Sustainability **2014**, *6*, 4558-4579; doi:10.3390/su6074558

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Changing Urban Form and Transport CO_2 Emissions: An Empirical Analysis of Beijing, China

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Received: 19 May 2014; in revised form: 30 June 2014 / Accepted: 14 July 2014 / Published: 22 July 2014

Abstract: Decentralization development and changing urban form will increase the mobility and contribute to global CO_2 emissions, in particular for developing countries which are experiencing rapid economic growth and urban expansion. In this paper, an integrated analytical framework, which can quantify the impact of changing urban form on commuting CO_2 emissions, is presented. This framework simultaneously considers two emission dependent factors, commuting demand and modal share based on the concept of excess commuting and accessibility analysis, and ensures its applicability to other cities where the detailed individual travel data is not available. A case study of Beijing from 2000 to 2009 is used to illustrate this framework. The findings suggest that changing urban form in Beijing did have a significant impact on commuting CO_2 emission increase. Changing to a more decentralized urban form in Beijing had a larger impact on commuting distance and increased usage of cars, which resulted in a significant rise in CO_2 emissions. There is a larger space and an urgent need for commuting CO_2 emission reduction, in 2009 in Beijing, by planning and by strategic measures in order to promote sustainable transport.

Keywords: decentralization; changing urban form; CO_2 emissions; excess commuting; accessibility; modal share; sustainable transport

1. Introduction

Decentralization development is taking place in many cities worldwide [1], which results in the relocation of populations, firms and infrastructures to areas far from the city center. The new growth areas, as a reflection of the changing urban form (defined as the spatial arrangement of jobs and workers' households), with the positional relocation and flexibility of populations' activities, are bound up with increasing mobility and transport CO_2 emissions [2–4]. As the second-largest sector in terms of emissions, transport accounted for 22% of global CO_2 emissions in 2010 [5], and its share in the overall energy consumption and emissions is continuously growing, which makes it one of the most important contributors to global CO_2 emissions [6]. Consequently, the dynamics analysis between changing urban form and its environmental implications to a sustainable transport system have received a great deal of attention and concerns [7–10], especially in the context of global warming.

Due to the rapid increase in economic growth and population, rising incomes in lower- and middle-income developing countries, and availability of cheaper vehicles, transport-related CO_2 emissions from developing countries will contribute in an increasing proportion to global CO_2 emissions unless mitigating measures are implemented soon [11]. As one of the most rapidly growing countries and the largest CO_2 emitter in the world [12], China is experiencing rapid and substantial economic growth and an increase in motorized transportation, while, at the same time, it is experiencing decentralization and suburban growth. The urban form and spatial organization is undergoing such tremendous changes that the compact urban structure of pre-reform Chinese cities has been replaced by a more dispersed or polycentric spatial pattern in today's Chinese megacities [13,14]. The ways in which different cities catered for the expanding urban population would have significantly different implications on the transportation sustainability of the cities [8]. The management of forms of urban development on the city fringe in order to encourage a sustainable transport system is usually overlooked in China, although it is increasingly attracting attention in developed countries [9]. To provide practical implications, and policy recommendations, to promote sustainable transport in China, it is imperative to investigate how the changing urban form affects transport and its CO_2 emissions in Chinese megacities.

There is a wealth of documented evidence that the urban form is a critical determinant for limiting the environmental impact of transportation systems after several decades of studies in developed countries or cities [15–18]. The first body of literature is concerned with the comparison analysis of the correlation between a range of "independent" urban form variables, such as density and settlement size, and transport energy or environmental characteristics across a group of cities. Hence, the observed differences are related to various urban design layouts and forms. One of the first and most influential studies was conducted by Newman and Kenworthy [19], who found a strong negative correlation between transport energy consumption and population density, by summarizing the data of urban transport from 32 large, international cities. However, some studies point out that the densification of urban populations worsen congestion, and does not necessarily contribute to energy conservation [20], and their work is only valid for certain conditions, *i.e.*, within the central business district (CBD); furthermore, the work has often been criticized by other researchers [21–24]. In addition to density, other quantitative measurements of urban form and structure features, such as size, mixed land uses, compactness, open space, accessibility, and so on, were also used to gauge environmental implications in terms of CO_2 emissions for different cities by employing various statistical methods [7,25–27]. These studies have produced mixed and, sometimes, controversial results, and comparability problems make it difficult to establish definitive relationships [7]. The second body of literature focuses on the impact of changing urban form on transport mobility in an intra-urban context, in terms of demand aspect (distance or time traveled), or mode shares (choice of transport mode), and is, thus, responsible for a large proportion of the consumed energy and emissions, which covers many developed cities, *i.e.*, New York [28], Washington DC [29], Hamilton [30], Dortmund [16], Montreal [31], Flanders [15], Wallonia [32], Hong Kong [1,8,33], and Seoul [34]. Moreover, significant efforts have been made to explore the relationship between urban form and CO_2 emissions from commuting, due to the availability of commuting data, especially based on the concept of "excess commuting" [30,33,35].

As presented above, a growing body of literature supports the notion that urban form plays a role in transport energy consumption and CO_2 emissions. However, conclusions are still mixed, and all these studies are based on detailed personal travel data, especially matching places with the origin and destination locations at disaggregate spatial levels, which are often unavailable in China. Therefore, this paper provides an integrated analytical framework to measure the effects of changing urban form on the travel patterns of commuting and related CO_2 emissions, in a Chinese megacity in a holistic manner. This framework considers both the impact of changing urban form on commuting distance and modal share, simultaneously, based on the concept of excess commuting and accessibility analysis, respectively, which can overcome the difficulty of lacking detailed individual travel data. Taking Beijing as a case study, this research is based on Beijing's population, employment, and home-to-work commuting travel characteristics data from 2000 and 2009. Section 2 describes the study area, data set, and the analytical framework. Section 3 analyzes the results of the case city of Beijing, including how the urban form changed during the study period, its impact on commuting demand, modal share, and CO_2 emissions from commuting. Finally, section 4 offers key discussions and conclusions.

2. Study Area and Analytical Framework

2.1. Study Area

Under direct administration of the national government, Beijing was divided into 18 districts and counties by 2009. As illustrated in Figure 1a, the Beijing municipal government had established a function position and assessment system for the districts and counties, and generally divided the whole city into four functional regions, from the inside outward are core districts of capital function (central area), urban function extended districts (new growth area), new districts of urban development (urban frontier area), and ecological preservation development districts (rural area) [36].

For the local level, the block (jiedao), town, and township (hereafter referred to as subdistrict) are the finest geographical units where census data are available. Although the number of subdistrict tracts increased during the last decades, due to the redivision of large subdistricts into smaller ones for the administrative purposes, this study adopted the subdistrict classification in 2004, and there are 282 subdistrict tracts, in total, in Beijing (Figure 1b). The subdistrict tracts vary in land area from 1.09 km^2 to 386.67 km^2 with a standard deviation of 68.11 (Table 1).

Figure 1. Study area. (**a**) The functional zoning map of Beijing. (**b**) The subdistrict tracts of Beijing.

