Are There Alternatives to Greenbelts?

Evidence from a New Land-use Transport Interaction Model for Greater Beijing

This dissertation submitted to the University of Cambridge for the degree of Doctor of Philosophy

by

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DECLARATION

This dissertation is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Acknowledgement and specified in the text.

It is not substantially the same as any that I have submitted, or, is being concurrently submitted for a degree or diploma or other qualification at the University of Cambridge or any other University or similar institution except as declared in the Preface and specified in the text. I further state that no substantial part of my dissertation has already been submitted, or, is being concurrently submitted for any such degree, diploma or other qualification at the University of Cambridge or any other University of similar institution except as declared in the Preface and specified in the text

It does not exceed the prescribed word limit of 80,000 words.

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ACRONYMS

The following acronyms are frequently used in this research. The list of acronyms may be helpful for the reader to refer to.

LUTI	Land Use Transport Interaction
SE	The Spatial Equilibrium Model
NCTD	The Non-Commuting Travel Demand Model
ST	The Strategic Transport Model
RD	The Recursive Dynamic Model
Ref	The Reference Scenario in policy tests
GB	The Greenbelt Scenario in policy tests
GB-NT	The Greenbelt-New Town Scenario in policy tests
GW	The Green-Wedges Scenario in policy tests

The frequently used mathematical notations are summarised in NOMENCLATURES on Page 276, after the main body of the dissertation.

ABSTRACT

Urban greenbelts are considered a key instrument for shaping sustainable urban growth and protecting the environment in a large number of cities in the world. In most cities, there is a widely shared belief that urban greenbelts are beneficial to the natural environment. By contrast, there is little consensus on their impacts on economic well-being. In the emerging economies, it is common to see that the greenbelt plans tend to falter – this is often attributed to weak planning regulation and governance, but there is little understanding of the underlying economic impacts of greenbelts and other green space configurations in fast growing cities.

The unprecedented rate and scale of urbanisation in the emerging economies has brought the role of greenbelts into an even sharper focus. In cities within these fast growing economies, the urban population is expected to double in the coming decades, which means that greenbelts are under great pressures to adapt to the large forthcoming growth. Few existing urban models are capable of addressing the dynamic nature of the urban transformations and predicting the impacts of urban greenbelts in the developing world. This prompts us to develop a new modelling method that is capable of assessing the impacts of different configurations, scales and locations of green spaces. We then use it to examine alternative futures to the greenbelt through a case study of Greater Beijing.

The method we developed is a new variant in the land use-transport interaction (LUTI) model family. This model is capable of addressing the non-equilibrium nature of urban land use and transport development and the equilibrium nature of the day-to-day adaptations made by businesses and citizens. This LUTI model aims to answer the following questions: what are the short-term and long-term economic impacts of a greenbelt on a fast growing city? Which alternative green space configuration performs better in terms of economic well-being and travel costs? Where and how much should the greenbelt land be progressively reshaped or released as the city grows?

The new LUTI model is calibrated and validated using data collected for 1990, 2000 and 2010 for Greater Beijing, The model is first tested retrospectively through revisiting the past greenbelt policies in Beijing from 1990 to 2010. Then the impacts of different future green space configurations from 2010 to 2030 are predicted and assessed through quantifying economic costs/benefits and travel costs for socio-economic groups.

The model results suggest that under rapid transformative urban change, the configuration, scale and location of a greenbelt have a significant impact on a city's economic efficiency. Such impacts will transcend the greenbelt boundary, and even the boundary of Beijing Municipality, onto the entire city region. A narrow greenbelt launched in the early age of urban expansion could lead to spatial mismatch of residents and jobs. A wide and strictly controlled ring-shaped greenbelt is not the highest performing intervention either, in terms of economic well-being. The green-wedges configuration is a remedial policy that balances the economic efficiency and environmental benefits. Intensive development around metro/rail stations in the designated greenbelt could reduce spatial costs and promote sustainable travel modes. This implies that a careful siting of new development within existing designations of the greenbelt can be beneficial in terms of economic well-being and sustainable transport.

This research develops an assessment tool to comprehensively examine of the short-term and long-term impacts of green space policies on four urban markets: the real estate market, labour market, product market and transport market. To the best of our knowledge, this is the first time that a LUTI model is empirically established over three cross-sectional years (1990-2000-2010) to test the impacts of green spaces on the four markets for a city in an emerging economy.

CHAPTER 1 INTRODUCTION

1.1 Background

Policies regarding land use and built-form can have significant impacts on local environmental quality, economy, and social equity (Echenique et al., 2012). A fringe of a city is a transitional zone where urban land use and rural land use mix and clash. Typically, this is the area where the bulk of new construction takes place, and it therefore plays a crucial role in shaping the city. As one of the most common policies in this arena, greenbelts, often favoured by local planning authorities, are considered as an instrument for preventing unwanted urban expansion and controlling the development of the urban fringe in order to achieve sustainable growth.

Greenbelt policies are common in the UK's Town and Country Planning System. Established in the 1930s, London's greenbelt has been considered one of the most successful urban containment practices across the world (The Economist 2012). Other European cities including Paris, Frankfurt and Vienna have followed with similar practice. They have also been implemented in the Asian-Pacific region, for example in Melbourne, Sydney, Hong Kong, Tokyo and Seoul (Amati 2008; Buxton & Goodman 2003; Kim & Kim 2008; Okata & Murayama 2011; Tang et al. 2007). In America, Ontario's greenbelt in Canada and Portland's urban growth boundary in the US are well-known (Carter-whitney & Esakin 2010; Staley et al. 1999). Cities in emerging economies also implement greenbelt policies to achieve a compact urban form, for example in Sao Paulo, Bangalore and Beijing (Adkin 2009; Han & Long 2010).

However, planners in developing countries are often discouraged by the fact that greenbelt policies from developed countries do not lead to the same outcomes when applied in their own countries. The planned greenbelts are often ignored, encroached upon or even completely built over as the cities expanded. This is not because cities do not recognise the expected environmental and social benefits, but because they find it hard to resist the development pressures from businesses and residents upon the greenbelts. A lack of understanding in the economic impacts of the greenbelts have proven detrimental towards the capabilities of the planners to safeguard their designs of greenbelts.

Even in cities of developed countries with a well-established greenbelt, such as London and Seoul, the debate on the economic effects goes on. Extensive research has questioned: does a greenbelt support compact development or prevent sufficient land supply? Does a greenbelt prevent environmental degradation or discourage positive land use in the urban fringe? Does it encourage long distance commuting? The effects of a greenbelt on a city's economic well-being remain unclear.

Moreover, even if the greenbelt policies had successfully contained urban growth as they were intended, would the planners and policy makers be confident that that would have been the desired outcome in the future? (For example, what would happen when their cities become much larger than they had foreseen?) The unprecedented scale of urbanisation in the emerging economies has brought an even sharper focus on the changing role of greenbelts, especially where the population sizes are now expected to double the past planning targets in the coming decades. Proposals for alternative configurations to the greenbelt have also been made in some cities to adapt the future growth.

In order to assess the performance of the greenbelt or any alternatives to it, a rigorous assessment tool is required. This tool is expected to be capable of: 1) predicting the likely policy consequences of the greenbelt and other green space configurations quantitatively on various urban markets; 2) assessing the policy impacts under different socio-economic contexts; 3) assessing the long-term impacts of large scale urban green space policies.

Urban land use and transport interaction (LUTI) models have been recognised as one of the most operational and effective approaches for developing and testing policy options (Wilson 1998; Batty 2009; Wegener 2014). They have been applied in many developed countries to predict and assess the policy performances (Echenique 2011; Echenique et al. 2012; Echenique et al. 2013; Abraham & Hunt 2013; Williams 1994; Jin et al. 2002). They originate from economic and econometric theories and provide insights into the complex interactions between different markets in the development process, and help to evaluate long-term effects of policies. In particular, there have been many studies to quantify the impacts of greenbelts on urban land markets and/or on transport markets (Brueckner 2007; Anas & Rhee 2007; Anas & Rhee 2006).

However, the LUTI models are not well established in most cities in developing countries, which are eager to establish greenbelts for environmental and social benefits. This is because of its sophisticated data and skill requirements, and such models require a significant time investment for model development and the costs are relatively high. Moreover, there has not been a LUTI model to test the effects of greenbelts against other configurations on several interdependent markets in rapid growing cities. On the other hand, it is crucial to predict and assess the possible effects of urban form policies on such cities rigorously ahead of time, so that the unnecessary costs of implementing an unpredictable urban containment policy can be avoided. That is to say, LUTI models are least available in the cities which need them most urgently.

1.2 Aims of this research

Under such a research context, we aim to assess and predict the impacts of greenbelts and alternative green space configurations on the economic well-being of fast growing cities through a rigorous assessment tool. We aim to answer the following questions: What are the short-term and long-term impacts of a greenbelt on a fast growing city? Which alternative green space configuration performs better in terms of economic well-being and travel costs? Where and how much should the greenbelt land be progressively reshaped or released as the city grows?

Existing LUTI models are not well placed to answer all the questions above. This prompts us to build a new variant of the LUTI model that aims to answer the above questions more fully. We then test the model in a case study of the Greater Beijing region, which represents a typical example of a fast expanding region with a live debate on the role of greenbelt policies.

1.3 Dissertation structure

This dissertation is structured as follows:

Chapter 2 presents a literature review of the greenbelts, and through this review, it outlines the current debates on whether the greenbelts are breakable and what possible alternative green space configurations there are.

Chapter 3 offers a review of the models that have been used to assess the different dimensions of the effects of greenbelts. It then summaries the features required for an integrated model that is capable of assessing the greenbelt and related land use and built-form policies in fast growing cities.

Chapter 4 establishes a theoretical modelling framework of the new LUTI model, and introduces the four sub-models, namely the Spatial Equilibrium Model, the Non-Commuting Travel Demand Model, the Strategic Transport Model, and the Recursive Dynamic Model. This chapter then describes the interactions among the sub-models and how they are linked to represent temporal dynamics.

Chapter 5 applies the theoretical model to a case study city region, which is Greater Beijing. This chapter specifies the model based on the data collected over 3 cross-sectional census years (1990, 2000 and 2010) in the Greater Beijing region, including the geographical zoning, the temporal dimensions, the demographic and land use data, and the transport networks. It also elaborates on the model calibration and validation methods.

Chapter 6 presents three model applications. The first application is a review of the evolution of land use and greenbelt configurations from 1990 to 2010. The second application is the scenario-based predictions of the performance of different greenbelt configurations from 2010 to 2030. It examines three broad types of growths: the concentric urban expansion following the past trend, the greenbelt (with or without the support of new town development) and the green-wedges. Their performance is assessed through pairwise comparisons among the scenarios. The third application investigates how future urban centre densification (2010-2030) affects the performance of different urban land use and built-form policies.

Chapter 7 draws conclusions by summarising the more general insights gleaned from the model results, assessing the strengths and weaknesses of our approach, and proposing possible topics for future studies.

CHAPTER 2 THE GREENBELT IN EVOLUTION

As an urban containment policy, the greenbelt, favoured by policymakers, is considered as a typology for controlling fringe growth in a sustainable way. The idea is to preserve a ring of open green land around the city. This land may be used for agriculture, forestry or as an open leisure space, in which urban expansion is resisted. New development should then take place in the existing urban area within the greenbelt, or beyond the greenbelt.

Greenbelt policies are common in the UK's Town and Country Planning System. The greenbelt policy has become one of the best known policies by the general public. For example London had a greenbelt in the late 1930s, while other cities, including Birmingham, Cambridge, Oxford, Bristol, etc. have followed the same practice (Miner & Sinden 2010). The total area of greenbelts was estimated to account for 13% of the total land area of England (Department for Communities and Local Government 2016).

As the first country carrying out greenbelt scheme, Britain claimed the fundamental purposes of a greenbelt were to check the unrestricted sprawl of built-up areas and to safeguard the surrounding countryside against further encroachment (Ministry of Housing and Local Government 1955). The fundamental aim of greenbelt policy is to prevent urban sprawl by keeping land permanently open (Department for Communities and Local Government 1995).

However, the greenbelt debate never stops. One strand of debate is over its effectiveness as a planning mechanism; the other is over its role in environmental management (Natural England & Campaign to Protect Rural England 2010). From the planning perspective, people argue 'do greenbelts support compact development or prevent sufficient land supply?' From the environmental perspective, people argue whether greenbelts prevent environmental degradation or discourage positive land use in the urban fringe. The fundamental questions are: what exactly are greenbelts for, what aims do they intend to achieve, and are they successful in achieving them (Hall 1974). In order to answer these questions, we first discuss the nature of greenbelts, and then we review the history of greenbelts in London, Beijing, Tokyo and Seoul. Then, we carry out analyses to find out why some greenbelts succeeded while others failed from the perspective of land use and transport coordination. Finally, we explain the necessity of considering other green space configurations as alternatives to the greenbelt in fast growing cities.

2.1 The nature of urban greenbelts

Greenbelts keep land permanently open and provide many environmental benefits, for example clean air and biodiversity. This concept is widely accepted by the general public. What they are less aware of is the role of greenbelts in urban economy. From the economic perspective, the greenbelt is an urban containment policy that shapes the spatial structure and aims at solving problems caused by excessive urban expansion. Therefore, we first define “excessive urban expansion”.

Urban built-up area expansion is considered as an economic phenomenon as a city grows, and there is an extensive literature explaining the evolution of urban spatial structure in economic terms (Anas et al. 1998). The Alonso-Mills-Muth monocentric model (AMM model) revealed fundamental driving forces in urban expansion: population growth, income rise, decline in transportation costs and low agricultural land rent. In the monocentric model, jobs concentrate in the central business area and residents commute to the centre to work (Mieszkowski & Mills 1993). Land rent falls with distance to the centre. Locational choice essentially represents a trade-off between land and travel (Wheaton 1974; Wheaton 1982). The spatial size of the city, which is represented by the distance to the city centre, grows as population or income increases, and falls as commuting cost or agricultural rent decreases (Brueckner 2001).

Although the standard model sees urban expansion as a natural process and economically efficient, Brueckner (2001) notes three types of market failure which lead to excessive spatial growth of cities: 1) a failure to take into account the social value of open space; 2) a failure to take into account the social costs of congestion; 3) a failure to take into account the costs of public infrastructure. The market failures explain the economic loss of urban expansion, associated with social and environmental problems, which have been witnessed in empirical studies as too much travel, pollution, congestion and vanishing urban open spaces (Anas & Pines 2008). An expansion resulting in such effects is considered as an excessive urban expansion.

Policies are put forward to solve the problems caused by excessive urban expansion. In general, these policies intend to control land use and increase the provision of transportation infrastructure (Anas et al. 1998). Such policies include urban containment policies (greenbelts or urban growth boundaries), fiscal rearrangements, infill and brownfield development, congestion tolls, and other policies. The greenbelt, as one of the many solutions, is to check excessive urban expansion, alleviate the aforementioned market failures and promote sustainable development.

The nature of greenbelts is always sound and very clear in government documents, but in practice, it has become disputable: is a greenbelt just an urban expansion stopper or can it act as a positive urban development director? Is a greenbelt a stringent land control tool or a dynamic planning policy? How effective is a greenbelt in checking excessive urban expansion and correcting market failure? Is a greenbelt a strict ring around city or a mixed open space configuration in an urban system? The answers to these questions will lead to an effective greenbelt design which provides better economic foundation for further policy implementation.

2.1.1 Negative development control versus positive guidance

Greenbelts originated from British land-use planning concepts and had a bias against development. It was a land use mechanism declared for the purposes of landscape and countryside conservation. However, Hall (1974) has commented in early days, after 40 years of reiterations by successive governments of different political complexion, the greenbelts are in effect a sacred feature of the British planning system – their protection today seems to be less a matter of planning policy than of planning politics. Is it a purely negative policy towards their management correct, or should we now be thinking of a more positive policy of development purposes (Hall 1974)?

There are two contradictory ideas about the purposes of the greenbelt policy. One concept stresses environmental protection and urban containment under the presumption that urban expansion is unwelcomed: “the town is an evil, the expansion of which should be stopped” (Warren-Evans 1974). The other stresses the positive use of the greenbelt land, for example for sports centres, golf courses, hospitals or therapeutic clinics, and further stresses its role on guiding future development.

It is valuable to combine the two ideas. As urban expansion is fundamentally propelled by population increase, greenbelts should not only define where should not be developed, but "whether within the greenbelt or not, to what use shall it be put (Warren-Evans 1974)" in the land. In this way, the greenbelt can positively handle urban expansion.

Inside the greenbelt, positive uses should be allowed, for example country parks, sport centres, and recreational parks. With such functions, greenbelts provide opportunities for access to the open countryside. The greenbelt land would not be considered as a waste but productive. Additionally, the positive function was a way of ensuring its implementation (Amati & Yokohari 2006). For example, in Hong Kong, recreation was greenbelt's initial planning emphasis. The development potential within Hong Kong's greenbelt has never been completely eliminated. Uses for 'small houses', and 'open storage' were favoured by the rural population, because they can get benefits from land within the greenbelt (Tang et al. 2007).

Beyond the greenbelt, land use policy should define where the new development should go. Development pressure cannot be eliminated because of a greenbelt surrounding the city. Without redistributing development beyond the belt, the greenbelt would be encroached anyway no matter where planners drew the boundary. Therefore, new towns are widely accepted as a complementary policy to the greenbelt policy, since Abercrombie proposed the Greater London Plan in 1945. In England, new towns located beyond the greenbelts absorb the overspill from the core cities and collaborate with greenbelts as a spatial development director. Adequate transport support to new towns are also crucial for successful implementation. In this way the greenbelt can be preserved and play its role for checking unwelcomed urban expansion.

However, it is worth noting that a greenbelt may lead to the dislocation of jobs and population as developments are not guided by market rule to the economically productive area, but by a static physical ring to new towns. For example, as London reached its greenbelt boundary in the 1940s, further development was redirected to either new towns or back to inner London. However, out of 8 new towns actually built, only 2 were in their proposed sites (Stevenage and Harlow) (Porter 1998, p.350). Development was encouraged beyond the greenbelt, but did not necessarily take place in the planned towns.

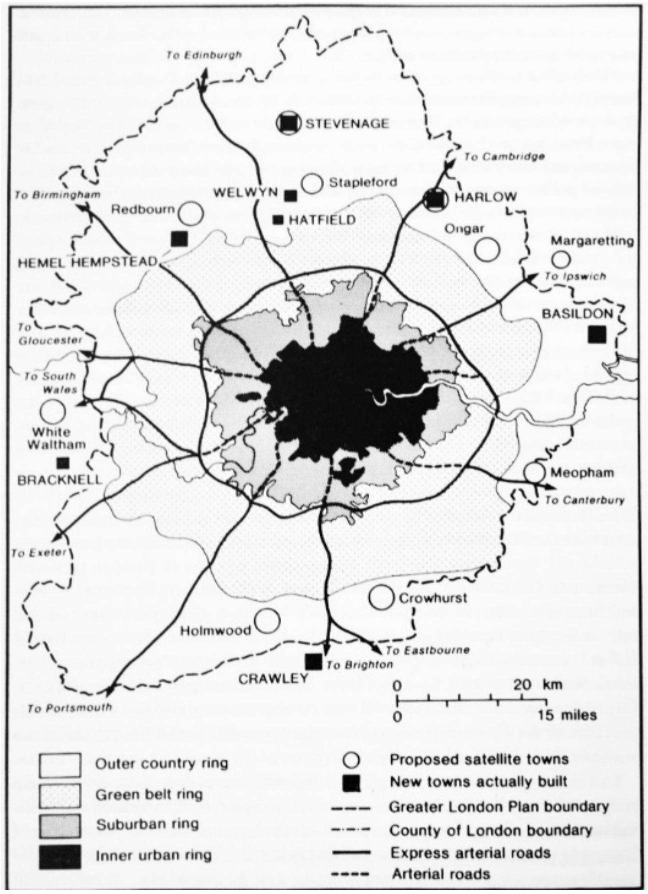


Figure 2-1 Greenbelt, proposed new towns and built-up new towns. Source: PORTER 1998, P.350

2.1.2 Static land use control versus adaptive planning policy

As a large scale urban land use policy, the greenbelt is likely to have an enduring effect in the future. A static and strict greenbelt policy reflects a government's credibility and is easy to implement by administrative power. For example, London's greenbelt has retained its shape since the policy was first launched in the 1930s.

However, critics pointed out that the greenbelt, as a static land use control tool, might be too rigid and have disadvantages in adapting to further urban development. As early as the 1970s, a British planner and developer Warren-Evans (1974) criticised that the greenbelt policy represents a view of the world which has no future and ought to have had no past. He commented on greenbelts as an antiquated planning idea from the 1930s and focused too much on land physical state. Rydin and Myerson (1989) cast doubt on how greenbelts can cope with urban change and conclude that a blanket restriction on urban growth is not an adequate response to this problem.

Development pressure and demographic structure vary over time. If a rigid greenbelt fails to work with such changes, it might limit land supply needlessly. When housing demand increases as population grows or family size shrinks, land scarcity leads to inappropriate escalation in housing costs and unwarranted increases in density (Brueckner 2001). The urban fringe land is normally where new development happens. The greenbelt, at the urban fringe, has been actively preventing houses from being built where they are most needed or most wanted (Cheshire 2014). For example, without its greenbelt, Seoul’s floorspace rent would have declined up to 13.7%, thereby indicating that Seoul’s greenbelt made a contribution to raising rents by limiting land supply (Jun 2011).

Therefore, though policy implementation should be strict, the “greenbelt” should be an elastic term, having quite diverse meanings across time and space in response to perceived needs and challenges (Freestone 2002, p.97). Hong Kong’s practice proved that the greenbelt is a transitional zone for potential future development rather than a zone for conservation (Tang et al. 2007). Many planners regard Melbourne’s green-wedges and greenbelt as a ‘holding zone’ for urban development to be released when needed (Buxton & Goodman 2003). In the US, the urban growth boundary in Portland allows sufficient land provided within the boundary to accommodate growth needs for 20 years (Buxton & Goodman 2003).

2.1.3 The economic loss versus the myth for social and environmental benefits

There is a common belief that greenbelts are open green land with environmental and social benefits. They provide city or town residents a chance to get close to nature. Of course, parts of the greenbelts are real environmental and amenity treasures. However, studies have revealed that the ecological and amenity value of wasteland inside the city can often be higher than the farmland and golf courses preserved by the greenbelt (Amati & Yokohari 2006). In England at least, most of the greenbelt land is privately owned and 60% is intensively farmed (which generates more environmental costs) with limited rights of access and thus have no amenity value at all (Cheshire 2013; The Economist 2012).

After being established for 50 years, research has indicated that half of the visitors to London’s greenbelt recreation sites live locally within the greenbelt and nearly 75% live within 6 miles, with only 5% coming from the inner cities (Rydin & Myerson 1989, p.473). Even now people intend to use parks near home for recreational purpose rather than drive to the greenbelt. It is noteworthy that a large piece of green land at the urban fringe does not offer the best amenity value and the best use of green spaces.

Meanwhile, instead of correcting the problems caused by excessive urban expansion, the greenbelt may lead to an economic loss. The housing crisis in London is one example and the greenbelt is believed to have contributed to it (Hilber & Vermeulen 2012). Long distance commuting is another economic loss which leads to further environmental loss: development often jumps greenbelts, meaning commuters must travel farther to work, emitting more pollution as they do so (The Economist 2012). As announced by the president of Royal Town Planning Institute, we need to look at the greenbelt beyond their recreational and aesthetic appeal, and assess how they can help to shape urban change in the most equitable way (Edgar 2016).

2.1.4 Urban fringe rings versus other configurations

A ring of green land at the urban fringe may not be the best configuration to realise the social and environmental benefits as per the purposes originally stated in the greenbelt policy. It is not the best configuration to offer economic benefits either.

First of all, the belt shape itself is hard to justify (Amati & Yokohari 2006) and the ring-shaped greenbelt at the urban fringe does not offer equal accessibility to the residents. Surveys at greenbelt recreation attractions suggest that 95% of visitors travel by car, and high proportions are in the managerial and supervisory socio-economic groups. This problem is most notable around London where travel times and distance to the greenbelt are greatest, and cost highest (Elson 1986, p.202). Although green spaces in the city involve higher opportunity costs, as they require land in areas where it is most valuable, they can benefit more residents.

Secondly, a wide and large greenbelt may not be necessary. The size of city parks has been proved to have positive effects in increasing an urban green spaces' marginal value: the value of the ecosystem services that parks in cities provide is likely to be disproportionately high. Nevertheless, for green spaces at the urban fringe, size plays a less important role (Perino et al. 2014). It indicates that a wider greenbelt occupying a larger area does not necessarily provide a better amenity value.

Combining the discussions on the shape, location and size of greenbelts, new configurations have been proposed to offer better accessibility, recreational and ecological value. These configurations also aim to mitigate the economic losses from ring-shaped greenbelts and to adapt to strong forthcoming growth. For example, London has proposed Metropolitan Open Land (Greater London Authority 2008) including strategic gaps and countryside buffer zones as alternatives. New forms may deal with urban expansion better due to their flexibility, as they are subject to review each time a development plan is revised (Natural England & Campaign to Protect Rural England 2010, p.19). These new patterns have lower control power than greenbelt and they are welcomed because of their flexibility.

