevertheless, Murphy and Killen (2011) have pointed out that Euclidean distance is a useful proxy for calculating EC and C_u in particular when compared with the results using network distance. While Euclidean distance underestimates the actual distances travelled between zones, it underestimates them roughly equally across all routes in the network, implying that the measure is a good proxy for measuring relative commuting cost between zonal units.

Moreover, for all trips (bus and car), intra-zonal travel distances were estimated by assuming that each zonal unit is approximately circular in shape, as treated in other studies (see Frost et al., 1998). Also similar to other studies, we excluded those trips originating in and destined for locations outside the study boundary (see Frost et al., 1998; Horner, 2002; Murphy, 2009).

3.2.2. Formulations

From the preceding discussion, it should be clear that a necessary prerequisite for attaining values associated with the efficiency indicators described in Eqs. (1) and (2) is the calculation of T_{min}, T_{max}, and T_{act}. T_{act} was calculated from empirical data. For T_{min}, the transportation problem of linear programming approach (TPLP) was used to determine the assignment of trips from origin to destination that minimised mean commuting costs. The objective function and constraints of the TPLP are given by:

$$\text{Min}: \quad Z = \frac{1}{N} \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} X_{ij} \tag{3}$$

$$\text{s.t.} \quad \sum_{i=1}^{n} X_{ij} = D_j \quad \forall j = 1, \ldots, m \tag{4}$$

$$\sum_{j=1}^{m} X_{ij} = O_i \quad \forall i = 1, \ldots, n \tag{5}$$

$$X_{ij} \geqslant 0 \quad \forall i, j \tag{6}$$

where m = number of origins; n = number of destinations; O_i = trips beginning at zone i; D_j = trips destined for zone j; c_{ij} = travel cost from zone i to zone j; X_{ij} = number of trips from zone i to zone j, and N = total number of trips. The objective function (2) minimises average transport costs. Constraint (3) ensures that trip demand at each destination zone is satisfied while constraint (4) limits the number of trips leaving each origin zone to the number of trips originating there. Constraint (5) restricts the decision variables, X_{ij}, to non-negative values. It should be noted that travel costs, c_{ij}, may be expressed in terms of any measure of zonal separation (for example, travel distance, travel time, or indeed a generalised cost measure).

T_{max} was also determined using the TPLP, where the objective function is the inverse of the minimisation problem discussed previously (5) and is given by:

$$\text{Max } Z = \frac{1}{N} \sum_{i=1}^{m} \sum_{j=1}^{n} C_{ij} X_{ij} \tag{7}$$

4. Results

Table 2 and Fig. 2 show the results emerging for the values associated with the travel scale T_{min}, T_{max} and/or T_{act}. They also show

Table 2
Excess commuting and related results for the Beijing metropolitan area.

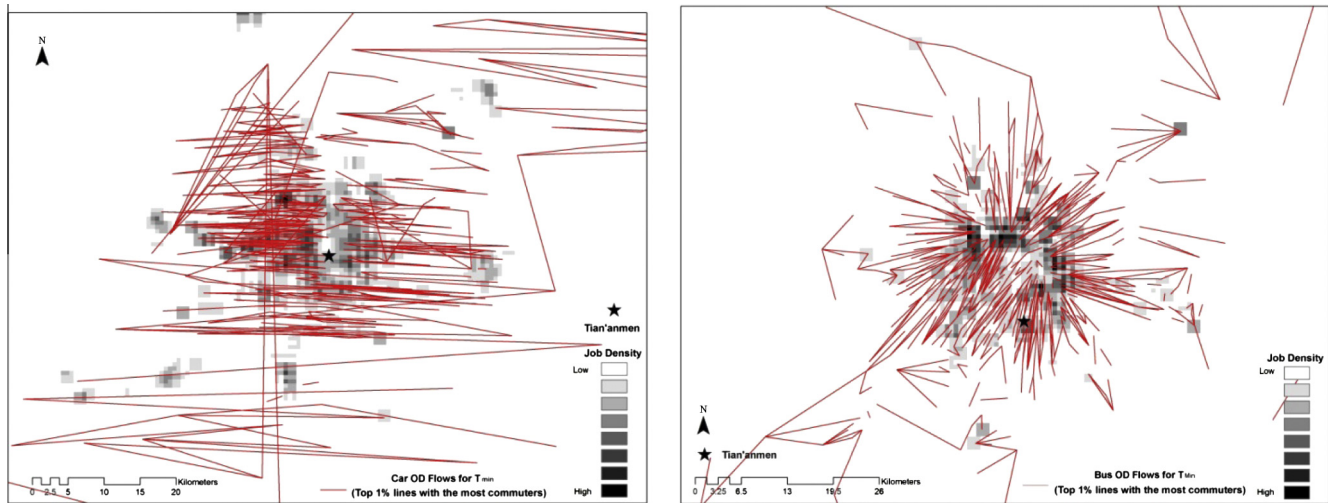|	T_{min}	T_{act}	T_{max}	Range ($T_{max}-T_{min}$)	EC (%)	CU (%)
Car	3.5	11.2	35.1	31.6	68.8	24.3
Bus	2.5	8.2	24.7	22.2	69.5	25.7