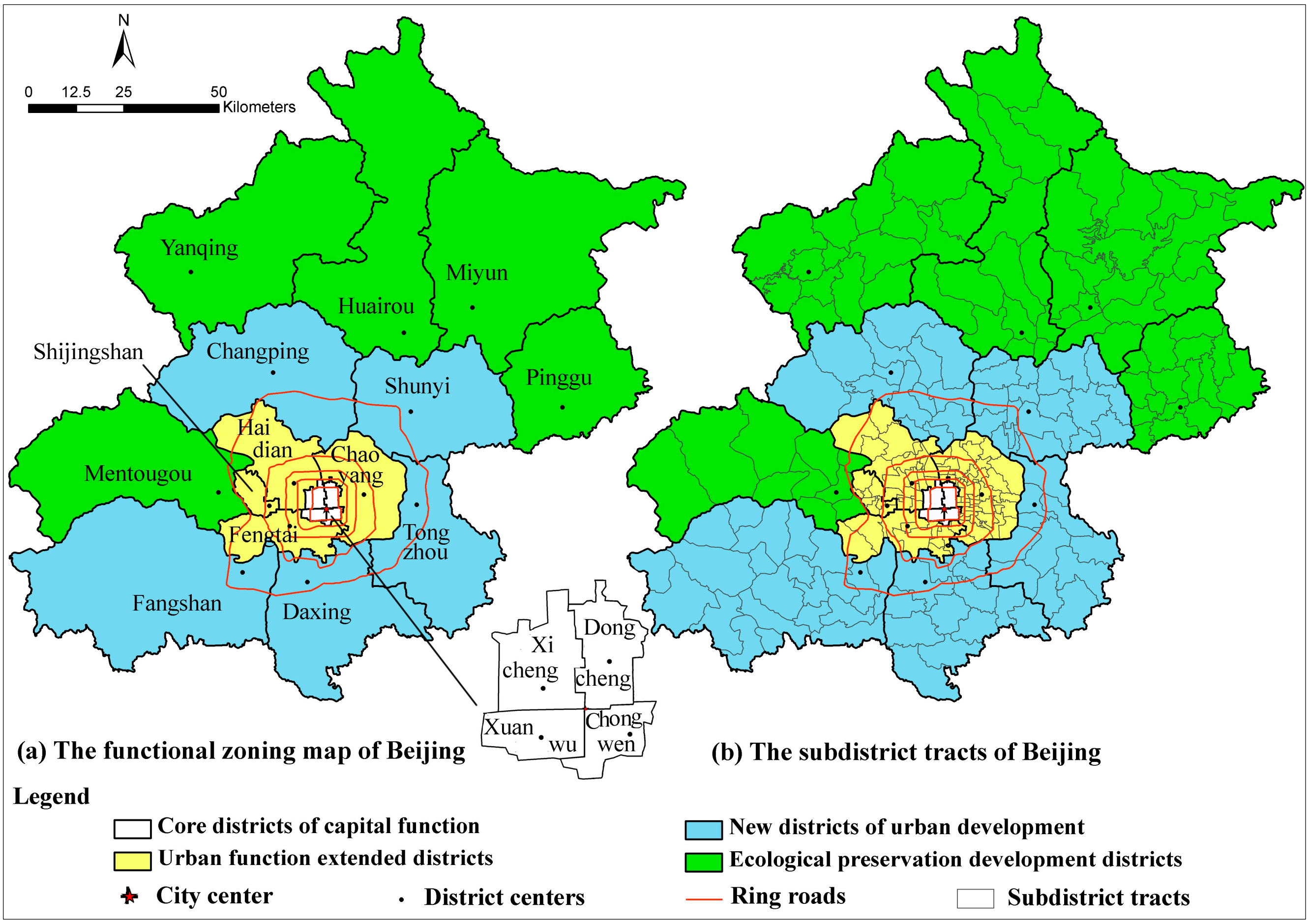


Table 1. The summary statistics for the subdistrict tracts in Beijing.

Subdistrict Tracts	Mean	Min.	Max.	Std. Deviation
Area in km^2	58.01	1.09	386.67	68.11

2.2. Data Collection and Process

The data used to measure urban form and commuting are drawn from various sources. The study period is from 2000 to 2009. Subdistrict level population data of Beijing, in 2000, is drawn from the 2000 population census [37], and the subdistrict level population data of Beijing, in 2009, is adjusted from the 2010 population census [38]. Regarding employment, by assigning the district level data “persons employed in the three industries” in the Beijing Area Statistical Yearbook of 2002 [39] and 2010 [40] into subdistrict level, based on the economic census data of Beijing in 2000 [41] and 2008 [42], we can get the subdistrict level employment data for the year of 2000 and 2009. Both population and employment data at subdistrict level are further assigned into 1 km × 1 km mesh scale based on the spatial distribution of residents and establishments for the calculation of commuting accessibility.

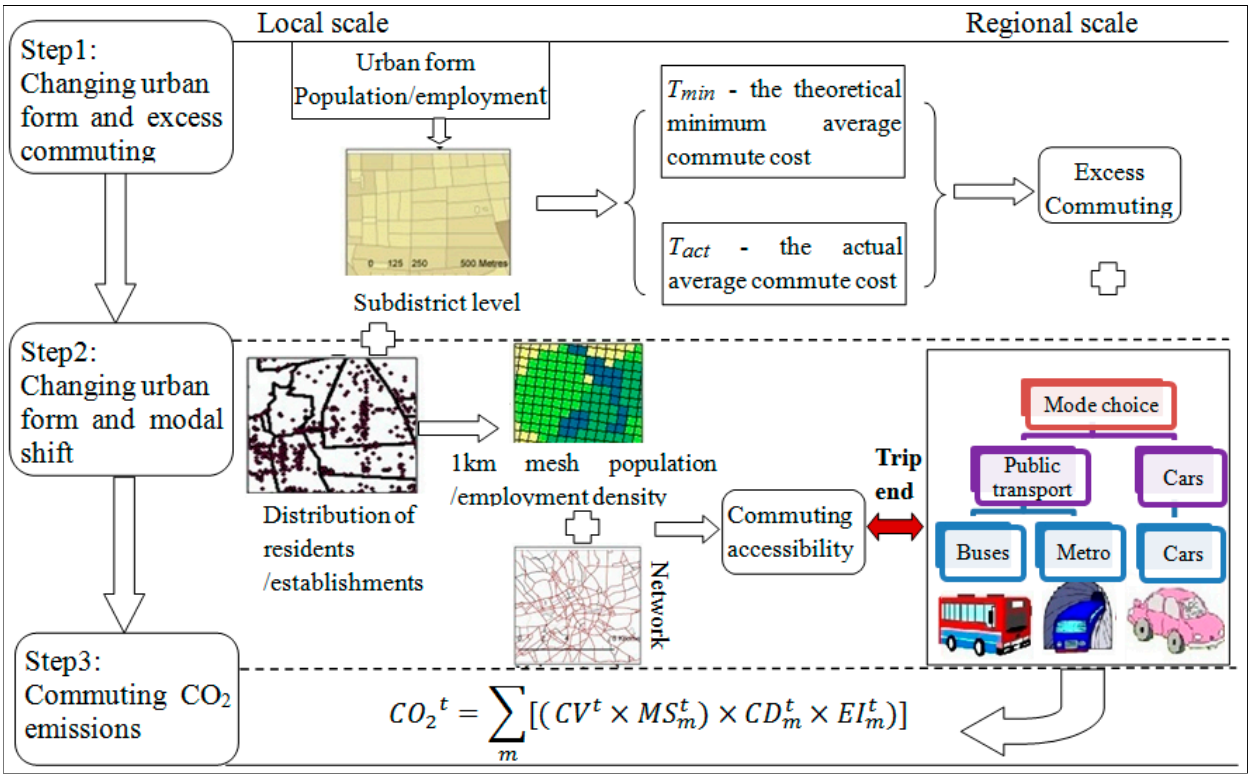
Data on commuting is all at the city level. The average commuting trip length per mode and modal share in 2000 is calculated from the Second Transportation Comprehensive Survey report of Beijing [43]. The average commuting trip length per mode and modal share in 2009 is calculated from Beijing 2010 Transport Annual Report [44]. Here, the modal share data is the proportion of passengers who commute by some mode, among all commuters rather than the proportion of passenger kilometers travelled (*PKT*). The energy consumption data for public buses and metro systems are from Transportation Administration of Beijing Municipal Commissions of Transport [45], while the energy consumption from private cars is estimated, based on sample investigations conducted annually by Beijing Transportation Research Center [44].