Green-wedges are proposed as an alternative to greenbelts in various plans. The hypothetical Uxcester Garden City plan, which won the Wolfson Economics Prize, argued that the best way to plan a new development on to the rootstock of existing cities is to take confident bites out of the greenbelt (Moore 2014). The plan proposed a snowflake spatial structure of the city. New developments radiate from the city centre, leaving green spaces between them (Rudlin & Falk 2014).

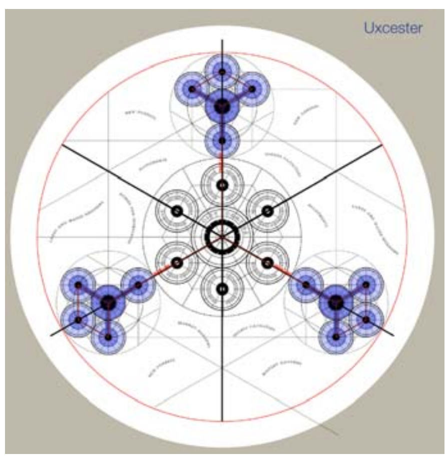


Figure 2-2 The snowflake structure of Uxcester Garden City. Source: Rudlin & Falk 2014

Green-wedges are distinctive features in Copenhagen's Finger Plan. There are five fingers, or corridors, of urban development along suburban railway lines from the centre. Each planned suburb is linked to the next one and onto Copenhagen's Central Business District (Knowles 2012). The five fingers allow new construction to happen to alleviate urban expansion pressure and provide better accessibility. Green-wedges are kept for farmland and recreational land between each built-up finger and also stretched into the urban core to maximise its accessibility.

Figure 2-3 Copenhagen finger plan. Source: Knowles 2012

The Green Swap idea was proposed in the Cambridge Futures research (Cambridge Futures 2000; Cambridge Futures 2004) in order to meet the future economic growth, and to provide enough housing. Buildings would be allowed within designated areas of the greenbelt. Developers would then be required to provide new public green areas outside the greenbelt to replace those used. This plan aimed to offer close connection between jobs and households and to achieve net increase in the public green facilities. The recent North-west Cambridge Development project has followed such a plan, and already established a built-up wedge in the greenbelt, following the Green Swap proposal in the Cambridge Futures.

Figure 2-4 Proposed Green Swap plan showing Cambridge greenbelt before and after development
Source: Cambridge futures 2000; Cambridge futures 2004

The joint Green Heart-City Ring concept has been central to Dutch planning doctrine for years (Van Eeten & Roe 2000; Kühn 2003). The four major Dutch cities: Amsterdam, Rotterdam, The Hague and Utrecht are separated by a large green area in-between which is the so called "Green Heart". Instead of a greenbelt encircling the cities, the four cities encircle the green heart. This is called the Randstad City Ring. Further development can only happen alongside the Ring, not in the green heart.

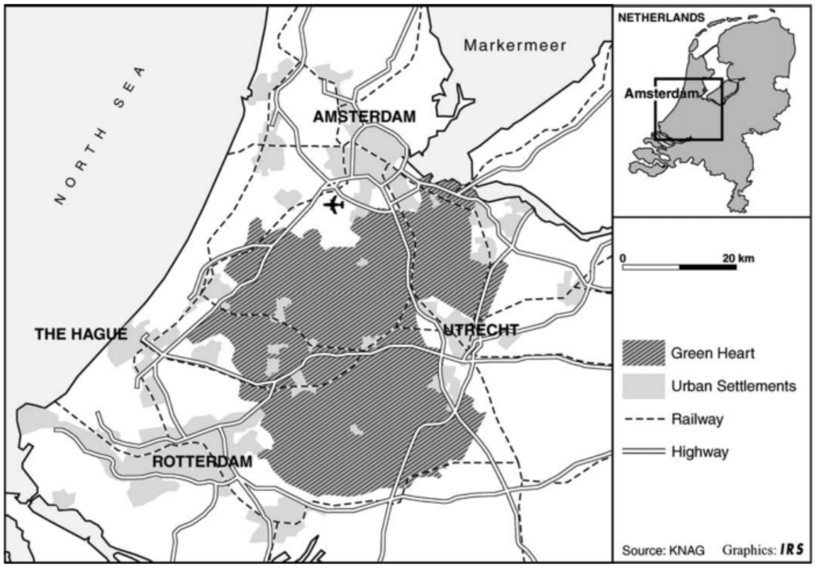


Figure 2-5 The Netherland green heart plan. Source: KÜHN 2003

To sum up, greenbelts are proposed to check the unwanted urban expansion, but they may not always be an effective planning tool. A greenbelt may lead to the increase of housing price and commuting costs, and the potential of bringing environmental and social benefits are also questionable. The ongoing discussions of the greenbelt point out that a successfully implemented greenbelt should act as a guide for future development together with land use and transport integrated policies. As a large scale urban land use policy, a greenbelt designation should avoid myopic development incentive but concern longer term effects and adapt to development pressure and demographic change. Besides the ring shape, other configurations for example the green-wedges and green heart have been proposed to work with transport network and accommodate future growth.

2.2 London's greenbelt: ideas and reality 1890 - 2016

As the capital of one of the largest empires in history in the 19th and early the 20th century, London is the first city that proposed and implemented a greenbelt, and also is one of the most successful cities that has a well-established greenbelt today. It provides the first and archetypal case to handle the overgrowth of a metropolitan area (Hall 1984, p.433).

2.2.1 Expansion of London 1890s-1940s

2.2.1.1 Urban expansion with population increase

Before 1890, Victorian London's growth was essentially within inner London at a relatively high density. From the late Victorian time, development began to spread radically into outer London. From 1890 to 1940, London saw an aggressive population growth of 54%, most of which was in the modern day outer London boroughs. Inner London first experienced an increase from 1891 till the year 1911 when it arrived its peak; after 1911 till 1941, population declined. During the same period, outer London's population went up and the net population increase of outer London was 229%.

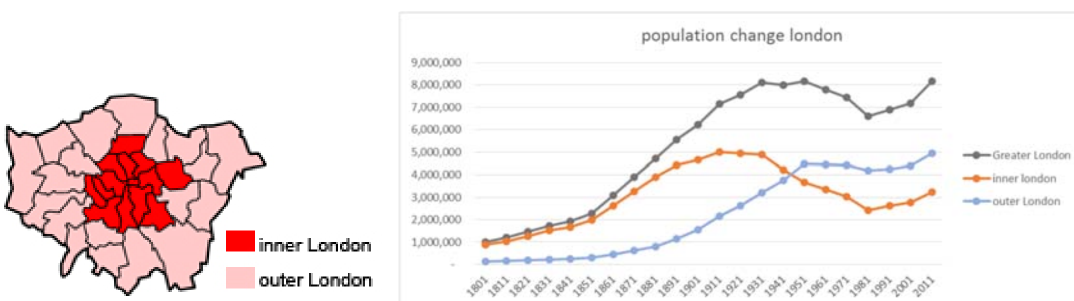


Figure 2-6 Left: Definition of outer London and inner London. Right: Population change 1801-2011 Source: Census of Population GB Historical GIS / University of Portsmouth, Inner London through time | Population Statistics | Total Population, A Vision of Britain through Time. URL: http://www.visionofbritain.org.uk/unit/10076845/cube/TOT_POP Date accessed: 07th January 2015

Year	1891	1941	Change	Percentage change
Inner London	4,422,340	4,224,135	-198,205	-4%
Outer London	1,143,516	3,763,801	2,620,285	229%
Greater London	5,565,856	7,987,936	2,422,080	44%

Table 2-1 Population change 1801-2011. Source: Census of Population. Unit: person

As central London became slums, deemed barely fit for human habitation, people began to move outwards (Hall 2002, p.14). First, suburban life became attractive to the middle class. The new suburbs developed before the First World War were predominantly residential in character, containing few industrial establishments. This befitted their status as dwelling places for London's more senior clerks and executives (Garside 1984, p.238). Secondly, a little lower down social group, for example middle managers, supervisors, and better-paid clerks also move to the fringe. Suburban houses offered more attractive and more sanitary alternatives to the inner area property, together with the opportunity, always eagerly grasped by this group, of improving social status (Jackson 1973, p.22). Thirdly, working class also moved to the fringe area for cheaper housing, as in the central districts of London, commercial and administrative expansion forced out residential rents to rise.

The population relocated to suburbs with the outwards movement of industries and job opportunities. Development of new industries, for instance aircraft, electrical, motor vehicles and films, required larger plots to expand and lower rent. New industries located to outer suburbs and those with growth potential tended to agglomerate. They expanded swiftly to meet the market demand.

2.2.1.2 Transport cost decreased by technology improvement

London's expansion has always been led by transport development. Electrification throughout the London railway system quickened journey to the distant suburbs, which reduced the generalised cost of travel. Better transportation resulted in rehousing to the outer suburbs along tram lines and undergrounds. From 1900 to 1940, the total length of underground increased by 146% (Stanilov & Jin 2013). Between 1902 and 1928 there was a 352% rise in the number of passengers carried by public transport (Porter 1998, p.327).

Road construction also triggered population to settle in London's suburbs and gave superb transportation routes for industries. The flexibility of motor transport lessened the importance of a central location, and made possible the building of factories and warehouses along the arterial roads with no specific focal point (Garside 1984, p.246). From 1900 to 1940, total road length increased by 62% in the Greater London (Stanilov & Jin 2013).

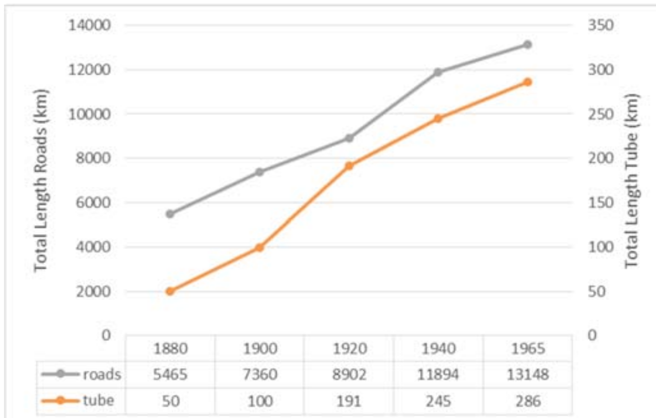


Figure 2-7 Total length of underground and road in Greater London
Source: STANILOV & JIN 2013. Unit: kilometre

2.2.2 Problems of urban expansion

With such a rapid expansion period till 1939, the start of the Second World War, traffic became stalled and urban expansion became offensive (Porter 1998, p.355). Overcrowding in central London was not relieved by the outwards motion of population, because commercial, administration, professional services, specialized shops, and colleges still concentrated in the central area. Inner London experienced a decay as the result of urban expansion. Working-class jobs were taken by new unskilled immigrants. Meanwhile, suburbs spread outwards and occupied a massive amount of land: From 1918 to 1939, within these twenty years, the suburbs spread over the vast belt between six and fifteen miles from central London, multiplying the area of London about four times (Hall 1963, p.28).

Commuting also became a problem although the transport system developed at fast speed. The ever-increasing burden of traffic along the main radial roads caused severe congestion. The action of simply widening the road failed to deliver solutions to the problems.

2.2.3 Greenbelt policies to deal with urban expansion

As problems intensified, Londoners began to realise that actions should be taken to deal with London's mess and muddle caused by this unseemly urban expansion. As Barlow said, employment in London would continue to grow unless the government restricted it. And the government should restrict it, because of the supposed disadvantages – social, economic, and strategic – which this growth brought in train (Hall 1963, p.46).

At the end of 19th century, Ebenezer Howard's Garden City concept provided a fundamental 'planned decentralisation' solution to overcrowding. He proposed a new 'cellular social city' form to solve the problems that industrialised cities had, including congestion, bad residential condition and defective sanitation. The Greenbelt was realised as a feature in this new social city form. The cellular cities were surrounded by narrow greenbelts so that they would not grow beyond the maximum size (Howard 1902).

Inspired by Garden City idea, Unwin, as the technical advisor of the Greater London Regional Planning Committee, argued that there was an urgent need to provide recreational fields within the Greater London Region by acquiring a green girdle (Greater London Regional Planning Committee 1933). In 1935 the official greenbelt loan scheme was announced. By 1939, 110 km^2 had been either purchased, covenanted, or was in the process of being acquired under that scheme (Munton 1983, p.18).

In the Greater London Plan 1944, the greenbelt acted as a barrier to the continuous expansion of London. In the greenbelt ring, there were numerous established centres and they would have strictly limited possibilities of extension. A series of new towns in the outer country ring were for the surplus population(Abercrombie 1945, p.26). As shown in the maps, between 1954 and 1958, the relevant county development plans were approved by the Ministry of Housing and Local Government creating a real greenbelt similar in size to that proposed by Abercrombie (Thomas 1970, p.86). This greenbelt successfully remains till today.

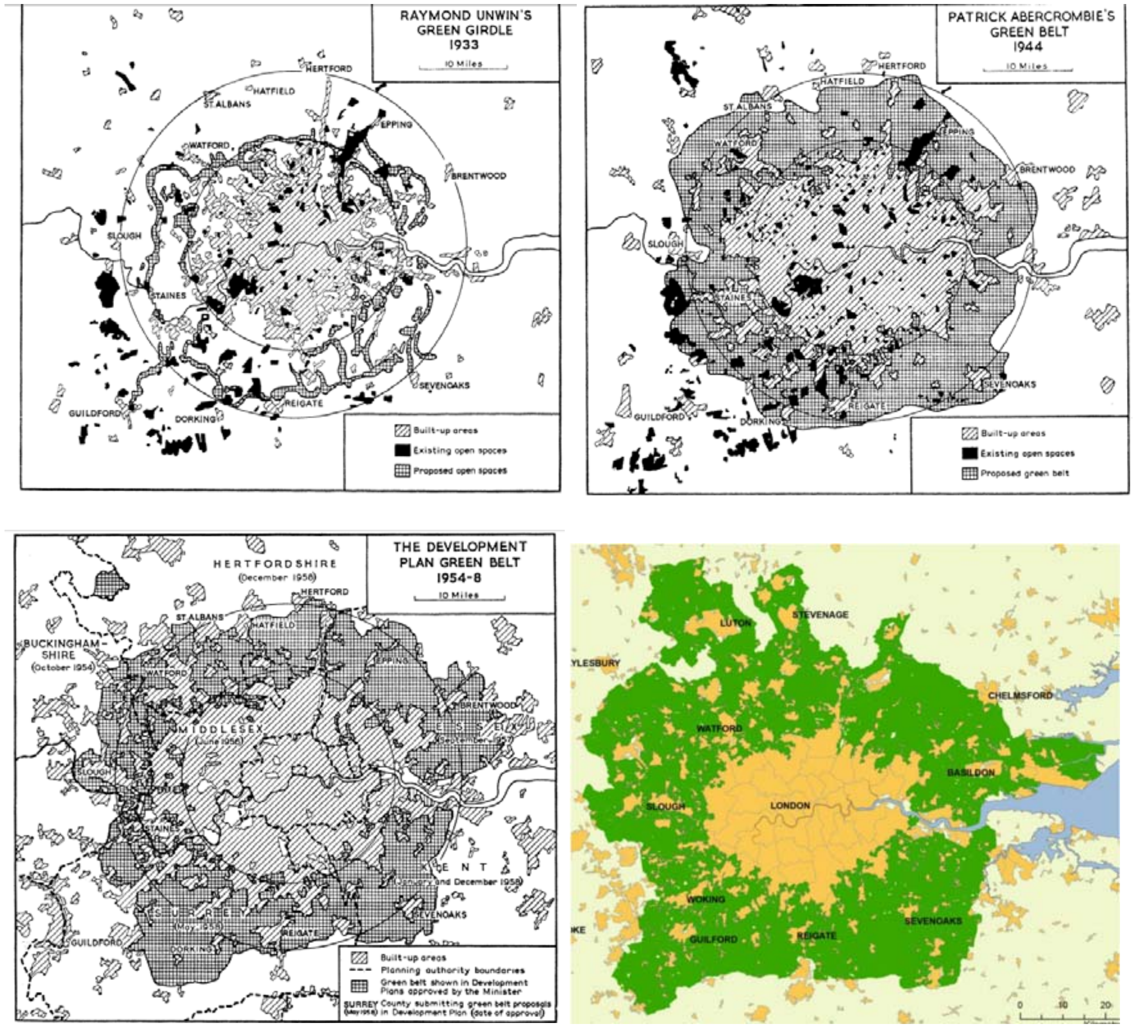


Figure 2-8 London's greenbelt evolution

Upper left: Unwin's green girdle proposal. Source: GREATER LONDON REGIONAL PLANNING COMMITTEE 1933.

Upper right: Abercrombie's greenbelt proposal. Source: ABERCROMBIE 1945, P.FACING 22.

Lower left: the development plan finally approved between 1954 and 1958. Source: MINISTRY OF HOUSING AND LOCAL GOVERNMENT 1955.

Lower right: greenbelt 2010. Source: CAMPAIGN TO PROTECT RURAL ENGLAND 2010.

Since the greenbelt policy was first launched, it had a very clear and preliminary policy aim to check the unrestricted sprawl of the built-up areas and to shape the decentralised urban form. New towns were essential parts in the greenbelt plan to accommodate growth. As Unwin commented: London's development might be planned so that units spring up detached from the main mass of the town, each with a self-contained economic and social life and with the permanent reservation of belts of open space to prevent the units coalescing with one another or with the central mass (Garside 1984, p.252).

After the Second World War, the greenbelt has remained remarkably stringently enforced to coordinate with London's evolution: London's suburbs suddenly stopped, frozen at the point they had reached in 1939. Today, the total area of London/wider South East[1] greenbelts has reached 554,700 hectares (Department for Communities and Local Government 2010).

However, the frozen greenbelt caused unpredicted policy outcomes against objectives in greenbelt policy implementation. The criticisms include: greenbelts increase car travel, divert development deeper into the countryside, increase development pressures within existing centres, they are a negative and inflexible means of development control (Freestone 2002).

2.2.4 Recent debates on London's greenbelt

London's greenbelt is by no means a successful case, judged by its perfect physical form – an encircled ring, which remains for more than 70 years. It is one of the world's most potent planning devices (The Economist 2012). Such a stringent greenbelt can be implemented not only because of London's strong governance power and high political credibility, but also because it was rigorously designed based on the integrated land use-transport development. A full set of policies – greenbelt, new towns, road construction and rail transit – were carried out to decentralise population and employment. The aims are not solely to stop central London's expansion but to tell where new development should go. Meanwhile, its aesthetic value and social value won wide public support. The greenbelt has a higher concentration of woodland, country parks, and reserves than land that is not designated as greenbelts (Natural England & Campaign to Protect Rural England 2010).

However, there are ongoing debates on its economic impacts and there are numerous pleas for breaking it (Moore 2014; Lynch 2015; Hill 2014; Priced Out 2014; Edgar 2016). The battle between those who want to build on the greenbelt and those who support environmental protection and an ideal size of London never stops. Recently, John Longworth the director-

[1] Information is not presented by the standard Government Office Regions. This is because London's greenbelt straddles the London, East of England and South East regional boundaries.

general of the British Chambers of Commerce, after the Conservative party was re-elected in 2015, proposed the possibility of greenbelt land relaxation: "Businesses would rather see the government focus their efforts on freeing up more land for much needed housing, including, where necessary, on the greenbelt." George Osborne, the former chancellor, has even hinted that councils should be more willing to allow building on greenbelt land (The Economist 2012). In the newly published Royal Town Planning Institute policy statement *Where Should We Build New Homes*, planners advocated that the greenbelt should be considered for housing (Edgar 2016). It stated that "New proactive remedial programmes are needed to remove constraints on development and to make places where people want to live which are accessible by sustainable modes of transport." The reasons are obvious: the greenbelt is blamed for the rising housing price and the long commuting time in London (Cheshire 2013; Cheshire 2014; Geoghegan 2014). So in the local authorities' plans in 2016, more than 117,000 homes are planned for London's greenbelt, a 35% increase on the number planned in 2015 (Campaign to Protect Rural England 2016).

Although parts of the greenbelt are planned to be built on, the greenbelt is still considered sacred (though it should not be), as there are many campaigns, even protests, for preserving it. The current debates have brought back the focus on the initial motivation of establishing London's greenbelt. It was to prevent urban sprawl by keeping land permanently open (Department for Communities and Local Government 1995). To put it in another way, it was to solve the problems caused by urban sprawl and promote sustainable development. Therefore, when debating on whether the belt should be broken or preserved, we need to ask what Professor Hall questioned decades ago: how far is the current greenbelt successful in solving the excessive urban expansion problems and promote sustainable development? If the current greenbelt fails to achieve some of the aims, for example to provide affordable housing and to promote eco-friendly commuting, is there a half-way house between greenbelts and no greenbelts? If the greenbelt is to be released, the question is where to be released and how much. A rigorous assessment is required before any further action, in order to ensure that the future development is sustainable, affordable and deliverable in a timely manner. Any alternative should be able to sustain the environmental benefits as well as to improve the economy of Greater London.

2.3 Beijing's greenbelts in transition: 1994 - 2016

Initially, Beijing's spatial planning was affected by the multi-nuclei garden city idea and the new town programmes in Britain (Yang et al. 2011). However, a strong monocentric pattern was established through time. Two proposed greenbelts failed to stop the concentric growth pattern and population was not effectively diverted to new towns. It is valuable to know why similar planning concepts lead to different historic outcomes.

2.3.1 Population growth and movement 1950-2015

In the past 60 years, the population of Beijing has increased at an annual average growth rate of 2.3% (1949-2008). After the Olympic Games in 2008, over the past 5 years, with rapid economic growth, the city accelerated its development. The annual population growth rate in Beijing has reached 3.8% (from 2009 to 2013) and the overall population has reached 21.7 million in 2015 (Beijing Bureau of Statistics 2016).

This development speed is relatively high compared with other mega-cities. Taking European cities as example, from 1890 to 1940, over 50 years the most rapid development, annual growth rate of Greater London reached 0.87% while its competitor Paris reached 0.94%. Beijing, from 1950 to 2000, reached an even higher growth rate of 2.29% over a same time span of 50 years. The total population of Greater London increased by 54%, and Paris by 60%. Compared to the most rapid development period of Beijing, over half a century, total population increased by 210%.

	1890	1940	Annual Growth	Change Rate
Greater London	5,638,000	8,700,000	0.87%	54%
Paris	4,128,000	6,598,000	0.94%	60%
	1950	**2000**	**Annual Growth**	**Change Rate**
Beijing	4,393,000	13,636,000	2.29%	210%

Table 2-2 Population growth of Greater London and Paris1890-1940, Beijing 1950-2000

Source: PORTER 1998, P.306;Beijing Bureau of Statistics & NBS Survey office in Beijing 2009. Unit: person

As shown in Figure 2-10, the registered population in the four inner city districts[2] remained steady with a slight decrease. This was because of the outward movement of local residents and old city demolition and relocation projects. Outer city districts became the most popular location for residents. New industries in these districts for example Central Business District and Science Parks offer job opportunities. Residential blocks and facilities were built along with industrial development which attracted more residents. The near suburb counties in the outskirts also increased in population size gradually with the satellite town movement of Beijing. Most townships served as residential locations and a large amount of housing was built, while there were also some townships such as Daxing and Shunyi, which developed industries such as an airport logistic park and car manufacturers. The far suburb counties grew slowly and mainly served as ecological preservation zones.

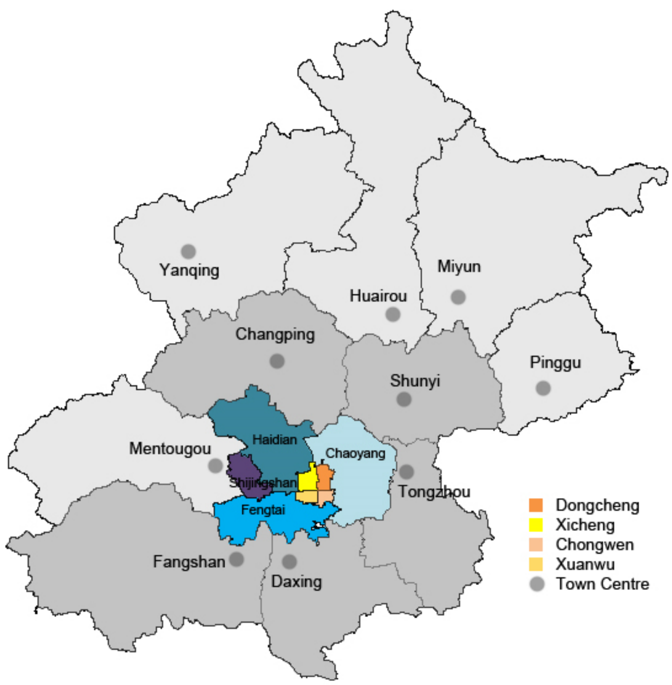


Figure 2-9 Beijing districts map

[2]Here the categories of districts and counties were: inner city districts were Dongcheng, Xicheng, Chongwen, Xuanwu; outer city districts were Fengtai, Chaoyang, Haidian, Shijingshan; near-suburb counties were Fangshan, Tongzhou, Changping, Shunyi, Daxing; far-suburb counties were Mentougou, Pinggu, Huairou, Miyun, and Yanqing.

