Transport Policy 92 (2020) 8–19

Contents lists available at ScienceDirect

Transport Policy

journal homepage: http://www.elsevier.com/locate/tranpol

Transport equity as relative accessibility in a megacity: Beijing

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ARTICLE INFO

Keywords:
Modal disparity
Spatial equity
Urban structure
Scenario simulation
Beijing

ABSTRACT

Megacities in China are undergoing transformation in urban functional structure brought on by rapid urbanization and spatial expansion, while private motorization connects disparate functional zones with ever-longer journeys. Policies to control growth of the car fleet while investing in mass public transport, in Beijing and in many other cities, have divided city residents into car users and those dependent on public transport. This paper examines these policies from the transport equity perspective by measuring accessibility disparity between public transport and private car. Cumulative accessibility is measured for each of the two transport modes, while an accessibility equity index (AEI) is developed based on numerical and spatial computation. The recent changes in spatial distributions of population and employment in Beijing are analyzed. Accessibility and AEI are measured using network-based Geographical Information System (GIS) and analyzed quantitatively and spatially. Nine scenarios with different employment location strategies are simulated to analyze their impacts on accessibility and AEI, with clear benefits among the scenarios with regard to accessibility equity for suburban populations. Results suggest that reducing the demand for car use and ownership can be supported through employment spatial redistribution policies, which can be used to raise relative accessibility by public transport. Land use policy can form part of a larger set of spatial and transport policies that includes regulation of the car fleet and public transport development. Such integrated approaches are of particular importance for the present and future megacities of China that are expanding rapidly, with relatively high volume flows on limited movement networks.

1. Introduction

Transport equity is attracting much attention in our time and now often takes a prominent place in the stated goals of transport projects worldwide (Di Ciommo and Shiftan, 2017; Karner, 2018). Among several interpretations, transport equity also means equitable access to modes. Many urban residents do not travel by car, while public transport systems may not provide adequate service for individuals to accomplish complex travel or easily access employment. Lower income individuals tend to rely more heavily on public transport (Sanchez, 1998). Access by public transport may not provide adequate service to their largely captive riders for often complex journeys (Blumenberg and Ong, 2001), that cumulatively comprise complex travel patterns over the city. Inadequate public transport may limit the available employment opportunities and public services for vulnerable individuals, who are then more susceptible to social and economic marginalization (Kain and Meyer, 1970). As a consequence of these outcomes, a major topic in the transport equity field is the mobility gap between captive and choice riders of public transport. Reducing the mobility disparity between car users and non-users is the focus of interventions in this domain (Welch, 2013).

Transport equity must also consider a redistribution of urban functions in a more complex overall structure in ongoing rapid urban expansion. To the extent that urban planning can influence the long-range functional structure of the city, then it should also include the coordination with new transport provisions. In reality, such an approach is challenged by quite different production modes for land use and transport. In the context of transport equity, it is important to know how these ongoing changes in urban functional clusters at the macro-scale have impact on transport equity. Employment figures prominently among land uses and accessibility to employment is often central in transport equity measures (Zhou and Long, 2015; Guzman and Oviedo, 2018). Consequently, accessibility to employment is a major focus of transport system planning. Transport equity must consider disparities in access to modes as well as the accessibility implications of a more compartmentalized and disparate land use pattern on a vastly expanded

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https://doi.org/10.1016/j.tranpol.2020.03.016
Received 25 July 2019; Received in revised form 26 February 2020; Accepted 31 March 2020
Available online 8 April 2020

territory.

Beijing is typical of the emerging disparity between public and private transport provision. The urbanized land area within the city administrative boundary increased from 467 km^2 in 1995 to 1401 km^2 in 2015, which was accompanied by enormous investment in transport infrastructure. Total road length increased from 4380 km in 2006–6423 in 2015, while urban rail line length also increased from 114 km to 554 km over the same period (Beijing Transport Research Center, 2016; Beijing Transport Research Center, 2007). Such heavy investment in mass urban rail transit failed to quell the demand for private car acquisition, however. Beijing felt compelled to limit the growth in the car fleet by inaugrating a car license lottery in 2011, with 2.56 million applications for a quota of 150,000 licenses in 2015 (Beijing Transport Research Center, 2012; Beijing Transport Research Center, 2016). Access to the car license is further restricted by limiting applications to those with local residential registration (*hukou*) (Zhang et al., 2018). These severe limitations on car ownership have made car owners an exclusive and privileged group, a situation that begs the question of the modal equity between users of private cars and public transit.

The planned decentralization of work and living environments in Beijing is contradicted by ongoing concentration of workplaces at the city core. A high rate of annual growth and a need for urban expansion beyond the densely occupied historic core led to the building of suburban new towns starting in the 1980s (Yang et al., 2011). Employment did not accompany the mass decentralization of living environments; rather, state-owned enterprises (SOEs) tended to concentrate their headquarters in city center clusters, especially after 2000 (Hu, 2015). A succession of attempts at decentralization of employment were tried, most recently, the relocation of municipal government and its related functions to the east of the 5th and 6th Ring Roads in Tongzhou district (Beijing Daily, 2018). So far, these policies have failed to slow down, let alone reverse, the rise in numbers of people entering the central urban area at the morning rush hour (Zhao et al., 2010). In this environment of contradiction between policies and practices, it is clear that transport equity is impacted by employment location policies. Employment in the contemporary economy is more mobile and has more inherent spatial flexibility than living habitats. To the extent that urban planning can direct the spatial distribution of employment, it is appropriate to consider how different employment location policies might impact transport equity. Localities are distinguished by differences in socio-economic status, car ownership rate, public transport provisions and service diversity, so it is important to know how employment distribution policies impact equity among such localities. In the case of Beijing, more than half of the office use is public sector, in the form of SOEs. How such public sector actors should support city development is the core question.

We propose the concept of accessibility disparity to address the question of variability in access to modes of transport. Transport equity is measured in terms of accessibility to employment, by private modes and by public transit. Network-based travel computation is used to measure available accessible employment amounts by given travel time. The relationship between accessibility by public transit and accessibility by private car is represented as the accessibility equity index (AEI). We measure the outcomes of a set of alternate employment distribution scenarios in Beijing, to consider effectiveness and their equity characteristics.

The hypothesis is that it is possible to bridge the equity gap between captive and choice public transit users through spatial development strategy. The spatial development strategy would augment employment accessibility by public transit. The emphasis on employment location in this work is consistent with the notable phenomenon of employment concentration at the center of Beijing, also the result of city planning. City authorities possess the capability to direct the spatial development of the city and have consistently done so with other objectives in mind. Our intention is to shine light on the ethical and social implications of such interventions on the part of the local authority.

2. Literature review

2.1. Transport equity

Transport equity became the focus of academic research during post-WWII motorization and suburbanization in the United States. The focus was initially on social impacts of a major transformation of the transport system to a largely private one, operating on public infrastructure. Curtailments in public transit provision left many lower income and especially inner city populations with limited mobility and reduced access to jobs (Kain and Meyer, 1970; Rosenbloom and Altshuler, 1977). Government attention to impacts of transport policies on vulnerable groups (e.g. Executive Order 12898, 1994, USA), was expanded to concerns about adverse environmental impacts (Gordon, 2015), including security, hazardous air pollutants and noise (Morello-Frosch et al., 2001; Brainard et al., 2004; Chakraborty, 2006). Impact assessments also included consideration of the equitable distribution of transport infrastructure (Delbosc and Currie, 2011; Welch, 2013).