The data on the networks of roads, public buses and metro systems of 2000 and 2009 are all extracted and corrected from the electronic map of 2001 and 2010. The running speed per mode at rush hours, in 2000, is from the 2nd Transportation Comprehensive Survey Report of Beijing [43], and the corresponding data for 2009 is from Beijing 2010 Transport Annual Report [44].

2.3. The Analytical Framework

The proposed analytical framework is shown in the form of a diagram in Figure 2. The first step involves understanding the role of changing urban form in shaping the commuting demands of a city over time. Such dynamics will be captured by three key commuting indicators in this paper: the theoretical minimum average commute cost (T_{min}), the actual average commute cost (T_{act}), and excess commuting (EC) under empirical population and employment distribution data.

Figure 2. Diagram presentation of the analytical framework.



The theoretical minimum average commuting cost can be calculated by rearranging the regional commute to a minimum level, through employees exchanging jobs, which are nearer to their homes, given an assumption of homogenous employees and jobs [1]. Pioneered by White [46], a linear programming approach is used to solve this transport optimization problem by determining the assignment of commuting trips from homes to workplaces that minimizes the mean commuting cost:

$$T_{min} = min \frac{1}{W} \sum_{i=1}^{n} \sum_{j=1}^{m} C_{ij} X_{ij} \tag{1}$$

Subject to:

$$\sum_{i=1}^{n} X_{ij} = D_j, \forall\, j = 1,2, \dots \dots . m, \tag{2}$$

$$\sum_{j=1}^{m} X_{ij} = O_i, \forall\, i = 1,2, \dots \dots . n, \tag{3}$$

$$X_{ij} \geq 0, \forall\, i, j. \tag{4}$$

where *n* represents the number of origin zones (home locations); m is the number of destination zones (job locations); C_{ij} is the travel distance or time from zone i to zone *j*; X_{ij} is the number of commuting trips or passengers from zone i to zone *j*; W is the total number of workers or employees; O_i is the number of workers or employees living in zone *i*; D_j is the total number of job opportunities in zone *j*. The various constraints specify that the number of commuting trips originating from a zone is equal to the number of workers living in that zone, the number of commuting trips ending in a zone is equal to the number of job opportunities within that zone, and the commuting flow between any pair of zones cannot be negative (the non-negativity constraint). In the case of Beijing, the zones for subdistrict level with working population and employment data are employed to generate the commuting measures at the city level, and the linear distance between any pair of subdistrict tracts, instead of time cost, is used because the former is a more precise reflection of the changing urban form. The lpSolve package in open-source R [47] is employed in solving this optimization problem.

Excess commuting, is simply the ratio of the difference between the actual average commute cost and the theoretical minimum average commute cost over the actual commute, expressed as a percentage in the equation below [48]:

$$EC = (\frac{T_{act} - T_{min}}{T_{act}}) \times 100\% \tag{5}$$

Step two is to measure the effects of changing urban form on the modal share of journey to work, based on commuting accessibility. The accessibility measurement combines land use patterns and the transport network, which makes it useful for transportation modeling and policy implementation [49]. Hansen [50] was the first researcher to employ the concept of potential to describe accessibility as the potential opportunity for interaction. Since then, potential accessibility measurements (also called gravity-based measurements) have been widely used in urban and geographical studies [51,52]. In this analysis, commuting accessibility was calculated using the potential accessibility measurement, considering all the employment centers as end points in Equation (6). Due to the lack of actual commuting trip pairs between origins and destinations in Beijing, here, the overall accessibility, which estimates the employment accessibility of zone *i* to all other zones where jobs are offered, is calculated. In order to highlight the spatial differences of road network, the evaluation of commuting accessibility was done in the scale of the 1 km × 1 km mesh, and there are 16,540 meshes in total in Beijing.

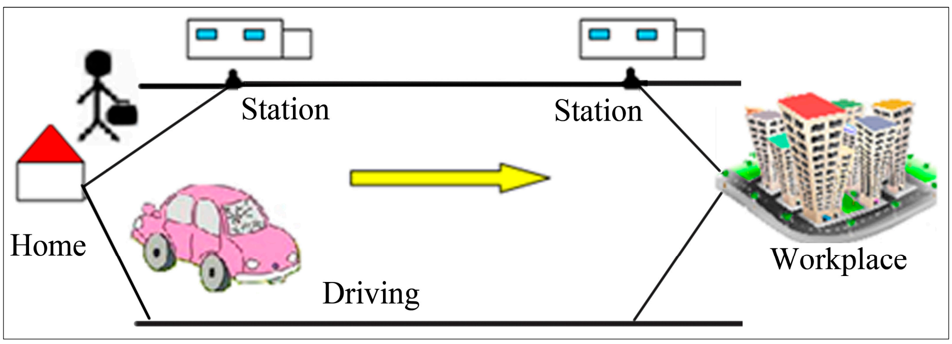
$$AC_{im} = \sum_{j}^{D} \{AT_j f(C_{ijm})\} \quad (6)$$

$$f(C_{ijm}) = exp(-\lambda C_{ijm}) \quad (7)$$

where the subscript *i, j, m* represent the origin zones, destination zones, and transport modes, respectively. Here, only the motorized commuting modes of public buses, metro, and private cars, are considered; AC_{im} is a measurement of commuting accessibility from origin zone *i* to all job opportunities in all destination zones *D* by mode *m*; AT_j is the attraction factor in zone *j*, which in this context, refers to job opportunities in zone *j*; $f(C_{ijm})$ is the impedance function, here negative exponential function is employed in Equation (7); C_{ijm} is the generalized cost between zone *i* and zone *j* by mode *m*; and λ is defined as an impedance parameter reflecting the distance deterrence.