Fig. 2. Top 1% of origin–destination flows for the minimum solution (T_{min}) by car and public transport.

the commuting range ($T_{max}-T_{min}$), as well as the efficiency indicators EC and C_u. It can be seen that T_{min} is considerably lower for the bus than for the car. What this suggests is that there is a greater inter-mixing of jobs–housing functions (i.e., a better jobs–housing balance) associated with users of that mode compared to the corresponding land-use arrangement for car users. The lower value of T_{min} for bus users suggests that, on average, users of that mode have easier access (in terms of commuting distance) to job opportunities than car users. However, this greater juxtaposition between origins and destinations for bus users may simply be a reflection of the fact that those commuters who cannot get easy access to their job destination via the bus simply switch to the car (if possible); those who can access destination opportunities relatively easily via the bus network continue with that mode for their commute. Overall, these findings echo those of Wang and Chai (2009) and Zhao et al. (2011), which show that *Danwei* is associated with a better jobs–housing balance and, ultimately, shorter commutes for Beijing residents.

To some degree, this phenomenon might explain why the modal results for T_{min} in Beijing are in contrast to other cities where similar analysis has been undertaken. For example, the general trend in the results contrast with those emerging for the case of Dublin, Ireland (see Murphy, 2009) where T_{min} values were consistently lower for car users than for public transport users. Murphy's (2009) public transport data included bus and train data rather than just bus data (as in this study) but, because train commutes tend to have longer average distances, the T_{min} results from Beijing would be even higher than at present if rail data were to be included. Thus, it is likely that the results for T_{min} would be higher if data on train trips were to be included, and this is a caveat associated with the results emerging from this study.

There is also another explanation as to why this trend is different in the case of Beijing, and it relates to differences in the overall spatial organisation of the city relative to Dublin. Beijing is a much more monocentric city than Dublin (which is highly polycentric) and has witnessed much less decentralisation of employment than not only Dublin but many Western cities in a more general sense. The decentralisation of employment functions allows car users, in particular, to access job opportunities closer to residential locations beyond the central area, thereby reducing the value of T_{min} to a considerably greater extent for users of that mode. The fact that this has not happened to the same extent in Beijing suggests that the maintenance of a monocentric city (and, thereby, maintenance of a largely centralised employment and decentralised

residential structure) has not afforded car users the same opportunities to access job opportunities closer to peripheral residential locations as has occurred in other world cities. Moreover, if it was assumed that all workers in Beijing were to commute to the city centre (i.e., Tian'anmen Square) where most employment opportunities are located, we found that the mean commuting distance by car is considerably longer (27.7 km) than by bus (14.8 km). This supports the previous assertion that car commuters tend to locate further from the central area (Tian'anmen), whereas bus commuters locate closer to the centre. In policy terms, it may be difficult to implement a zone-based jobs–housing balance strategy in Beijing given the current orientation towards market-based development. However, a corridor-based jobs–housing balance approach would, perhaps, be most appropriate for Beijing because that would facilitate public transport to a greater extent than a zone-based jobs–housing balance approach, which tends to facilitate more favourable commutes for car users to a greater extent. Indeed, the introduction of a BRT line and metro line 6 has already improved the jobs–housing balance along Beijing's west-east axis.