There are three fundamental concepts of equity in the literature that help inform how we are to conceive of transport equity and its application. They are generally known as egalitarianism, utilitarianism and Rawlsianism (Thomopoulos et al., 2009), and have the following general characters. Egalitarianism implies that every individual enjoys the same level of benefit and without special consideration for any groups or individuals (Litman, 2007). Such an approach might not be considered entirely fair, however, because of differing social contexts, needs and possibilities in the real world; fair outcomes are achieved at the price of granting privilege to some people (Pereira et al., 2017). Utilitarianism involves considerations of efficiency in attempting to produce the greatest good for the whole society as the top priority. In pursuing such an overarching goal, transport systems may operate optimally for mass demand, but individual needs may be ignored and there remain questions about the distribution of benefit within society (Martens, 2011). Rawls proposed distributive principles that could be transposed into the transport field (Martens et al., 2012). For example, the effort should focus on maximizing average transport benefit while those most disadvantaged by the system would be awarded extra consideration and benefits.

There are two critical components in transport equity studies: firstly the definition of transport benefit or cost, secondly the distribution (Litman, 2002). Transport benefits are mainly about improvements to accessibility, transport system efficiency and economic vitality, while accessibility to employment is one of the most common indicators for transport equity analysis (Bills and Walker, 2017). As the transport benefit or transport good, accessibility should distribute solely according to social needs, and its distribution among the population should be guided by social purpose-adapted policy rather than being driven by wealth distributions (Martens, 2012). The two types of distribution, both essential to equity assessment, are geographical and social (Karner, 2016). Geographic distribution refers to scales, geographic units of analysis and spatial patterns, while demographic group identification for understanding transport equity could be understood as choice and dependent transit riders. Choice riders have access to private vehicles and hence their choice to use transit must be understood within a larger choice set, while dependent transit riders rely entirely on transit to access destinations (Benenson et al., 2011; Taylor and Morris, 2015). Extensive car ownership can capture public resources to support ever-increasing demand for roads, which may lead directly or indirectly to reductions in public transit improvement. The resulting disparity in benefit between private road-based transport and public transit is then exacerbated by significant differences in the socio-economic profiles of the two user groups. As a consequence, it is often stated as the highest priority to consider the relative accessibility of those operating private cars and those confined to public transit when considering the distribution of transport benefits (Benenson et al., 2011). Accessibility gap between private and public transit riders is of appropriate use as a core indicator of transport equity.

In considering transport equity, one must also take into account urban structure. Commute behavior will depend on the spatial distribution of employment and how the transport system serves those commutes (Schleith and Horner, 2014). The complexities of transport provision increase considerably when urban structure evolves, especially under conditions of rapid growth. New spatial relationships between residential and employment zones, with variable coverage by a variety of transport systems, will have important transport equity effects (Zhao and Pendlebury, 2014). The extent of impact from urban employment distribution on transport equity has not been sufficiently explored. This paper is devoted to a consideration of impacts on accessibility of strategies to direct urban structure, in particular the allocation of employment concentrations.

2.2. Accessibility measurement

Accessibility is the generally accepted metric for measuring transport equity. It already features prominently in transport-related studies to explore the relationships between transport systems and various urban functions (Delbosc and Currie, 2011; Tilahun and Fan, 2014; Guzman et al., 2017). Here we are concerned with the accessibility to employment as a key indicator of transport equity. Karner and Niemeier (2013) proposed a three-step procedure for transport system analysis as follows: define target populations; define equity metrics; assess equity. They further propose that accessibility to employment and important destinations as the best metric to represent benefit in the second step above (Martens, 2012; Golub and Martens, 2014; Bills and Walker, 2017).

There are various approaches for measuring accessibility, which need to be considered with regard to transport equity. A series of reviews are available (Liu and Zhu, 2004; Geurs and Van Wee, 2004; Neutens, 2015). From this literature (Geurs and Van Wee, 2004), four approaches to measuring accessibility can be discerned. Firstly, there is the infrastructure-based approach, which focuses on the performance of transport infrastructure with respect to such issues as congestion and travel speed. Secondly, there is the person-based approach from time geography, which finds all accessible activities within certain temporal constraints (Hägerstrand, 1970). Third is the utility-based economic analysis, based on random utility theory combined with accessibility for individuals, places and activities, usually examined with MNL models. Fourth is the location-based approach, where the spatial distribution of opportunities is described, as defined by the relationship between urban structure and the transport system (Kawabata, 2009). This last approach offers the possibility to interpret urban structure at the urban scale, and thus the effects of differentiated spatial distributions on the accumulation of opportunities, as suggested by Kawabata and Shen (2006).

In the present study, we need to distinguish and then choose the specific methods of location-based accessibility approach among the usual measures categorized as gravity measures and distance measures (Geurs and Van Wee, 2004). Gravity measures are also called potential measures, which are adjusted according to a gravity principle, with nearer opportunities more accessible and farther ones with diminishing accessibility according to certain distributions. Distance measures consider initially place connectivity. A typical method is cumulative accessibility, counting the number of cumulating opportunities reachable from a given location within a given travel cost. The literature suggests that gravity or potential measures tend to overestimate accessibility scores in areas that are relatively isolated, but also have the inconvenience of complex computation and more difficulties in interpretation (Kwan, 1998; Luo and Wang, 2003). The cumulative opportunities method is structurally similar to gravity methods, but is easier to interpret and easier to use in discussion of policy with decision-makers (El-Geneidy and Levinson, 2006), and has been successfully applied in many recent studies (Casas et al., 2009; Moniruzzaman and Páez, 2012; Ben-Elia and Benenson, 2019). The cumulative approach is adopted in the present research in order to make clear the combined effects of transport design and the structure of urban activities over space.

3. Methodology

3.1. Transport equity metrics from accessibility

As discussed above, accessibility can be seen as a transport good. Under ideal equitable conditions, accessibility could be distributed independently from other privileges (Martens, 2012). However, in the real environment, many intervening factors reduce this equitable distribution of public and private transport resources. The metro line might be far away and constantly overcrowded. A private car is a remote option unless a person already has a private car. There are various taxi services as well, where accessibility may also vary by location.

Accessibility is a much-used indicator of transport equity, but has not been adequately considered in the context of employment redistribution. In a comparison of mode accessibility, it can be straightforward to measure the disparity as the ratio of modes (Kawabata, 2009). Since equity is a relative concept, the magnitude of the difference in transport equity is the recommended approach. In this study, transport equity is defined as the Accessibility Equity Index (AEI), measured as a ratio of the public to private modes, as follows:

$$AEI_{i,tb} = \frac{A_{pt}}{A_{pc}}$$

$$A_i = \sum_j O_j f\left(t_{ij}\right) \text{ and } f\left(t_{ij}\right) = \begin{cases} 1, & if\ t_{ij} \leq tb \\ 0, & if\ t_{ij} > tb \end{cases}$$

where i is any location in the city; tb was the time budget decided previously; A_i is the accessibility of i by public transport or private car under the time budget of tb; O_j is number of jobs in location j, which represents all the employment locations; t_{ij} is the travel time between point i and j. In the actual computation process, every i location is represented by a point (with population of specific spatial granularity behind it) which is connected within the urban transport system. The accessibility by each mode is calculated by network analysis using cumulative methods with specific time budgets. This metric unambiguously adds information about the disparity of these two travel modes while accessibility by only one mode could not achieve the result.

The public transport and roads networks in Beijing were used as a base for the measurement of accessibility, since travel is constrained to this network (Miller, 1991; Kwan, 1998). Travel time is estimated for trips on these networks (Delamater et al., 2012). Inhabitants and employment are distributed in a 1-km raster, to measure travel time along the alternate networks between home and employment, for example. In this way, we detect the variable performance of the whole system and local geographies in terms of accessibility. The measure averages for local geography, so we lose applicability to local user groups in favor of a simple, but evocative metric.