In the case of Beijing, the estimation of generalized cost is divided into two types: private cars and public transport (Figure 3). For private cars, travel cost is measured by road network distances and the average travel speeds during the rush hours for different road types, such as the expressway, major road, collector road, and highway [43,44]. For public transport, the travel cost throughout the whole travel process from home to workplace are all under consideration, including walking time to the access point, waiting time and transferring time, in-vehicle travel time, walking time from the egress to the workplace, and fare. During a trip, end travel for ingress and egress, by way of walking, is considered (travel speed for walking is set to be 4 km/h), as walking is the most dominant mode of traffic access for public transport in Beijing, accounting for over 70% [53]. Additionally, the waiting time is set to be half of the time interval between the two times of pit stop, estimated based on the operation frequency at rush hours. Especially important is that the travel speed data for public buses and BRT employed in this measure is the average operation speed because of the absence of travel speed by different classes of road sections, such as cars. The different units of costs are changed to the value of money by the time value, estimated from the average wage (20 CNY/hour in 2005). The shortest-path travel costs between each pair of zones for both cars and public transport were calculated using network analyst function in System for Automated Geoscientific Analyses (SAGA) [54].

Figure 3. The generalized cost estimation between homes and workplaces.



The well-known gravity model explaining the level of spatial interaction between locations was used to estimate the impedance parameter λ. T_{ij} represents the magnitude of commuting flow (trips) between zones i and j; γ, θ are balancing factors that transform the activity units into the flow units, and serve to ensure that the magnitude of commuting flow originating from zone i equals the number of activities in zone i (labor forces) and the magnitude of commuting flow destining at zone j equals the number of activities in zone j (jobs), respectively; $f(d_{ij})$ is the impedance function, a negative exponential functions is also employed here; d_{ij} is the network distance between zones i and j; and δ is parameter.

$$T_{ij} = \delta O_i{}^{\gamma} D_j{}^{\theta} f(d_{ij}) \tag{8}$$

$$f(d_{ij}) = exp(-\lambda d_{ij}) \tag{9}$$

Subject to:

$$\sum_j T_{ij} = O_i; \sum_i T_{ij} = D_j \tag{10}$$

In Beijing, data at the district scale in 2005 is used to estimate the parameters $\delta, \gamma, \theta, \lambda$. In Equation (8), are the actual commuting flow sample data between origin districts and destination districts for 18 districts and counties from the third Comprehensive Transport Survey in Beijing [55], the workers and employment data in 2005 [56], and the shortest travel distance matrix between any two districts calculated by GIS. The value of λ is assumed to be same for all transport modes in Beijing because of the absence of origins and destinations flow data by different transport modes, and it does not change with time. Using ordinary least-squares (OLS) estimation, the results of $\delta, \gamma, \theta, \lambda$ are 0.0000224, 0.877, 0.861, and 0.002296, respectively.

Based on commuting accessibility, the probability P_{im} that a given individual in zone i will choose mode m within the choice set M (cars, metro, public buses) is estimated by a trip-end type multinomial logit (MNL) model, shown in Equation (11), the utility function is represented as a linear function of the accessibility for commuting, where α_m and $\beta_m$are the coefficient and the constant for mode m, respectively. During this process, one assumption is made: all workers select the mode that maximizes the commuting accessibility.

$$P_{im} = \frac{exp(U_{im})}{\sum_{m \in M} exp(U_{im})} \tag{11}$$

$$U_{im} = \alpha_m AC_{im} + \beta_m \tag{12}$$

At city level, the ratio of travelling by mode m MS_m is calculated according to Equation (13), where W is the total workers in the entire city, and O_i is the number of workers living in zone i. Then the parameters α_m and β_m can be estimated by performing a logistic regression using maximum likelihood estimation (MLE), based on the commuting data and accessibility results in 2000. Finally, the accessibility results in 2009 were employed to test their validity by comparing the observed modal share of the study area with model estimates. Here, the mode choice from the trip-end type modal split model, based on commuting accessibility, is only affected by the spatial distribution of population and employment (urban form), the transport network, and running speed, which affect the generalized cost by holding the personal preference constant.

$$MS_m = \frac{\sum_i (O_i \times P_{im})}{W} \tag{13}$$

Step three is to estimate the commuting CO_2 emissions based on the results of step one and step two. Because there is no detailed personal commuting data, here, the estimation of commuting CO_2 emissions is based on the statistical data at city scale. It is the combined result of the total commuting volumes (total motorized commuters*average trip frequency/year), average commuting distance per mode, modal share, and emission intensity per mode by using Equation (14):

$$CO_2{}^t = \sum_m [(CV^t \times MS_m^t) \times CD_m^t \times EI_m^t)] \tag{14}$$

where CV^t is the commuting volumes in year *t* (passengers); MS_m^t refers to the proportion of passengers who commute by mode *m* among all commuters in year *t* (%); CD_m^t is the average commuting distance by mode *m* in year *t* (km); and EI_m^t is CO_2 emissions intensity, which represents the relationship between the amount of CO_2 produced and the amount of passenger kilometers travelled for each mode (kg/PKT).

