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Evaluating the effectiveness of urban growth boundaries using human mobility and activity records

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ABSTRACT

We proposed a methodology to evaluate the effectiveness of Beijing's Urban Growth Boundaries (UGBs) using human mobility and activity records (big data). The research applied data from location check-in, transit smart card, taxi trajectory, and residential travel survey. We developed four types of measures to evaluate the effectives of UGBs in confining human activities and travel flows, to examine the conformity of urban activities with the planned population, and to measure the activity connections between UGBs. With the large proportions of intra- and inter-boundary travel flows and an overwhelming majority of check-ins inside the UGBs, the research concluded that Beijing's UGBs were effective in containing human mobility and activity. However, the connections between UGBs, indicated by the spatial differentiation of the travel flows, were not consistent with the plan's intention and strategy. It indicated the potential underdevelopment of the public transit serving several new cities.

1. Introduction

Evaluation of plan implementation is important because it reflects the extent to which a plan succeeds in predicting, guiding, and controlling future urban development. One common way to determine what a plan has accomplished is to measure the conformance degree between the actual outcomes or impacts and the proposed plans. By doing so, planners can acquire insights on how the planning decision-making process operates and validate whether planning efforts do contribute to goal achievement (Alexandar & Faludi, 1989; Alexander, 2009; Laurian et al., 2004; Talen, 1996b). This evaluation helps establish a responsive and accountable plan-making and -implementation process, thus improving the overall quality of planning. Since the early 1970s, numerous studies have contributed to the theoretical and methodological understandings in the field of planning evaluation. A few studies have illustrated the evaluation approaches with one particular aspect of planning, including land development (Alterman & Hill, 1978; Berke et al., 2006; Chapin, Deyle, & Baker, 2008), environmental planning (Brody & Highfield, 2005), public facilities and infrastructure (Laurian et al., 2004; Talen, 1996a), and urban sprawl control (Altes, 2006; Brody, Carrasco, & Highfield, 2006; Nelson & Moore, 1993).

In this study we focused on assessing plan implementation in terms of the effectiveness of urban growth boundaries. As one of the most widely adopted urban containment policy tools, urban growth boundaries (UGBs) have been used to control the expansion of urban areas, increase urban land use density, and protect open spaces (Pendall, Martin, & Fulton, 2002). The basic concept of implementing a UGB is to set a physical boundary separating urban and rural areas. Usually, urban developments are not allowed outside the predefined boundary. Broadly speaking, the implementation of UGBs also encompasses various regulatory techniques such as zoning and land development permits. Proponents argue that urban growth boundaries may have at least the following six merits (Staley, Edgens, & Mildner, 1999): (1) preserve open space and farmland; (2) minimize the use of land generally by reducing lot sizes and increasing residential densities; (3) reduce infrastructure costs by encouraging urban revitalization, infill, and compact development; (4) clearly separate urban and rural uses; (5) ensure the orderly transition of land from rural to urban uses; and (6) create a sense of community. An increasing number of cities in the U.S. and Europe have regarded UGBs as a key tool in controlling urban sprawl. However, the empirical

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studies measuring the effectiveness of UGBs are not common. This is partly because that plan implementation evaluation has rarely attracted adequate attention in the planning profession. It has been an afterthought to the planning decision-making or implementation framing (Berke et al., 2006; Talen, 1996a). The lack of data, robust evaluation theories and methodologies, as well as of the linkages between theory and practice are among some of the major reasons for its limited applications in planning practices (Brody, Highfield, & Thornton, 2006; Laurian et al., 2004; Oliveira & Pinho, 2010; Talen, 1996a, 1996b).

In addition to these general issues, the development of UGBs implementation evaluation has also been constrained by the over-simplified evaluation dimension. To date, most relevant studies focused on assessing the physical outcomes, that is, the degree to which the actual urban extent and development layout conform to the proposed UGBs. For instances, several studies utilized remote sensing images and geographic information system to track land use/cover changes (e.g. Hasse, 2007; Hepinstall-Cymerman, Coe, & Hutyra, 2013). Among them, Han, Lai, Dang, Tan, and Wu (2009) examined the effectiveness of the UGBs in Beijing over two planning implementation periods, 1983–1993 and 1993–2005, and concluded that the UGBs failed to contain urban growth. Some studies focused on analyzing the driving forces of the urban expansion (Boarnet, McLaughlin, & Carruthers, 2011; Brueckner & Fansler, 1983; Burchfield, Overman, Puga, & Turner, 2006; Long, Gu, & Han, 2012). Using quantitative techniques such as regression models, these studies helped identify the effects of particular variables (e.g. planning and political elements like UGBs, built environments, and socioeconomic attributes) on urban expansion or land development. Ideally, one could look into the land use data to examine the land use changes. However, in China, an accurately and timely monitoring of land use changes is never an easy task. A comprehensive land use survey of a Chinese city may take as long as 10 years, and even longer in some large cities. Even after planners acquire the results of the most recent land use survey, they may find that the data are either inadequate or inaccurate. Polygons in land use maps are usually very big, omitting much useful information. Also, some areas that have been lately developed as urban uses or urban infrastructures may still be marked as agricultural use (Long & Liu, 2013). Due to the burdensome task to provide real-time changes of land uses, a relatively easier way to acquire a city-scale change of human activities would be a helpful supplement to the traditional land use examinations with poor reliability. Moreover, one of the major problems associated with these studies is that they simply equal urban expansion to the changes in land cover or use. What has been ignored is the assessment of how human activities actually react to the UGBs when people utilize urban spaces and development where UGBs intend to regulate. What are the relations between urban activities and UGBs? Do the UGBs really work on shaping and controlling human mobility and activities? Unfortunately, previous studies have provided few clues or solutions to these questions.