3.2. Study area

Beijing had an official population of 21.7 million in 2015, with 4.52 million registered private motor vehicles. The city has a concentric urban form with six ring roads, which constrains the movement of citizens to a considerable extent. As the basic statistical unit of employment data is the township (*jiedao*), all townships located within the Sixth Ring Road were included as well as the highly urbanized townships and the towns where district government is located beyond the Sixth Ring Road, to make up the study area. There were 196 townships in the study area, 3612 km^2 in total with the built-up area constituting 74.6% of the overall built-up area in the city (Fig. 1). Townships vary from 2 to 3 km^2 to tens of km^2. Employment was assumed to be distributed similarly across townships regardless of size, so employment could be reduced to a 1-km^2 grid.

3.3. Data preparation

Data used in this paper were from a variety of sources as follows (Table 1). Population density map was from the 6th Nation Census Statistics (2010), and the spatial dataset was derived from the Thematic Database for Human-Earth System (TDHS) in the China Academy of Science (CAS), with 1 km×1 km accuracy. Population data at township level of 2000 and 2010 respectively from 5th and 6th Nation Census Statistics were also collected from Beijing Statistical Bureau. The employment datasets with accuracy at the township level were chosen from the 2nd and 3rd National Economic Census in 2013, because this period matches with the population data relatively well, as does the built-up area dataset from Gong et al. (2013). Because no later accurate data were published publicly, datasets at the township level were chosen firstly in this research (Fig. 2). In order to correct the employment data, non-built-up area was hypothetically regarded as without employment provision, so the non-built-up area was excluded while overall employment in each town was equally divided into the built-up area since the employment distribution in every town could be seen as similar.

3.4. Measurement of accessibility and AEI based on GIS

As discussed above, a widely used accessibility method which was measured as cumulative opportunities based on network analysis and is introduced here. The public transport network was constructed from Long and Thill (2015) while private vehicles were assumed to travel along the common transport network. Origin-destination analysis was employed to estimate accessibility. Parameters for different vehicle modes were based on previous studies of Beijing listed below (Table 2), with different time budgets – 30, 45, 60 and 90 min – were employed to cover nearly all commuting travel. Note that morning and evening peak travel time in a taxi is 44.2 min and 47.5 min (Beijing Transport Research Center, 2016), from which we derive a typical commuting time budget of 45 min. The population dataset from the 6th National Census Statistics in 2010 was introduced, and the spatial dataset with a population density above zero was converted into a point grid. Employment datasets which were corrected according to the built-up area was converted into a point grid as well. An O-D matrix which includes 3396 residential points and 1514 employment points, with the above time thresholds were employed in the private vehicle and public transport accessibility analysis respectively.

AEI was measured here based on the accessibility results which were estimated by the networks of private car and public transport respectively as well as the time budget and speed parameters. Speeds are reported mean values for road or rail modes across their respective systems. All points in the 1 km×1 km population grid were computed and composed a completed AEI spatial distribution map (see Fig. 3).

Table 1
Original data source.

Data	Year	Accuracy	Source
Population density	2010	1 km×1 km	TDHS Database of CAS
Population	2000/2010	Township	Beijing statistical bureau
Employment	2004/2014	Township	Beijing statistical bureau
Built-up area	2013	30m resolution	CEES Database of THU

4. Analysis and result

4.1. Spreading population and centralizing employment

Population density change between 2000 and 2010 is illustrated at the township level (Fig. 4). In the central areas within 3rd Ring Road, there was minor population increase, while substantial amounts of new residential development occurred between the 4th and 5th Ring Roads. Employment distributions also changed dramatically, with the area within the 2nd Ring Road seeing major increases in employment, while relatively little growth occurred outside the 4th Ring Road.

The cumulative percentage of population and employment change occurring at increasing distance from Tiananmen square (TAM) square reveals the increasing separation between home and workplace (Fig. 5). It can be seen that from 2004 to 2013, 21.7% of the employment increment is located within 5.5 km of Tiananmen, while the population decreased marginally over the same distance. Yearly additions in employment are four to five times those in population until well beyond the 4th Ring Road.

4.2. Accessibility analysis

Retaining the same analytical framework, the disparity of accessibility by different modes of private car and public transport can also be investigated. At different time budgets, accessibility was high in the centre while decaying through the various rings to the fringe. As the time budget increased, the cumulative opportunities rose consequently (see Table 3). For the private car mode, when the time budget was 30 min, only 3.7% of the population could access 70% of the employment, but 100% of the population had access to 70% of employment when the time budget was 90 min. Accessibility level of public transport was lower than by private car mode generally. For example, when the time budget was 30 min, only 15.1% of the population could access 10% of the employment by public transport, while 66.1% of the population had access to the same amount of employment by private car in the same

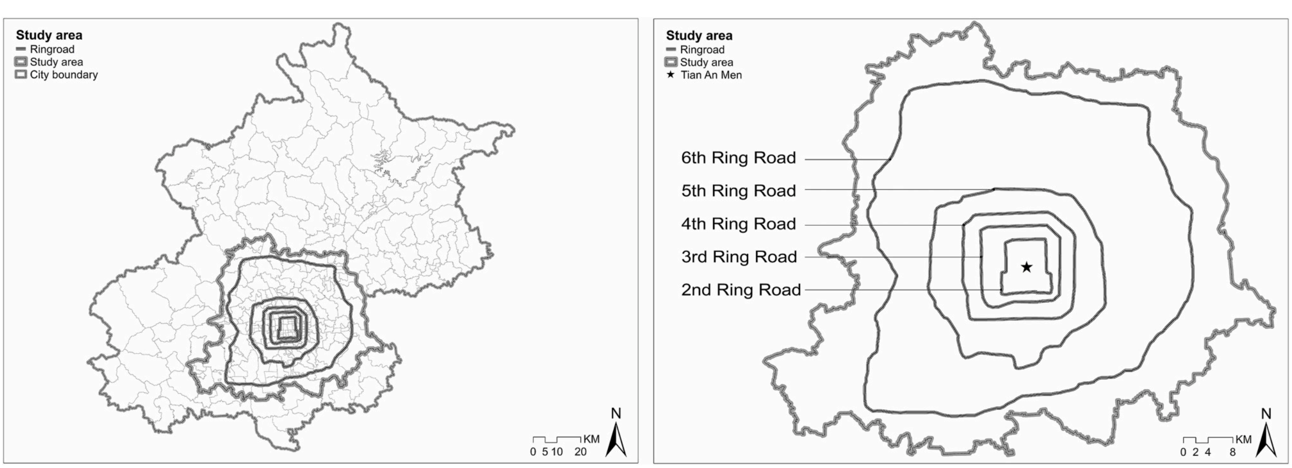

Fig. 1. Study area.