3. Results

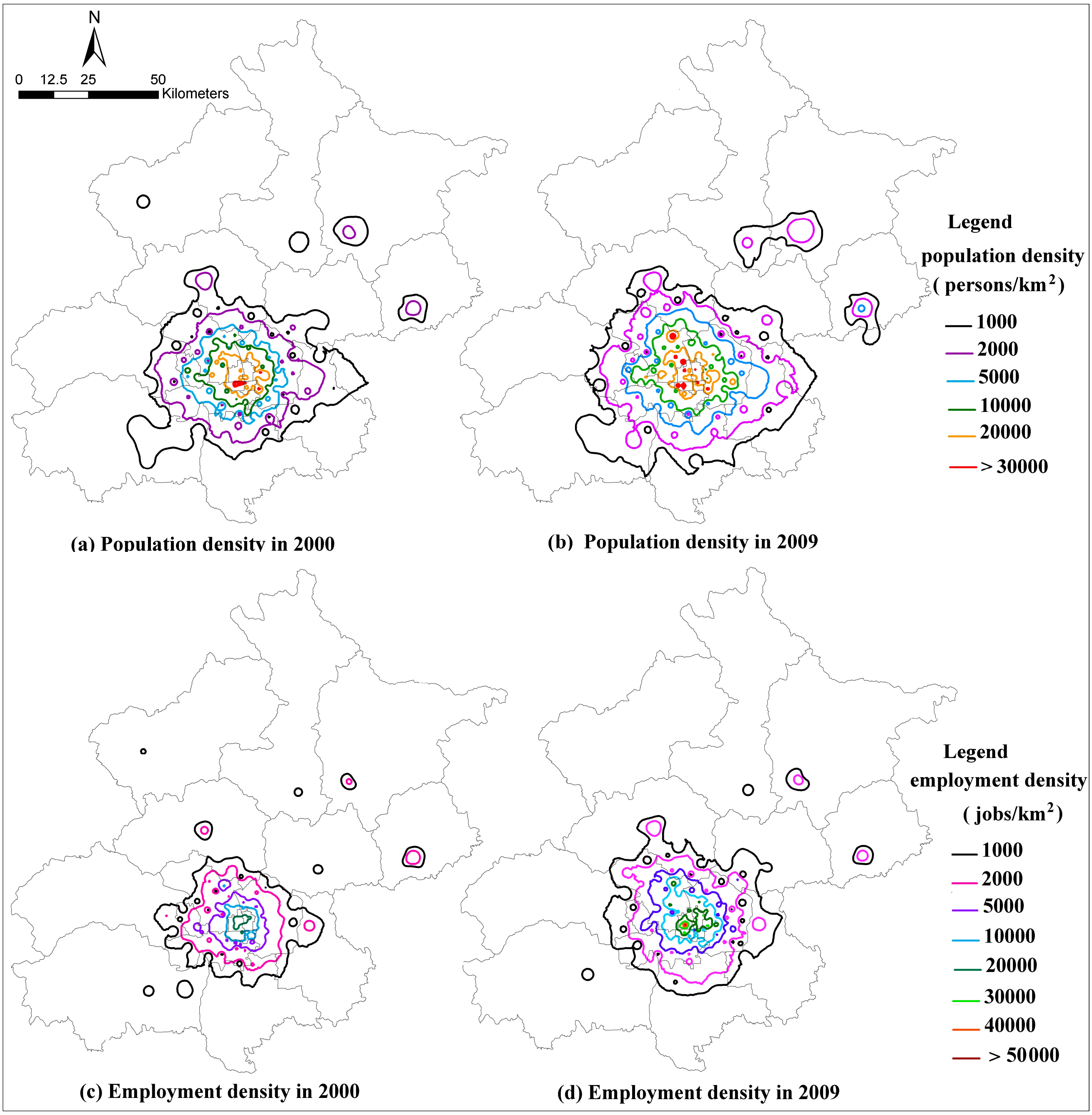
3.1. Changing Urban Form in Beijing

Beijing has been undergoing rapid urban expansion, stimulated by suburbanization, since the 1980s [9]. In order to capture this expansion process, the contour maps of population and employment were created by employing the Kriging method [57] in the software ArcGIS, based on the gross density for population and employment at subdistrict level (Figure 4) Contour maps show that both the deconcentrated spatial distribution of population and employment were observed in Beijing, and the growth has expanded to the urban frontier area from the new growth area, from 2000 to 2009. Table 2 summarizes the population, employment size and their growth rate of the central area, new growth area, urban frontier area and rural area. The distribution of population and employment opportunities can give additional insights about the changing urban form.

Table 2. The summary statistics for the change of population and employment.

	Year	Central Area	New Growth Area	Urban Frontier Area	Rural Area	Total
Population Million (Share)	2000	2.13 (16%)	6.42 (47%)	3.42 (25%)	1.67 (12%)	13.64 (100%)
	2009	2.11 (12%)	8.69 (50%)	4.92 (28%)	1.83 (10%)	17.55 (100%)
	growth rate	−1%	35%	44%	10%	29%
Employment Million (Share)	2000	1.52 (25%)	2.87 (46%)	1.25 (20%)	0.55 (9%)	6.19 (100%)
	2009	1.87 (19%)	5.06 (51%)	2.25 (23%)	0.80 (8%)	9.98 (100%)
	growth rate	23%	76%	80%	45%	61%

Figure 4. Contour Maps of Beijing. (**a**) Population density in 2000. (**b**) Population density in 2009. (**c**) Employment density in 2000. (**d**) Employment density in 2009.



From 2000 to 2009, the total population of Beijing increased by 29%, from 13.64 million to 17.55 million. In 2000, a large density peak ($\geq 30{,}000/km^2$) appeared within 5 km of the city center in the western and southern direction of the central area (Figure 4a). This peak had dropped and was no longer visible in 2009, with more, and smaller density peaks scattered in the eastern, western, and northwestern parts, beyond 5 km and within 40 km of the city center (Figure 4b). These small peaks were mainly some marginal residential parks with the single function of residence in the new growth area, and new towns in urban frontier area. As a consequence, the population in the central area decreased by 1%. In comparison, the new growth area and urban frontier area had the highest growth rates of 35% and 44%, respectively, while the rural area only had a minor increase in population from

2000 to 2009. These figures justified the decentralization development of population, moving away from the city center to the new growth area and urban frontier area, as a reflection of the changing urban form in Beijing.

Simultaneously, there was also a marked tendency for workplace decentralization; however, the spatial decentralization degree was different with that of population. From 2000 to 2009, the total employment opportunities of Beijing increased by 61%, from 6.19 million to 9.98 million, and the growth, in space, almost covered the whole city, although the growth in the central area was the lowest. In 2000, the area with the largest employment density was mainly located in the north and east of the central area, with the top value of 28,080/km^2 in the Beijing Financial Street (Figure 4c). In 2009, Beijing had developed two separate CBDs, in both the east and the west parts of the city (Figure 4d). One is the so-called CBD, and occupies 3.99 km^2 in the new growth area on the east side of the city, sandwiched between the 3rd ring road and the 4th ring road, with a employment density of 33,968 per km^2 in 2009, the other is the above-mentioned Beijing Financial Street in the central area, in which employment density increased to 64,175 per km^2 by 2009. Moreover, there were some small peak employment density areas in the new growth area, including various industrial development zones, such as Zhongguancun Science Park. As for the urban frontier area, the greatest growth area, 80% growth happened in the form of projects, such as suburban real estate and commercial housing, housing with commercial and residential purposes, economic development zones, large suburban shopping malls, and retail parks.

Despite the different degree of decentralization of population and employment in Beijing, the urban form of Beijing is still highly centralized by physical form. The 2000 urban form was found to be characterized by an urban form with more population residing and working in the central area, while the 2009 urban form had more population relocated to the new growth area and, especially, the urban frontier area. Moreover, employment is typically more centralized in the central area than population, similar with the trends of megacities in developed countries [58].

3.2. Changing Urban Form and Excess Commuting in Beijing

The patterns of population and employment decentralization in Beijing, summarized above, obviously have profound implications for commuting. A different decentralization degree between population and employment in Beijing would cause intensified spatial mismatch problems, and the separation between residence and employment sites. The excess commuting concept provides a very useful benchmarking tool for measuring the jobs-housing balance, especially when it is applied to one city over several time-periods [1]. Table 3 shows the results of the theoretical minimum average commute distance and excess commuting of Beijing in 2000 and 2009, based on a distance measurement.

In 2000, the actual average commuting distance was 7.15 km and the theoretical minimum average commute distance was 5.90 km. This means that the difference between the actual average commuting distance and the minimum average commute distance (7.15 − 5.90 = 1.25 km) was attributable to jobs-housing imbalance. In 2009, the actual and minimum average commuting distances were 9.44 km and 6.01 km, respectively, suggesting that 3.43 km was attributable to the jobs-housing imbalance problem. It is notable the jobs-housing imbalance got worse between 2000 and 2009. Jobs-housing imbalance is related, not only the numerical imbalance and mismatch between jobs and housing at regional level in the physical urban form, but also non-physical aspects of urban form, such as the spatial distribution of persons of different sex, education, income, occupation, affordable housing, personal preference, *etc.*, which seriously affect the interaction and choice between population and employment at a local level.