In this study, we evaluated the effectiveness of UGBs from the perspective of human mobility and activities using location check-ins from social network, taxi trajectories from GPS devices equipped by a large number of taxis, and smartcard records from public transit system. The increasing availability of these urban big data has provided unprecedented opportunities for urban researchers and planners to better understand and manage urban systems. These data have enabled us to describe and analyze real-time human behaviors and movements in a more precise, reliable, and economic way. We also see the potential of applying these data in planning evaluation, particularly in developing countries where official statistics are less sufficient or reliable. Based on the analysis of the massive data on human mobility and activities, the study aims to (1) evaluate the effectiveness of UGBs in confining human mobility and activities, (2) examine whether the intensity of urban activities correlate to that of planned population across UGBs, and (3) measure the interconnections between UGBs and examine whether they conform with plan intentions.

This study selected Beijing as a case to illustrate how the evaluation is developed. Beijing has undergone rapid urban development in the past two decades and can be regarded as a representative among rapid-developing cities. Considering the nature of the methodology adopted in this study, it can also be applied to developed cities. In Section 2, we introduced the study area and data sources. In Section 3, we elaborated the methodology and presumptions, as well as the evaluation results. In Section 4, we discussed the findings in details. In Section 5, we concluded by summarizing our findings, suggesting the strength and weakness of our study and giving recommendations for potential subsequent studies in future.

2. Study area and data

2.1. Beijing's recent urban planning

As the capital of China, Beijing is one of the most populous cities in the world. The population at the end of 2013 was 21.15 million. The Beijing Metropolitan Area (BMA) is 16,410 square kilometers. According to land use dataset of Beijing Institute of City Planning, the total urban area as of 2012 was 1675 square kilometers. The BMA currently comprises 16 administrative subdivisions (districts), as illustrated in Fig. 1.

Since the latest adjustment of the Beijing administrative boundaries in 1958, five urban master plans have been drafted in 1958, 1973, 1982, 1992 and 2004 respectively. Each master plan includes an official land use map. Individual land parcels in the map were assigned according to a classification of either urban (residential, commercial, industrial, public green land, and mixed-use land) or non-urban (farmland, forestland, and wetland) uses (Long et al., 2012). The map guided the future urban development, and uses were expected to conform to the plan.

The BMA has experienced an unprecedented increase in population growth and urban development since early 1990s. By the year 2003, Beijing's population and urban built-up area had already surpassed the capacity set forth in the 1992–2010 Master Plan. To cope with new challenges in the future, the Beijing Municipal Commission of Urban Planning updated the city's master plan for a 2020 planning horizon. Approved in 2005, the revised plan was sought to outline general principles and create new guidelines for Beijing's long-term economic, social, and physical development (Ding, Song, & Knaap, 2005).

In this new plan, the projected population of Beijing was 18 million in 2020. From a spatial perspective, the plan promotes a "two-axes, two-belts, and multi-sub-centers" urban development pattern. A total of 1650 square kilometers of planned urban built-up area would be allocated to the central city and eleven new cities. Urban developments were planned to occur within the planned urban construction areas. The boundaries of these areas can be regarded as the Chinese UGBs which functioned in a similar way as the UGBs in the U.S. The issuance of land use permits outside these boundaries was generally forbidden in order to curb urban expansion and protect open spaces. Four types of UGBs are identified, including those in the central city, new cities, towns, and other small isolated areas.

2.2. Date sources

2.2.1. Location check-in data

Compared to traditional approaches to obtaining information of urban activities, the use of data acquired from mobile devices

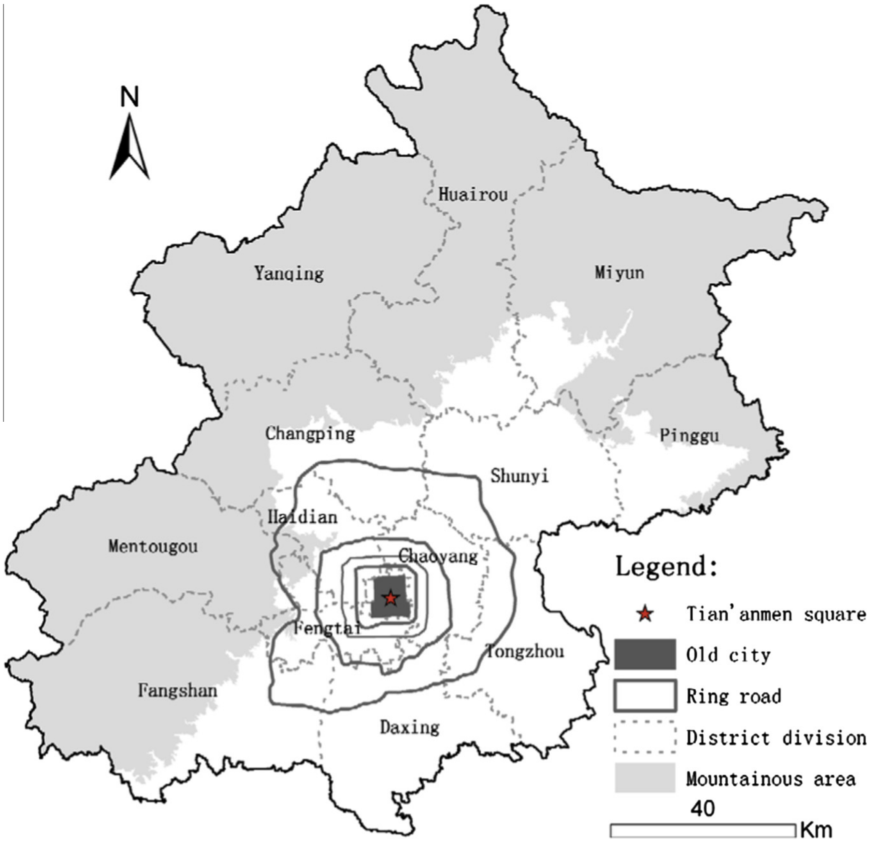


Fig. 1. The Beijing Metropolitan Area.