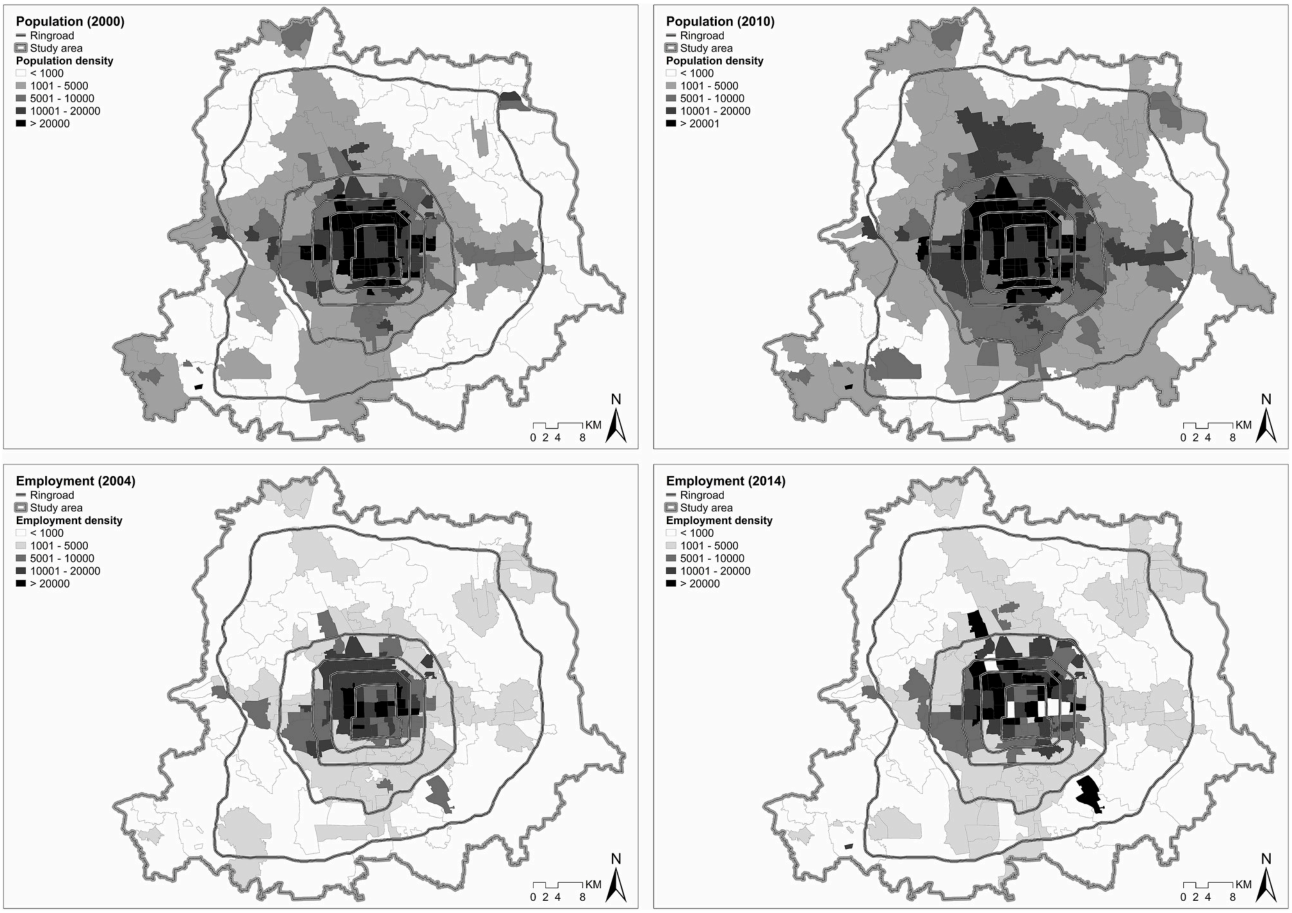

Fig. 2. Population and employment datasets at township level.

Table 2
Speed parameters in the network analysis simulation.

Mode	Speed	Source
Private car	40 km/h	Lv et al. (2013)
Bus	16.9 km/h	Lv et al. (2013)
Metro	31.3 km/h	Deng et al. (2012)

time budget.

The spatial distribution of accessibility by private car mode was generally concentric, and revealed little difference by direction from the core (Fig. 6). It was found that accessibility by public transport was more dependent on the essential structure of the metro network system, especially when the time budget was not higher than 60 min. When the time budget was raised to 90 min, accessibility by public transport did not show significant difference for the metro lines within the study area.

4.3. Analysis of transport equity

As discussed above, transport equity can be measured as a cumulative accessibility index. Spatial distribution of AEI is illustrated in Fig. 7. It can be seen that the core area of Beijing has relatively high transport equity, and the area of this core zone expands as the time budget increases. At the time budget of 30 min, the core zone within the 2nd and 3rd ring road has the highest AEI, dropping subsequently in the area between the 4th and 5th Ring Road, then rising again at the core of Beijing peripheral counties. It can be seen that the AEIs along the metro network were higher than in the surrounding area, making clear the important contribution of metro to public transport accessibility. Though it may not initially be obvious, there is a difference between public accessibility distribution and the AEI metric, especially in the periphery. In these peripheral areas, since the employment concentrates in the center, public transit accessibility is lower than in core areas; however, the disparity between car drivers and public transport travellers is less than at locations in the center.

Considering the average commute duration of Beijing residents is around 45 min (Meng et al., 2011), the AEI begins to drop dramatically near the 5th ring road area in the north and even 4th ring road area in the south. This result means that in these urban areas, commuting by private cars has significant advantage over public transport, even though these areas have been the main growth areas for residential development most recently.

AEI was constructed to represent the disadvantage of public transport relative to the private car, so the reciprocal of the AEI could represent the relative advantage of private car to public transport. Here the cumulative population percentage and the corresponding 1/AEI at different time budgets are illustrated (Fig. 8). It can be seen that, at the time budget of 45 min, 1/AEI rose to 1.20, with the cumulative population percentage beginning above zero. This means that maximum accessibility of public transport could only be 0.83 times that of private car. When 1/AEI was 4.00, the cumulative population percentage was 67.2%, so the remaining 32.8% of the population had accessibility by private car four times that of public transport. Ideally, the population-AEI curve could be as near as possible to the Y axis, at a time budget as limited as possible.

4.4. Beijing development scenarios

The above analysis reveals the importance of the spatial pattern of residence and employment, together with the transport network system