Fig. 2 displays the top 1% of O–D flows associated with the minimum solution (T_{min}) for car and bus. In other words, it shows what the pattern of commutes would look like in a perfect efficiency scenario where individuals were commuting, on average, to the closest possible workplace. The results are interesting in that they demonstrate graphically the difference in the complexity of origins and destinations associated with the two modes of transport. For the car, origin and destination flows are much more dispersed and complex, whereas the bus flows are remarkably radial in nature and are oriented towards flows along radial routes converging in the centre. For the car, they highlight that, even under the perfect efficiency assumptions of the minimum solution, origin and destination flows associated with the existing distribution of car users are highly dispersed and more random in nature. This suggests that, in the specific case of Beijing, the primary role of the car is to accommodate more complex trips that, in the main, involve more inter-suburban or cross-commuting trips not oriented towards the centre.

The results for T_{max} are considerably higher for car users than for public transport users. This is consistent with research that has calculated these values by different modes (see Murphy, 2009). This demonstrates that, in the case of Beijing, the private transport network facilitates the possibility of longer trips than those afforded by the bus network. Thus, individuals who have longer commuting distances to their workplace are more likely
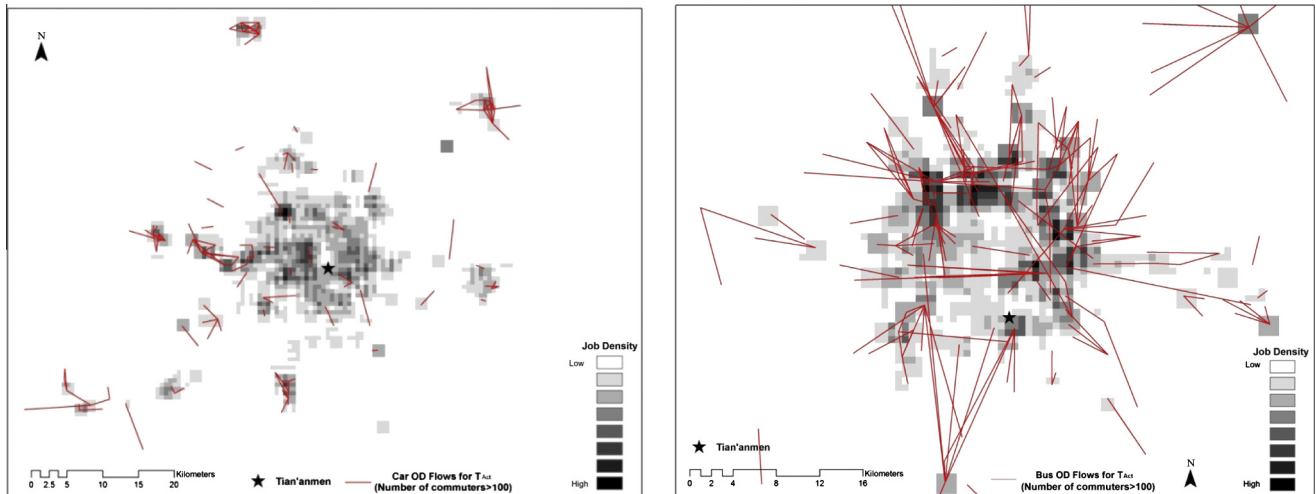
Fig. 3. Origin–destination flows for the actual pattern of trip making (T_{act}) by car and public transport.

to use the car over the bus than for shorter journeys. In effect, the T_{max} results for the bus (24.7 km) show that individuals commuting more than 24 km to work simply cannot use the bus network and must transfer to the car in order to reach their destination. This result has significant policy implications for Beijing because it suggests that any moves toward decentralisation of employment could undermine the role of the bus network in serving commuting trips and would likely lead to a considerable modal shift towards the car.

The foregoing result is also highlighted by the respective travel ranges for the two modes (Table 2). They show that the commuting range for car users is 9.4 km greater than for bus users. This reinforces the previous point emerging from the T_{max} results and, ultimately, highlights the possibility for car users to live further from employment destinations than bus users. Thus, the results suggest, quite concretely, that the car facilitates a greater separation between home and work land uses than the bus. Moreover, it suggests that the greater intermixing of the jobs–housing relationship associated with the bus (i.e. T_{min}) has not facilitated an improvement in the range of commuting possibilities for bus users.[2]

Unlike Figs. 2 and 3 presents a graphical display of all O–D pairs with greater than 100 commuters for car and bus for the actual pattern of trip making (T_{act}).[3] The results show that more red[4] lines are visible for the bus than for car users, indicating more highly concentrated flows for the bus network; by way of contrast, the considerably lower number of red lines for the car network indicates that there are less O–D pairs associated with concentrated flows. Given that public transport systems generally work best with high volumes of users along a limited number of routes, it is hardly surprising that the bus is associated with a greater concentration of flows. Nevertheless, it does demonstrate the extent to which car flows are characterised by low volume, dispersed, and complex patterns of O–D flows compared with those for the bus.