enables a real-time representation of urban dynamics and their evolution over time and space (Ratti, Pulselli, Williams, & Frenchman, 2006). In this study, we used location check-in data provided by Sina Weibo (having a similar function as Twitter in China) to proxy the actual urban activity. A total of 890 million check-in records were collected during the time period. These check-in records from May 16 throughout July 28, 2013 (74 days) were linked to a total of 102,826 Point-of-interests (POIs). POIs generally have eight types based on land use classifications. They are (1) shopping, (2) entertainment, (3) hotel and public, (4) sports, (5) firm, (6) residential, (7) educational institute, and (8) restaurant. The check-in dataset was transformed into a POI-based attribute table, in which each POI record was comprised of a full range of information including land-use classification, latitude and longitude, number of total check-ins, and some other geographic features.

2.2.2. Transit Smart Card Data

Transit smart card system of Beijing was introduced in 2003. By 2005, over 90% of bus/subway riders in Beijing had used the transit smart card for payment. The transit smart card system records a set of cardholders' information including trip origins and destinations, boarding and/or alighting time, card numbers, and card types (e.g. student card or regular card). Unlike a subway system which requires a swipe in and out, not every bus trip keeps an alighting record. That is because Beijing's bus system uses two fare schemes – a flat fare scheme and a distance fare scheme. In a flat fare scheme, a 0.40 CNY is charged for every single trip and it does not require riders to swipe the card on the way out. As a consequence, the Smart Card Data (SCD) for the flat fare lines doesn't store any information about trip's arrival time or destination stop. A distance fare line requires cardholders to swipe twice both on boarding and alighting a bus, so the SCD contain trip's full information.

In this study, the SCD of bus and subway system were obtained from Beijing Municipal Administration & Communications Card Co. (BMAC). These data were collected from April 5 to 11 in 2010. For bus system, though incomplete flat fare trips' information might result in the failure of identifying travel patterns, it would be useful when a flat fare trip was taken as a transfer between two distance fare trips. Therefore, data from both flat and distance fare schemes were used for human mobility analysis. A total of 97.9 million bus/subway trips were generated by 10.9 million cardholders during the time period. The summary of bus and subway SCD is shown in Table 1.

2.2.3. Taxi trajectories

Taxi trajectories were collected within one week from November 7 to 13 in 2011, with a total of 2,254,068 origin–destination trips from over 20,000 taxis. The location of each trip's origin and destination were stored in the system.

2.2.4. Resident travel survey

In addition to the aforementioned three types of urban big data, we also introduced traditional sampling data in the study to cross-check the findings. As the major data inventory of daily travel, the Resident Travel Survey (RTS) has assisted planners and

Table 1
A summary of Smartcard Data.

Variables	Number of records (million)
# cardholders	10.9
# Total SCD records	97.9
# Bus records	82.7
# Distance Fare	23.4 (28.3%)
# Flat Fare	59.3 (71.7%)
# Subway records	15.2

decision makers in providing comprehensive data on resident travel behavior in Beijing. RTSs were made in 1986, 2000, 2005 and 2010 respectively. Data were collected on daily trips taken by individual residents over a 24-h period, including purposes of trips, means of transportation, time, durations, trip's origins and destinations, and individual's socio-economic attributes. All of these individual travel data were aggregated at the traffic analysis zone (TAZ) level.

In the present analysis, we used the most recent RTSs in 2005 and 2010. We only looked at the trips to work. The 2005 RTS dataset included 70,091 home-work records from 1118 TAZs, and the 2010 RTS included 56,619 home-work records from 1911 TAZs.

3. Methodology and results

If a city's UGBs were effective in confining undesirable human mobility and activities outside the boundaries and adhered to the statements set forth by the 2004 master plan, one would expect that:

(1) Only a small amount of urban activities occur outside the boundaries compared to the amount within the UGBs.
(2) There is strong positive correlation between the actual amount of urban activities and the planned population across UGBs.
(3) People's movements, particularly commuting travel flows, would be less likely to start or end at places outside the boundaries.

According to these presumptions, we developed three measures used for UGBs assessment. They quantified the effectiveness of UGBs with respect to urban activities, the correlation between urban activities and planned population, and human mobility, respectively. In addition, we also developed the fourth measure: to examine the strength of connections between UGBs based on travel flows.

Methodology for each measure and corresponding results were elaborated in this section. The structure of the overall assessment process was presented in Fig. 2 below.

3.1. The effectiveness of UGBs on urban activities

The effectiveness of UGBs in terms of urban activities was measured using location check-in data. We identified the locations of the check-in data after preliminary data processing. In total, there were 7,416,012 valid check-in records. The positions of urban activities can be determined according to each check-in record and classified into two groups: inside and outside the UGBs.

Fig. 3 presents the locations of selected check-in data in relation to Beijing's UGBs using ArcGIS.

The effect of UGBs in terms of urban activities, therefore, was measured by the ratio of check-in number inside the UGBs to the total check-in number. This measure was defined as E_a and stated as follows:

$$E_a = CI_{in}/CI \tag{3-1}$$

where CI_{in} refers to the number of check-in inside the UGBs, and CI refers to the total check-in number.

Of a total of 7,416,012 check-in records, the number of urban activities occurring within the UGBs was 7,187,191, accounting for 96.91%. Given an overwhelming majority of check-in records occurring within the UGBs, it is safe to conclude that Beijing's UGBs were effective in containing urban activities.