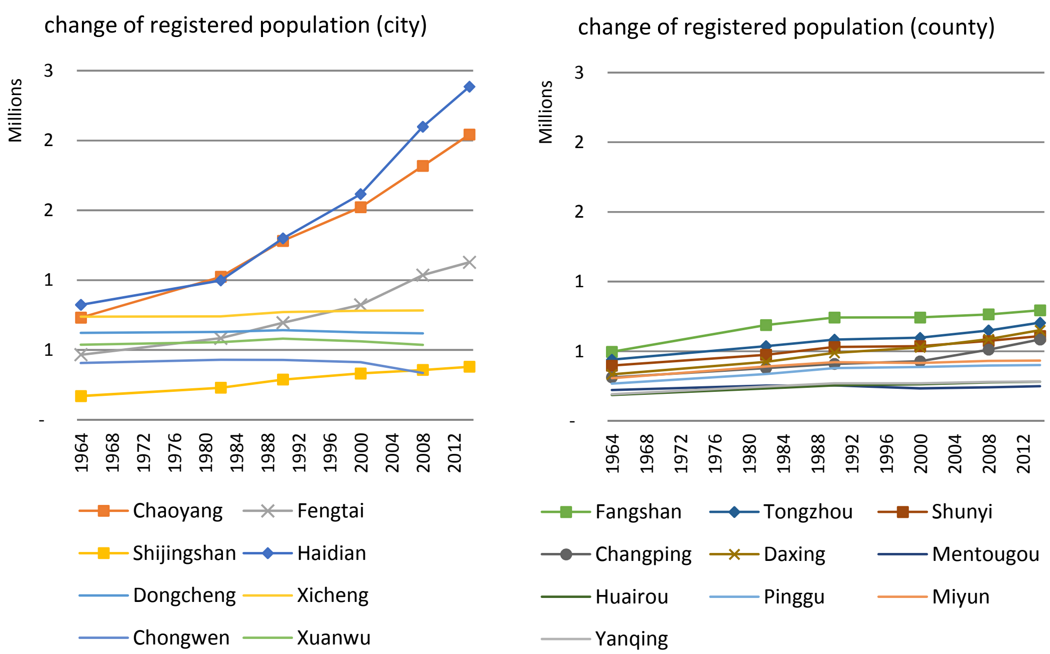


Figure 2-10 Population change in urban districts (left) and surrounding counties (right)

Source: BEIJING BUREAU OF STATISTICS & NBS SURVEY OFFICE IN BEIJING 2009. Unit: person

Moving to the urban fringe is a popular trend pursued by various social-economic groups. First, urban villages in fringe area became a popular choice for low skill migrants, because housing rent is low. There is normally cheap public transport, for example suburb buses, which enhances suburban accessibility and provides migrants a means of relatively cheap transport in addition to bicycles for commuting to jobs in the central city.

Secondly, newly developed Science Parks in Daxing, Haidian and Fengtai provide high profile jobs and also attract high skill migrants to the fringe area. As commented by the deputy mayor of Beijing, it is a urgent task to meet the housing demand of high skill migrants, who seek stable, sanitary and safe housing (Chen 2010). A huge amount of gated neighbourhoods which were close to job centres were developed in the past decade, in order to meet such a demand. The big difference in housing rents between the city and the suburb also pushes high skill migrant workers to live in the fringe area.

Thirdly, as they become richer, local residents in the old central city who sought larger flats and a better environment also purchase properties in the suburbs. The tendency of the middle class to live in the suburbs has been reinforced by transport innovations. It is easy for them to drive or take the underground back to the city centre to work, or meet friends. With the urban demolition and relocation projects of the historical city, low-income indigenous families were also gradually moved to the suburbs.

2.3.2 Concentric expansion of built-up areas

With the suburbanisation trend of population, built-up areas have been expanding rapidly from 100.2 km^2 in 1950 to 1210.2 km^2 in 2005 (Ai et al. 2008) following a concentric pattern of expansion.

Before 1951, the development of Beijing mainly concentrated within the old city wall, which these days is approximately the 2nd ring-road. The municipality had a population of 4.6 million in 1951 (2 million in city and 2.6 million in countryside) (Beijing Bureau of Statistics & NBS Survey office in Beijing 2009) and occupied approximate 100 km^2 of built-up area (Wu 2010). From 1951 to 1983, the city expanded in a concentric manner, in order to exploit new industrial areas and administrative institutions in the suburbs. Independent settlements such as Nanyuan Airport, Shijingshan Town, Haidian Town and Fengtai Town (refer to Figure 2-12) also expanded. From 1983 to 1991, as the main city grew larger, independent settlements in the fringe were absorbed into the main built-up area. Townships outside the 6th ring-road expanded in a concentric manner based on their historic sites. From 1991 to 2000, Beijing accelerated the efforts of old city redevelopment whilst continuing to expand following the monocentric pattern. From 2000 till now, Beijing continued this "pancake" pattern of expansion. The underground system throughout Beijing encouraged long-distance commuting and yet more people resettled in the suburbs. Urban renovation projects in the old city decelerated due to resistance from local residents, lack of funding and an appeal to preserve historical buildings. More development shifted to the suburbs. As the urban fringe moved outwards, townships gradually became popular for both migrants and residents in the city. Figure 2-13 shows the population and built-up area growth from 1951 to 2005.

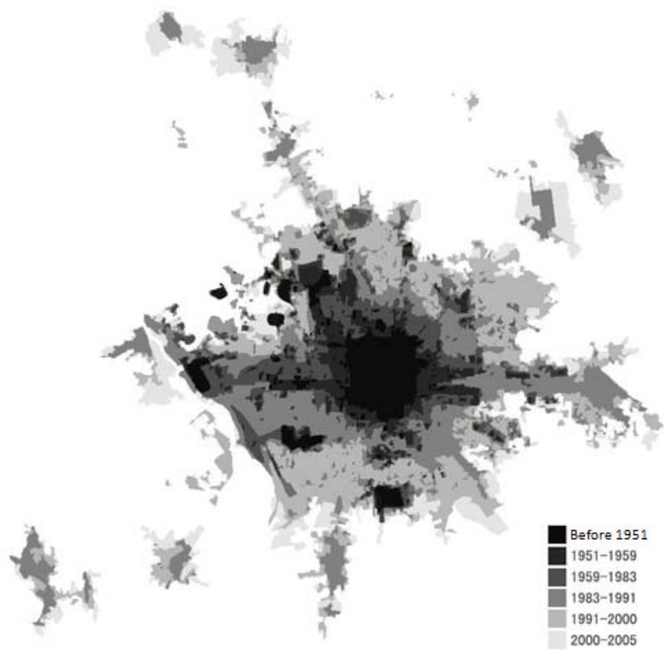


Figure 2-11 Expansion of built-up area of Beijing 1951-2005. Source: WU 2010

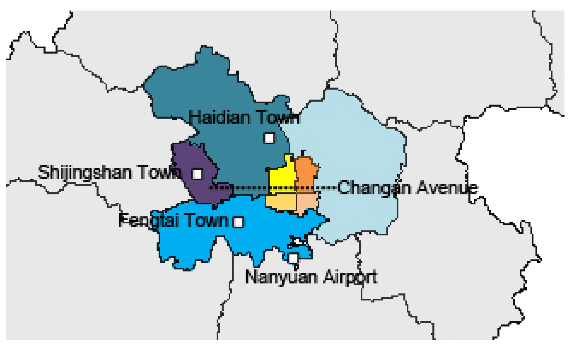


Figure 2-12 Locations of main development sites 1951-1083

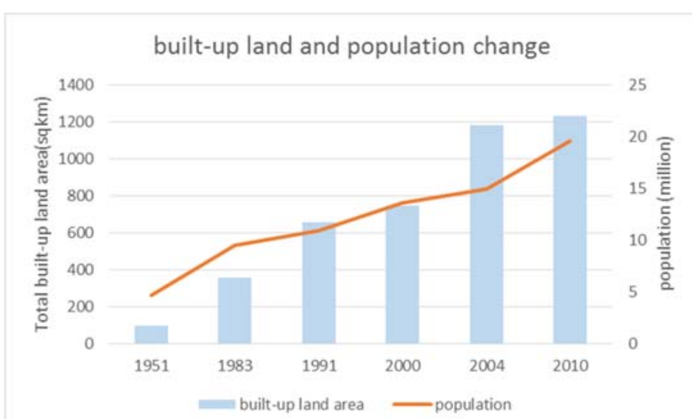


Figure 2-13 Built-up land and population change of Beijing 1951-2005

Source: 1951-1991 built-up area data from Wu 2010, 2000-2010 built-up area data from China Urban Construction Statistical Yearbook 2001, 2005, 2011 (Ministry of Housing and Urban-Rural Development 2001; 2005; 2011a)

2.3.3 Problems of excessive urban expansion

Continuous expansion caused the vanishing of urban open spaces. As the central area spread, some suburban towns became amalgamated to the main urbanised area. Individual suburban villages also began growing very fast and many of them merged into each other. There were once green spaces between such settlements which separated built-up areas, but now they have been filled up as the 'pancake' spreads.

Inner Beijing never became relieved. Administrations and commercial districts still stayed in the centre while finance and banking industries also came in. Workers and customers travelled from the suburb to the centre by underground and caused congestion and long queues during peak hour at underground stations.

Most suburban villages suffered from the dirty, noisy and disorderly living conditions. The high crime rate, which resulted from poor living conditions and a high density of floating population with low income caused severe social problems (Zhang et al. 2014). Although the gated neighbourhoods for the middle class have better sanitary conditions, such housing without facilities such as schools and hospitals makes the fringe area under-provisioned "dorm-towns".

Figure 2-14 Typical suburban residential environment

With the shutdown of many factories in inner Beijing, the remaining factories that would no longer be accepted in the main city moved into the fringe from the 1970s onward, seeking lower rents, space to expand, better communications and lower labour costs. However, they also brought contamination to the suburbs. Out of the 375 contaminating factories listed as "should be shut down factories" in 2014 (Zhang 2014), 273 were in the near suburb counties, most of which were in the foundry industry, electroplating industry, brick and tile manufacture, furniture manufacture, and printing and dyeing industry.

While construction spread into the fringe, most job opportunities remained in the central city. Data from the 2000 statistical yearbook show that the 8 city districts had a population of 6.6 million and provided 3.6 million jobs. The counties had a population of 4.4 million but only 0.8 million jobs. Separation of jobs and housing caused long commuting times. New town residents spent 95 minutes on average on commuting. Congestion is commonly found on main ring-roads and radial roads. In 2010, 135 km of roads within Beijing's 6th ring-road were ranked as congested in the morning peak, and 250 km in the evening peak. Compared to 2009, the length of congested roads increased by 18% in the morning peak within one year (Beijing Transportation Research Centre 2012).

2.3.4 Greenbelt policies to deal with urban expansion

The multi-nuclei decentralisation idea to mitigate urban expansion problems is not new in Beijing. The first Beijing Master Plan of 1958 proposed to limit the growth of the central city and relocate industries into the suburbs. Green spaces were embedded in the city to separate residential and industrial districts. This plan was not applied due to the Cultural Revolution, during which construction spread arbitrarily without a clearly defined spatial plan. In the Beijing Master Plan of 1982, the idea to "separate built-up patches" was reinforced. However, the development inertia cannot be deterred by one plan. The Beijing Master Plan of 1991 emphasised the decentralisation concept and proposed the satellite town development plan. There were several pilot projects to establish the use of greenfield as segregations; however the outcomes were not satisfactory and buildings without permits corroded the greenfield land. The Beijing Master Plan of 2004-2020 introduced a poly-centric urban structure to stop urban expansion. However, this pancake-like expansion has not shown any signs of abating. In order to tackle the expansion pattern, two successive greenbelt policies have been put forward with the Master Plan of 1991 and the Master Plan of 2004-2020 (Beijing Municipal Government 1994; Beijing Municipal Government 2003b).

The first greenbelt policy was introduced in 1994 as an integral part of the decentralisation concept from the Beijing Master Plan of 1991. 240 km^2 of green areas around the 4th ring-road of Beijing were designated as the First Beijing Greenbelt (1994_No.7 policy). The aims were to stop the central city expansion and separate built-up settlements, to improve living conditions for the farmers in the urban-rural fringe which were currently dirty, noisy and disorderly (Beijing Municipal Government 1994). The long-term goal was that by the end of 20th century, 35% of the total area of Beijing would be "greened". Recreational facilities were allowed to be built in the greenbelt but the only 2-3% of the land could be used for construction.

The nature of 1994_No7 policy was a negative stopper. First of all, the decentralisation strategy and new town ideas were proposed in the Beijing Master Plan of 1991 but the greenbelt policy of 1994 did not cooperate to accommodate the over-spilled population. The two plans were isolated. Secondly, if we look at the 1994_No7 policy itself, it stated the function of the greenbelt was as an antidote to urban expansion and it also identified settlements beyond the greenbelt as the local farmers' new place of residence. However, it did not clarify where the development pressure from the central city should be shifted to. The 2000_No12 greenbelt policy, as a supplementary to 1994_No7 policy, shifted policy aims to: bettering the environment and enriching life for farmers in the greenbelt. The following supplementary 2000_No20 greenbelt policy even allowed for commercial housing to be built in the greenbelt to balance upfront investment. Nothing about the poly-centric pattern was mentioned.

From the perspective of urban containment, the first greenbelt is a failure: the urban expansion spread across it. The total built-up area within the designated first greenbelt increased from 33.3% in 1993 to 49% in 2005, with a corresponding decrease in the green area from 66.7% to 44.3% (Han & Long 2010). In the later version Master Plan of 2004-2020, the government still stuck with the original first greenbelt idea and set the target population in the belt as only 400,000, but population in this area has exceeded the limit by 8 fold and reached 3,300,000 in 2010 (Rong 2016). Data in 2015 show that the actual greenfield left in the first greenbelt is even less than 11% (Wang 2015).

The Second Beijing Greenbelt was introduced in 2003 and emphasised in the Beijing Master Plan of 2004-2020 and the Beijing Main Functional Areas Plan 2012, with a designation of 1650 km^2 of green area between the 5^{th} and 6^{th} ring-roads. The primary aim was to limit the successive wave of urban expansion and to shape the poly-centric urban structure. Satellite towns were mentioned in this version's greenbelt as the main area where dislocated population should go. The long-term aim is that in 2020, 50% of this area will be covered by vegetation.

From the perspective of urban containment, the second greenbelt is more close to the nature of London's greenbelt. It is a relatively positive guide. However, in the implementation guideline (2003_No.15 policy), only the ecological matters are emphasised. This guideline mainly explained how to achieve the target area of green space and the market mechanism to fund vegetation planting.

The second greenbelt policy had some positive effects as the total green area increased from 366 km^2 to 566 km^2 from 2001 to 2008 (Gan 2012). However, this number was still far from the policy aim, and it was lower than the original total green area in the 1990s, which was 757 km^2.

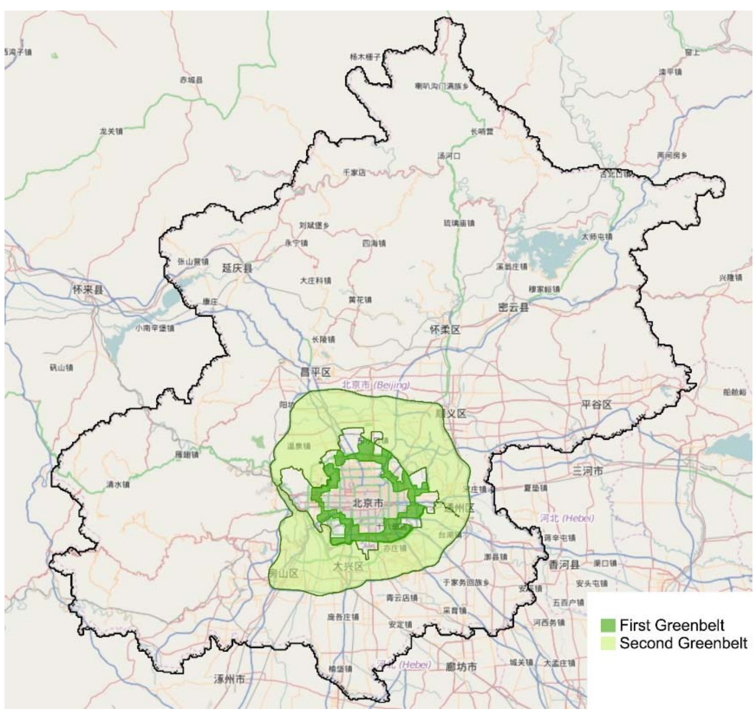


Figure 2-15 Greenbelt boundaries

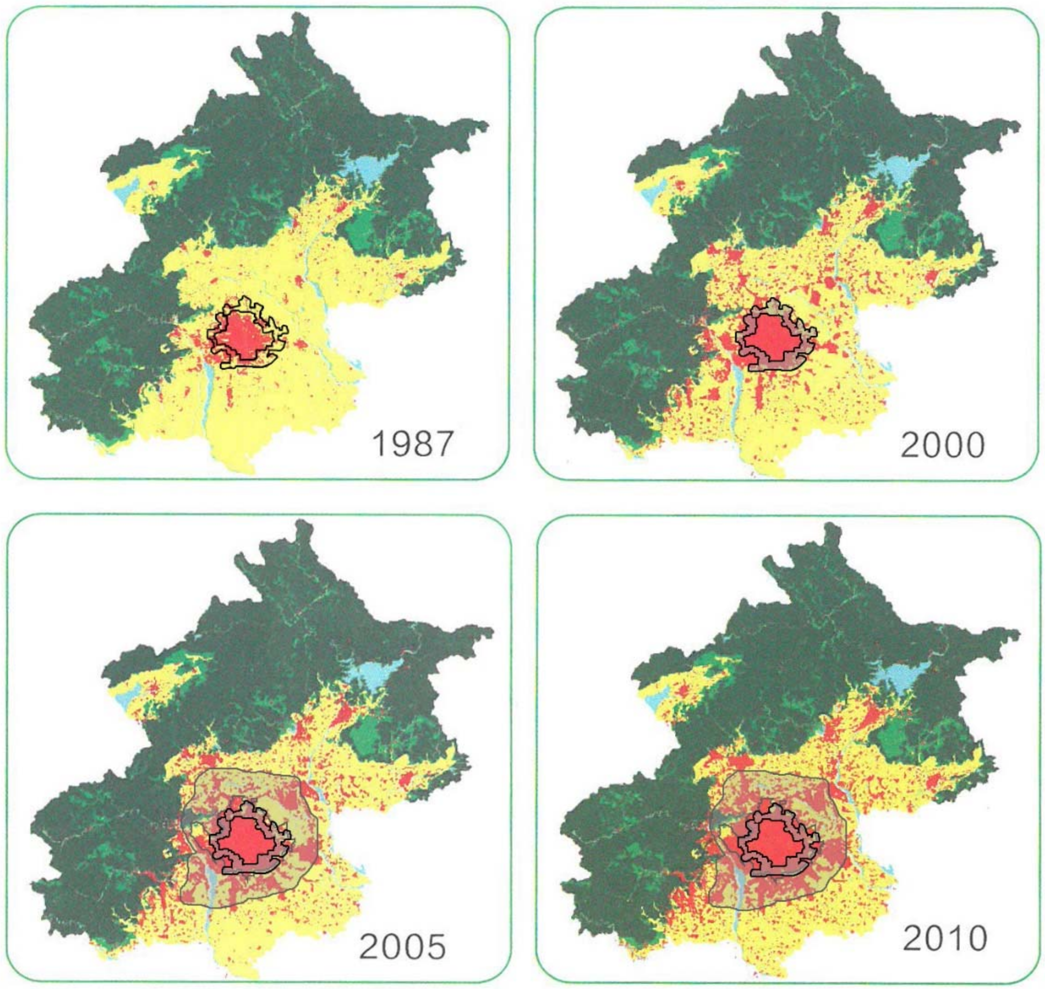


Figure 2-16 Urban land use change before and after greenbelt policies

2.3.5 New green space configuration

The Beijing Master Plan of 2004-2020 is under revision and Beijing is considering to accommodate growth in a new way. The Beijing Sub-centre Plan has been recently approved by the government (Central Political Bureau of China 2015). This sub-centre is being built in the eastern part of the originally designated greenbelt, which will break the belt into wedges. Different from the previous new town plans, this new sub-centre – Tongzhou - will not function merely as a support for the main city, but as a self-contained city with various industries. This new centre should grow to a similar size (48 km^2) as the Beijing old city (64 km^2) in next 10 years. This plan is considered as a good opportunity to introduce new spatial form into Beijing.

Moreover, Beijing has also proposed green-wedges and patches to form a coherent ecosystem (Beijing Urban Planning and Design Institute 2007). The ecological functions of the wedges have been emphasised, but the green-wedges have not been combined with the entire greenbelt and urban land use - transport structure.

To sum up, Beijing's expansion originated from population aggregation and economic buoyance. Although the poly-centric pattern has been mentioned several times in master plans and the ecological benefits of greenbelts are widely agreed upon by the public, the "greenbelt-satellite new town" pattern has not been well formed. In implementation, the main focus of greenbelt is not to stop urban expansion and shift new development to new towns, but to urbanise the fringe area, plant trees and relocate farmers. Such efforts are of course crucial, but with such a nature, the greenbelt policy must be a failure, assessed from the perspective of effectively stopping urban expansion and providing public open spaces.

2.4 Greenbelts in other countries

2.4.1 The failure of Tokyo's greenbelt

After the Second World War, Tokyo experienced an explosive growth. The population of the Tokyo region (including Tokyo and 3 surrounding prefectures, Kanagawa, Saitama and Chiba) grew from 13 million in 1950 to 35 million in 2010. This growth speed is relatively high even compared to other fast growing Asian cities (refer to Figure 2-17). Built-up areas expanded from the centre of Tokyo city following a concentric pattern as well as along main transport links and the Bay of Tokyo (refer to Figure 2-18).

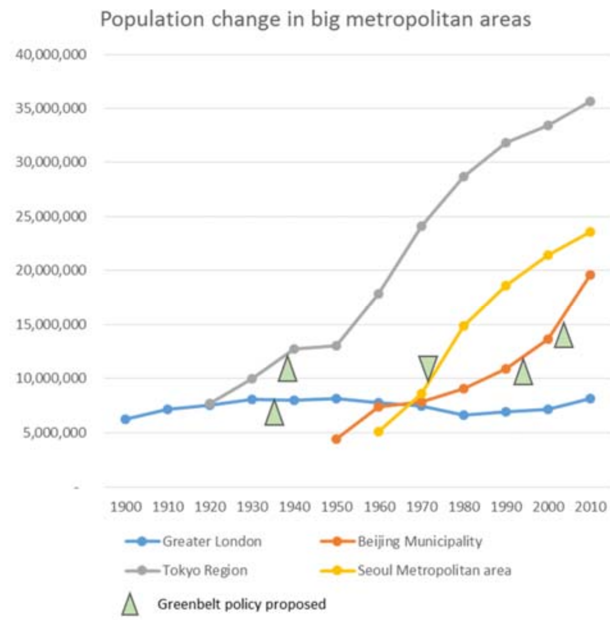


Figure 2-17 Population change over time and greenbelt policy proposed time

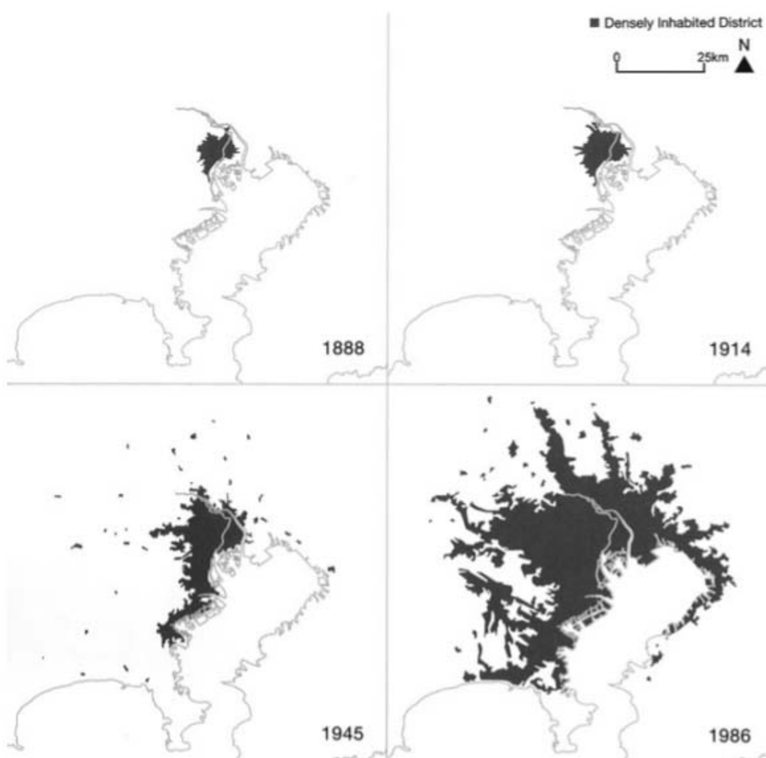


Figure 2-18 Expansion of built up areas in Tokyo. Source: OKATA & MURAYAMA 2011

As one of the biggest megacities in the world, overcrowded train systems, poor but costly housing, and environmental problems were commonly found. In 1939, Tokyo installed a comprehensive parks and open space master plan (refer to Figure 2-19 left) and this plan included a greenbelt on the boundary of central Tokyo (Yokohari et al. 2000). This version then evolved into a double-layer greenbelt in the Air Defence Belt Plan of 1941 (refer to Figure 2-19 right): the greenbelt around central Tokyo extended inward to the city and also outward to the outskirt. The greenbelt was mainly for military purposes. After the Second World War, the Ad Hoc City Planning Act 1946 proposed a greenbelt to prevent the coalescence of towns and check the outward growth of towns. However, in practice, a number of projects were permitted within the designated greenbelt area, including shrines, hospitals and agricultural housing. The government were seeking agglomeration economies by concentrating development in Tokyo in the 1940s (Amati 2005). Although there were several subsequent policies (National Capital Sphere Redevelopment Act 1956 (see Figure 2-20), City Planning Act 1968, Productive Open Spaces Act 1973) to support greenbelt, there was never a real greenbelt established in Tokyo, apart from some green girdles as parks.