All of these assertions are consistent with the observed values of T_{act}. Given the lower values of T_{min} for bus users over car users, one would expect T_{act} to be lower for that mode. The results show

that this is indeed the case (Table 2). T_{act} for bus users (8.2 km) is 3 km lower on average than for car users. Indeed, T_{min} is 40.0% larger for car users than for bus users and, similarly, T_{act} is 36.6% larger for car users than for bus users. This implies a close correlation between T_{min} and T_{act}, indicating that the greater intermixing of jobs–housing functions associated with bus users allows individuals who use that mode to reduce their observed commuting costs to a greater extent than car users.

The results for the commuting efficiency indicator, excess commuting (EC), also reinforce this relationship between T_{min} and T_{act} for bus and car users, in that they show that excess commuting is similar for both modes. However, despite bus users having a lower T_{min} and T_{act}, they show that excess commuting is slightly higher for bus users (69.5%) than for car users (68.8%). This implies that relative to the existing distribution of home-work land use arrangements for each mode (i.e. T_{min}), there is little difference in the commuting efficiency between modes as evidenced by the EC statistic. For the case of Dublin, the EC for public and private transport was 59.8% and 78.4% respectively. It is clear, then, that excess commuting for the bus in Beijing is considerably higher than the corresponding results for public transport in Dublin; for the car they are considerable lower. However, when compared with other Chinese cities, Beijing exhibits relatively high levels of excess commuting. Liu et al.'s (2008) analysis of excess commuting in Guangzhou during 2005 found (for all trips) only 44.7% of commuting to be excessive. While they used simulated data and relatively small samples that might undermine the strength of the results, the difference, nevertheless, is remarkably large and implies that commuting patterns in Beijing are more inefficient than those in Guangzhou.

Turning to the C_u statistic, which highlights the extent to which a city's existing commuting capacity is being utilised, it is clear that the differences are also only marginal between car and bus modes (Table 2). However, the results show that the C_u values are slightly lower for car users than for bus users, implying that car users consume less overall of their available commuting resources than bus users, albeit only marginally. This general trend is similar to the results emerging from Murphy's (2009) research on Dublin. However, the magnitude of the difference in the modal results is quite different between Dublin and Beijing. In Dublin, the difference in car and public transport C_u values was almost 7.0%, whereas in Beijing the difference is only 1.4%. Taken together, Beijing's results for EC and C_u highlight that, within the context of the existing

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[2] In similar studies, a lower T_{min} normally translates into a higher T_{max} but this is not the case for our results.

[3] We chose this because using a similar approach to that adopted for the minimum solution (Fig. 2) would have yielded unreadable maps.

[4] For interpretation of color in Figs. 2 and 3, the reader is referred to the web version of this article.

distribution of jobs and housing functions, bus use is associated with slightly more inefficient commuting patterns than car use. However, this must be viewed within the context of the T_{min} and T_{act} values that demonstrate a better jobs–housing balance for bus users, and also that bus users commute, on average, 3 km less per trip than car users in Beijing. Thus, while actual commuting is more inefficient for bus users relative to the arrangement of land uses compared to car users, bus users do still take, on average, shorter trips in absolute terms than car users. Of course, the implication here is not that we should encourage more car travel, which has a whole range of additional negative sustainability implications beyond EC and C_u measures alone, but that policymakers should attempt to put in place arrangements to ensure that travelling along the bus network is more efficient than on the car network so that commuting via public transport will be encouraged over the car.