3.2. Relationship between urban activities and planned population

This section discussed the relationship between urban activities and population. To do so, we calculated the correlation coefficient to examine the linear relationships between the number of check-ins and planned population. This calculation was made by two steps: first, the whole city was examined to indicate the overall situations; and second, areas excluding the central city were

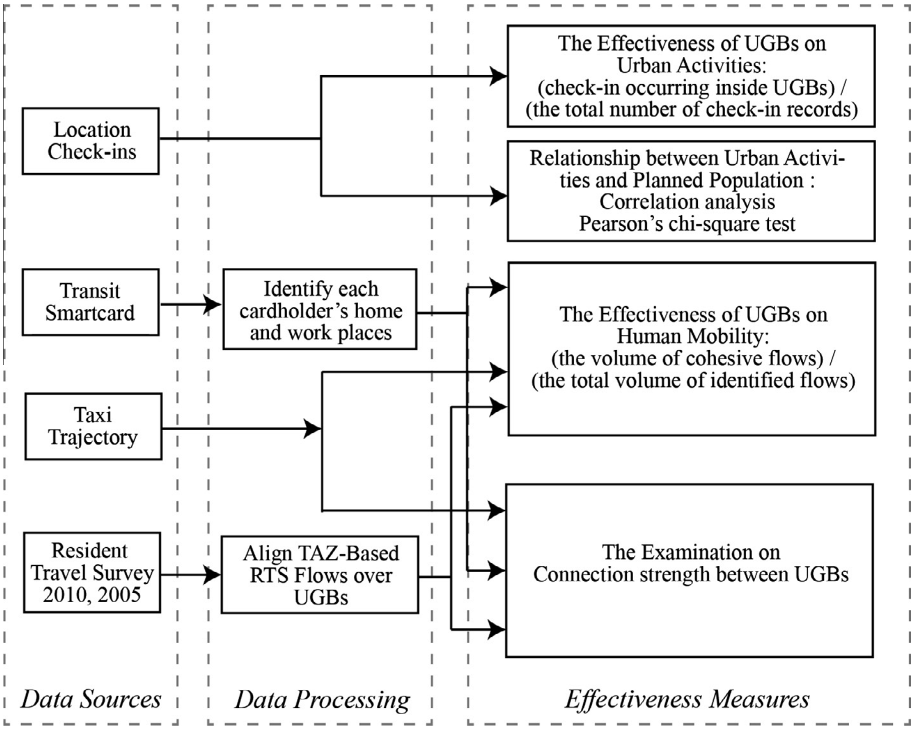


Fig. 2. The assessment process.

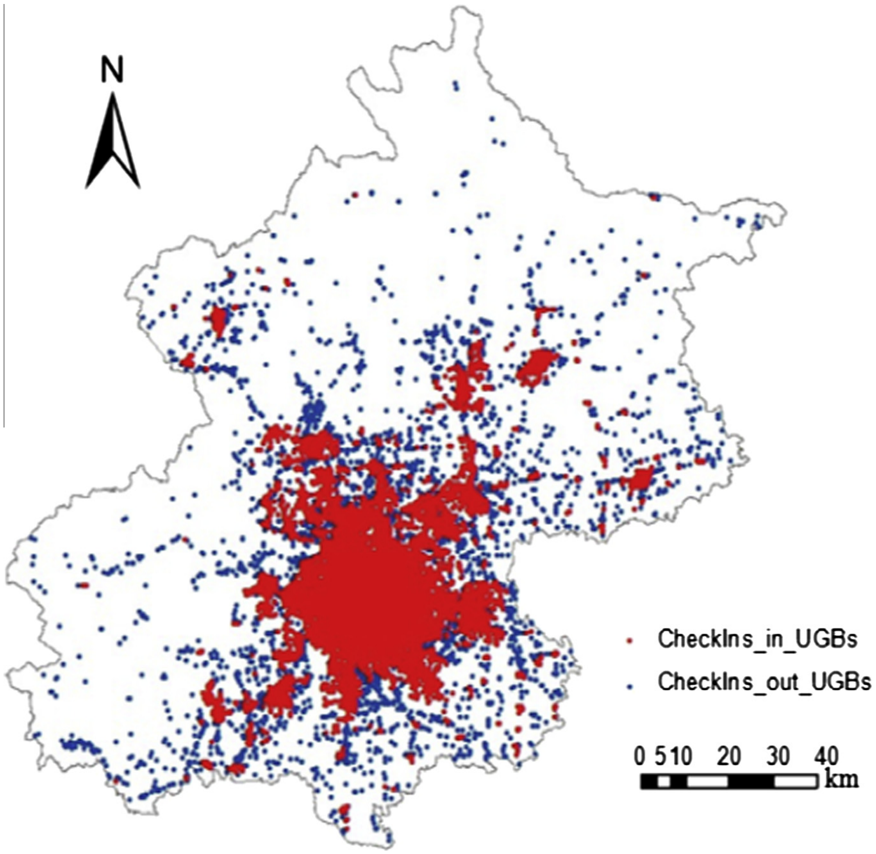


Fig. 3. Distribution of check-ins.

examined to show the situations of the newly developed areas. We also used Pearson's chi-square test to check how likely the observed differences between the check-in numbers across the UGBs reflected the relationships between planned population across the central city and new cities.

The results were presented in Tables 2 and 3. When the central city was included, the correlation coefficient between check-ins and population was 0.655, significant at the 0.05 level. While when the central city was excluded, the correlation coefficient was 0.881, significant at the 0.01 level.

In addition to the correlation analysis, we also examined whether or not the actual distribution of urban activities, presented by check-in data, fitted the distribution of planned population across the UGBs. We used Pearson's chi-square test for the central city and new cities. The null hypothesis in this case was that the proportions between each group's check-ins were consistent with the proportions between each group's planned population. The value of the test-statistics is:

$$\chi^2 = \sum_{i=1}^{n} \frac{(O_i - E_i)^2}{E_i} \tag{3-2}$$

where χ^2 is Pearson's test statistics, O_i stands for the observed check-ins frequency, E_i indicates the expected check-ins frequency, and n equals to 12 (the central city and 11 new cities).