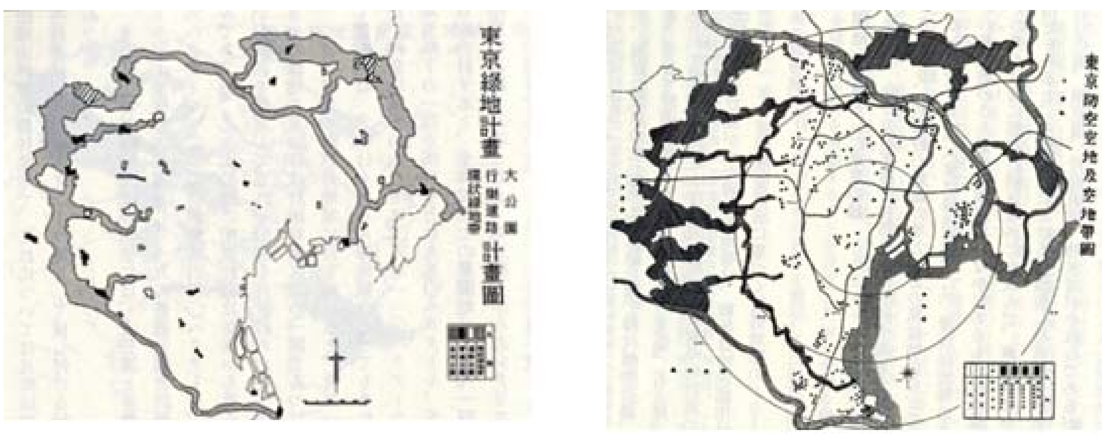


Figure 2-19 Left: Tokyo's 1939 greenbelt plan. Right: Tokyo's greenbelt implemented through the air-defence plan in 1943. Source: AMATI 2005

Figure 2-20 The 1956 National Capital Sphere Redevelopment Act 1956. Source: WATANABE ET AL. 2008

There were many reasons that lead to the failure of Tokyo's greenbelt. Institutional reasons, for example, private landownership and lack of governmental support, were of course partly liable for the failure. In this research, we focus on the land use-transport pattern to interpret the failure of greenbelt implementation. We argue that a well-designed land use-transport pattern is able to make the implementation easier and obtain support from landowners. There are 3 possible reasons from such a perspective to explain the failure.

Reason 1: Dormitory new towns were unable to stop central area expansion

The initial idea of Tokyo's greenbelt was greatly influenced by the 1924 Amsterdam International City Planning Conference. At that time, the Japanese representatives defined seven principles that were subsequently highly influential on planning in Japan. The first three principles were: 1) the never-ending growth of cities should be stopped; 2) the urban population should be redistributed using satellite cities; 3) town areas should be surrounded with greenbelts (Amati 2005).

However, unlike British new towns which are self-contained and have local employments, Japanese New Towns are mainly suburban dormitory settlements (Tanabe 1978). New towns in the 1960s were built to meet the urgent demand for housing from Tokyo. For example, Tama, one of the biggest new towns of Tokyo, had no industrial area and few service jobs. It did not provide residents a chance to work locally and did not attract population from outside the town. Most jobs were still concentrated in central Tokyo and the central government sought agglomeration economies by adding more industrial development in Tokyo. Although the number of residents in central Tokyo decreased, the number of workers in Tokyo increased in the 1960s (Tanabe 1978). Central Tokyo was never released due to the development of new towns in the 1960s. As it expanded in a concentric manner, pushing the urban fringe outwards, a ring shaped greenbelt was never established.

Reason 2: Unplanned railway development did not cooperate with the greenbelt plan

Tokyo's urban expansion was largely led by railway construction which were popular in the 1920s. The rapid suburbanisation started without being controlled by a strong urban land use plan. The big earthquake in 1923 accelerated the suburban development (Okata & Murayama 2011). Private railway companies purchased huge areas of land in the suburbs and developed housing. They used the money from housing development to fund railway construction. Public corporations also developed massive housing estates, eg. Tama New Town, along railway lines, in order to solve the housing problem in Tokyo. Individual landowners had a clear incentive to develop their land and let out their property, because of the high urbanisation pressure at the time. Railway development ignored the greenbelt boundary and opened stations with high density construction. Medium to low density housing spread from stations concentrically. The railways made commuting easier and attracted more housing development in the suburb, but left jobs in the city centre.

Reason 3: The role and timing of Tokyo's greenbelt in master planning

In Tokyo, after the Second World War, urban growth issues had not been considered explicitly in relation to environmental issues or sustainability issues. Although the existing green infrastructure was enhanced and improved, there was no explicit policy to re-organise or redesign the existing urban form or land use pattern in order to enhance the sustainability of Tokyo (Okata & Murayama 2011). In such a context, Tokyo's greenbelt was solely considered as a green space, or an open space for military purposes. It was neither part of the master plan nor the new town development plan. The greenbelt was not considered as a large scale urban containment policy which would have long term impacts on the entire city.

Meanwhile, wrong policy timing caused inefficiency. An effective greenbelt was supposed to have been implemented before development reached the designated greenbelt boundary and give enough development buffer to land demand in the future. However, because Tokyo's greenbelt was simply taken as a green space, it was carried out over the most rapid development era – when Tokyo was recovering from the War. It did not consider leaving land for future development. Therefore, neither private landowners nor developers supported it.

2.4.2 The relaxations of Seoul's greenbelt

Seoul's has the second oldest greenbelt in the world (Bae & Jun 2003). Although there were appeals of stopping urban expansion by a greenbelt back to the 1930s, it was not taken seriously until rapid urban expansion started in the 1960s. Then the greenbelt proposal was considered seriously and established in the early 1970s with a total area of 1567km, 29% of the National Capital Region as shown in Figure 2-21 (Kim & Kim 2008). Seoul's greenbelt was successful due to strong legal controls and martial power. The impetus to the greenbelt was personal intervention by President Park (Jun & Bae 2000). Debate and objections were not allowed to interfere with this decision (Bengston & Youn 2006).

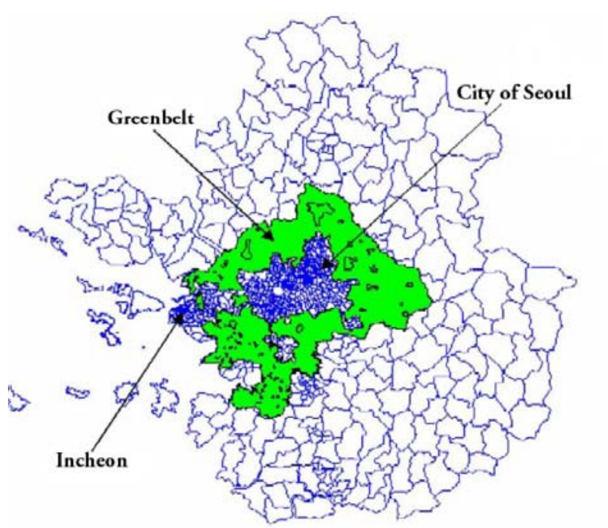


Figure 2-21 Seoul's greenbelt Source: Bengston & Youn 2006

This strict greenbelt is now facing several challenges. Although it succeeded in controlling urban expansion, it caused a housing shortage and deprived landowner's right for future development. People living in the greenbelt have negative opinions on the development restriction policy. It also resulted in an expansion of satellite towns just beyond the outer greenbelt boundary. The increasing democratisation from landowners led the Korean government to think how to release land from the greenbelt area for development – which piece of land should be selected to be taken out of the greenbelt?

In 1998, National Committee for Green Belt Policy Reform published a report on how to release and reform greenbelt land. Boundaries were redrawn based on environmental assessments, such as topography, land suitability, ecological sensitivity, and environmental vulnerability (Bengston & Youn 2006). Each factor was assigned a weight and a score. Geographical rules were applied when calculating the environmental values and making the decision of which piece of land could be released. Some local landowners regained the development right if their land was small and not environmentally sensitive; others whose land was still designated as greenbelt were compensated. However, decisions of releasing the greenbelt simply based on the analysis from Geographic Information System (GIS) was criticised for being too naive (Amati 2005).

The government also introduced a system of Transferable Development Rights to allow the local residents to exchange their land, especially if located in environmentally sensitive areas, for developable land outside the greenbelt (Bae 1998). However, this scheme was extremely difficult due to the complexity and inflexibility of land use laws.

Apart from individual landowners, the central government also saw the opportunities of releasing greenbelt land. The National Policy Business Area was intended to develop the surrounding areas of a station, located in the greenbelt. The government also tried to develop the greenbelt for rental housing (Kim & Kim 2008). Central government made such decisions based on economic benefits of developing greenbelt land to meet housing demand.

The Seoul Metropolitan Integrated Urban Model (SMIUM) by Jun (2011) was applied to simulate the effects of releasing greenbelt land. The model can help to assess if the greenbelt was released, who would benefit and how people and employment would move. Such an attempt put the greenbelt in a bigger picture of the entire metropolitan area and predicted the loss and gain of greenbelt land relaxation. It provided more robust evidence to the government when deciding which plot should be taken out of the greenbelt.

2.5 Why some greenbelts succeeded while others failed?

The aforementioned four cities all tried to establish or established a greenbelt as a policy instrument for environmental benefits, or for urban containment purposes (to check urban expansion and solve environmental, social and economic problems caused by excessive urban expansion). While the greenbelts in London and Seoul stand out as successful examples, the greenbelts in Beijing and Tokyo were ineffective at forestalling city growth. Different implementation efforts and political power are of course one of the reasons contributing to the success or failure of greenbelts. However, here we try to unveil the differences in policy design which led to distinct implementations. The main argument is that a rigorously and dynamically designed greenbelt interacting with land use policies (eg. new towns) and transport development (eg. railways and underground) is likely to be effectively and smoothly implemented. Since the reviews in section 2.4 already covered the analyses of the greenbelts in Tokyo and Seoul, this section will focus on the comparison between London and Beijing.

2.5.1 Greenbelt and self-contained new towns

When London's greenbelt plan was first launched, most local planning officers agreed that the greenbelt should be primarily regarded as a planning tool coordinating with new towns (Munton 1983, p.34). Ten new towns were to be built beyond the greenbelt (8 towns were actually built, based on the older towns or the newly spawned transport nodes) to receive thousands of former Londoners, some commuting to London, others forming local centres of employment.

London's new town development was not simply an outcome of moving population and industries from the city centre to the new towns. The agglomeration of population and industries generated demand for housing and infrastructure investment. Such an investment then created employment locally and funded for reinvestment in new towns. As new town commerce emerged, jobs no longer concentrated in central London but were also generated locally. Recreational activities also localised with more local pubs, shops and cinemas opening. The strict greenbelt reservation prevented them coalescing with the main city and the detached new towns then have self-contained economic and social life.

However, Beijing's new towns were not self-contained and employment was not generated locally. In 2000 the near suburb counties where new towns were located held 36% of the population but only of 12% jobs, which implied most of workers could not work locally and had to travel to the city. Local amenities were under-provided. For example, only 60 hospitals (13% of the total 459 hospital in Beijing) served 2.8 million people. Suburban agglomeration of population and jobs did not meet the level to attract abundant investment. More than 70% of the fixed assets investment (FAI) went to the main city. Near suburb counties including new towns, although benefitting from special investment policies[3], only attracted 19% FAI. It was therefore hard to generate local employment and made reinvestment in the new towns less possible.

2.5.2 Greenbelt and transport links

London's development has always been led by infrastructure investment. When the Greater London Plan was proposed in 1944, there were already 9 metro lines in London, connecting the centre to the suburbs. New towns beyond the greenbelt were treated as "a railways state… a state of existence within a few minutes walk of the railway station, a few minutes walk of the shops, and a few minutes walk of the fields." (Hall 1973, p.741). Railways and arterial roads would provide links so that new town residents commute easily to central London. Lines which stopped abruptly in the inner edge of central London were extended to serve further suburbs. Not only were new stations opened along the main trunk lines, branches were thrown out to open up the profitable areas between them (Hall 1964, p.64). The population distribution followed a pattern that very high densities were within walking distance of the town centre and fell off quite rapidly outside that radius to rural levels. Not before long, buses served at the suburban stations in a 4-mile radius as supplementary transport in the 1920s (Hall 1964, p.73).

Although the Beijing Master Plans proposed several new towns to accommodate the overspilled population, infrastructure never met the demand of decentralisation. The Master Plan of 1991 designated 10 "fringe settlements" beyond the first greenbelt for the purpose of stopping urban expansion and decentralising population. However, when the first greenbelt policy was introduced in 1994, Beijing had only two metro lines that could link only one fringe settlement with the central city. The total metro length was 54.1km, most of which served the central city.

[3] There were special policies for new town development in Beijing. For example, companies that hired local farmers in new town area could obtain pension from the municipal government; apart from zero tax, there was award for business incubator to attract professionals in new towns.

Private car was not an option until the Auto Mobile Industry Policy of 1994 (The State Council 1994) announced for the first time that the state encouraged private car ownership and legal private car ownership was protected by law. Under-provision of transport links discouraged the decentralisation to "fringe settlements" and spontaneous expansion took place in the immediate fringes of the main built-up area and forced through the first greenbelt.

When the second Greenbelt policy was introduced in 2003, only one new metro line was added and one metro line was extended to support such a massive decentralisation ambition. Line 1 extended eastwards from 31 km to 50 km by the end of 2003. Line 13 opened in 2002 to support the development of the northern part of the city. More "fringe settlements" were connected by metros with the main city. The total subway length reached 114km. New lines encouraged population to live beyond the first greenbelt but forced through the second greenbelt. People who lived beyond the second greenbelt had to suffer long distance commuting and extreme crowding in the suburban trains and buses. Considering time, money and degree of comfort, the generalised travel cost was rather high, which failed the purpose of decentralising population.

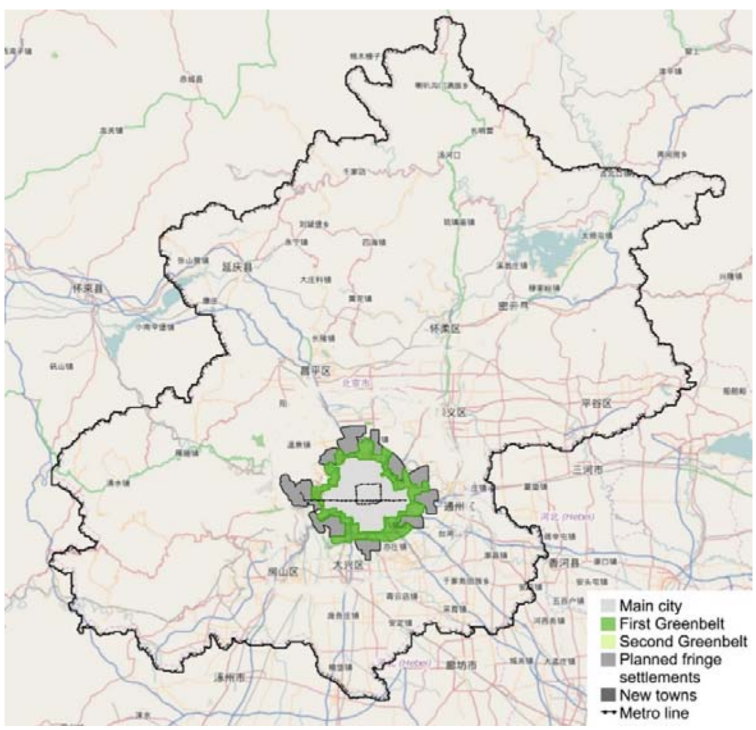


Figure 2-22 Beijing's metro system when the first Greenbelt was introduced in 1994

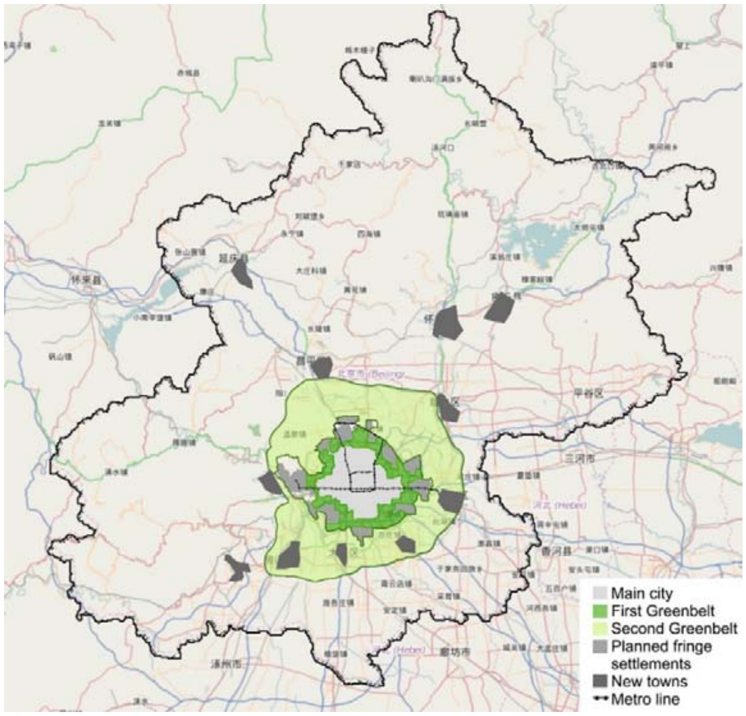


Figure 2-23 Beijing's metro system when the second Greenbelt was introduced in 2003

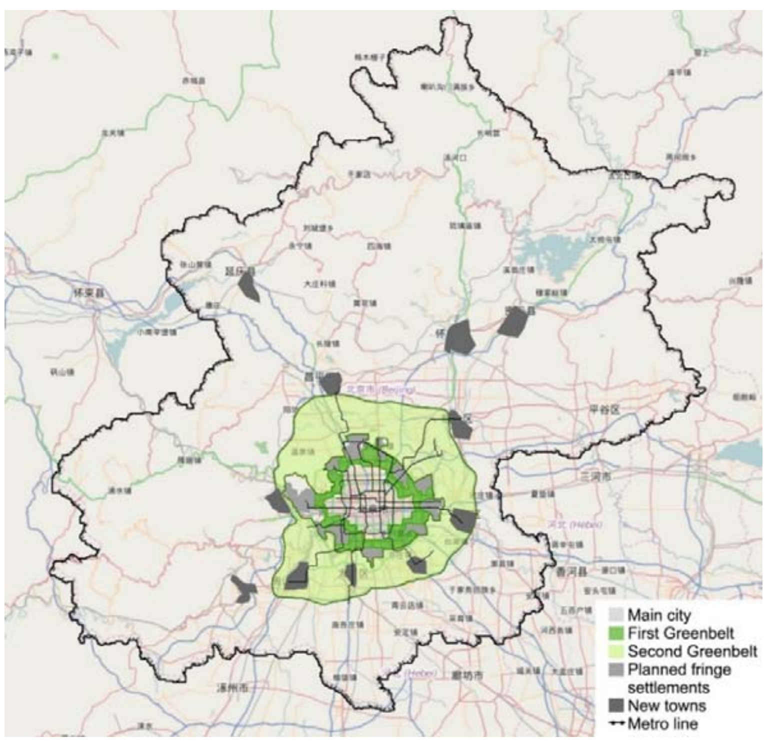


Figure 2-24 Beijing's metro system in 2014

12 years after the implementation of the second greenbelt, half of the new towns were connected with metros. Since these new towns were not self-contained, commuting was a must. However,

when the greenbelt was launched, without sufficient rail transit, most residents still concentrated in the main built-up area and were not able to move beyond the greenbelt. New road construction led them to the fringe of the main city which caused the main city to expand spontaneously in concentric circles into the greenbelts. With ring-roads and radial roads adding accessibility to undeveloped land planned for greenbelts, developers competed for those land parcels that were adjacent to the central built-up area and served by roads. This choice was backed by government's interest in land-lease revenue. These infill parcels were more likely to be leased with a high land price than those in the suburban communities. The revenue-seeking governments were more likely to prioritise these infill parcels than others (Yang et al. 2011). This trench war between those who wanted the greenbelt and those who wanted short-term economic gains led to a concentric fringe expansion.

Popularisation of cars after 2005 increased passengers' accessibility to the suburbs, but in a haphazard way. By the end of 2014, the total number of automobiles in Beijing had reached 5.4 million, 4.3 million of which were private cars (Beijing Bureau of Statistics 2015). As shown in Table 2-3, cars became the most popular travelling mode in 2012. Cars enabled people to travel further within the same time, which decreased the generalised travel cost but pushed urban boundary outwards. Unlike rail based transportation which confines social activities within a distance of the station, cars spread people everywhere.

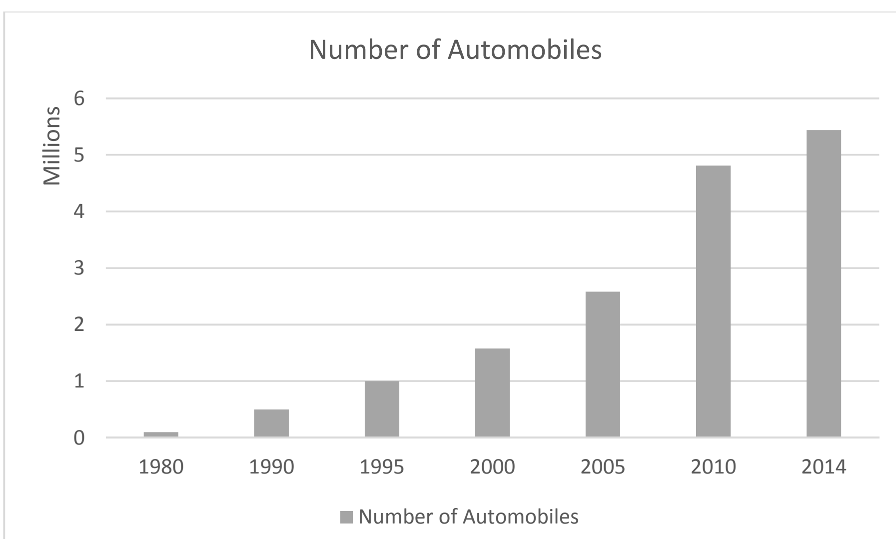


Figure 2-25 Number of automobiles in Beijing

Source: http://www.bjjtgl.gov.cn/publish/portal0/tab118/

http://www.people.com.cn/GB/jinji/32/178/20020912/821181.html

Mode	1986 Share (%)	2012 Share (%)
Bus	26.5	27.2
Subway	1.7	16.8
Taxi	0.3	6.6
Car	5.0	32.6
Bike and walking	62.7	13.9
Other	3.8	2.9
Total	100	100

Table 2-3 Travel mode in Beijing

Source: BEIJING TRANSPORTATION RESEARCH CENTRE (BTRC) 2013

Assessed as an urban containment policy, London's greenbelt stood out as a spatial development guide and remained steady in the past 70 years with stringent implementation. The greenbelt was positively involved with public transport development. Meanwhile, urban activities were generated locally from new towns to support the poly-centric pattern shaped by the greenbelt. However, the rigidness of London's greenbelt caused several market distortions, for example, the increase of land rent and car usage, which gave rise to the debate of flexibility of greenbelts in practice. Various green space configurations were proposed to adapt development change and coordinate with the strict greenbelt.

Initially put forward as an urban containment policy, Beijing's greenbelt gradually moved its focus from shaping a poly-centric urban structure onto its environmental benefits. The first greenbelt almost disappeared and the second greenbelt is being encroached upon gradually. Insufficient infrastructure provision and less developed new towns with rigid design caused difficulties in implementation and resulted in an ineffective policy outcome.

2.6 Summary

This chapter gives four brief stories of the greenbelt policy designs and implementations under different socio-economic contexts. London represents a developed city with a successfully established greenbelt. Although the greenbelt brought many environmental and social benefits, it is still disputed and under the pressure of being released. Seoul has followed London's practice and established a greenbelt with strong bureaucratic power. This greenbelt is also under the pressure of being broken. Parts of the greenbelt have been released or swapped with green field further from the city.