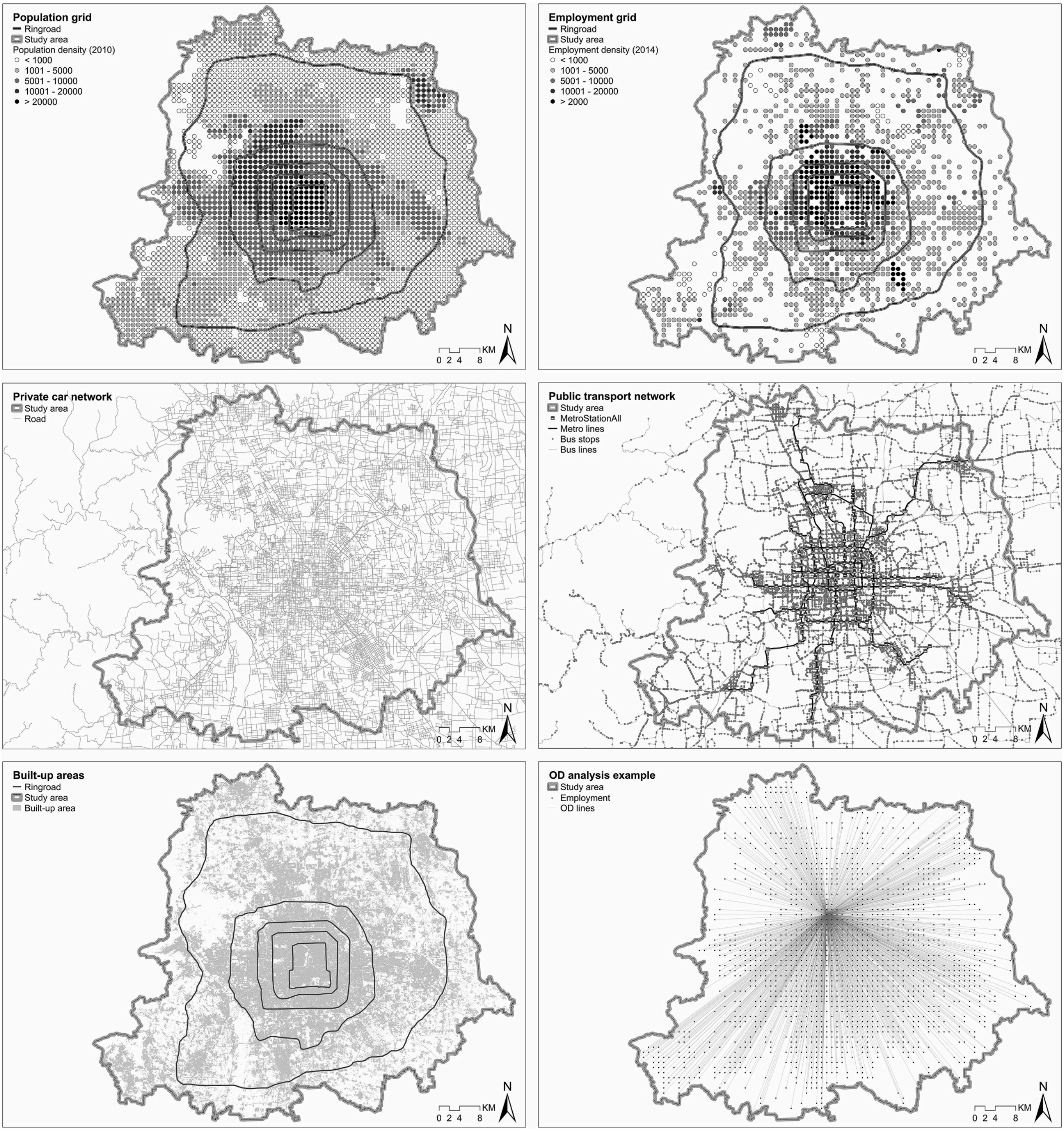

Fig. 3. Datasets for accessibility measurement.

in people's daily commutes. It then becomes relevant to simulate the differences between macro policies of employment distribution of Beijing from the transport equity perspective. Following annual practice of the government, the planned urban employment increment was 360,000 in 2015 (Beijing Daily, 2015). Nine spatial scenarios (S1∼S9) for the total planned employment amount were applied, such that their locations were between different ring roads (see Table 4). The location of the employment increment was considered in scenarios 1 to 5, while dispersion of the inner ancient city within the 2nd Ring Road was also considered in scenarios 6 to 9. The increments or decrements of employment in these scenarios had the same ratio for every employment point respectively.

The time budget of 45 min was applied to all 9 scenarios. Efficiency is measured in terms of total increase in accessibility. Though overall employment increased, but in S6 to S9 with the strategy of dispersing the ancient city, some areas saw a decline in employment, with the result that some locations also had lower accessibility. In order to measure the effects of different scenarios simulated here, the current AEI of the population grid points were computed and divided into 4 quartiles. Q1 was the quartile with the lowest AEI while Q4 had the highest AEI.

Results show that in scenarios of employment increments in the central areas (S1, S2, S3), the current areas with relatively higher AEI

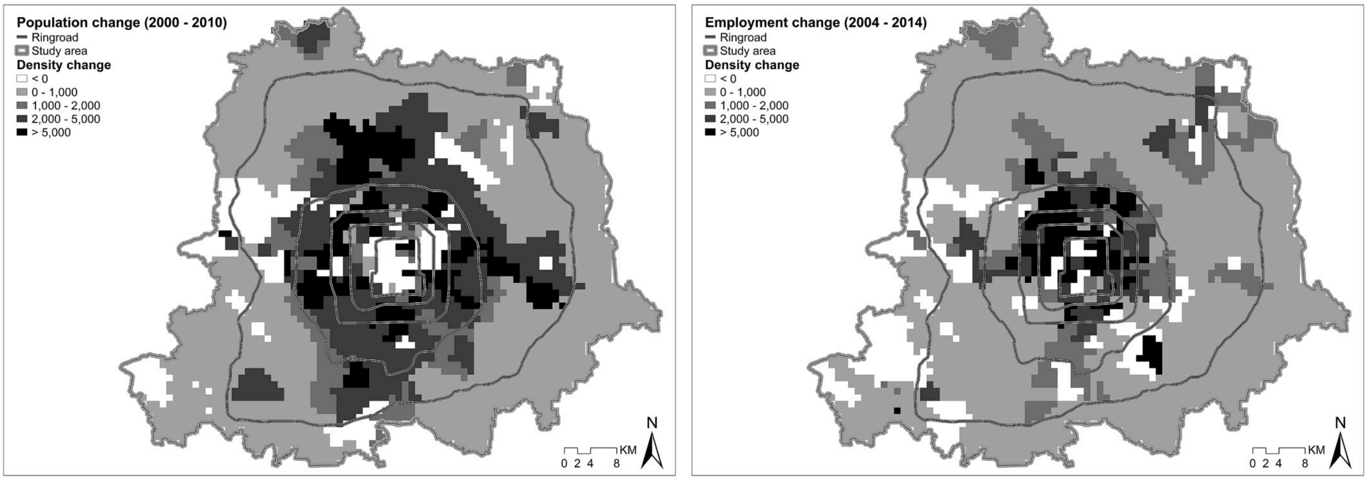

Fig. 4. Population and employment change.

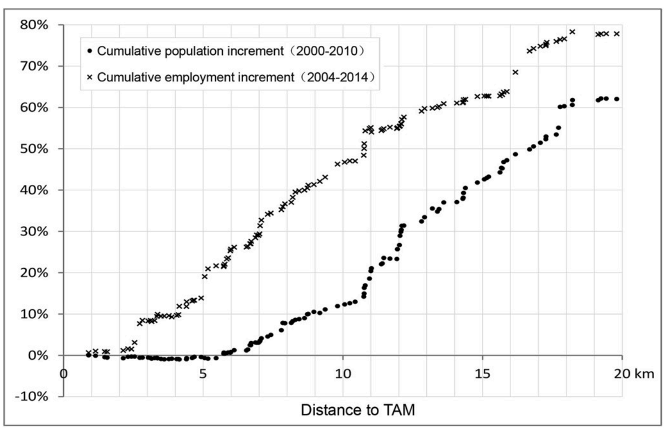

Fig. 5. Distance to TAM and cumulative increment of population and employment.

quartiles (Q4) would have further AEI increment while the currently lower AEI quartiles (Q1, Q2, Q3) would experience declines in AEI. In these scenarios, transport equity rises significantly inside the 5th ring road (Fig. 9).

For the scenarios which increased employment outside the central area (S4, S5), areas with relatively higher AEI (Q4) decreased. The average AEI change of Q4 at S4 was −0.0037, and −0.0100 at S5, but average AEI changes of Q1, Q2 and Q3 all declined at the same time. AEI changes of Q4 decreased on S5, while AEI changes of Q1, Q2 and Q3 all showed increase. It could be concluded that areas outside the 5th Ring Road became the main area with AEI increment, and areas inside the 5th Ring Road generally decreased (Table 5).

There were AEI changes in S6 to S9, which also represent a dispersal of the ancient, inner city. In S6, areas with currently higher AEI (Q4) had an average increment 0.0040 of AEI change–mostly areas inside the 4th Ring Road and some parts outside the 5th Ring Road also had significant AEI increment. At S7 with employment increments between the 3rd and 4th Ring Road and decrements inside the 2nd Ring Road, average AEI change at Q4 was −0.0026, but AEI in currently lower AEI (Q1, Q2) both decreased as well. Scenarios with employment dispersion from the inner ancient city to outside the 4th Ring Road areas (S8, S9) had similar AEI change as S5, but the accessibility improvements were less than S5, which meant that the effectiveness of these 2 scenarios was not as much as S5.