Table 4 listed the number of check-in records, planned population, areas, and densities for central city and new cities. In addition to the overall chi-square value, we also calculated a test statistic that excluded the central city check-ins (92.71% of total records). By doing so, we can preclude the potential influences of the overwhelming check-ins concentrated in the central city and can better understand the relationship among new cities. The chi-squared test of check-ins including and excluding central city were presented in Tables 5 and 6, respectively.

The chi-square value for the central-city-included case was 3,491,957.5 with a p-value of 0.000, proving a significance at 0.01 level. When the central city's data were excluded from the dataset, the chi-square value was 64,558.1 with a p-value of 0.000, also proving a significance at 0.01 level. Therefore, the null hypothesis was rejected and we could conclude that the distribution of urban activities, represented by check-ins, didn't correlate with the distribution of population.

3.3. The effectiveness of UGBs in containing human mobility

When UGBs are effectively implemented, one would expect that most of urban land uses and facilities are built inside the UGBs, and the majority of travel flows, particularly commuting travel flows, should start and end inside the UGBs. Therefore, the effectiveness of UGBs in terms of human mobility can be measured by the number of travel flows occurring within UGBs relative to the total number of travel flows.

Prior to the examination of travel flow patterns, it is crucial to determine the locations of a flow's origin and destination. According to the origins and destinations relative to the UGBs, flows can be classified into "cohesive flows" and "disperse flows". A cohesive flow refers to a trip where both the origin and destination are located within the UGBs. A disperse flow refers to a trip where at least one end of the trip is outside any given UGBs. An illustration of cohesive and disperse flows is presented in Fig. 4.

Similar to the approach to the evaluation of urban activities, this effectiveness measure, defined as E_f, was calculated as follows:

$$E_f = F_I/F \tag{3-3}$$

Table 2
Correlation analysis of check-ins and planned population with the central city included.

		Planned population
Check-ins	Pearson Correlation	.655*
	Sig. (2-tailed)	.021
	N	12

* Correlation is significant at the 0.05 level.

Table 3
Correlation analysis of check-ins and planned population with the central city excluded.

		Planned population
Check-ins	Pearson Correlation	.881**
	Sig. (2-tailed)	.000
	N	11

** Correlation is significant at the 0.01 level.

Table 4
Check-ins and planned population of the central city and new cities in Beijing.

UGB	Check-ins	Planned pop. in 2020	Area (km^2)	Density of check-ins	Density of planned pop.
Central city	7,251,872	8,500,000	1196.4	6061.6	7104.8
Huairou	50,960	350,000	41.0	1243.8	8542.6
Shunyi	84,831	900,000	130.2	651.4	6911.0
Mentougou	8937	250,000	36.4	245.8	6876.0
Miyun	32,729	350,000	56.0	584.9	6255.2
Fangshan	46,381	600,000	65.6	707.3	9149.7
Yanqing	11,001	150,000	18.5	596.2	8129.5
Tongzhou	113,512	900,000	89.9	1262.9	10,013.2
Pinggu	8069	257,000	27.9	289.8	9229.1
Changping	75,057	600,000	73.42	1022.3	8171.8
Daxing	89,178	600,000	71.93	1239.8	8341.2
Yizhuang	49,265	700,000	101.4	485.7	6901.8

Table 5
Chi-square test of check-ins with the central city included.

UGB	Actual check-ins (*a*)	Excepted check-ins (*b*)	$(a-b)^2/b$
Central city	7,251,872	4,696,279.7	1,390,686.3
Huairou	50,960	193,376.2	104,885.6
Shunyi	84,831	497,253.2	342,063.3
Mentougou	8937	138,125.9	120,830.1
Miyun	32,729	193,376.2	133,457.6
Fangshan	46,381	331,502.1	245,229.3
Yanqing	11,001	82,875.5	62,333.8
Tongzhou	113,512	497,253.2	296,141.5
Pinggu	8069	141,993.4	126,313.9
Changping	75,057	331,502.1	198,382.1
Daxing	89,178	331,502.1	177,136.0
Yizhuang	49,265	386,752.5	294,497.9
Sum	7,821,792	7,821,792	3,491,957.5

where F_l refers to the volume of cohesive flows, and F refers to the total volume of identified flows.

3.3.1. An examination of Smart Card Data

The raw SCD collected from bus and subway system need to be pre-processed to extract valid journeys to work travel flows. A proper study of the journey to work is important because it can provide us with insights into the city's structure and the relations between various types of urban elements. The analysis, therefore, focused solely on the journey to work and did not look at leisure travel or other non-work-related trips, including school trips.

Table 6
Chi-square test of check-ins with the central city excluded.

UGB	Actual check-ins (*a*)	Excepted check-ins (*b*)	$(a-b)^2/b$
Huairou	50,960	34,995.1	7283.3
Shunyi	84,831	89,987.4	295.5
Mentougou	8937	24,996.5	10,317.7
Miyun	32,729	34,995.1	146.7
Fangshan	46,381	59,991.6	3087.9
Yanqing	11,001	14,997.9	1065.2
Tongzhou	113,512	89,987.4	6149.8
Pinggu	8069	25,696.4	12,092.2
Changpin	75,057	59,991.6	3783.3
Daxing	89,178	59,991.6	14,199.4
Yizhuang	49,265	69,990.2	6137.0
Sum	569,920	569,920	64,558.1

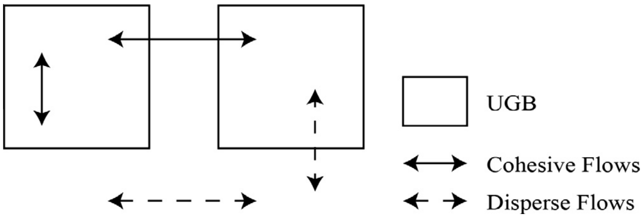


Fig. 4. An illustration of cohesive and disperse flows.