Both Tokyo and Beijing are examples of failing to implement the greenbelt plan. At first glance, the failure was always attributed to the weak implementation power. However, it is worth noting that because the policies were initially designed purely aiming at gaining environmental benefits, and the underlying economic effects were not taken into consideration, the greenbelt plans were destined to fail. The following insights might be helpful for the fast growing cities like Beijing when considering establishing or reviewing their greenbelts:

First of all, although London and Seoul's experience cannot be copied entirely due to different social and legal background, what Beijing and Tokyo could learn from the successful examples is to decentralise population with public transport investment and self-contained new towns. Urban expansion is a dynamic process and cannot be stopped by a static boundary. Therefore, it is crucial that the greenbelt works with economic mechanism in a package of infrastructure investment and new town development.

Secondly, the current greenbelt configuration should be modified to accommodate the incoming growth, especially in fast developing cities, as well as in developed cities which are revisiting their greenbelt plans. As shown in London and Seoul's experience, a fully-realised greenbelt may cause unwanted increase of spatial costs because of its stringency. They both proposed new configurations to deal with the issue. For Beijing's moving urban fringe, a ring-shaped greenbelt may not be the only solution. Green-wedges as an alternative is easier to adapt to the land use-transport pattern. The remnants of Beijing's left-over greenbelts also point to the wedges as an alternative.

Thirdly, while talking about releasing the greenbelt, cities should be extremely careful and using rigorous tool to assess the impacts. The greenbelt in London is still a sacred spatial feature and any change to the greenbelt needs to go through various examinations and revisions. Seoul's government is using ecological and environmental models to assess the possible effects of the greenbelt releasing or swapping. The economic and transport models are also used by researchers in Seoul. As a large scale urban form policy, a greenbelt will have enduring impacts on the city's economic well-being. Any new configurations or changes to such a policy requires rigorous assessment.

CHAPTER 3 MODELLING THE GREENBELT – A REVIEW

3.1 Overview

As reviewed in the last chapter, the unprecedented rate and scale of urbanisation have brought a reconsideration of the role of greenbelts in cities. Some developing cities, for example Beijing, are still struggling with whether a ring-shaped greenbelt can be established. Meanwhile, cities in developed economies are revisiting the configuration of greenbelts in order to meet new development challenges. For example, while London is considering if the greenbelt should be built upon, some other cities, for example Seoul and Cambridge, have decided to break it.

Such actions have brought attentions from planners and policy makers to how to assess the greenbelt performance and how to justify the configuration of the greenbelt rigorously. They need to answer questions like: what are the short-term and long-term impacts of the greenbelt? Which green space configuration performs better in terms of economic well-being, social influence and environmental impact? If there is a need to release the greenbelt land, where and how much should the greenbelt land be progressively reshaped or released as the city grows?

Urban models are often used to help planners and policy makers to evaluate policy effects in developed countries. They provide insights into the complex interactions between various urban markets in the development process (Batty 1971; Batty & Torrens 2005). In particular, there have been many studies to model the possible policy outcomes of greenbelts[4].

In this chapter, greenbelt models are reviewed from aggregate level to micro level, and from static models to dynamic models. Firstly, models focusing on specific effects of greenbelts are reviewed in section 3.2. These models clearly and directly show one of the many effects of greenbelts on cities. For example, they make the causal relationship between the land supply

[4] Models reviewed in this chapter are not limited to only modelling greenbelts. Models simulating the effects of Urban Growth Boundary (UGB) are also included.

constraint due to the greenbelt implementation and the increase in housing price explicit. Micro-simulations focusing on representing physical development process and predicting future urban growth boundaries are also reviewed in this section. Secondly, models examining the overall effects of the greenbelt on the whole city are reviewed in section 3.3. The whole-city models reveal various effects of the greenbelt on the entire city scale, including the effects on price, transport, amenity value, job and household distribution and so on. The whole-city models also unveil how such effects mutually influence each other. Thirdly, we explain the necessity of incorporating a temporal dimension in the greenbelt models and introduce several dynamic and recursive dynamic models in section 3.4 and 3.5.

3.2 Models focusing on specific effects of greenbelts

As Brueckner (2001) commented: the greenbelt, as one form of urban growth boundary, is set to correct excess urban expansion, but it is difficult to gauge the extent of market failure. In spite of numerous greenbelt studies, there is no agreement about their effectiveness. Therefore, empirical models are commonly used to quantify the performance of greenbelts. Such models assess the policy impacts within the framework of urban economics, and commonly use regressions to reveal certain effect from the greenbelt explicitly and directly. Some of the models focus on the effects on the land use market while others focus on the effects on the transport market.

3.2.1 Effects on aggregate land use

Existing research has identified amenity value changes as probable consequences from greenbelt policies (Lee & Linneman 1998; Lee & Fujita 1997; Lee 1999; Correll et al. 1978) and land and house price differentials due to supply constraints (Nelson 1986; Nelson 1988; Knaap 1985; Ball et al. 2014).

3.2.1.1 Greenbelts increase amenity value

The initial purpose of the greenbelt was to provide environmental and aesthetic benefits. Therefore, researchers devote effort in investigating greenbelts' amenity value. Early models which were applied to quantify the amenity value were mainly regression models used by economists. They gave empirical evidence to support the initial motivation of establishing greenbelts: for the positive social and aesthetic values.

Correll et al. (1978) proved the significant impact of greenbelts, as public goods, on property value adjacent to it. They identified the weights of the greenbelt variables, including, proximity, size, shape, aesthetic quality, on the housing price. Lee and Linneman (1998) analysed the amenity effects of the greenbelt over time on land market of Seoul using an empirical hedonic model. They assessed the accessibility to the greenbelt through cross-sectional data dynamically, and concluded that the amenity value would change as the city grew. Similarly, Lee (1999) measured the net benefit/cost of releasing Seoul's greenbelt over time. He concluded that the amenity value of the greenbelt changed as the city grew, and therefore the current policy should be re-examined periodically. The time dimension developed in the regression models highlighted the nature of greenbelt as an adaptive policy.

Lee and Fujita (1997) examined the relationships between the types of amenities generated by a greenbelt and the efficient location of a greenbelt by a theoretical partial equilibrium model. Their economic model identified explicit players (residents, landowners and government) and the constraints. This model used sophisticated maximisation algorithm to decide the location of the greenbelt. It converted the greenbelt amenities into cost and utility for the players in the optimisation process. They showed that the economic efficiency of urban development beyond the greenbelt depended on the location of the greenbelt itself, as well as on the distance-decaying nature of the amenities that the greenbelt can provide.

The amenity value is the most straight-forward greenbelt impact known by the public. Models mentioned above justified the greenbelt's amenity value and quantified the impacts of various features contributing to the amenity value, for example the location and size of the greenbelt. From the modelling perspective, such models are pioneers to assess the greenbelt empirically. They supported the policy motivations and gave planners insights into designing the greenbelt.

3.2.1.2 Greenbelts push up land price

Checking the excessive urban expansion serves as another main policy aim of the greenbelt. Limiting the land supply in the urban fringe is a common intervention, in order to address such a policy aim. There are numerous models testing the equilibria of the land market due to such an intervention. Knaap's regression model (Knaap 1985) measured the effects of Portland's urban growth boundary on urban and nonurban land values. Thus the demarcation of where the zoning regulations should change were defined. In addition to measuring the effects of supply constraint, Nelson's regression model (Nelson 1986) also measured the effect of speculation on land value, because the greenbelt not only limited land provision, but may eliminate the speculation of farmland development. Following this model, Nelson extended the research to the exurban land market beyond the greenbelt (Nelson 1988). Theoretical analysis of the supply side impacts seems to be self-evident as land is a major input to housing and limiting land supply pushes up prices. Ball (2014) empirically proved this presumption using Melbourne's greenbelt as a case study.

These models are not fundamentally different from the regression models reviewed in the last section. They justified the criticism that the greenbelt pushes up property price and they have made the underlying effects explicit. Such models only focused on the housing markets and examined one of many possible effects, but they initiated the quantitative analysis of the greenbelt's effects on other potential markets.

3.2.2 Effects on transport

The impacts of the greenbelts on transport costs can be seen as the greenbelt changes the distribution of travel demand. As jobs and residents move according to the greenbelt intervention, commuting travel demand changes. Such models are built on the mutual effects between the land use market and the transport market. However, in models reviewed in this section, the two markets did not reach an equilibrium interactively.

Jun and Bae (2000) noticed the effect of growth control on spatial distribution of employment, and they applied a regression model to predict job densities, assuming there would not have been a greenbelt in Seoul. They generated a counter-factual Origin-Destination (OD) matrix, and then the increase of commuting cost caused by the greenbelt constraint could be quantified. However, the regression model only showed the distance decaying character of job density. Therefore, it was not an integrated land use-transport interaction model. Similarly, Jun and Hur (2001) assumed if new towns were built 10 years earlier within Seoul's greenbelt and they used a gravity model to simulate the change of travel demand caused by the counter-factual new town and greenbelt policy. Bae and Jun (2003) assumed there had been no greenbelt. Then they applied a regression from a standard urban economics model to predict commuting demand.

Empirically, Jun (2004) showed evidence that Portland's UGB resulted in longer travel times and distances, which proved the criticism that the greenbelt increased travel cost (Freestone 2002).

The aforementioned studies revealed a less direct effect of the greenbelt. The increasing transport cost was shown through the spatial re-distribution of population and jobs. These models explained the influences from the land use market to the transport market in a relatively simple way. The impacts were only shown on an aggregate level of travel times and distances. None of the models gave more detailed analyses and predictions of the impacts on travel behaviour, for example the impacts on travel mode choices. Moreover, the models did not show how the changes of the travel times and distances feedback to the land use market.

3.2.3 Micro-simulations

The greenbelt policy is a top-down urban containment policy by definition. However, from the history of its implementation, we can see how the bottom-up power has shaped it. Individual behaviour and development decisions on each piece of land had to be taken into consideration in a policy making process. Models for the greenbelt therefore require finer scale micro-simulation to support this need.

3.2.3.1 Geographical algorithms to represent the greenbelt encroachment

Geographical rules are used to represent urban expansion process and to analyse urban development patterns. Remote sensing, landscape metrics, image processing and geographic information system (GIS) are widely applied. In developing countries, it is an effective way to monitor and interpret the change of the greenbelt. The key factors which are most relevant to the urban expansion pattern can be identified by spatial algorithms, and then how the greenbelts are encroached upon can be targeted.

For example, Shi (2012) collected historic Landsat images for Lianyungang, a fast-growing city in China, and developed spatial rules to identify edge-expansion as the main urban growth type. He suggested that the integration of a zoning approach associated with the greenbelt can play a key role in the transitional stage of urbanisation. Zhou and Wang (2011) provided insights into how the greenbelt changes in response to the concentric expansion. They reproduced the changing boundary of the greenbelt in Kunming, China from 1992 to 2009 through landscape metrics. Tayyebi et al. (2011) presented a GIS model to predict the urban boundary of Tehran. It identified spatial indicators that can define future urban growth boundary.

These representative models are able to summarise the process of the encroachment of greenbelts dynamically. They intended to quantify the weights of spatial indicators, for example, river, altitude, slope, vegetation, etc. in defining an urban growth boundary, based on geographical rules. Such models are helpful to policy makers when drawing the greenbelt boundaries, because they encapsulate the key phenomena in urban expansion that policy makers need to consider. Nevertheless, these models do not interpret the fundamental driving forces of urban expansion economically. They are therefore not widely used in policy tests. Two crucial factors of urban expansion, human behaviour and price mechanisms, are not considered.

3.2.3.2 Cellular Automata and Agent Based Model to predict the greenbelt boundary

Improved theories and growing knowledge about human behaviour, and a growing potential of individualisation make researchers start to seek the most appropriate level of spatial disaggregation. Microsimulation is therefore becoming popular. Cellular Automata (CA) and Agent Based Model (ABM) are the most widely-used non-equilibrium micromodels. In such models, no market reaches equilibrium. These models are able to incorporate the spatial and temporal dimensions of urban development and can model at high spatial resolution with computational efficiency. In CA models, agents are cells which change their state based on their neighbour's state. It offers a method that emphasises the role of neighbourhood effects on social change at intra-urban scale. Arguably CA models may be used to understand push-pull factors between residents (Caruso et al. 2009).

Caruso et al. (2007; 2009) revealed the path-dependent nature of urban sprawl patterns using a CA based microeconomic model. They visualised changes in spatial patterns through time and space and undertook sensitivity analyses to show how the pattern and timing of sprawl were affected by imposing a greenbelt. Long et al. (2009; 2010; 2011) set up a model series to predict Beijing's urban growth boundary using constrained CA. The model series considered the spatial attractiveness of the central city and new towns, characteristics of neighbouring cells, policy constraints, and natural constraints.

Brown et al. (2004) introduced an Agent Based Model to evaluate the temporal effectiveness of greenbelts. The model tested the effect of the greenbelt for delaying development outside it.

The model revealed the interactions between the greenbelt location and width and the resultant amount and timing of development beyond the greenbelt. Irwin's Agent Based Model (Irwin et al. 2003) simulated agent's decision of developing a fringe parcel. Thus future land use pattern and growth boundaries were predicted. The locational choosing process of the two Agent Based Models is fairly simple. A lack of constraints makes the model easy to be manipulated. The Agent Based Model dynamically showed where development might happen, but it was hard to calibrate using real data.

CA and ABM facilitate the theoretical exposition of greenbelt control through the time dimension. However, they have tended to use abstract representations of time rather than chronological, explicit representation of temporal dynamics (Simmonds et al. 2013). Additionally, the randomness on a fine level is a major concern. There have been a substantial number of applications of such models, but few have been used to test urban policies as transportation was handled rather crudely or even excluded in such models (Batty 2009). Micro-simulations help to delineate urban change patterns in a finer granularity, and outline changing rules of urban expansion. The finer granularity is helpful in the design process when making decisions on each piece of land from a bottom-up perspective.

The models reviewed above are capable of revealing a certain impact of the greenbelt. The possible policy outcomes resulted from land supply restriction or releasing/increasing green space can be predicted by those models. However, these models only show a cross-section of the city and one of the many effects from greenbelts. Normally, these impacts, such as land supply restriction and a new distribution of jobs, work dependently and simultaneously on a city's economic efficiency. It is difficult to empirically isolate one impact out of the other impacts, because of the multitude of concurrent changes of other factors in the whole urban system (Wegener 2004). Policy makers and planners are not able to dissect these impacts and solely look at one policy consequence. Scholars doing partial empirical models also claim the necessity of holistic models (Jun 2012; Jun 2004; Jun 2011; Correll et al. 1978; Ball et al. 2014).

3.3 Whole-city models – Land use and transport interaction

In this dissertation, whole-city models refer to the models that include the main markets of a city, including land, transport, labour, product markets and so on. Whole-city models are able to reveal interactions amongst urban markets and generate the spatial pattern of travel demand at a point in time in the future (Wegener 2014). This concept is based on the notion that all markets, including housing, real estate and transport markets and so on, tend to move toward equilibrium between demand and supply through price adjustment in a whole economy. These models differ largely from those based on articulated physical development processes and bottom-up decision processes. They are more testable and operational in focus (Batty 2013, p.273). As greenbelts can shape patterns of urban development at the sub-regional and regional scale (Department for Communities and Local Government 1995), they are expected to have influence on all the aforementioned markets of a city from micro to macro scale. Whole-city models are applied to simulate such influences.

Land use-transport interaction (LUTI) models as a subset particularly reveal the interactions between land use and transport markets: spatial development, or land use, determines the need for spatial interaction, or transport, but that transport, by the accessibility it provides, also determines spatial development (Wegener 2004).

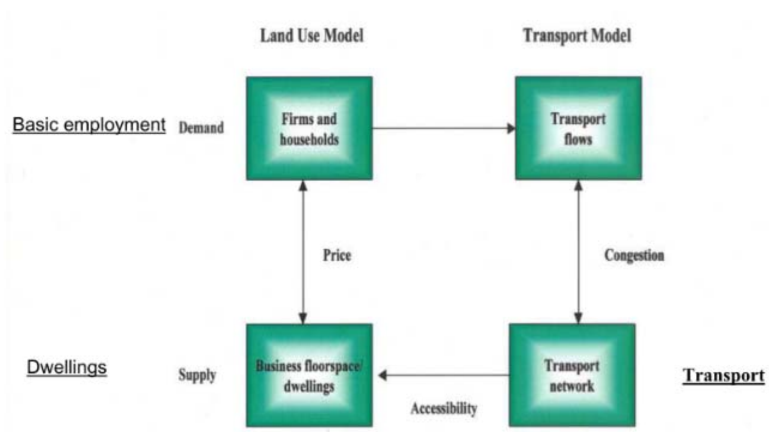


Figure 3-1 LUTI model structure. Source: ECHENIQUE ET AL. 2010

The pioneering efforts of the LUTI model stemmed from von Thuenen's model of agricultural land use and were developed by Alonso-Muth-Mills into a monocentric city model, concerning trade-offs between location (transport) and plot size (land use). Lowry's "A Model of Metropolis" (Lowry 1964) was the first operational land use-transport interaction model.

Following these efforts, a wide range of different land-use transport models[5] have been developed. Recent studies also include the real estate market in the LUTI framework (Anas & Liu 2007).

3.3.1 Trade-offs between land use and transport

According to Alonso's theory, an economic man makes his/her locational choice based on two main concerns: plot size and location, namely how large a plot he/she would purchase and how much time and money he/she would spend on traveling to the centre of the city, subjected to an income constraint. The aggregative individuals' locational choices constitute the equilibrium solution for the city (Alonso 1960).

In the monocentric model, jobs concentrate in the central business area and residents commute to the centre to work. Land rent falls with distance to the centre. Locational choice essentially represents a trade-offs between land and travel (Wheaton 1974; Wheaton 1982). The spatial size of the city grows as population or income increases, and falls as commuting cost or agricultural rent decreases (Brueckner 2001). Greenbelts, if they work efficiently, control urban size by increasing commuting cost or adding amenity value to farmland (Anas & Rhee 2007; Anas & Rhee 2006).

3.3.2 The Lowry Model

Lowry's "A Model of Metropolis" (Lowry 1964) was the first attempt to implement the urban land-use transport feedback cycle in an operational model (Wegener 2004). Instead of a monocentric continuous choice model, Lowry's model is a discrete choice model. There were no artificial presumptions of a monocentric pattern with a job centre and residential areas. The model is divided into zones and people discretely choose where to live according to the costs. The principle use of a Lowry-type model is to allocate a fixed amount of population and employment to zones, given known locations of some of the employment and transportation characteristics of the region (Horowitz 2004).

[5] There are a wide range of LUTI models in operation, see reviews (Batty 2009; Wegener 2004; Wegener 2014; Iacono et al. 2008; Wilson 1998)

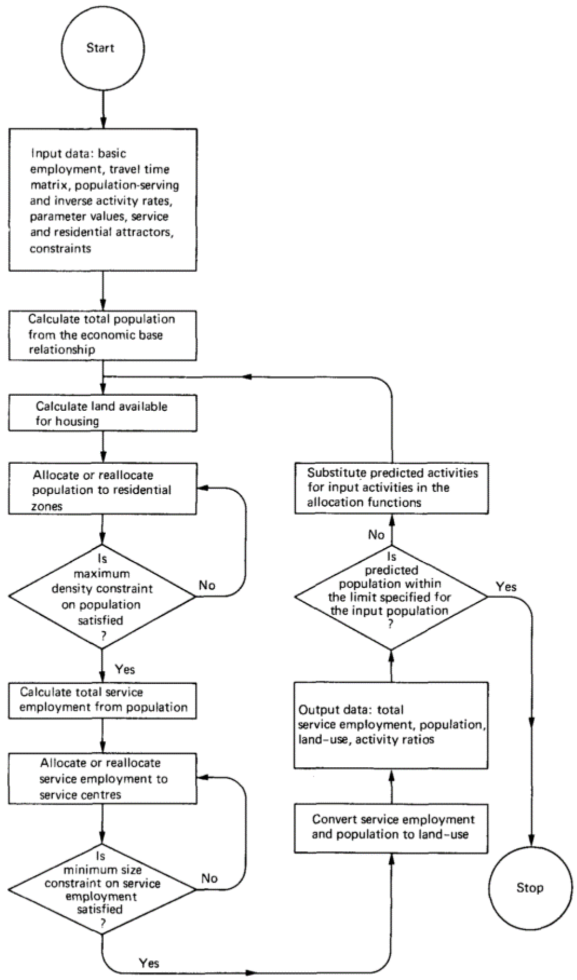


Figure 3-2 Flowchart of the Lowry Model. Source: BATTY 1976

The first iteration starts with the given distribution of basic workplaces by zone. The computer distributes around each cluster of workplaces a residential population which can supply an appropriate size of labour force. Then the population is available as a base for the location of service activities. Subsequently, the residences of service employees are located. This changes the distribution of residents. Iterations proceed in this manner until a stable co-distribution of all employment and all residences is achieved within the land, density and population constraints (Lowry 1964).

The model follows the social physics in residential spatial allocation, namely the gravity model. The model assumes that workplaces of basic industries have fixed locations, but residences can move around. Residents generated from workplace choose where to live based on the disutility of travelling to work. The number of households N_j in each living zone j is a function of that zone's accessibility to employment opportunities in zone i, which is the social gravity law.

$$N_j = g\sum_{i=1}^{n}\frac{E_i}{{T_{ij}}^2} \qquad \text{[Equation 3-1]}$$

E_i is the number of employment in the employment zone i while T_{ij} is the distance between i and j. g is a coefficient, subject to the sum of total population in all zones.

The number of service jobs is determined by the number of households in the surrounding area and the number of persons employed nearby. Total employment is a determinant of the market potential for retail establishment. Thus service business locational choice incorporates both competition and distance as determinants of the probability that a particular buyer will do shopping at a certain zone.

$$E_j^k = b^k[\sum_{i=1}^{n}\frac{c^k N_i}{{T_{ij}^k}^2} + d^k E_j] \qquad \text{[Equation 3-2]}$$

Similarly, E_j^k is the number of type k service jobs in the zone j. E_j is the total number of employment in that zone. N_i is the number of households in zone i. T_{ij}^k is the distance between zones i and j for home based shopping trips. b^k, c^k, and d^k are constants.

Transport cost in Lowry's model is the driving force for locational choice. It is represented as the distances between zones. As the locations of residents and service employment change, distance changes accordingly.

The Lowry model generates the entire activity pattern of the city. It is operational and of great significance, because many other LUTI models following a spatial interaction framework have similar structures. It is a static model at the aggregate level. This model applied in Pittsburgh had no time dimension and it therefore generated an "instant metropolis".

3.3.3 MEPLAN

3.3.3.1 Model structure

The Lowry model is the conceptual ancestor of a broad class of urban activity models that combine input/output analysis with spatial choice theories, such as MEPLAN (Horowitz 2004). MEPLAN is a more integrated land use transport modelling package developed in the Martin

Centre at the University of Cambridge since the 1970s. As an operational model, it has been applied in many cities all over the world[6].

The land use sub-model in MEPLAN estimates the location of households and employment in different zones of a city. It also estimates the transactions between households and employment and amongst themselves that give rise to the demand for transport (Echenique 2011). The transport sub-model in MEPLAN distributes traffic flows to door-to-door travel modes and assigns trips on links. It also updates transport costs for locational choices in land use sub-model.

The model uses an input-output framework as illustrated in the following figure. The core sectors are A, B, D and E. A represents the producer sector between different employment factors and normally includes a standard input-output model. B represents household consumption of industrial sector A. D represents labour provision from household to industries. E represents the conversion from labour to households in socio-economic groups. Following this framework, the model summarises the spatial flow of labour and goods and the interactions amongst them.

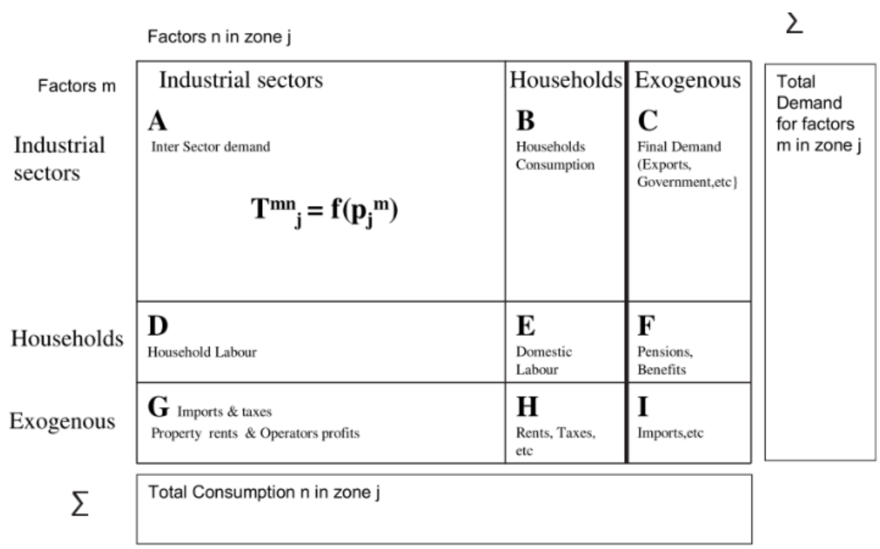


Figure 3-3 Input-output matrix MEPLAN. Source: ECHENIQUE 2011

Unlike the Lowry Model, the spatial allocation models in MEPLAN are based on logit random utility models (McFadden 1974), which makes them more behavioural and easier to interpret

[6] For the applications of MEPLAN, see the paper Employment Location Modelling within an Integrated Land Use and Transport Framework (Jin & Echenique 2012).

than strict gravity models, and also allows the inclusion of price information (Abraham 1998). Unlike Lowry's model which treated travel cost as the distance, MEPLAN treated transport cost as the generalised travel cost, which is the disutility generated from travel monetary cost, time cost and discretionary cost. The generalised travel cost together with price information are the determinants of locational choices. In MEPLAN, employment is defined exogenously and households are "attracted" to the employment locations from residential zones. Then housing floorspace, goods and services are "attracted" to residential zones.