Table 3. Empirical commuting measures in Beijing.

Year	T_{min} (km)	T_{act} (km)	EC
2000	5.90	7.15	17%
2009	6.01	9.44	36%

In the case of Beijing, the numerical inequality between jobs and homes in the physical urban form, from 2000 to 2009, did not change a great deal, especially on an aggregated scale. This is consistent with the result of the theoretical minimum average commute distance, which is determined only by the spatial locations of employees and jobs, showing the physical level of the jobs-housing balance. The theoretical minimum average commute distance had been relatively stable throughout the decade, only increasing slightly by approximately 0.11 km. Although there was a minor increase of minimum commute distance in Beijing, the city level actual average commuting distance rose from 7.15 km in 2000 to 9.44 km in 2009 (an increase of 32%). Accordingly, the rates of excess commuting in Beijing increased from 17% in 2000 to 36% in 2009. As with studies conducted in Western cities, the analysis of the Beijing case found that the overall commuting efficiency has deteriorated over the years, with a worse jobs-housing balance. However, for different stages of urban sprawl, the driving force is different. Since the 1980s, China has been undergoing social and economic transformation, and Beijing is still in the transformation process with tremendous changes in land development management and the real estate market [59]. The public housing provided by danwei (a state or collectively owned work unit) is gradually being replaced by commercial housing and subsidized housing. In addition, most subsidized housing is located in the fringe of the new growth area and even in the urban frontier area. Hence, many employees, especially low income ones, who still work in the urban core, have to choose to live farther away from the traditional urban core in favor of more affordable housing. The previous jobs-housing balance in small disaggregate levels, dominated by the danwei housing system, were gradually broken, which resulted in an increase in the need for long-distance travel, in particular, commuting between the city center and suburban areas, and would have negative effects on sustainable transportation.

3.3. Changing Urban Form and Model Share in Beijing

In addition to the commuting distance, the individual worker's travel mode for the journey to work would also be significantly influenced by urban form [60]. Linking by accessibility measurement, relationship between urban form, and modal choice, were simulated by Equations (11) to (13), and the estimated results of parameters and *t*-statistical values, based on the data in 2000, are shown in Table 4. In order to test its validity, the calculated results of commuting accessibility of Beijing in 2009 were employed to estimate the mode choice in 2009 and check the performance in producing outputs. Table 5 compares the observed modal share result for commuting in Beijing [44] with model estimates, and shows a good predictability where the largest relative error is 4.23%.

Table 4. Estimation for the parameters and *t*-values.

Mode choice	α_m	*t*-value	β_m	*t*-value
Cars	0.0022	−5.40	−0.44	5.06
Metro	0.0005	1.99	0.0055	3.18
Public buses	0.0001	2.34	0.0062	3.40

Table 5. Aggregate result of the multinomial logit (MNL) model and errors estimation.

Mode choice	Observed Result (%)	Estimated aggregate result (%)	Relative error (%)	Absolute error (%)
Cars	39.64	39.14	1.26	0.50
Metro	13.72	13.14	4.23	0.58
Public buses	46.64	47.72	2.32	1.08
In Total	100	100	-	-

In Figure 5, (a) to (d) illustrate the evolution of the mode choice for commuting activities in Beijing, in terms of number of passengers, only considering the motorized modes. It is clear that, between 2000 and 2009, there was a significant shift away from public buses to cars and metro. The number of cars, in particular, increased more than tenfold over this decade, and greatly contributed to the popularity of car use. The modal share of cars increased to 39.14% in 2009 from 22.78% in 2000. Moreover, the proportion of commuting by metro increased to 13.14% in 2009 from 8.26% in 2000. The modal shift for commuting, occurred in Beijing, presents an integrated effect of changing urban form, transport network improvement, and other factors, such as increasing income, personal preferences, *etc.* Based on the potential model in accessibility analysis, the urban form and transport network both play an important role in shaping worker' commuting choice, jointly and simultaneously. In order to quantify and separate the effects of changing urban form on modal share change, in the case of Beijing, we disassembled this process by only considering the impacts of changing urban form and transport network improvement by holding other factors constant, based on commuting accessibility evaluation.

Sensitivity analysis offers some useful possibilities for investigating the impact of changing urban form, and transport network improvement, on the commuting modal shift during 2000 and 2009. In this regard, the urban form of Beijing in 2000 was placed on the transport network of 2009 to evaluate new accessibility, and then, a new modal choice by employing Equations (11)–(13). By comparison, the impact of transport network improvement on the commuting modal share can be investigated; additionally, opposite, the transport networks of 2000 were placed on the urban form of Beijing in 2009 to examine the effect of changing urban form on the commuting modal share. In Figure 5, (b) and (c) show revised results for the modal share, and Table 6 displays the saving and addition effects of the changing urban form and the transport network improvements on the modal share. The actual process, from (a) to (d), shown in Figure 5, can be disassembled into two trajectories: (1) The upper path (red arrow) from (a) to (b) shows the impact of transport network improvement by holding the urban form constant, and then (b) to (d) shows the impact of changing urban form by holding the transport network constant; (2) The blue path below, from (a) to (c), and then from (c) to (d), shows the impacts of the changing urban form and transport network improvements, respectively.

Figure 5. The evolution of commuting modal choice in Beijing. (**a**) Modal choice in 2000. (**b**) Revised modal choice by transport network. (**c**) Revised modal choice by urban form. (**d**) Modal choice in 2009.

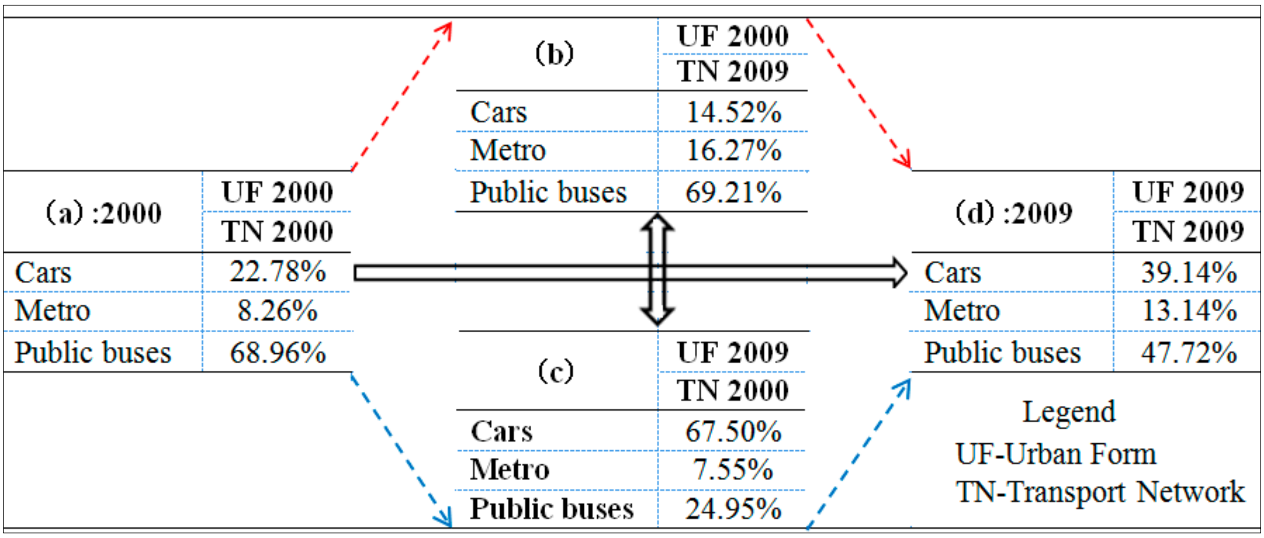


Table 6. Savings and additions associated with interchanging urban form and transport network.