In terms of the bus/subway system, we used the one-day data to locate a cardholder's home and work places and repeated this process for every single weekday. Based on the repetitive patterns of the journey to work in the given week, these one-day data of individual cardholders were compiled and refined to determine the final home and work locations. Data from the subway system were processed in the same way. This methodology has been elaborated by Long and Thill (2015). The overall identification process can be briefly summarized as follows.

If a place meets the following conditions, it is regarded as a cardholder's working place:

(1) The card type is not student card.
(2) D_w >= 6 h, where D_w is the duration that a cardholder stays at place *w*, which is within 500 m of any given bus stops/subway stations.
(3) *w* <>1, which means that *w* is not the first place that the system records in a day.
(4) The place where a cardholder visited most frequently in five weekdays would be defined as the final job place.

Similarly, a place is regarded as a cardholder's home if it meets the following conditions:

(1) The card type is not student card.
(2) The cardholder has an identified workplace.
(3) The place where a cardholder gets on a bus/subway most frequently in the morning of five weekdays would be defined as the home.

As a result, a total of 703,293 cardholders (approximately 6.5% of all 10.9 million cardholders) have been identified to have both the work and home locations. Based on these records, E_f – the overall effectiveness measure – was calculated. Of 703,293 commuting flows, 664,968 have both the origins the destinations located within the UGBs, accounting for 94.6% of the total.

3.3.2. An examination of taxi data

Unlike the SCD which require additional process to obtain valid travel flow information, taxi trajectory data contain detailed and

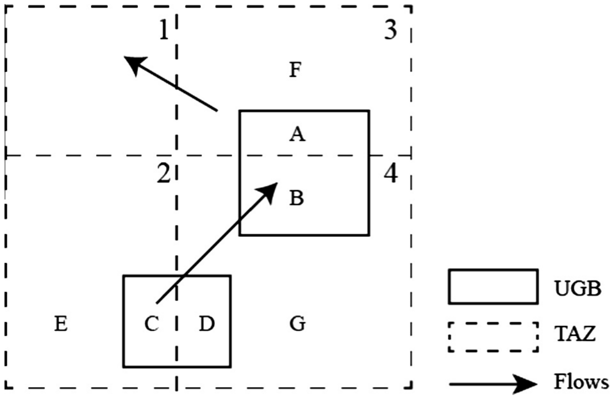


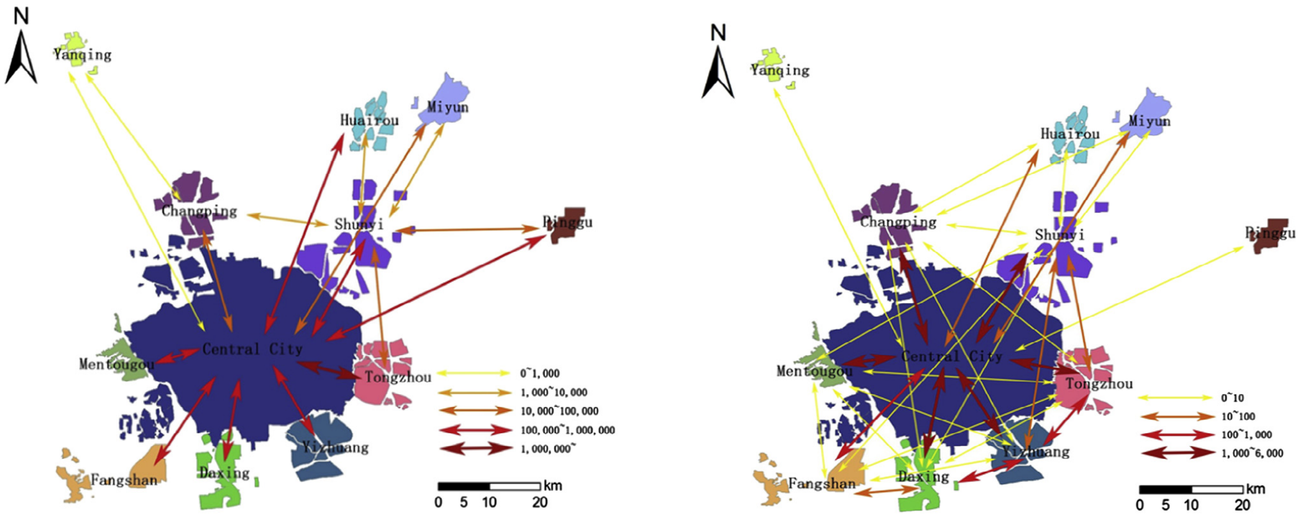
Fig. 5. An illustration of RTS flows over UGBs and TAZs.

accurate travel logs that can be directly used to geocode origins and destinations of trips. Based on the cohesive/disperse flow criteria listed above, 2,185,777 of taxi records were identified as cohesive flows, accounting for 97 percent of total flows (2,253,437).