5. Conclusions

Contemporary Chinese cities are highly dynamic. The rapidity of urban transformation right across the country is quite remarkable, with transport infrastructure and land use functions witnessing rapid change over the last two decades in particular. In Beijing, for instance, the subway network length more than doubled from 184 km to 465 km between 2008 and 2013 alone. Thus, the geography of transport patterns is changing rapidly over much shorter periods of time than we have traditionally become accustomed to. This means that for excess commuting and related transport studies, dynamic input data are needed to assess more quickly the nature of change. Indeed, Shen et al. (2013) have demonstrated that commuting in Beijing is highly complex, with many people using both the bus and car on various weekdays because of the existing car-use restriction law. In this sense, then, the commute mode being utilised by urban residents is not as fixed as might be the case in other jurisdictions. While our study only provides a snapshot of transport patterns in a Chinese city, our approach, which used smartcard data as input for analysing the efficiency of trip patterns along the bus network, has the potential to be a much more dynamic source of data for input into transport studies than traditional survey data. This study has demonstrated how these data can be manipulated and utilised for assessing very recent public transport patterns and, therefore, has the potential to incorporate more dynamic analyses of a city's transport patterns as technology moves increasingly towards the use of 'big data' for aiding urban planning (see Kitchin, 2014). However, it is important to note that our analysis only incorporates bus data for public transport and, because of this, a significant proportion of commuting is missed within our analysis. Thus, our results and associated conclusions are limited in this regard. Yet, while the absolute values are likely to change if other public transport trips were included, it is unlikely that the overall trend would change significantly given that subway use accounts for only 10% of overall commuting in Beijing. Nevertheless, it would be useful for future research to incorporate all public transport trips in a similar analysis with a view to determining how the current results might change.

Our results show that T_{min} is lower for the bus than for the car, indicating a better jobs–housing balance associated with the former mode. However, it is possible (although further research would be needed to gain more certainty) that this is related to the residential self-selection phenomena and less due to the deliberate efficiency choices of bus users. This phenomenon refers to situations where individuals choose their residence based on their travel needs, abilities, and preferences that are constrained by an individual's place in the socio-economic hierar-

chy, modified by the opportunities and constraints provided by society (Van Wee, 2009). In the context of our results, this may suggest that those commuters who cannot gain easy access to their employment destination via the bus simply switch to the car or, alternatively, choose an alternative origin (home location) that allows them the opportunity to commute by car rather than by bus.

The results also highlight that Beijing is a considerably more monocentric city than many Western cities. The upshot of this is that modal shifts from bus to car do not confer huge efficiency benefits upon car users relative to bus users due to the fact that employment has not been decentralised to anywhere near the same extent as in many Western cities. This is evidenced by the relative T_{min} values for both modes. Where employment is decentralised, it clearly confers significant additional benefits on car users relative to public transport users (see Murphy, 2012). The fact that Beijing has not gone down this route, and has maintained a more monocentric-like urban structure, has actually allowed the bus to increase its modal share in recent years. This is contrary to what has happened in most Western cities that have pursued decentralisation strategies via polycentric urban models. In terms of efficiency indicators, such as excess commuting and capacity utilisation, our study shows that Beijing's excess commuting is high for the bus and low for the car relative to other cities that have assessed these indicators by mode. Quite why this is the case would require more detailed research with a temporal component to map changes in commuting efficiency with changes in land use arrangements.

More broadly, the generally lower values of T_{min} for Beijing relative to other similar-sized cities suggest that the legacy/impacts of the *Danwei* phenomenon persists in Chinese cities. However, as shown in other studies, the dismantlement of *Danwei*, rapidly changing residential preferences, broader motorisation, and suburbanisation can undermine the positive efficiency impacts of *Danwei*. In our view, there are lots of uncertainties in terms of the phenomena's impacts on the jobs–housing balance and commuting patterns. However, this also means that rich opportunities exist for further research on the issue, which, to some extent at least, our study provides insights into even if they are somewhat indirect.

Our graphical maps of key origin–destination flows are an innovative approach to demonstrating flows of actual travel patterns, as well as those associated with the minimum solution of the TPLP. In this sense, they are a useful addition to aid with the interpretation of results emerging via the excess commuting framework. They demonstrate spatial variations in flow patterns associated with T_{min} and T_{act} and provide useful insights into the geography of transport flows associated with these solutions, which are otherwise lost in previous studies of the same nature.

Finally, despite the merits of this work, it can still be improved by future research. First, it would be beneficial to link smartcard data to local household travel survey data. This would provide much richer information on various socio-economic variables, which could help explain commuting behaviour more concretely. However, in the Chinese context, this is a key barrier to be overcome because there is, generally speaking, a tradition among local agencies of withholding data from scholars. Second, the data and our understanding of public transport trip making would be greatly improved if smartcard data were also available for subway users. While the addition of this data would certainly make smartcard data processing and validation more complicated, it would likely be worth the effort as it would enable us to better understand the efficiency of a broader range of commuters, but also would provide important insights about the relative efficiency of that mode relative to others.

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