Various interpretations of these results are possible. Overall accessibility is most improved in S1, meaning that S1 is the most efficient result in terms of the accessibility increment; however, those already in lowest quartiles of transport equity experience a decrease in accessibility. As a result, S1 could be understood as an efficient but inequitable scenario. From the Rawlsian perspective, the least advantaged groups should have priority. In terms of employment allocation, S5, S8 and S9 all make the biggest improvements for those currently experiencing lower disparity between public and private transport modes, but with overall poor accessibility. To compromise between a transport equity increment and efficiency improvement, S5 is seen as the choice with enhanced transport equity and acceptable increase of efficiency. Since the goal of “higher quality, efficiency and equity” is written in the guiding document of Beijing municipal government for implementation in the next 5 years, S5 is a practical application to allocate resources in the future (Beijing Municipal Government, 2016).

Table 3
Population (%) accessing employment (%) with corresponding mode and time budget.

Level of accessed employment (%)	Population by private car mode (%)				Population by public transport mode (%)			
	30 min	45 min	60 min	90 min	30 min	45 min	60 min	90 min
10	66.14	98.05	99.91	100.00	15.14	37.34	62.55	94.35
20	45.68	92.06	99.62	100.00	0.00	26.06	51.50	89.32
30	34.75	84.20	99.15	100.00	0.00	18.30	39.94	85.11
40	26.79	72.01	98.18	100.00	0.00	13.73	33.10	80.32
50	18.16	61.41	96.78	100.00	0.00	10.63	26.79	74.24
60	10.94	48.33	92.51	100.00	0.00	5.14	19.30	66.13
70	3.72	37.02	84.81	100.00	0.00	0.67	12.11	55.56
80	0.00	22.66	70.79	99.89	0.00	0.00	1.91	35.63
90	0.00	1.23	35.64	99.03	0.00	0.00	0.00	10.04
100	0.00	0.00	0.00	15.10	0.00	0.00	0.00	0.00

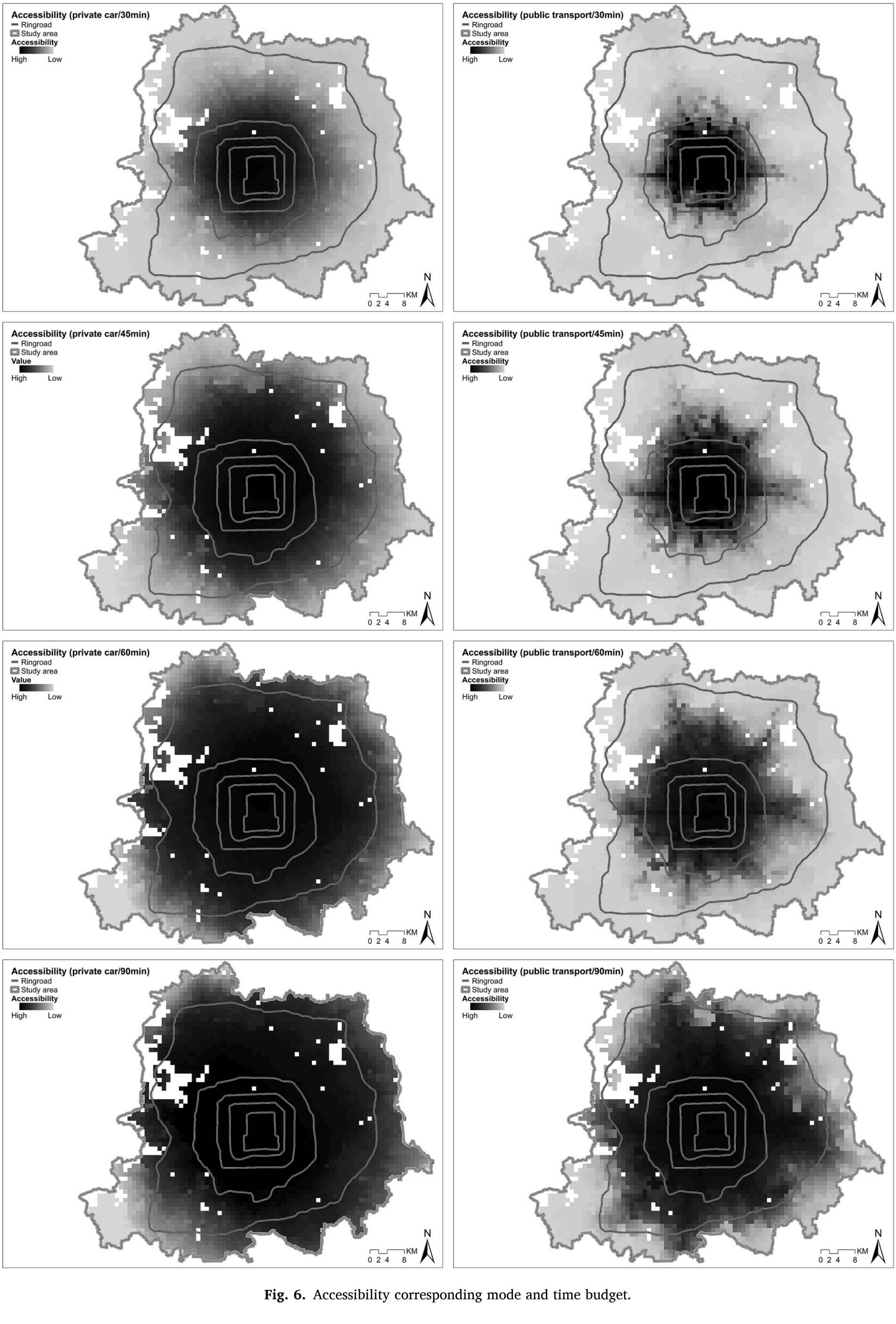

Fig. 6. Accessibility corresponding mode and time budget.