3.3.3. *An examination of resident travel survey*

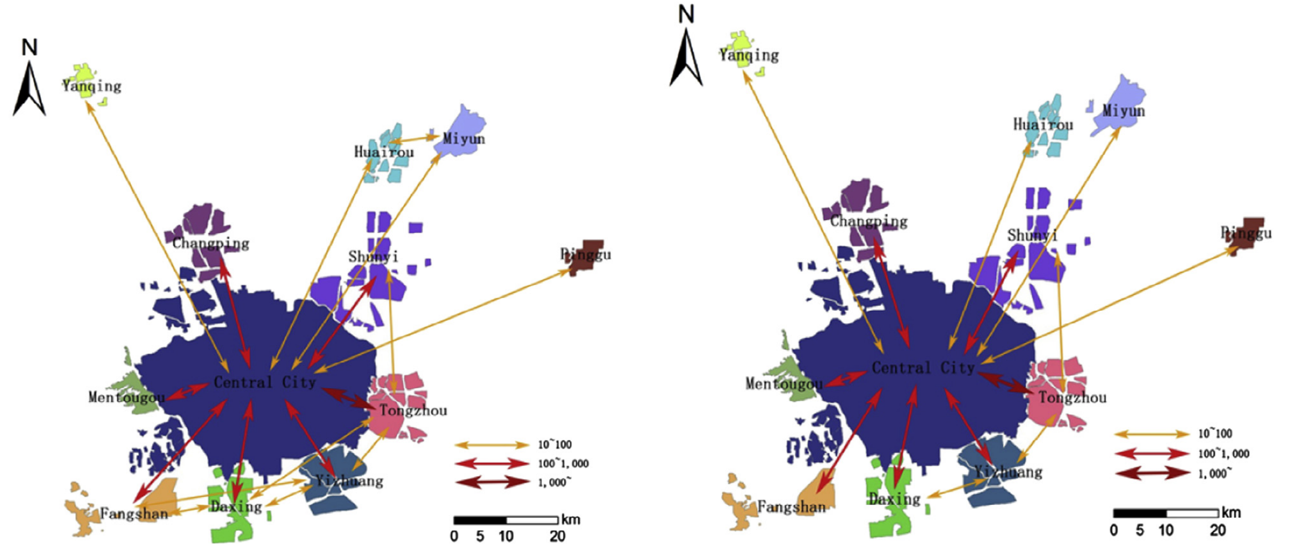
For RTS, commuting related data were accumulated at the traffic analysis zone (TAZ) level. But in reality, the boundaries of TAZs do not fit well with the UGBs. An illustration of this situation was presented in Fig. 5, as two UGBs were cut into four pieces (A, B, C and D) by four TAZs (1, 2, 3 and 4).

Consequently, we proposed a flow-dividing methodology to assign home and work places from RTS to UGBs. We assumed that flows' origins and destinations were spatially homogeneously distributed in each TAZ. Therefore, the probability of a flow's origin or destination falling into a given UGB was proportionate to the share of overlapping area between UGB and TAZ relative to the entire TAZ. Correspondingly, the probability of this trip to work occurring in certain direction can be calculated by multiplying these two probabilities. As Fig. 6 illustrates, assume that Parcel C and E account for 10% and 90% of the total area of TAZ 2, while Parcel B, D, and G account for 20%, 10%, and 70% of the total area of TAZ



Based on SCD

Based on Taxi Data



Based on RTS 2010

Based on RTS 2005

Fig. 6. Connections between UGBs by four data sources.

Table 7
An illustration of flow-dividing method for assigning TAZ flows over UGBs.

Origin (TAZ 2)	Proportion (area) (%)	Destination (TAZ 4)	Proportion (area) (%)	Probability (flow)	Type
C (inside UGB)	10	B (inside UGB)	20	0.02	Inter-UGBs
		D (inside UGB)	10	0.01	Intra-UGBs
		G (outside UGB)	70	0.07	One-end-inside-UGBs
E (outside UGB)	90	B (inside UGB)	20	0.18	One-end-inside-UGBs
		D (inside UGB)	10	0.09	One-end-inside-UGBs
		G (outside UGB)	70	0.63	Outside-UGBs

Table 8
Cohesive and disperse flows by four data sources.

Date sources	No. cohesive flows	No. total valid flows	Cohesive flows percentage
Smartcard Data	664,968	703,293	94.6
Taxi Data	2,185,777	2,253,437	97.0
TAZ Data (2010 RTS)	48,794.8	56,435	86.5
TAZ Data (2005 RTS)	63,618.3	69,858	91.1

4, respectively. The probability of flows in each directions then calculated, as presented in Table 7.

Furthermore, we classified flows into four types based on the locations of their origins and destinations relative to the extent of UGBs. They were inter-UGBs, intra-UGBs, one-end-inside-UGBs, and entirely-outside-UGBs flows. Given the definition mentioned earlier, inter- and intra-UGBs flows belong to the cohesive flow group. Examining data from RTS in 2010 and 2005, we found that 86.5 percent and 91.1 percent of journeys to work happened within the UGBs.

A summary of cohesive and disperse flows from these four data sources was presented in Table 8.

3.4. Flows between UGBs

A strong connection between two places usually incurs large amount of travel flows. By counting commuting and other trips, we can measure the strength of connection between the UGBs, and have a better understanding of the area's overall connection structure.

For SCD and RTS data, the work and home places of each trip had already been identified through the process mentioned above. These trips' origins and destinations were then aggregated at the UGB level. Origins and destinations extracted from taxi trajectories data were also geocoded and collected at each UGB.

The final results with four types of data input were presented in Table 9. UGBs were grouped into two types: the central city and new cities.

Fig. 6 visualized the connections between central city and new cities. We also ranked these 11 new cities by connection strength (see Table 10). Tongzhou, Daxing, and Yizhuang had the strongest connection with central city; while cities in the north, including Miyun, Pinggu, Huairou, and Yanqing, had relatively weaker connections with central city.

4. Discussion

The results of the present analysis suggested that Beijing's UGBs were effective in containing human mobility and activities. In terms of the urban activities, over 96% of check-ins occurred inside the UGBs. For the human mobility, 94.6% of all commuting travel flows identified through transit smartcard data and 97% of all taxi trajectories were "cohesive flows", whose origin and destination were both located within the UGBs. Based on the conventional Residential Travel Survey (RTS) data, "cohesive flows" accounted for 86.5% and 91.1% of the overall "journey to work" flows in 2010 and 2005, respectively.