The land use sub-model simulated key relationships between industries, employed residents, households and floorspace. From the land use sub-model, travel demand was generated and input into the transport sub-model. Then the transport model assigned travel demand to modal networks and calculated the monetary and time cost of travel. The costs were then fed back into the land use sub-model. Thus a spatial interaction loop was formed. General equilibrium can be achieved between transport cost, land rent and commodity prices. MEPLAN itself contains a fairly sophisticated transport model, allowing it to examine detailed transportation infrastructure plans and to produce results describing the conditions of transport networks (Abraham 1998). Given the forecast of the quantities and prices, the model is capable of evaluating the impacts of policies on the spatial economy in a sound manner (Echenique 2004).

3.3.3.2 Application

A model of London and the South East of England was developed based on MEPLAN since the 1960s (Williams 1994). It then developed into a later version of land use-transport interaction model: London and South East Region (LASER) Model Version 3.0. The model was intended for use to forecast the future location of land use activities and of transport demand under different policy scenarios, thus providing a consistent basis for assessing the packages of infrastructure schemes and regulatory measures under consideration (Department of Transport & ME&P 2002). LASER3.0 was used in the SOLUTIONS London Case Study. The model aims to predict growth trend in the study region to 2031, and to evaluate the effects of various planning options, using a range of indicators which reflects the economic efficiency, social inclusion, and environmental impacts. However, the location of a substantial number of jobs are not estimated within the model, but are input into the model exogenously.

Cambridge Futures is another MEPLAN based project to test possible policy outcomes. This study considered 7 options for the future physical form of Cambridge since 1996. Each option was analysed with the model. The study is widely acknowledged to have played an invaluable role in the planning debate about the future of the area, which modified the Structure Plan for the County of Cambridgeshire in 2003. The new Structure Plan led to the revision of the greenbelt boundary allowing the city to expand for the first time in 50 years (Echenique 2011).

3.3.4 RELU-TRAN

3.3.4.1 Model structure

In 2007, Anas developed the RELU-TRAN model to explain the behaviour of supply, demand and price in a city area with several or many interacting markets (Anas and Liu, 2007). In MEPLAN, household are treated as industries producing labour and consuming commodities, where job locations are fixed in many applications. RELU-TRAN is a more advanced spatial equilibrium model as it models the locational choices of both where to work and where to live.

Apart from this, the hybrid Cobb-Douglas CES production function is used in the model, which is rendered constant returns. It takes the inputs of capital, labour, floorspace and intermediate goods, while considering the effects of input varieties within each input group. This production function is more responsive to input changes.

Apart from markets that MEPLAN already modelled (labour market, product market, and transport market), RELU-TRAN also models the dynamics of land and the existing floorspace market. Developers are modelled as looking forward 1 year at a time. At the beginning, a developer buys a unit of land and then decides if he will build on the land or leave it vacant. If building on it, he asks how much and what type of floorspace will be constructed. In the middle of the period, a developer acts as a landlord to decide whether to offer a unit amount of floorspace for rent or withhold it from the rental market. At the end of the period, he decides whether to demolish the assets or maintain the assets. The time horizons in the model are abstract. This process is modelled based on the logit model to calculate the probability of constructing or demolishing, taking into account the profit in development and maintenance. There are two zero excess markets: zero excess demand in the residential and commercial markets for floorspace; zero excess demand in land market in each zone at the end of modelling year.

RELU as a land use sub-model generates trips which are fed into TRAN; while TRAN updates travel time and monetary cost which are fed into RELU. TRAN follows the conventional 4-stage transport modelling formula (Williams 1994). It covers the commuting trips and shopping trips, both of whose origin-destination pairs are generated from RELU. This feedback loop is not different from MEPLAN and most LUTI models. The following figure shows how the two algorithms are linked together to unify the sub-models.

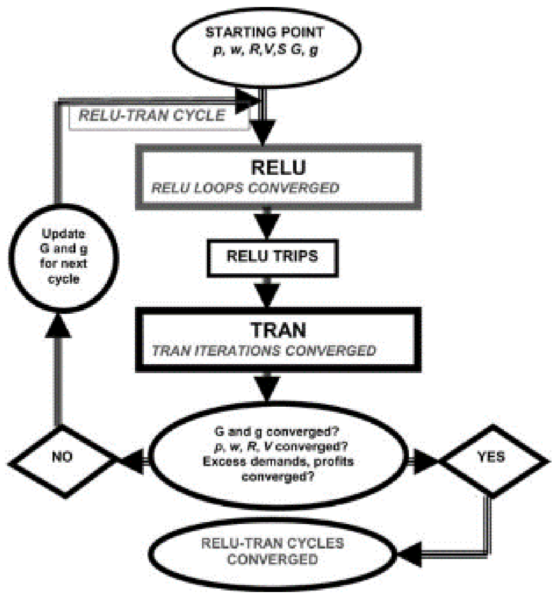


Figure 3-4 Cyclical linking of the land use and transport algorithm. Source: ANAS & LIU 2007

3.3.4.2 Application

Based on the RELU-TRAN model, Anas and his colleagues published 3 articles (Anas & Rhee 2006; Anas & Rhee 2007; Anas & Pines 2008) to compare performance of stringent urban growth boundaries versus congestion tolls. The articles cast doubts on the ability of stringent urban growth boundaries to control urban fringe sprawl, and the greenbelts as a certain form have the same effects.

Anas and Rhee (2006) juxtaposed congestion tolls and urban boundaries as two alternative policies for eliminating sprawl for a monocentric city. The greenbelt was assigned for a weight as an extra term in the utility function. The greenbelt acted in two ways: 1) it acted as a public good that increased consumers' utility; 2) it constrained land supply. However, it was not clear at all how the weight of the greenbelt utility term should be as there is no quantitative evidence. So the modellers did a sensitivity test by applying different weights to the greenbelt utility and modelled the compensating variations. They concluded that in dispersed city a greenbelt of any stringency is absolutely harmful compared to tolls. Anas and Rhee (2007) established a dual-centric prototypical model and claimed that if there was cross-commuting between the city and the suburb, congestion tolls could shrink city size by relocating economic activities while UGBs of any stringency could be inefficient. Anas and Pines (2008) tested the policy's sensitivity to elasticity of substitution between lot size and other goods. They found that the effects of urban growth boundaries are subject to the urban structure and elasticity of substitution of production inputs. In the three papers, the real-estate dynamic equilibrium sub-model has not been applied yet.

The three simulations internalised UGBs within the urban economic system and combined the land use policy with price mechanism. The RELU-TRAN approach to model the greenbelt is for discrete time horizons and can predict the performance of a greenbelt on the end state equilibrium.

3.4 Dynamic models

Equilibrium models assume that urban land and transport converge to equilibrium between supply and demand and focus on comparative static analysis of these equilibria (Simmonds et al. 2013). However, urban policy will have enduring effects over time and not every market can reach equilibrium within the modelling period. Greenbelts take a long time to shape themselves and dynamically change over time with incremental interventions accompanied by encroachment. For example, the performance of Beijing's first greenbelt was assessed a decade after its establishment, and the second greenbelt was put forward as a remedy since then. Cities have development inertia and path dependence, and the urban sub-systems do not change at one time simultaneously. It is necessary to understand the inherent inertia of different sub-systems of a city to assess its response to land use and transport policies.

Figure 3-5 shows that there are different speeds of urban change: travel behaviour may respond to policy within one day, but building stock will take decades for demolition and reconstruction. Some of the sub-systems are inert while others do not pass information to next time horizon. Urban models intended for planning should take account of the retarding forces, frictions, and delays responsible for development inertia (Simmonds et al. 2013). For the greenbelt modelling, land supply restrictions will have distinct effects over time. Transport mode choice and residential location changes may react acutely to the greenbelt intervention, but building stock changes and transport infrastructure transitions may react slowly, even in fast developing cities. Such a differential can only be shown with time horizons.

Level	Change Process	Stock Affected	Response Time (years)	Response Duration (years)	Response Level	Reversibility
1 Slow	industrial construction	industrial buildings	3-5	50-100	low	very low
	residential construction	residential buildings	2-3	60-80	low	low
	transport construction	transport system	5-10	>100	low	nearly irreversible
2 Medium Speed	economic change	employment/ unemployment	2-5	10-20	medium	reversible
	demographic change	population/ households	0-70	0-70	low/high	partly reversible
	technological change	transport equipment	3-5	10-15	medium	very low
3 Fast	labour mobility	workplace occupancy	<1	5-10	high	reversible
	residential mobility	housing occupancy	<1	5-10	high	reversible
	daily mobility	traffic	<1	2-5	high	reversible

Figure 3-5 Urban change process. Source: WEGENER ET AL. 1986

Equilibrium approaches generally assume that all agents are freely and instantaneously mobile, have full information, and will relocate whenever conditions change to make their current location sub-optimal (Waddell 1998). In the contrast, dynamic models assume that there are time lags and agents responding at different speed. Additionally, not all the information will feedback to the system in one time period. In the following section, three dynamic models which cover multiple time periods will be reviewed.

IRPUD

IRPUD is an accessibility based model of intra-regional location and mobility decisions developed in Germany. It predicts locational choices of households and firms with discrete choice models using multi-attribute utility functions in which accessibility indicators as the determinants are combined with other attributes (Wegener 2014). Accessibility is the opportunity for spatial interactions at potential locations. It divides time into periods. For each simulation period: the distribution of land uses determines the locations of human activities; the distribution of human activities requires trips to overcome the distance; the distribution of infrastructure creates accessibility; the distribution of accessibility affects location decisions and changes the land use system.

As transport market responds rapidly to change, transport sub-model can reach equilibrium within one simulation period. All other sub-models (ageing, public programmes, private construction, labour market, and housing market) are incremental. Each sub-model passes information to the next one in the same period and to its own next iteration in the following period (Wegener 2011). The dynamic features enable IRPUD to simulate change of stocks and in the microsimulation land use sub-model, in which land uses are allowed to change through ageing (Iacono et al. 2008).

DELTA

DELTA is another accessibility based dynamic model system of land use and transport interaction. The views have much in common with those underlying the IRPUD model. It rejects Lowry's approach of modelling locational choices and argues that the Lowry type models seem to overemphasise the importance of the trip to work as the determinant of residential location. DELTA assumes that residents consider a more general, multipurpose 'accessibility' variable (Simmonds 1999).

DELTA works in small time steps, normally one or two years. It allows for a mixture of rapid and slow responses in urban activities to happen in this time scale. Unlike equilibrium models which simulate the entire picture of a city at a cross-sectional time point determined by all interactions, in DELTA there should only be simultaneous linkages in the model where these are logically necessary. Any tendency towards equilibrium should come about through the gradual interaction of different processes over time (Simmonds 1999). This process is close to the reality of urban change.

Instead of using floorspace as inputs, DELTA uses land use permits as boundary conditions and allows floorspace remaining vacant to adjust to market demand. The process does not necessarily assume that all of the permissible floorspace is developed rather, as in the real world, the amount developed will reflect demand. Some sites will remain either wholly or partially undeveloped (Dobson & Simmonds 2009). In term of modelling the greenbelt, this dynamic feature allows the modeller to test the elasticity of the greenbelt policies more realistically.

We used DELTA for a preliminary test of releasing the greenbelt in Glasgow region in March 2016 (DELTA package was provided by The David Simmonds Consultancy. We set up the model with the help from Nikolaos Patias). We found giving permissible land quota to the greenbelt area did not necessarily attract development to the greenbelt. A time lag existed between the policy launching year and the time when development actually happened. Without transport improvement, some released greenbelt areas would remain vacant and unattractive over the next 20 years, regardless how much land development permits were granted. The dynamic feature of the model allowed us to test the appropriate policy timing of the greenbelt and how different markets reacted to it.

UrbanSim

UrbanSim is a package of dynamic model components with micro-simulation, including model components reflecting the key choices of households, businesses, developers, and governments (as policy inputs) and their interactions in the real estate market (Waddell 2002). As urban planning is no longer the exclusive domain of planners or politicians, but must accommodate increasing levels of public participation, UrbanSim addresses two important trends of models. First of all, urban models are expected to consider the response and cumulative effects of a certain policy. Secondly, finer granularity is required to model individual and community efforts in urban planning. Therefore, the UrbanSim design pursues an approach that is disaggregate and based on predicting changes over small time steps. The basic structure of UrbanSim has a similar approach to IRPUD and DELTA in the use of a sequence of models run in each annual time step.

UrbanSim has been used to address the policy analysis requirements of the metropolitan growth boundary in Oregon (Waddell 1998). UGB was modelled in the Profitability of Development component. This component took a mostly bottom-up view, in which the developers' decision of developing a certain parcel was modelled dynamically based on the costs and expected revenues. If the UGB was changed as a policy alternative, the resulting changes in the distribution of population, employment, physical development, land values and housing costs would be monitored through time. UrbanSim was also applied in the San Francisco Bay Area to predict the urban fringe growth (Waddell 2013). It had a representation of each parcel in the region, so the planners could compare the development status at the beginning of the simulation with the end of the simulation.

3.5 Recursive (quasi-dynamic) models

Dynamic models provide policy makers the insights into interdependencies of urban markets at any point in time and also into how cities evolve. However, data requirements for establishing such models are hard to achieve for many developing cities. Today, the most common form of temporal representation in dynamic urban models is through recursive models (quasi-dynamic models) in which the end state of one time period, serves as the initial state of the subsequent time period (Simmonds et al. 2013). The quasi-dynamic models partially serve the purposes of dynamic simulation. Meanwhile they can be built-upon technical data that most cities already have.

3.5.1 Recursive simulations in the Lowry model

Recursive components can be found as early as in the Lowry model. Lowry had already pointed out the problem of time: it should be a dynamic system with variables whose values continuously change under the impact of external forces and internal momentum (Lowry 1964). He proposed two ways towards dynamics through recursive simulations. The first one was to suspend iterations for insertion of further exogenous change. These changes would direct the system toward a new equilibrium solution. For example, the change of initial input of basic employment would lead to redistribution of population and service employment. The solution to each iteration could be interpreted as representing changes over time. The second approach was to incorporate lag variables. There were three adjustable constraints in the Lowry model: available land, minimum market potential, maximum residential density. These parameters were built into the model. They could be held in first several iterations and released till a certain urban pattern had been reached. In such a way that, through them, the dynamic sequence was subsequently altered.

However, neither approach was implemented in the Pittsburgh model, because Lowry argued the instant metropolis was approximated by a simultaneous system without a lag variable: the model performed this replicative function correctly in a broad outline, but was unreliable in detail (Lowry 1964). Lowry's approach of representing time was still within one spatial equilibrium cross-section, but breaking one simulation into different stages of iterations.

3.5.2 Incremental simulations in MEPLAN

MEPLAN is able to link more than one equilibrium simulation to represent time. It combines the equilibrium models which simulate instant change, with an incremental sub-model which allows for a wide variety of formulations describing how development and redevelopment occur through time (Abraham 1998). The durability of physical building stock, the development process, the planning system and wider decision-making are only partially responsive to price signals and policy actions within any given time period (Jin & Echenique 2012). The responsive parts are included in the MEPLAN equilibrium model while building and transport supply, demographics, and foreign trade conditions which are inert are simulated in the incremental sub-model. The incremental sub-model adjusts the spatial constraints and the arrangement of basic activity using variables from the previous time period. Floorspace development is modelled in the incremental sub-model, not in the spatial equilibrium model. So developers' behaviours are represented through time but not in a horizontal supply curve.

3.5.3 The Recursive Spatial Equilibrium Model under development

Following the tradition of MEPLAN, the Recursive Spatial Equilibrium (RSE) model is being developed in the Martin Centre at the University of Cambridge. This model uses a more advanced spatial equilibrium model which shares some similar characteristics with RELU-TRAN. It not only examines the impacts of policies on economic indices in individual time period, but also examines the dynamics of people and investment in response to economic indices (Jin et al. 2013).

RSE shares the same structure as MEPLAN when tracing time and adding incremental changes to the housing and business floorspace markets. RSE's equilibrium part is more responsive to policy variables, which leads to more effective inputs in the recursive sub-model. The recent development includes a more sophisticated calibration mechanism and the capability to represent choice between housing types and labour types (Wan 2016).

3.6 Summary

Models applied for the greenbelt simulation have different foci. Partial empirical models aim to reveal a particular effect or a particular changing process at a given point of time. They are able to reveal the direct effects from the greenbelt intervention explicitly. Such models are preferred by researchers and planners because of their directness. Whole-city models are more complex and the interactions between many markets cannot be seen linearly. Such models put the greenbelt in the picture of the entire urban area and can assess the overall effects of the greenbelt policies. Adding a time dimension to the whole-city models makes the models closer to the reality of urban change process.

Combining all the models reviewed in this chapter, modelling the effects of a greenbelt in a city which is facing major growth and restructuring would require a model that meets the following demands:

1. As the greenbelt has profound impacts on a city's overall economic performance, which has been proved empirically and theoretically, the model should be able to assess the effects on a whole range of economic indices, including employment density, population density, wages, rents, utilities and so on, on a whole city scale.
2. The model needs to be able to reveal the complex interactions between the greenbelt policy and transport pattern changes, including changes on finer scale travel mode choice and route choice for various travel purposes.
3. As the greenbelt is treated as an adaptive and long-lasting planning policy, and it has enduring effects over time, the model needs to collate temporal dimension dynamically and/or recursively, instead of only looking at one time horizon, so that the slow market changes of building stocks and transport networks can be captured.
4. As the greenbelt has impacts on the neighbourhood level (for example increasing built-up density), and the policy is designed at the land plot scale for implementation purposes, the model is required to reveal the implicit impacts on a finer scale built-form.

In the following chapter, we will build a theoretical model that meets the four demands in order to examine the overall greenbelt impacts: an operational land use and transport interaction model that links more than one time period and represents micro scale changes.

CHAPTER 4 THE THEORETICAL MODEL

4.1 Overview

In this chapter, we present a theoretical model that can meet the four demands summarised in the last chapter. This model can examine the short to long term effects of greenbelt policies on the urban land use market and transport market. This proposed model inherits the general framework of the LUTI models such as MEPLAN and incorporates the advanced spatial economic theories such as RELU-TRAN. The recursive-dynamic structure such as in RSE links the equilibrium and the non-equilibrium models, which enables the simulation of the enduring effects and path-dependency along the development trajectories of the greenbelt scenarios.

The theoretical model consists of four sub-models:

1. The Spatial Equilibrium Model (SE) predicts the employment and residential locational choices under a simultaneous equilibrium in the production market, labour market and real estate market. It generates the locations of commuting activities for the transport simulation. It also gives employment-residence locations to facilitate the non-commuting activity generation. It also offers the starting point of the development trajectories and defines the inertias and trends for the next decade.

2. The Non-commuting Travel Demand Model (NCTD) predicts locational choices of non-commuting urban activities based on an input-output social accounting matrix and market constraints. It generates non-commuting travel demand for the transport simulation, not only for employed residents, but also for non-employed residents and floating population.

3. The Strategic Transport Model (ST) is the transport simulation package. It takes the locational predictions from SE and NCTD, and splits traffic flows to travel modes and assigns them on the transport network. By doing this, it gives the zone-to-zone travel costs back to SE and NCTD which are the bridges for the land use and the transport market interaction. ST also

considers the micro level built-form differences and reflects such differences in the zone-to-zone generalised transport cost.

4. The Recursive Dynamic Model (RD) predicts the real estate market stock constraints under a non-equilibrium assumption. The constraints are updated periodically based on the endogenous outputs from the SE, market inertia and exogenous policy interventions. It also updates the transport network and travel costs periodically subject to the policy interventions and endogenous travel demands.

Spatially, the modelled area is divided into discrete but contiguous model zones. Spatial activities can move within and between zones and the choice of location is modelled on a zonal scale. Urban development is represented in terms of changes in the stock of housing and business floorspace and changes in the multimodal transport network, all of which are inputs into the model periodically based on exogenous policy scenarios and endogenous market performances. The four sub-models share the same geographical extent and zoning.

The four sub-models will be explained in detail from section 4.2 to section 4.5 respectively. Then in section 4.6, we discuss how the sub-models are assembled in the LUTI framework and how the information flows are passed amongst sub-models in one time section, and across several time periods.

4.2 Spatial Equilibrium Model (SE)

Following the tradition of Anas and Liu (2007) , Jin, Echenique and Hargreaves (2013) and the latest model development in the Martin Centre by Wan (2016), the SE model for producer and consumer behaviour follows a parsimonious design. This allows the users of the model to understand and check easily the causal relationships. SE does not currently include explicit agency of developers or government, although these can be added at a later date which will result in a more complex model to calibrate and use. Taxes are not modelled explicitly; instead, the model assumes that the city balances its consumption with its production, and any increase in the property sales/rental income is shared equally among all households. The choice of this structure is to highlight the key interactions that are most relevant to the broad thrust of urban development and its impacts on production and consumer welfare.

4.2.1 Producers

The production function follows a hybrid Cobb-Douglas CES form. Producers can choose any zone to locate. The output X_{rj} of a certain industrial type *r* in a zone *j* is:

$$X_{rj} = E_{rj}A_{rj}(K_r)^{\nu_r}\left(\sum\nolimits_f \kappa_{rfj}L_{rfj}^{\theta_r}\right)^{\frac{\delta_r}{\theta_r}}\left(\sum\nolimits_k \mathcal{H}_{rkj}B_{rkj}^{\zeta_r}\right)^{\frac{\mu_r}{\zeta_r}}\prod\nolimits_s \left(Y_{rsj}\right)^{\gamma_{rs}} \qquad \text{[Equation 4-1]}$$

In this hybrid Cobb-Douglas CES function, primary inputs are the capital K_r, labour force L_{fj}, business floorspace B_{kj} and intermediate inputs Y_{rsj}. The subscripts *f*, k and *s* stand for the types of labour force, business floorspace and goods respectively. E_{rj} is scale parameter. $A_{rj}$is the economic mass parameter which represents the urban agglomeration effects. This function is rendered constant returns by $\nu_r + \delta_r + \mu_r + \sum_s \gamma_{rs} = 1$. The elasticity of substitution between any two types of labour forces and building floorspace are $\frac{1}{1-\theta_r}$ and $\frac{1}{1-\zeta_r}$. κ_{rfj} and $\mathcal{H}_{rkj}$ are input-specific constants for choosing between types of labour forces and business floorspace.

At this initial stage of the model, two simplifications are applied in this production function. First of all, the intermediate goods term will not be included in the model as the city produces only one kind of conceptual goods and service. Secondly, the capital term is not included. Only the labour and floorspace inputs are highlighted as the main input factors. Then given the endogenous price p_{rj}, the production function can be written as:

$$L_{rfj} = \frac{\kappa_{rfj}^{\frac{1}{1-\theta_r}} w_{fj}^{\frac{1}{\theta_r - 1}}}{\sum_f \kappa_{rfj}^{\frac{1}{1-\theta_r}} w_{fj}^{\frac{\theta_f}{\theta_r - 1}}} \delta_r p_{rj} X_{rj} \qquad \text{[Equation 4-2]}$$

$$B_{rkj} = \frac{\mathcal{H}_{rkj}^{\frac{1}{1-\zeta_r}} R_{kj}^{\frac{1}{\zeta_r - 1}}}{\sum_k \mathcal{H}_{rkj}^{\frac{1}{1-\zeta_r}} R_{kj}^{\frac{\zeta_r}{\zeta_r - 1}}} \mu_r p_{rj} X_{rj} \qquad \text{[Equation 4-3]}$$

w_{fj} is the hourly wage of labour type f; R_{kj} is the average rent for business floorspace type k.