	The effects on modal share		Total effects (a) to (d)
	Urban form (a) to (c)	**Transport network (a) to (b)**	
Cars	196.3%	−36.3%	71.8%
Metro	−8.5%	97.2%	59.2%
Public buses	−63.8%	0.3%	−31.8%

On one hand, it is evident that the changing urban form from 2000 to 2009 in Beijing had a negative effect on modal shift to public transport, but a positive effect on the modal shifting to private cars, from (a) to (c) and from (b) to (d) in Figure 5. This is opposite to the findings of Bertaud and Richardson [61], that there would be more use of public transport with a higher population density. Although the population in most places in Beijing increased, except in the central area, the modal share of commuting by public buses and metro lessened, respectively. From 2000 to 2009, the population decrease occurred only in the central area, where most of the public transport network was concentrated, while the population increased to a large degree in the new growth area and urban frontier area, where less or no supply of public transport services were provided, especially in the urban frontier area. Furthermore, the lag of public transport services encourages people to travel by private modes, hence, the modal share of cars in Beijing increased by 196.3% during the process from (a) to (c).

On the other hand, the change of modal share from (a) to (b) and (c) to (d) in Figure 5 shows that the effects of transport network improvements are negative to cars and positive to public transport in Beijing from 2000 to 2009. During this period, the network of road, public buses, and metro system increased by 55%, 17%, and 322%, respectively, based on the statistical data. From (a) to (b), it is clear that car users in 2000 were able to attain dramatic savings by using the metro and public transport of 2009 because of the faster expansion of the metro network and the low price policy for public buses. While for car users of 2009, from (c) to (d), the effects of road expansion from 2000 to 2009 were almost offset by the decrease of road speeds because of the surge of private cars.

On the whole, from 2000 to 2009, the changing urban form of Beijing had a larger impact on the use of cars (196.3%) and public buses (−63.8%), while the improvement of the transport network of Beijing had a larger impact on metro users (97.2%) (Table 6).

In many Western cities, households in sprawl areas are better-off social classes, seeking larger floor space and a better living environment, while those living in the inner core are typically minorities and less affluent households [8,62,63]. This is not the case in Beijing, although urban sprawl in Beijing has an influence on social segregation [64]. Although gated low-density communities and villa areas, along several highway corridors in the new growth area and urban frontier area, attract middle and high-income populations that have cars and prefer to have better access to highways, open, and green spaces. As a legacy of the traditional planned economy, the central area of Beijing is the region with the highest satisfaction, considering livable conditions, including healthcare, safety and security, culture and environment, education, and infrastructure [65], where it is mainly occupied by the rich and middle class. By comparison, low and middle-income people live in subsidized housing and new development commercial housing with a lower price, in the new growth area and urban frontier area. Rapid population growth in the outlying areas, without the massive new infrastructural development supply, especially for the public transport, has promoted car travel in Beijing, and there were a higher proportion of car commuters in the new growth area. For example, in 2008, the proportion of commuting by private cars in Tiantongyuan, the largest residential community with subsidized housing in Beijing, located in the urban frontier area, was much higher (23.2%) than that of four communities (16.4%) in the central area [66].

3.4. Changing Urban Form and Commuting CO_2 Emissions in Beijing

Figure 6 presents the trends of commuting CO_2 emissions in Beijing, which were based on the actual commuting volumes (only motorized volumes), commuting distance, modal share, and emission intensity over time in Beijing. Aggregate commuting CO_2 emissions was more than four-fold from 1.37 million tons in 2000, to 6.35 million tons in 2009, with a robust average annual growth rate of 19%. Among each mode, the share of each mode was largely different. For personal transport modes, CO_2 emissions from cars increased more than four times, and its share reached 85% in 2009, from 74% in 2000. As for the public transport modes, the share of public buses declined to 14% in 2009 from 21% in 2000, although the amount of CO_2 emissions from public buses increased 1.98 times in this period; The metro, which had the lowest passenger transport CO_2 emissions, had a share that was still relatively low (2%), although its emissions increased 88% due to the network expansion and the increasing number of passengers carried per year.

Figure 7 shows the commuting CO_2 emissions, based on the minimum scenarios in 2000 and 2009, which were based on the actual commuting volumes, emission intensities, the minimum commuting distance, and their corresponding modal share. From 2000 to 2009, the commuting CO_2 emissions, based on the minimum scenario, increased from 1.13 million tons to 4.04 million tons, which, to a large degree, was due to the increasing commuting distance and modal shift caused by the changing urban form to a more decentralized structure, in addition to an increase of total commuters. Compared to the actual commuting CO_2 emissions in Beijing, the mitigation potential from the improvement of interaction between jobs and housing, under the existing urban form, became larger with a figure of

0.24 million tons in 2000 to 2.31 million tons in 2009. In other words, for Beijing city, a more decentralized urban form in 2009 had a larger space, and an urgent need for commuting CO_2 emission reduction by implementing some policies for the improvement of interaction between jobs and housing.

Figure 6. Commuting CO_2 emissions increasing in Beijing.