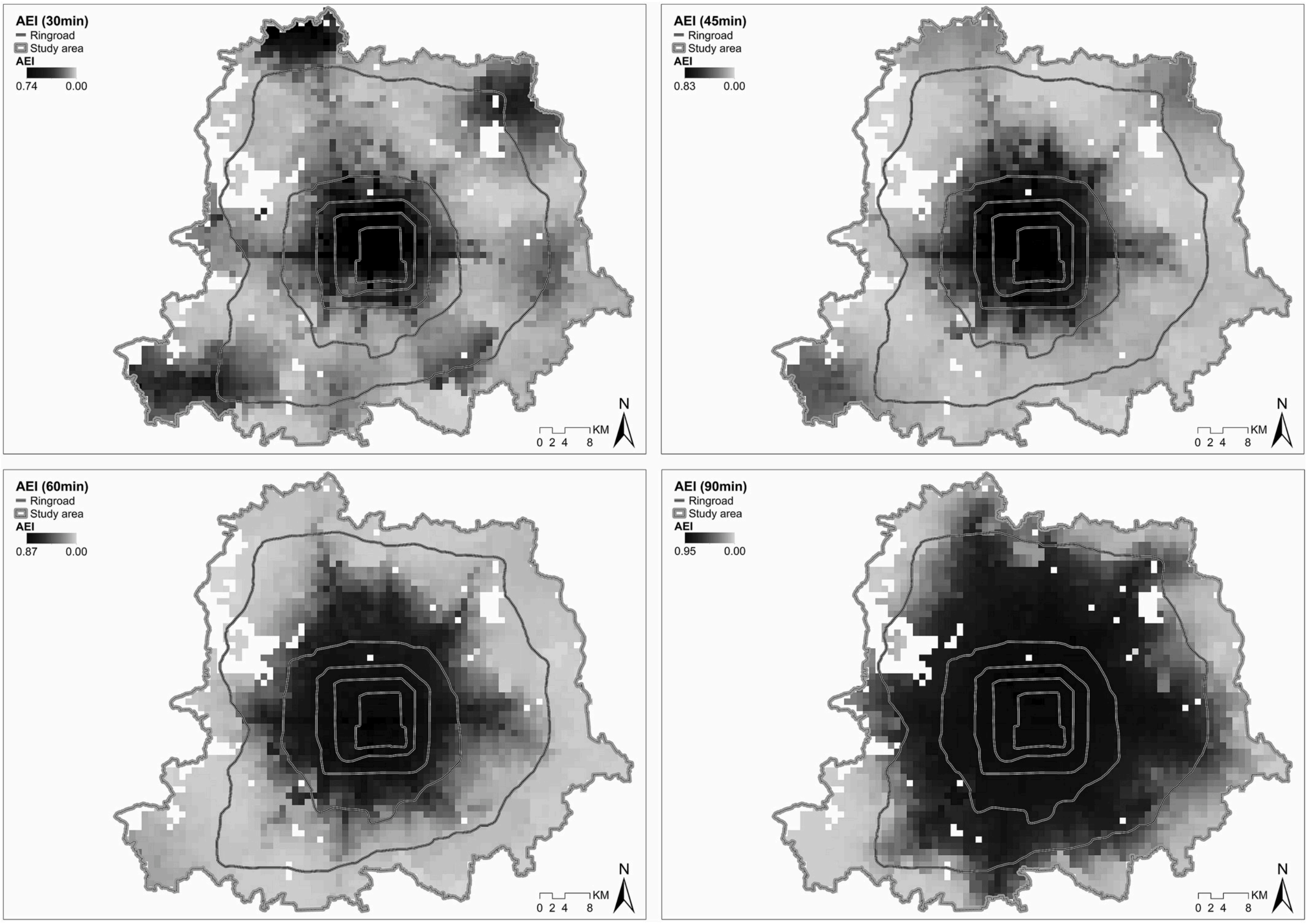

Fig. 7. AEI and corresponding time budget.

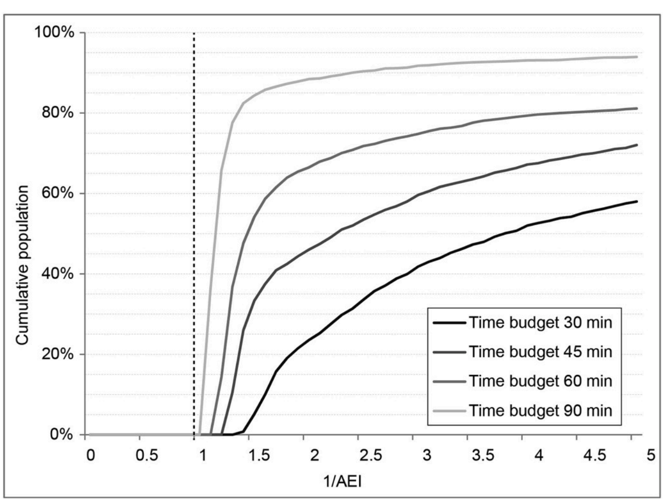

Fig. 8. Cumulative population percentage and corresponding 1/AEI.

Table 4
Scenario simulations of different employment locations.

Scenarios	Increment zones	amount	Decrement zones	amount
Scenario 1 (S1)	in 2nd ring road	360, 000	–	–
Scenario 2 (S2)	2nd to 3rd ring road	360, 000	–	–
Scenario 3 (S3)	3rd to 4th ring road	360, 000	–	–
Scenario 4 (S4)	4th to 5th ring road	360, 000	–	–
Scenario 5 (S5)	5th to 6th ring road	360, 000	–	–
Scenario 6 (S6)	2nd to 3rd ring road	720, 000	in 2nd ring road	360, 000
Scenario 7 (S7)	3rd to 4th ring road	720, 000	in 2nd ring road	360, 000
Scenario 8 (S8)	4th to 5th ring road	720, 000	in 2nd ring road	360, 000
Scenario 9 (S9)	5th to 6th ring road	720, 000	in 2nd ring road	360, 000

5. Strengths and limitations

The use of a cumulative measure provides a clear image of accessibility represented as public modes over private ones, across the geography of the city. From a policy perspective, this approach enables quick identification of areas deprived of public services and the consequent likely recourse to private motorized modes. In this application, we have wanted to highlight the relation between public services and private means as a guide to the adjustment of global policies of motorization and public transport provision. The method could also be applied to consider combinations of sustainable modes. The method also interfaces well with the related questions of land use allocation. Employment distribution in particular can be evaluated for its impact on AEI and the relative impacts of provisions for public transport and motorized access.