4.2.2 Consumers

Consumers are also categorised into *f* types by their socio-economic status. They can work in any zone, live in any zone and purchase goods in any zone, subject to the maximised individual utility. Each consumer decides where to be employed and where to live based on a combined utility. Following the random utility framework (McFadden 1974), an individual in the population has a utility function which can be written in the form:

$$U_{fij} = V_{fij} + e_{fij} \quad \text{[Equation 4-4]}$$

Where V_{fij} is non-stochastic and reflects the representative taste of the population, and e_{fij} is stochastic and reflects the idiosyncrasies of the population. e_{fij} measures the unobserved utility variance among individuals. The non-stochastic observed utility V_{fij} consists of three parts: the quantity of retail goods and service a consumer buys, the quantity of floorspace he/she rents, and the time he/she contributes to work or leisure. An individual utility of a type *f* consumer living in zone *i*, working in zone *j* and shopping in any zone *z* is written as:

$$V_{fij} = \alpha_f \ln\left(\sum\nolimits_r \left(\sum\nolimits_z Z_{rz|fij}\right)^{\eta_f}\right)^{\frac{1}{\eta_f}} + \beta_f \ln\left(\sum\nolimits_k \iota_{kfi}\left(b_{kfi}\right)^{\sigma_f}\right)^{\frac{1}{\sigma_f}} + \gamma_f \ln l_{fij} \quad \text{[Equation 4-5]}$$

$\alpha_f, \beta_f, \gamma_f$ are the shares of disposable income spent on the retail goods and service $Z_{rz|fij}$, housing floorspace b_{fij}, and annual leisure time l_{fij} for socio-economic group *f* and they follow the Cobb-Douglas constant returns by defining $\alpha_f + \beta_f + \gamma_f = 1$. The subscripts *r* and *k* stand for the type of goods and the type of housing floorspace respectively. ι_{kfi} is the input-specific constant for choosing the housing type k for type f consumer in zone i. $\frac{1}{1-\eta_f}$ and $\frac{1}{1-\sigma_f}$ are respectively the elasticities of substitution between any two retail goods and any two types of housing.

Two constraints are set for the consumers to maximise the utility: the income constraint and the time constraint. The income constraint is comprised of the wage income and non-wage income which is the rent dividend shared by all the residents in the modelled area. The income constraint is written as:

$$\sum_{r,z}(p_{rz}+c_f 2g_{fiz})Z_{rz|fij}+\sum_m r_{ki}b_{k|fij}+\Delta_f 2Dg_{fij} = w_{fj}\left(N-2DG_{fij}-\sum_{r,z}c_f Z_{rz|fij}2G_{fiz}-l_{fij}\right)+M_{fj}$$

[Equation 4-6]

The right-hand side of the income constraint equation is the total income and the left-hand side is the total expenditure. p_{rz} is the mill price for goods and services type r produced in zone z; g_{fiz} and G_{fiz} is the expected one-way monetary cost and travel time from i to z for customers of type f. They are the weighted average travel cost and time over all travel modes from zone i to z. g_{fiz} and G_{fiz} are calculated from the Strategic Transport Model. c_f is an exogenous coefficient that measures the cost of delivering a unit of goods and services as percentage of the normal trip cost. r_{ki} is the housing rent of type k in zone i. The right hand of the equation is the income, including wage and rent dividend. w_{fj} is the hourly wage rate for labour type f working in zone j. The time constraint $N-2DG_{fij}-\sum_{r,z}c_f Z_{rz|fij}2G_{fiz}-l_{fij}$ is the total time available for working, which is the total time endowment N minus the commuting time $2DG_{fij}$, the shopping time $\sum_{r,z}c_f Z_{rz|fij}2G_{fiz}$ and the leisure time l_{fij}. M_{fj} is the rent dividend that is shared equally amongst households in the region.

Non-employed households are modelled as a fixed number of non-employed individuals per household. There is no employed individual in such households. Their income is only from the rent dividend M_{fj}.

4.2.3 Commuting disutility and locational choice

The travel disutility function that is linear with the generalised travel cost is commonly used. However, while modelling large city regions, it is often found that the slope of travel disutility decreases with trip length (Fox et al. 2009). For city regions with a reasonably self-contained commuting catchment, which is about 50 km or more, extensive analyses of travel choices data show that the linear travel disutility function will have difficulties in representing realistic demand elasticities. Therefore, we adopt a log-linear form function to represent the commuting disutility d_{fij} (Jin et al. 2013).

$$d_{fij} = a_f \chi_{fij} + (1 - a_f) \ln \chi_{fij} - a_f \qquad \text{[Equation 4-7]}$$

where χ_{fij} is the generalised travel cost and a_f is a log-linear parameter. We define $\chi_{fij} = 2DG_{fij}/12$. D is the total working days per annum. G_{fij} is the weighted average one way commuting time over all travel modes which can be obtained from the ST model. χ_{fij} is essentially the monthly total commuting time.

In order to derive the probability of locational choice for a combined employment-residence decision, a discrete choice model is adopted by specifying the distribution of the idiosyncratic utilities e_{fij}. Assuming e_{fij} follows a Gumbel distribution, the probability of the combined locational choice can be derived through a nested logit form.

For a given employment location *j*, the non-stochastic residential utility $v_{fi|j}$ for living in any zone *i* is specified as:

$$v_{fi|j} = V_{fi|j} - d_{fi|j} + E_{fi|j} \qquad \text{[Equation 4-8]}$$

$V_{fi|j}$ is the consumption utility specified in [Equation 4-5]. $d_{fi|j}$ is the travel disutility specified in [Equation 4-7]. $E_{fi|j}$ is the residential residual attractiveness term which is calibrated empirically. For a given working zone *j*, the conditional probability for living in zone *i* is represented in a logit form:

$$P_{fi|j} = \frac{S_i \exp(\lambda_{f|I} v_{fi|j})}{\sum_i S_i \exp(\lambda_{f|I} v_{fi|j})} \qquad \text{[Equation 4-9]}$$

S_i is a size parameter that corrects for the bias introduced by the uneven sizes of zones in the model. $\lambda_{f|I}$ is the concentration parameter for residential location choice.

Meanwhile, by working in zone j, an individual obtains a non-stochastic employment utility v_{fj}:

$$v_{fj} = \ln M_{fj} + E_{fj} \qquad \text{[Equation 4-10]}$$

M_{fj} is the non-wage income and E_{fj} is the employment residual attractiveness term which is calibrated empirically.

The probability for an individual of choosing to work in zone *j*, regardless the residential location is:

$$P_{fj} = \frac{S_j \exp\left(\lambda_{f|J}(v_{fj} + V_{f|j})\right)}{\sum_j S_j \exp\left(\lambda_{f|J}(v_{fj} + V_{f|j})\right)} \qquad \text{[Equation 4-11]}$$

Similarly, S_j is a size parameter and $\lambda_{f|J}$ is the concentration parameter for employment location choice. $V_{f|j}$ is the log-sum utility represents the expected utility that an individual can obtain given working in zone *j* while living in any zone *i*:

$$V_{f|j} = \frac{1}{\lambda_{f|I}} \ln \sum_i S_i \exp\left(\lambda_{f|I} v_{fi|j}\right) \qquad \text{[Equation 4-12]}$$

Then the probability of choosing a combined employment-residence location can be expressed as the product of the probability of working in zone *j* and the conditional probability for living in zone *i* :

$$P_{fij} = P_{fj} P_{fi|j} \qquad \text{[Equation 4-13]}$$

Non-employed individuals in non-employed households denoted as socio-economic type F only make residential locational choices based on the residential location utility υ_{Fi}, which includes the non-stochastic consumption utility V_{Fi} as specified in [Equation 4-5] and the residential attractiveness E_{Fi}.

$$\upsilon_{Fi} = V_{Fi} + E_{Fi} \qquad \text{[Equation 4-14]}$$

The probability of non-employment household residential choosing a residential location *i* is:

$$P_{Fi} = \frac{S_i \exp(\lambda_F\, \upsilon_{Fi})}{\sum_i S_i \exp(\lambda_F\, \upsilon_{Fi})} \qquad \text{[Equation 4-15]}$$

4.2.4 Spatial equilibrium conditions

Conditional on the travel cost and time g_{fiz} and G_{fiz} from ST, the Spatial Equilibrium Model requires the following standard assumptions, subject to the zonal floorspace stock constraints by type B_{rkj} and b_{kfi} :

1) All consumers maximise utility subject to the housing floorspace, money and time constraints.
2) All producers minimise cost subject to the input factors, which are the floorspace and labour provision.
3) A zero profit condition is set for producers in an open competitive market. The market is zero excess demands in floorspace market, labour market and product market. In labour market, total working hours demand equals total non-leisure hours minus travel time. In product market, total goods and services produced equals total goods and service consumed by consumers.

The Spatial Equilibrium Model will follow the algorithm below (Figure 4-1) to solve the price related variables (wages, prices and rents) and output the modelled zonal number of residents and jobs for NCTD, ST and RD. The algorithm starts with arbitrary inputs of wages, prices and rents. Then,

- The prices are solved first, conditional on the zero economic profit assumption.

- The total demand of product (which is also the total output based on the assumption of zero excess demand in product market) and the total labour required to produce such a demanded quantity of product are solved given the prices.
- Given the assumption of zero excess demand in the housing market, housing rent is solved, subject to the income constraint.
- Given the assumption of zero excess demand in the business floorspace market, business floorspace rent is solved, subject to the demand of total production.
- Given the assumption of zero excess demand in the labour market, wage is solved conditional on the total time available for working.

This algorithm will run iteratively until all quantities and prices converge.

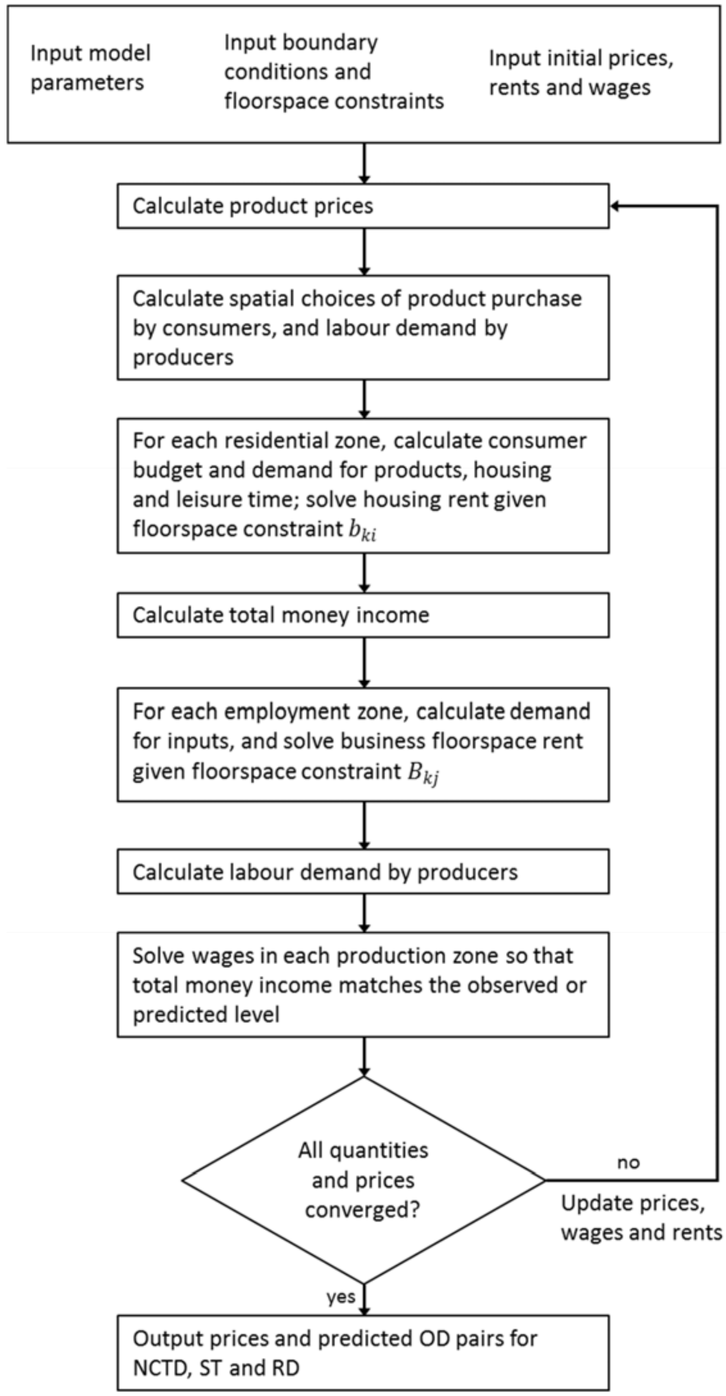


Figure 4-1 Model solving algorithm (adapted from Jin et al., 2013)

4.3 Non-Commuting Travel Demand Model (NCTD)

Apart from the commuting related urban activities simulated in SE, other activities, such as shopping, education, business and visiting family or friends are simulated in the Non-

Commuting Travel Demand Model. Such activities are considered as "secondary" urban activities, as they will be simulated once the employment-residence locations are given.

4.3.1 Conversion of individuals to households

First of all, the zonal residents in type f N_i^f from SE are converted into households type h H_i^h through an inverse household composition matrix. The household composition matrix a^{hf} defines the number of each type of employed individuals in a certain household type. ${a^{hf}}^{-1}$ is the inverse matrix of the household composition matrix.

$$N_i^f = \sum_h H_i^h a^{hf}$$
$$H_i^h = \sum_f N_i^f {a^{hf}}^{-1}$$
[Equation 4-16]

4.3.2 Non-commuting activity generation

Given the zonal households numbers in the last step, NCTD generates non-employed individual persons within each type of household into different categories *c*. Such categories are in line with the non-commuting travel demand segments. For example, the model generates the number of school kids which are used to model educational trips. The equation below is applied.

$$Y_i^c = \sum_h a^{ch} H_i^h$$
[Equation 4-17]

Y_i^c is the number of individual of *c* socio-economic category, H_i^h is the employed households type h, and a^{ch} is a matrix that defines the non-employed individual composition of household. It gives the information of how many individuals in each category *c* in a certain household type h.

There are also individuals who are do not belong to any household, for example tourists. They also generate travel demand and are treated as exogenous inputs. Employed individuals, non-employed individuals and exogenous individuals all together generate non-commuting trade.

$$T_i^t = \sum_c a^{tc} Y_i^c \qquad \text{[Equation 4-18]}$$

T_i^t is the total number of non-commuting trade type *t* generated at the origin zone *i*. Y_i^c is the number of individuals of category *c* in zone *i*, and a^{tc} is the trade generation matrix. It gives the rates for trade type *t* and person category *c*, which is derived from the detailed segmented survey data.

4.3.3 Non-commuting trade distribution

As the trades are generated from the origins in [Equation 4-18], another discrete choice model is used to select the destinations of trades.

$$T_{ij}^t = T_i^t \frac{S_j^t e^{-\lambda^t (d_{ij}^t + w_j^t)}}{\sum_j S_j^t e^{-\lambda^t (d_{ij}^t + w_j^t)}} \qquad \text{[Equation 4-19]}$$

T_{ij}^t is the trade flow of non-commuting activities *t* from zone *i* to zone *j*. T_i^t is the total trip generated from zone *i*. S_j^t is the size parameter of type *t* activities in zone *j*. d_{ij}^t is the travel disutility of type *t* activities from zone *i* to zone *j*. w_j^t is a constant, which varies according to the types of activities and zones.

d_{ij}^t is defined differently from [Equation 4-7]. It is the log-sum travel disutility over all possible travel modes. As travel disutility is the dominant factor in non-commuting locational choice, using this log-sum form highlights the importance of travel mode choices. The log-sum disutility is always less than the lowest disutility of the possible travel mode. This means that by giving more mode choices, the travel barrier will be less. D_{ijm}^t is the travel disutility on a certain mode, including monetary cost, travel time, and other perceived disutility of travel (the form of D_{ijm}^t is defined in [Equation 4-24] in ST).

$$d_{ij}^t = \frac{-1}{\lambda_m^t} \ln \sum_m \exp\left(-\lambda_m^t D_{ijm}^t\right) \qquad \text{[Equation 4-20]}$$

SE and NCTD together generate the travel demand of all urban activities. In the current model, activities are generated from the origin of a trip, instead of in the middle of the trip. For example, a person does not do shopping on the way back home from work. He/she only does shopping from home to the shop. Therefore, at this stage, we add the commuting and non-commuting urban activities side by side to generate the full activity pattern.

4.4 Strategic Transport Model (ST)

The demand of transport for the study area is generated in SE and NCTD, represented by production-attraction matrices of trades. The supply of transport is represented by a multi-modal network, comprised of a set of nodes and a set of links. The ST model adjusts the demand to be consistent with the supply.

The structure of ST is a four-step transport model (Ortuzar & Willumsen 2011) which includes: 1) trip generation; 2) trip distribution; 3) modal split; 4) link assignment. The first and second steps to generate travel demand have been carried out in the land use models. Then, there is an interface to convert the travel demands (urban activities) in the format of production-attraction matrices in trade unit into Origin-Destination (OD) flows in trip unit. Then step 3 and step 4 are to examine how the traffic flows are distributed to the roads and among travel modes.

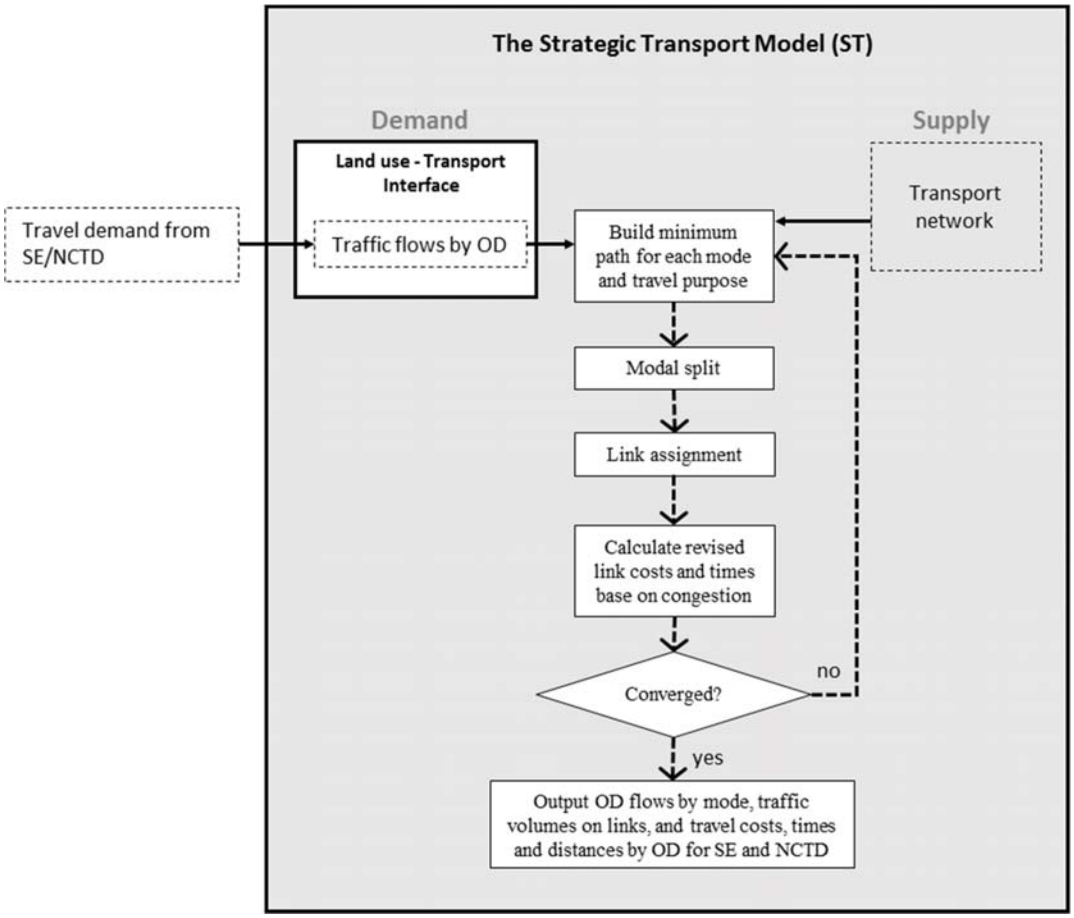


Figure 4-2 The Strategic Transport Model (ST) structure

4.4.1 Conversion of trade matrices to OD matrices in the land use – transport interface

The travel demand in SE and NCTD is in production-attraction matrix format. For example, the trade of commuting flows are in the format of number of employed workers required in attraction zone j from production zone i, but not in the format of number of trips. The following equations convert the production-attraction matrices into the number of trips by origin-destination for a particular time.

For commuting trips:

$$F_{ij} = \sum_{f} \left(\alpha_{ijf} \Phi_f T_{ijf} + \omega_{jif} \Phi_f T_{jif} \right) \qquad \text{[Equation 4-21]}$$

Where F_{ij} is the commuting trips during the morning peaks from zone i to zone j, which includes both outwards journeys generated by trade T_{ijf} from home zone *i* to work zone *j* for a socio-economic group *f*, and return journeys generated by trade T_{jif}. The amount of return journeys is usually very small. For example they are generated by people who take night shifts. α_{ijf} is the proportion of outwards trips, while ω_{jif} is the proportion of return trips. Φ_f is the average commuting trips rate per month of an employed resident in socio-economic group *f*.

For non-commuting trips, a similar equation is applied to convert trade to OD flows for the morning peak period:

$$F_{ij}^t = \sum_f \left(\alpha_{ijf}^t \delta_f^t T_{ijf}^t + \omega_{jif}^t \delta_f^t T_{jif}^t\right) \qquad \text{[Equation 4-22]}$$

Where F_{ijf}^t is the amount of type t trips for a typical week day morning peak from zone i to zone *j*. Other notations are similar to [Equation 4-21] . δ_f^t converts monthly trips into an average number of trips for a typical week day.

4.4.2 Modal split and network assignment

The ST model distributes trips between zones (inter-zonal trips) and within zones (intra-zonal trips) among different travel modes on each link, given a certain network supply. Given the total inter-zonal trip flows F_{ij}^t for a specific OD pair from *i* to *j*, the model distributes inter-zonal trips into modes based on a logit model:

$$F_{ijm}^t = F_{ij}^t \frac{e^{-\lambda_m^t D_{ijm}^t}}{\sum_m e^{-\lambda_m^t D_{ijm}^t}} \qquad \text{[Equation 4-23]}$$

$$D_{ijm}^t = \phi^t c_{ijm}^t + t_{ijm}^t + p_{jm}^t + \Omega_m^t \qquad \text{[Equation 4-24]}$$

Where F_{ijm}^t is the trips of type t from zone i to zone j on mode m. The modal disutility D_{ijm}^t consists of four elements: out-of-pocket travel cost c_{ijm}^t converted into time units through the marginal utility of money ϕ^t, travel time t_{ijm}^t, destination disutility (such as off-network travel time and parking fee) p_{jm}^{t}, and modal specific constant Ω_{m}^{t} (Jin et al. 2002). λ_{m}^{t} is the concentration parameter for inter-zonal mode choice.

For intra-zonal trips, the modal split step is a logit based hierarchical discrete choice model (Jin et al. 2002). Given the total intra-zonal flows F_{ij}^{t}, the model firstly splits intra-zonal trips into distance ranges and then into modes within each distance range. The modal disutility function within each band $D_{ijm|B}^{t}$ consists of four elements, the same as the inter-zonal modal disutility function. The disutility function for each band *B* is a log-sum of the disutility on modes:

$$D_{ij}^{Bt} = \frac{-1}{\lambda_{m|B}^{t}} \ln \sum\nolimits_{m} \exp\left(-\lambda_{m|B}^{t} D_{ijm|B}^{t}\right) + \Omega^{Bt} \qquad \text{[Equation 4-25]}$$

$\lambda_{m|B}^{t}$ is the concentration parameter for mode choice within each band. Ω^{Bt} is the band constant which is calibrated empirically. Then the model follows the basic form of a discrete choice model:

$$F_{ijB}^{t} = F_{ij}^{t} \frac{e^{-\lambda^{Bt}(D_{ij}^{Bt})}}{\sum_{B} e^{-\lambda^{Bt}(D_{ij}^{Bt})}} \qquad \text{[Equation 4-26]}$$

$$F_{ijBm}^{t} = F_{ijB}^{t} \frac{e^{-\lambda_{m|B}^{t}(D_{ijm|B}^{t})}}{\sum_{m} e^{-\lambda_{m|B}^{t}(D_{ijm|B}^{t})}} \qquad \text{[Equation 4-27]}$$

Where F_{ijB}^{t} is the number of trips of type *t* from zone *i* to zone *j* in band *B*. F_{ijBm}^{t} is the trips of type *t* from zone *i* to zone *j* in band *B* using mode *m*. λ^{Bt} is the concentration parameter for band choice. $\lambda_{m|B}^{t}$ is the concentration parameter for mode choice within a band *B*.

In order to assign flows on each link, the model first calculates the travel cost on each link. Then Dijkstra's algorithm is applied to find all the possible paths and the shortest path between the OD nodes in the network. A similar logit-based discrete choice model is used to assign the traffic flows onto the possible paths. There is normally a capacity restraint procedure to adjust travel time and re-assign traffic on network.

$$t = t_0 + f\frac{F}{C} \qquad \text{[Equation 4-28]}$$

t is the updated congested travel time on a link. t_0 is the free-flow time to start with. F is the estimated flow volume on the link and C is the link capacity. f is the capacity constraint parameter. However, in our ST model, we start with congestion link speed and keep this speed constant. In this way, the capacity restraint is skipped and total computing time is greatly reduced. The reasons that we use the constant congestion speed are: 1) we assume the government in our study area will try the best to maintain the current congestion level, not letting it get worse. 2) Historically the congestion speed turns to be relatively stable in big cities. 3) Applying congestion speed does not preclude the option of applying capacity restraint. With better road capability data, the restraint can be added in the future.