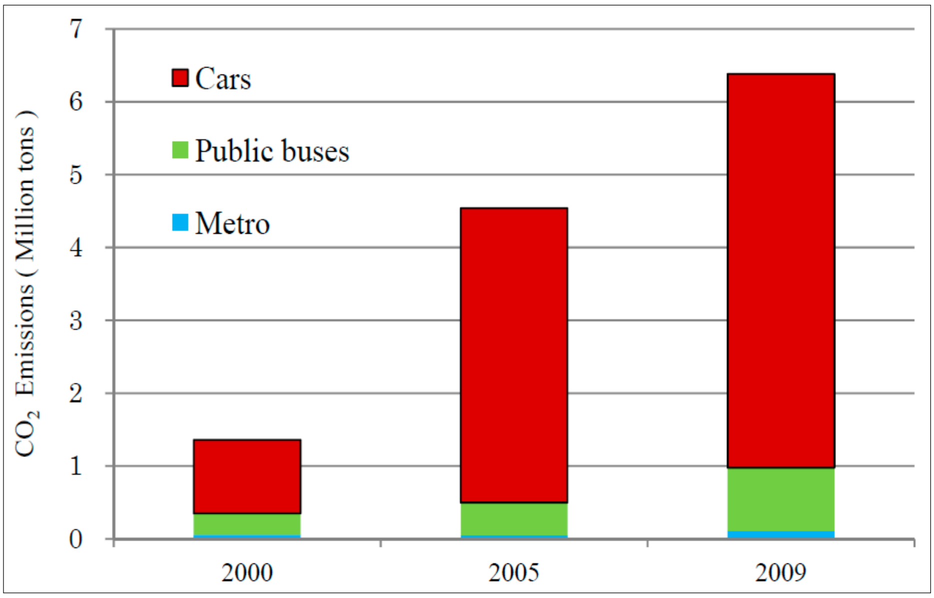
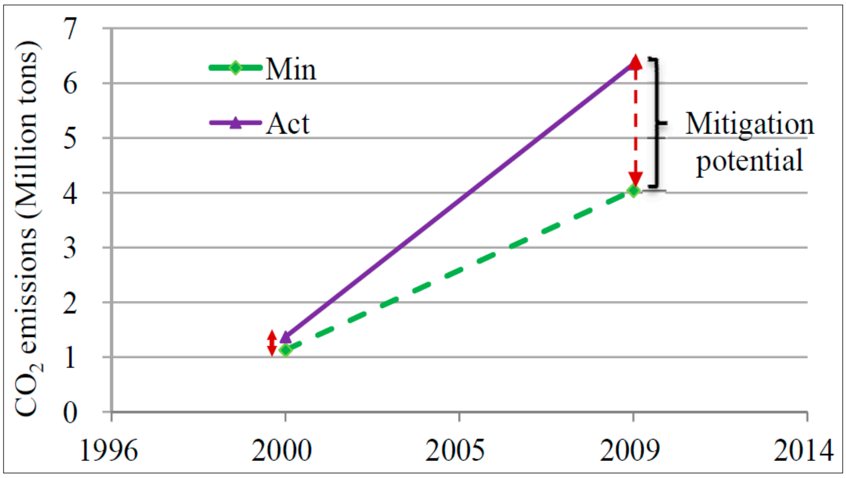


Figure 7. Urban form oriented mitigation potential of commuting CO_2 emission in Beijing.



4. Conclusions and Discussions

As a major contributor to energy consumption and CO_2 emissions, sustainable transport has become a key issue, particularly for the rapidly growing megacities of China, which are experiencing dramatic decentralization development and rapid motorization, simultaneously. Urban form provides the physical rationale for travel, along with socio-economic and cultural factors. Being short of detailed disaggregate personal travel data, this paper introduced a geographical approach to the study of the impact of changing urban form on commuting, and related CO_2 emissions, from the perspectives of excess commuting and commuting accessibility. Taking the dynamic of decentralization development of population and employment as endogenous, this methodology simultaneously evaluates the impact of changing urban form on travel demand and mode choice in an integrated analytical framework, and ensures its general applicability, especially in cases where there are data limitations, or the disaggregate data are not available.

The application of this analytical framework to Beijing city adds another interesting empirical study to the relatively few longitudinal studies of excess commuting, accessibility evolution, and will advance the debates on how to lessen the environmental burden in order to promote sustainable development. Like many cities experiencing urban sprawl, the preliminary decentralization development of population and employment were observed in Beijing from 2000 to 2009, and employment, rather than population, was typically more centralized in the central area. The analysis of the Beijing case confirms that a worsening jobs-housing balance did have profound implications for commuting.

As with many studies conducted based on the concept of excess commuting, this study has found that urban form and spatial configuration play an important role in shaping commuting distances, and that commuting distance is, to a very large extent, a determinant for the CO_2 emissions of the commuting system [1,34]. However, considerations that only focus on travel distances or excess commuting cannot fully promote sustainable transportation. Both consequences of the changing urban form, and mobility in terms of demand aspect and mode shares, are important issues for researchers and planners who seek ways to reduce transport CO_2 emissions. It is important to note that the processes do not act independently, and cannot be separated. The mode used is of much more importance in contributing to CO_2 emissions during rapid motorizations. Being distinct from ignoring the modal shift caused by changing urban form [1], or estimating it based on a great deal of personal survey data [15,30,32], this study quantifies the effects of changing urban form on modal shift, and separate them from transport networks, based on accessibility measurements. Except for the increasing commuting distance, the changing urban form in Beijing also promotes more car usage. As a whole, for Beijing city, the more decentralized urban form in 2009 has a great deal of space and an urgent need for the reduction of commuting CO_2 emissions.

A jobs-housing balance policy has been considered as a strategically useful tool to alleviate congestion and automobile emissions. Although in the long run, growth management and planning policies in land development can affect jobs-housing balance and transportation patterns in many ways—through increasing densities and concentration, through mixed use development, through housing location, such as the "Live Near Your Work" (LNYW) program in Baltimore City, Maryland [67], and promoting job decentralization in a city with population decentralization, to help workers reduce long-distance [1]. However, policies in urban planning to promote a high level of jobs-housing balance, as the single strategy for facilitating sustainable commuting, are unlikely to meet the expectations of policymakers because workers consider many factors, in addition to commuting costs, such as affordable housing, good schools, neighborhood quality, and environmental amenities, in locational choices. Quantitative jobs-housing balance is a necessary, but not sufficient condition for more efficient commuting [68]. Market-based strategies affecting travel behavior directly are proven more effective in reducing environmental externalities because they alter cost, such as road pricing [69], environmental levies or tradable permit systems [70]. In this respect, we notice that the current travel policy in Beijing is very much focused on managing the demand for automobiles, such as the staggering of working hours, car-using restriction, and license plate "lottery". As congestion and emissions continue to threaten the quality of urban environments in Beijing, there is a growing need to evaluate all strategies that have the potential to improve commuting efficiency and promote sustainable transport. Models simulated integrated land-use and transportation planning considering both the travel demand and modal choice, such as our framework, are sophisticated tools ideally suited for this task.

It is necessary to note the limitation of the proposed framework's application. The issue of geographical scale and possible modifiable areal unit problem (MAUP) [71] effects should receive more attention when dealing with jobs-housing, excess commuting, and accessibility measures as these are typically based on a zonal structure. Analysis with different geographical scales may produce different conclusions and implications, bringing certain challenges for spatial comparison analysis. Instead, when linking analysis and policy assessment in different time scales for the same area, the application of this framework will prove a useful tool. A longitudinal study of the same city, over time, enables a comparison and evaluation of different spatial structures and planning strategy, and other policy implications.

Acknowledgments

This research was financially supported by National Key Basic Research and Development Plan (2012CB955501) of China Ministry of Science and Technology, China Postdoctoral Science Foundation (2013M540058), and the Environment Research and Technology Development Fund (S-6-5) of the Ministry of the Environment, Japan. The authors appreciated valuable comments and suggestions from two anonymous reviewers and help from Jing Li, the editor of Sustainability.

Author Contributions

Yunjing Wang made substantial contributions to the design of the study, acquisition, analysis and interpretation of data, and drafting and revising the article; Yoshitsugu Hayashi helped to analyze the result and provided good advice throughout the paper; Jin Chen and Qiang Li both helped to revise the manuscript, and produced the final approval of the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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