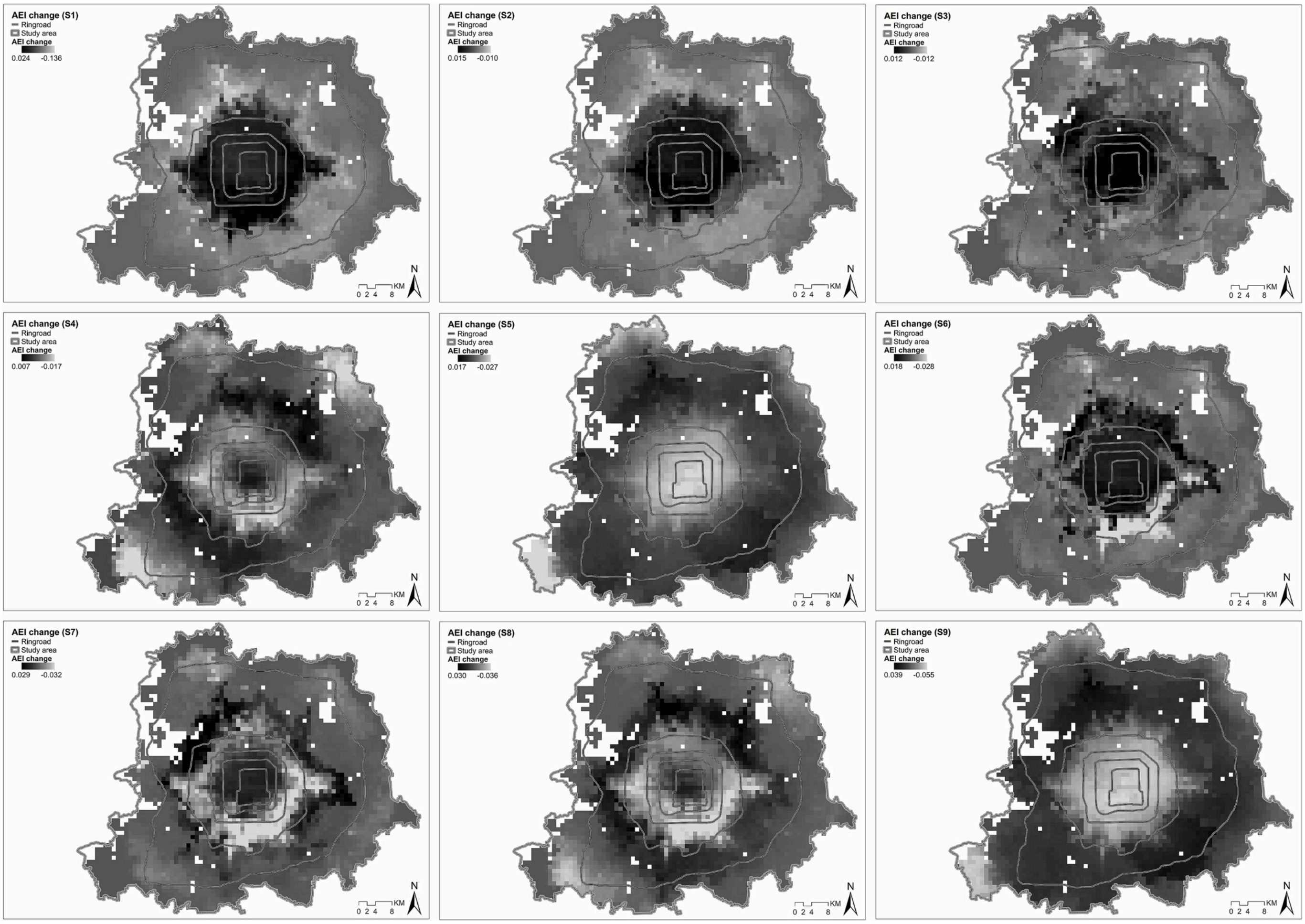

Fig. 9. AEI change of different scenarios.

Table 5
AEI and accessibility result of 9 scenarios.

	Average AEI change				Accessibility change (%)	
Scenarios	Q1	Q2	Q3	Q4	Private car	Public transport
S1	−0.0009	−0.0027	−0.0025	0.0083	4.07	4.94
S2	−0.0010	−0.0025	−0.0019	0.0062	3.94	4.46
S3	−0.0011	−0.0021	−0.0009	0.0029	3.79	4.1
S4	−0.0008	−0.0010	−0.0024	−0.0037	3.61	3.22
S5	0.0018	0.0043	0.0012	−0.0100	2.94	2.29
S6	−0.0010	−0.0022	−0.0013	0.0040	3.82	4.31
S7	−0.0012	−0.0014	0.0008	−0.0026	3.5	3.49
S8	0.0000	0.0021	0.0006	−0.0077	1.67	1.71
S9	0.0046	0.0116	0.0055	−0.0285	1.78	−0.21

This paper concerned only the impact on accessibility of employment distribution, because it relates directly to standing government policy. This is not to suggest that this policy alone is ideally suited to address spatial equity and accessibility issues, although it is one that can be acted upon and quickly. Given the sustained growth rate of Beijing, employment distribution is a potentially powerful tool. At the same time, supportive policies are needed in other domains such as in urban planning. Specifically, the present paper does not consider the impact on spatial equity of major transformations of the road network to support public transport. Also, improvements to the public transport system itself, which should also have significant impact on AEI, are not considered in this demonstration.

A major limitation of the method is that individual information is lost so we cannot know how vulnerable users are distinguished from the majority. In addition, during the scenarios analysis we assume other factors are fixed, including population distribution change. Finally, the information used here is from the township level, which is large for understanding local transport conditions that might be informing the AEI metric. Data at a much finer resolution are increasingly available to planning authorities such that this concern is likely to disappear.

6. Conclusion and discussion

In this study, transport equity effects from employment redistribution are evaluated and used to build a practical indicator for accessibility, in order to evaluate the disparity between different modes and spatial locations. Accessibility was measured by the network-based cumulative opportunity method. The concept of the AEI metric is proposed to measure the disparity in accessibility by different modes, in order to address insufficiencies in the accessibility indicator. Taking Beijing as a case, accessibility by private car and public transport were estimated numerically and spatially, with the AEI characteristic of the research area analyzed. Nine scenarios with different employment location strategies were considered for their impacts on accessibility. After comparing the AEI and accessibility changes of different scenarios, it was found that S5 with employment increment between the 5th Ring Road and 6th Ring Road had advantages in both effectiveness and equity perspectives.

The vital task of transport equity is to protect the population from disproportionate harm from transport-related policy and to ensure equitable resource allocation (Fruin and Sriraj, 2005). Analysis of transport equity can play a role in helping to define spatial and transport policies as part of the transport management policy. While car license lotteries appear fair in affording everyone the same opportunity to acquire limited goods, the effects are anything but evenly distributed. Relatively higher transport equity, when measured as accessibility, is achievable under this policy of restrictive car licensing by implementing supportive employment distribution. However, such employment distribution, through land use policies, would also require consideration of the capacities of the existing movement networks, which this paper did not take into account. Raising the attractiveness of Beijing's urban area between the 5th and 6th Ring Roads for employment may also require further investment in transport services in this area. Such concentration of new transport provisions within the already built-up area would be in contrast with the current policy of extending the reach of the transport system to the far-flung suburbs while emphasizing connectivity in the core area.

The allocation of resources to deliver transport services to a large city has also to consider not only the investment resources but also the spatial resources of development land, and road and rail infrastructure. That is, new infrastructure provision may well have impacts on accessibility across the urban area, but re-allocating road space and improving the efficiency of the public transport system may also have significant impacts on local accessibility. These could, in turn, have impact on the demand for car ownership. Under current conditions, it remains highly attractive to obtain a car for the daily commute. Indeed, the Beijing lottery attracted 2.69 million entries competing for 13.5 thousand license plates in the in October 2016.

The AEI metric provides a simple measure of how well the city is doing in supplying a necessary public good to a particular location. It is the measure of the relation between public and private means to access some good or service, such as work. Thus it only relativizes the provision of transport services at the local level, so cannot alone measure the distribution of benefit across the urban area. As such it generally identifies those areas of the city, typically at the periphery and isolated, which should benefit from redistributive policies. However, those peripheral residential areas were the outcome of land use policies for the whole region. Continued expansion of the urban region could be bolstered by invoking the same AEI analysis in support of public transport investments in those areas. That is to say, measures like AEI need to be integrated into a larger framework of policy analysis, leading to urban planning practices.

Accessibility to work and services is fundamental to urban life and is to a considerable extent tributary to policies regarding transport development and urban development in general. Land use can be manipulated effectively to mitigate commuting travel, in particular through land use conversion in lands farther away from the city center. Accessibility could also be enhanced by raising the residential density of the core areas. Such approaches might be seen as viable alternatives to the present course of gradual improvements in the public transport network, which have struggled to keep up with demand, but do not compete in time terms with private transport.

The approach in Beijing has been to develop rapidly into suburban areas with extensive road networks while gradually building up the public transport network. The consequence has been to stimulate a demand for private transport, that has been countered by limitations on the number of new licenses. The argument here is that such a control policy, even if were to be successful in limiting the total number of vehicles on the road, has not resulted in compensatory measures to raise overall accessibility. Rather, it is arguably more efficient to use land use measures and the re-allocation of existing transport resources to dampen the demand for cars. It may not be possible to transform Beijing spatially after decades of intensive development, but it may be possible to adjust its accessibility characteristics through a set of interrelated land use, transport investment and public resource re-allocation policies.

The Beijing case is particularly interesting for this analysis of cumulative accessibility because it has grown very rapidly over the last two decades and undergone considerable transformation. The changes in accessibility are correspondingly sharper. All large cities face similar issues of spatial inequality, but megacities see these issues magnified. As the number of world cities attaining megacity status will accelerate, transport equity becomes an important issue at the megacity end of the city size scale.

CRediT authorship contribution statement

Zhe Sun: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing. **John Zacharias:** Methodology, Writing - review & editing.

Acknowledgements

The authors thank the editor and anonymous reviewers for their comments and suggestions to improve the quality of this paper. The financial support from Social Science Foundation of Beijing (No. 19GLC065) and the State Administration for Foreign Experts Affairs, People's Republic of China are gratefully acknowledged.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tranpol.2020.03.016.

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