The actual distribution of check-in data did not fit with the distribution of planned population across the UGBs according to our statistical test. This showed that the relationship between urban activities and population was very unlikely to be linear. One merit of this examination is to provide a quick and explicit way to monitor the urban activities pattern over time and space and to identify potential imbalance of development. For example, Fangshan, Changping, and Daxing each have a planned population of 600,000, but their numbers of check-ins are significantly different (presented by 46,381, 75,057, and 89,178, respectively). This observation can serve as a starting point for planners to make further analysis of urban development issues, such as the separation of workplace and residence and the vitality of a new city. More hidden reasons can be explored based on the analysis of human activities.

The examination of the flows between UGBs indicated that Beijing's plan had generally accomplished the basic intention to decentralize population. The results of inter-UGBs connections analysis also suggested the limited achievements of the 2004 Master Plan in new cities development. The comparison between RTS data in 2010 and in 2005 showed that there had been a decrease in the number of "journey to work" occurring inside the central city, and a slight increase in the number of trips occurring inside new cities and between the central city and new cities. It indicated that new cities have been effective in attracting population from the central city. According to the plan, Tongzhou, Shunyi, and Yizhuang were listed as the top three pilot development districts. The transportation infrastructures (e.g. new subway lines) in these three cities should be built in priority in order to provide stronger connections with the central city. However, the results of analysis revealed that, Shunyi failed to accomplish that. The

Table 9
Flows structure by four data sources.

Flows	SCD	Taxi	RTS (2010)	RTS (2005)
Inside CC[a]	31,475,282 (73.6%)	2,120,745 (94.1%)	39,934.9 (70.8%)	58,814.5 (84.2%)
Inside NC[a]	1,259,984 (2.9%)	13,827 (0.6%)	2635.8 (4.7%)	569.9 (0.8%)
Between NCs	51,388 (0.1%)	346 (0.0%)	249.4 (0.4%)	117.8 (0.2%)
Between CC and NCs	2,813,781 (6.6%)	21,635 (1.0%)	5055.9 (9.0%)	4041.1 (5.8%)
Between CC and OU[a]	2,607,835 (6.1%)	63.985 (2.8%)	4158.8 (7.4%)	4785.0 (6.9%)
Between NC and OU	2,825,294 (6.6%)	6587 (0.3%)	3150.5 (5.6%)	933.4 (1.3%)
Two ends OU	1,878,338 (4.4%)	26,312 (1.2%)	1249.6 (2.2%)	566.0 (0.8%)
Beyond Beijing[b]	0	631 (0.0%)	0	0

[a] "CC" stands for "central city", "NC" for "new cities", and "OU" for "outside UGBs".

[b] It refers to a flow with origin or destination located outside Beijing.

Table 10
Connection strength between the central city and new cities.

New cities	Rank (SCD)	Rank (Taxi)	Rank (RTS, 2010)	Rank (RTS, 2005)	Rank[a] (arithmetic mean)	Strength
Tongzhou	1	3	1	1	1	Strong
Daxing	6	2	2	2	2	Strong
Yizhuang	2	1	4	3	3	Strong
Mentougou	4	5	3	7	4	Medium
Shunyi	5	4	7	4	5	Medium
Fangshan	3	7	5	6	6	Medium
Changping	10	6	6	5	7	Medium
Miyun	9	9	9	8	8	Weak
Pinggu	7	11	8	9	9	Weak
Huairou	8	8	10	10	10	Weak
Yanqing	11	10	11	11	11	Weak

[a] Rankings were derived from the sum of flows by four data sources divided by 4.

disparity between the smartcard and the overall flow rankings also implied a need for more investment in public transit. For example, Daxing ranked 2nd in terms of the overall flow connections, but its SCD ranking was only 6th. It implied that though there had been a strong commuting connection between Daxing and the central city, people may primarily rely on automobiles instead of transit. In addition to that, the shares of SCD flows “between CC and NCs”, “between CC and OU” and “between NCs and OU” are almost the same, although those “between CC and NCs” had been expected to be much more than the others. This indicated that the public transit between new cities and the central city was relatively weak and needs improvement in future.

5. Conclusions

In this paper, we proposed a framework on evaluating the effectiveness of urban growth boundaries using human mobility and activity records and applied it to the city of Beijing. We synthesized datasets from various sources, including the location check-in records, transit smart card records, and taxi trajectories as well as the conventional residential travel survey. With the significant majority of check-in records and travel flows occurring within the extent of UGBs, we found that the evaluation results inferred by each type of human mobility and activity data were consistent, and that Beijing’s UGBs were successful in containing human mobility and activities. This was quite different from previous studies based on land use examinations, such as Han et al.’s (2009) findings. It suggested that most of the areas outside the UGBs might not be efficiently used due to the evident lack of human mobility and activities.

The contribution of this study lies in the following aspects. First, we extended existing research on UGBs evaluation from physical development to the dimension of human mobility and activities. With the increasing availability of urban big data, our straightforward methodology can be easily applied to other areas and regions. Second, we applied our methodology with various large-scale datasets and could therefore avoid potential data bias. For instance, transit smart card data are limited to those who travel by bus or metro. The analyses with all type of data confirmed the consistence between human mobility & activities and Beijing’s UGBs, suggesting a sound conclusion based on both big and small data. Third, in addition to the typical conformance degree measure, we added the connectivity and intensity measures to analyze UGBs’ effectiveness, creating a more comprehensive evaluation framework.

Future research can explore the temporally dynamic effectiveness of UGBs using human mobility and activity records in a longer time horizon. Moreover, as we have collected urban data and information on UGBs for over 200 Chinese cities, we also expect to further analyze different types of cities and examine the feasibility of this methodology.

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