4.4.3 Access link and built-form

In this proposed model, we work with spatially aggregated data on a zonal level. That is to say, all activities are assumed to start from the zonal centroid. In inter-zonal travel, journey starts from a centroid and ends in another centroid (or the same centroid for intra-zonal travel). We are able to measure the travel cost and distance on each link, but unable to accurately measure the cost from/to the centroid to/from the road access node, where people begin to use the road. This is because the aggregate centroid does not accurately reflect the disaggregated locations of activities (Miller & Shaw 2001, p.212).

A common method to gauge this distance is to build a virtual access link from the centroid to the network. If travelling by car, traffic will be passed from the centroid to the nearest road access node, and through this node to links (see Figure 4-3). Then the model will compute the optimized paths to another zone. If travelling by metro, traffic will be passed from centroid to a certain station that can minimise the distance to the destination zone (see Figure 4-4). For example, if travelling from Zone A to B, the station at the right end of Zone A will be used. The access distance is the straight line distance from the centroid to the station.

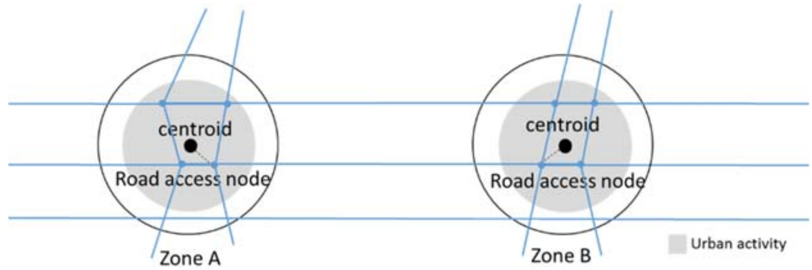


Figure 4-3 Building access link in homogenous urban area with ubiquitous roads

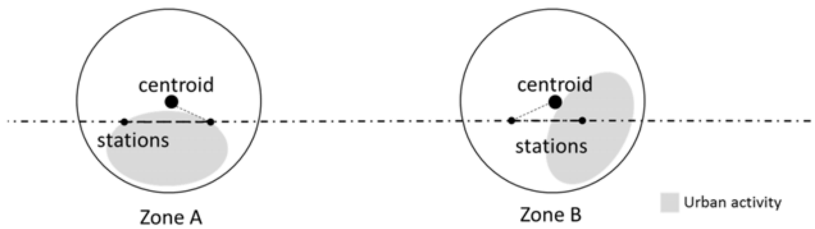


Figure 4-4 Building access link for stations

This widely-used method works well in the city zones with ubiquitous urban activities and ubiquitous roads. However, this common method needs improvement for the zones where road density is not as high as the city and built up patches do not distribute homogenously, for example, in the greenbelt zones. In such zones, the access link length includes a large proportion of distance of "not-on-link" travel (see Figure 4-5). In that case, the common method of using the nearest road nodes or stations should be improved.

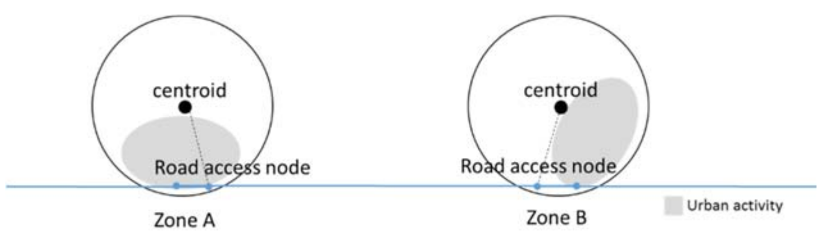


Figure 4-5 Building access link in heterogeneous urban area with sparse roads

In practice, it is unrealistic and impractical to measure built-up patches one by one to find the access link length. Therefore, one of the solutions is to relate the access links length to the geometric features of the zone, namely the radius, in order to estimate the access link length change due to *built-form* change. In such a way, although the land use information is inadequate, we can still obtain a reasonable gauge of the access link length.

Built-form in this research is defined as a group of zonal characteristics, including the density and layout of transport network, the density of the built-up area in the zone, and how close the built-up areas are to the transport network. These characteristics are selected because they have been identified to have impact on travel behaviour (Miller et al. 1999).

Defining the built-form for each zone is a case by case matter. After tracing the road layout, locations of metro stations, locations of built-up patches in the greenbelt zones in our study area, we categorise the greenbelt zones into 3 built-forms: 1) low density rural houses with sparse road; 2) relatively ubiquitously built-up patches in medium to high density with enough road provision; 3) relatively densely built-up only around stations while roads are sparse elsewhere. For the greenbelt zones where the conventional method to calculate access link length requires improvement, the following equation is applied:

$$A_l = a_l r \qquad \text{[Equation 4-29]}$$

Where A_l is the access link length for built-form l. r is the radius of the zone. a_l is the ratio of access link length to radius for built-form l. a_l is calculated using a generic urban form model (Holroyd 1966).

4.5 Recursive Dynamic Model (RD)

As the greenbelt is a long-lasting planning policy and it has cumulative effects over time, the model needs to collate the temporal dimension, so that the slow market changes of building stocks and transport network can be captured. The Recursive Dynamic Model links the cross-sectional SE, NCTD and ST across time periods, by updating constraints for the next cross-sectional simulation.

The constraints which are treated as exogenous for the cross-sectional models (SE, NCTD and ST) are the floorspace, locations of non-employed households and transport infrastructure provision. The total floorspace stocks remain exogenous for any model year while the zonal floorspace stocks are updated periodically by RD. The locations of non-employed households are updated periodically by RD as well. The transport infrastructure provision is updated periodically according to the policy variation in RD.

4.5.1 Floorspace stock update

As a city grows, the newly built floorspace stocks will take place subject to regulation, planning, speculation, procurement, construction/renovation, commission and decommission, and inertia (Jin et al. 2013). The total floorspace stock is user-defined, because this is likely to be the most appropriate in order to reflect policy targets. On a zonal level, the Recursive Dynamic Model distributes the total floorspace stock, subject to the spatial pattern from the last decade in SE and the background policy trend. Then the updated floorspace stocks from RD are subsequently used in the next decade SE as constraints. The zonal floorspace for a certain type is described in the equation below:

$$B_{ki}^{T+1} = B_{ki}^{T} + nB_{k}^{T\rightarrow T+1}\frac{B_{ki}^{T}}{\sum_i B_{ki}^{T}} + (1-n)B_{k}^{T\rightarrow T+1}\frac{\exp(\lambda_b V_{ki})}{\sum_i \exp(\lambda_b V_{ki})} \qquad \text{[Equation 4-30]}$$

B_{ki}^{T} is the zonal floorspace stock at zone *i* for time *T*. B_{ki}^{T+1} is the zonal floorspace stock at zone *i* for the next time section *T*+1. $B_{k}^{T\rightarrow T+1}$ is the total regional stock change of floorspace from time *T* to *T*+1 defined exogenously. This equation considers not only the stock durability and development inertia, but also the policy variables. The added regional stock $B_{k}^{T\rightarrow T+1}$ is split into two parts: natural growth $nB_{k}^{T\rightarrow T+1}\frac{B_{ki}^{T}}{\sum_i B_{ki}^{T}}$ and added growth $(1-n)B_{k}^{T\rightarrow T+1}\frac{\exp(\lambda_B V_{ki})}{\sum_i \exp(\lambda_B V_{ki})}$. n is a user-specified portion of natural growth. The zonal natural growth is proportional to the existing stock size. The zonal added growth distribution follows a logit model with a concentration parameter λ_b.

V_{ki} is a non-stochastic location-based utility. The variables selected to represent this utility are a case-by-case matter. Here we follow Wan (2016)'s specification.

$$V_{ki} = \beta_1 \ln \sum\nolimits_k B_{ki}^{T} + \beta_2 \frac{\bar{R}_{ki}^{T}}{\bar{R}_{D}^{T}} + \beta_3 \mathcal{D}_{ki}^{T} + \beta_4 M_{ki}^{T} + \beta_5 \beth_{ki} + E_D \qquad \text{[Equation 4-31]}$$

Variables in the equation are respectively the existing zonal stock size $\sum_k B_{ki}^T$, average rent over provincial average rent $\frac{\bar{R}_{ki}^T}{\bar{R}_D^T}$, zonal floorspace density $\mathcal{D}_{ki}^T$, economic mass M_{ki}^T, policy dummy variable $\beth_{ki}$ and provincial residual term E_D.

4.5.2 Non-employed household location update

Non-employed households do not have to make employment-residence locational choices. Their movement is slower compared to the employed households. Therefore, their locational choices are not modelled under the spatial equilibrium assumption, but in the Recursive Dynamic Model. The total change of non-employed households $H^{T\to T+1}$ remains as exogenous input. The zonal number of non-employed households H_i^{T+1} for year *T*+1 is represented in a logit form:

$$H_i^{T+1} = (1-\rho)H_i^T + (\rho H_i^T + H^{T\to T+1})\frac{\exp(\lambda_H \upsilon_{Fi})}{\sum_i \exp(\lambda_H \upsilon_{Fi})} \quad \text{[Equation 4-32]}$$

H_i^{T+1} is split into two parts. $(1-\rho)H_i^T$ represents those who remain in the same locations as they were in year *t*. $(\rho H_i^T + H^{T\to T+1})\frac{\exp(\lambda_H \upsilon_{Fi})}{\sum_i \exp(\lambda_H \upsilon_{Fi})}$ represents those who make new locational choices. ρ is the proportion of non-employed households who choose to relocate. υ_{Fi} is the observed location utility for non-employed households. Its components are defined in [Equation 4-14]. υ_{Fi} does not consider commuting disutility, but only includes consumption utility V_{Fi} and residual attractor E_{Fi}.

4.5.3 Transport supply update

Transport condition evolves over a long time span. Transport construction is classified as a very slow urban change process (Simmonds et al. 2013; Wegener et al. 1986). Major transport constructions tend to be the most durable and irreversible urban changes. This is due to the heavy investments in the transport infrastructure for example roads, railways and metro lines. Such efforts are always done by the government. Therefore, the most appropriate way to update the transport supply, namely the network in the model, is to add or demolish infrastructure according to the long term official development plan.

The greenbelt zones may change their built-forms to represent policy variables. This built-form change is captured in the access link length change.

Besides the network change which is updated periodically as exogenous inputs, as income level grows, price related parameters need to be updated. The marginal utility of money ϕ^{tT} is to measure how sensitive people are to the out-of-pocket travel cost given certain income level, which is updated with income level changes endogenously. Other price related parameters, for example, petrol price, bus and metro ticket price, remain unchanged. This is because we assume the government in the study area will maintain the petrol price stable and continue to subsidise public transport heavily. Moreover, the monetary costs are not the dominant factor to determine travel disutility. Even if the prices for petrol and public transport will increase in the future, they do not seem to overturn the main modelling results.

4.6 Model Assembly

Some urban activities turn to change more quickly than others. For example, the labour mobility, residential mobility and daily pattern of trips respond to shock in less than a year's time (Wegener et al. 1986). Such changes are captured by the cross-sectional models SE, NCTD and ST. They offer a platform to compare performance of policy scenarios at a cross-sectional time horizon.

Meanwhile, some other urban activities are more inertia-prone and change slowly. For example, the construction of buildings and infrastructure may take several years and then there might be a delay from the decision to investment and completion. The entire project could take as long as 10 years to complete. RD represents such slow changes over a long time period. It links the independent cross-sectional time horizons and updates building stock and transport supply constraints periodically.

In the following section, we will first present how SE, NCTD and ST are linked for a LUTI simulation within one time horizon. Then we present how RD links the several time horizons.

4.6.1 Land use and transport interaction for a cross-sectional year

The generic LUTI model explores interactions between urban activities, transport demand, land supply and infrastructure supply. On the land use side, urban activities generate travel demand so that people and goods can move within and between different zones. On the transport side, travel costs affect people's locational choice and therefore affect land use patterns. Traffic flows generated by the land use model are substituted into the transport model. At the same time, the transport model generates updated travel times, costs and distances which feed back into the land use model. In this way, an equilibrium is reached.

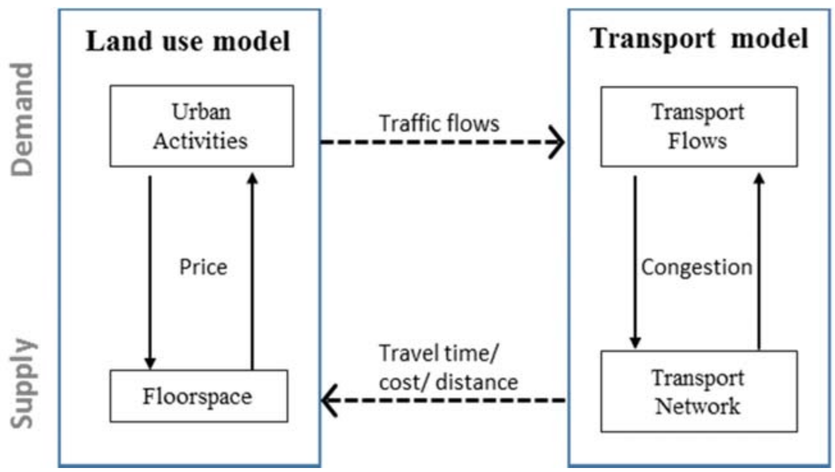


Figure 4-6 Generic LUTI framework

Base on this generic form, we assemble the three models (SE, NCTD, ST) to represent a cross-sectional year (Figure 4-7). SE and NCTD are the land use models which predict locations of activities and generate travel demand. ST is the transport model which generates travel costs, times and distances. The travel matrices are the driving forces for locational choice in the land use models.

The cross sectional simulation starts from ST. Given the transport network, it outputs travel cost and travel time matrices for the two land use models. Then the SE model calculates the employment and residential location choice for employed residents based on spatial equilibrium assumptions. SE offers the employment-residence locations, together with exogenous non-employed household locations from RD, for NCTD to generate non-commuting urban activities. The combined commuting and non-commuting travel demands by OD pair are converted into trips through a land use-transport interface. The trips are then used as inputs in ST, for modal split and link assignment. Given the amount of flows on each link, ST calculates congestion levels and adjusts travel times, costs and distances matrices. The updated travel matrices will be input into the two land use models for a new iteration until the LUTI model reaches an equilibrium.

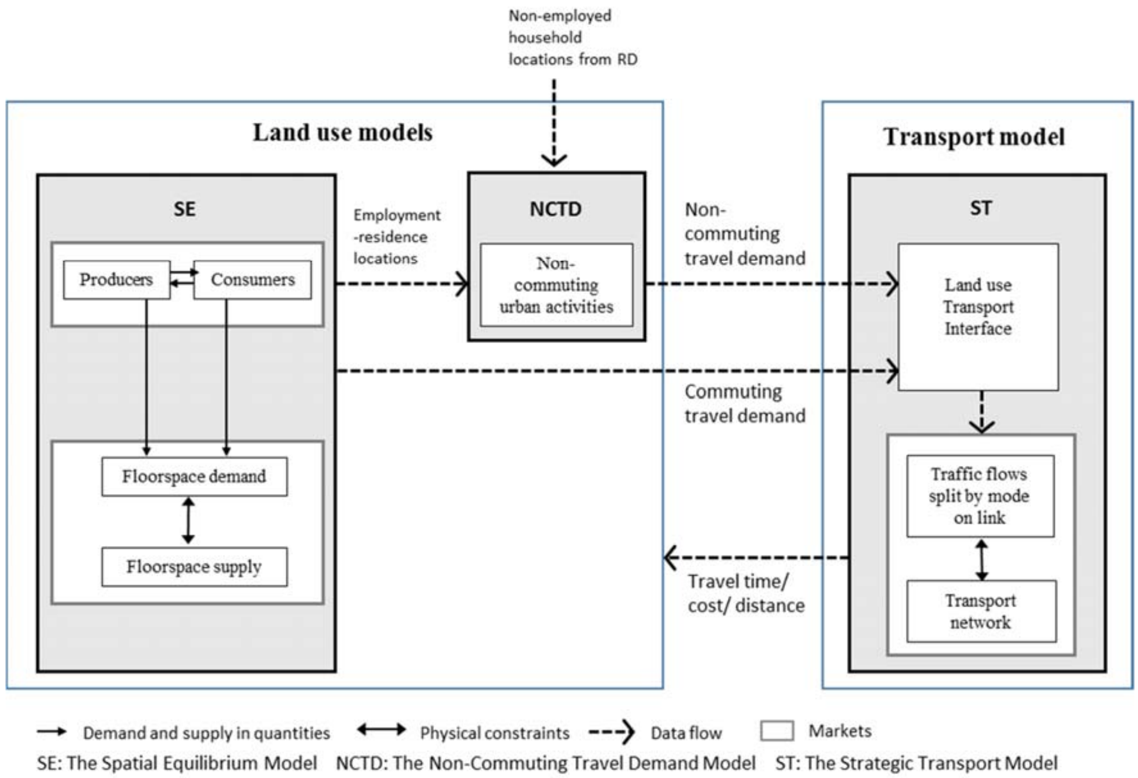


Figure 4-7 LUTI model assembled for a cross-sectional year

We recall that in 4.4.2, the congestion speed is used for the current model package. Therefore, the travel matrices that ST gives at the starting point will remain unchanged after the first iteration. At this stage, there is no need to run the land use sub-model and the transport sub-model iteratively as the travel times, costs and distances matrices are not updated after the second ST run. Of course, obtaining the congestion speed is a great challenge for transport modellers. Methods and processes are reported in detail in Deng (2015).

4.6.2 Modelling urban change through time

An appropriate articulation of the model components through temporal dimensions has to be considered for model calibration, validation, and forecasting (Jin 2013) (Figure 4-8). The proposed recursive LUTI model starts with a cross-sectional year static run. This is normally the base year. In the base year, the models (SE, NCTD, ST) run under calibration mode and model predictions are compared with known zonal quantities and prices to refine the parameters. The parameters will be validated and re-estimated. The validation normally requires a second observed cross-sectional year to test the suitability of the calibrated parameters. The calibration-validation loop may have to be repeated many times until a satisfactory goodness of fit has been achieved. After validation, the parameters are then accepted for future year cross-sectional runs; the prediction results will be used for the Recursive Dynamic simulations in order to draw boundary conditions for the next cross-sectional year.

The base year provides a starting point to initiate the RD model. The RD model updates 3 types of constraints: the floorspace stocks, the locations of non-employed households, and the transport network. The floorspace stock update requires the information from the base year, including the existing floorspace stock, rent, density, and economic mass. The update also considers the user-defined policy variables. The non-employed household update requires the locational information from the base year. The network update considers the exogenous policy variables such as infrastructure construction and demolition, and also the built-form change at the micro level.

An effective way to calibrate and validate the RD model is to extend the cross-sectional runs through time. Ideally, it requires at least 3 cross-sectional years to calibrate and validate RD. The parameters for RD will be calibrated based on year 1 and year 2, and validated using year 3 (or even more years).

As RD updates the boundary conditions for the next cross-sectional simulation, the LUTI package will follow the ST-SE-NCTD-ST sequence as discussed in 4.6.1, but this run will be under the prediction mode. The difference between running the model in calibration mode and prediction mode is: Calibration mode calibrates the parameters to match the observed data; prediction mode uses the parameters from the calibration mode to predict future scenarios. In prediction mode, the modeller may also intervene and revise the boundary conditions and some parameters to represent policy interventions.

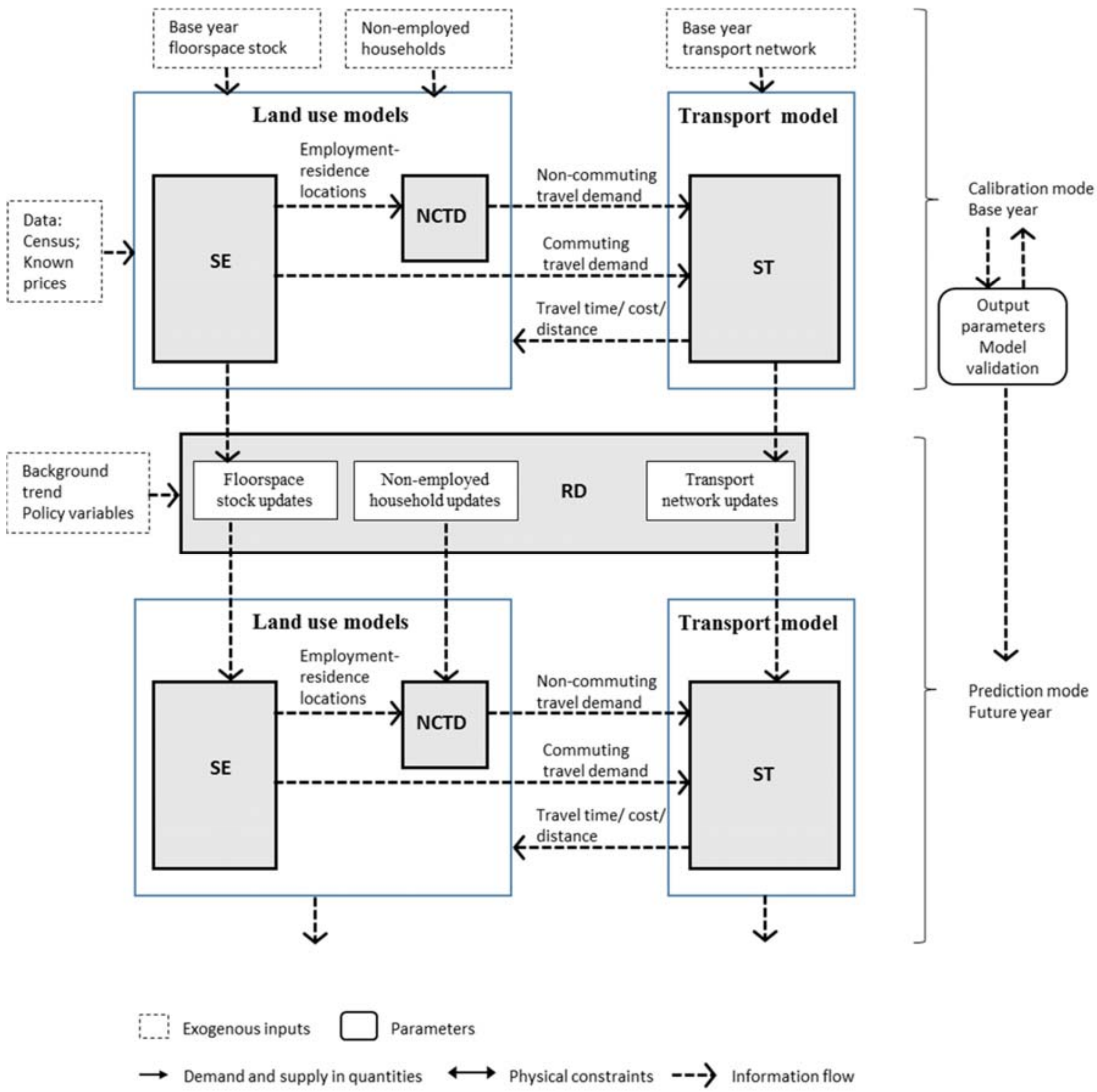


Figure 4-8 LUTI model assembly through time

4.6.3 Model outputs

The main land use model outputs show the average economic productivity and household utility under different policy trends. Such economic indices can be presented either in quantities or in prices by zone. The main outputs from SE include zonal number of population and employment, rents, wages, household utility by socio-economic group. The main outputs from NCTD include the travel demands for shopping, educational and other personal trips by socio-economic group.

The transport model outputs show the balance of travel demand and supply under different policy trends. The main outputs from ST include the average travel times, distances and costs by socio-economic group and by travel purpose, the travel mode share, the flow volume on each link (roads, railways and metro lines).

The RD model outputs show the development inertia. It gives the floorspace stock update, transport network update, and non-employed household locational choices as the main outputs. The outputs from the 4 sub-models provide the basis for assessing economic and social impacts of the greenbelt policy scenarios.

CHAPTER 5 THE GREATER BEIJING LUTI MODEL

5.1 Overview of the model

The theoretical sub-models proposed in the last chapter follow four well-established model traditions, but the newly assembled LUTI model still needs thorough real-world tests. This chapter applies the theoretical LUTI model to one of the world's largest and fastest growing city regions – Greater Beijing. This region had a population of 110.5 million (8% of the national total) in 218,363 km^2 (2% of the national total) in 2014. The total gross regional product in 2014 was 6647.89 billion yuan (10% of the national total) (National Bureau of Statistics of China 2016).

In this chapter, firstly, we define the geographical and temporal dimensions of the Greater Beijing LUTI Model. Then we discuss the settings of parameters and boundary conditions for the four sub-models: Spatial Equilibrium Model (SE), Non-commuting Travel Demand Model (NCTD), Strategic Transport Model (ST) and Recursive Dynamic Model (RD) respectively in section 5.2 - 5.5. A calibration is then put forward to link the sub-models and refine the unknown parameters in section 5.6. Finally, sensitivity tests are carried out to investigate how this assembled model responds to changes in section 5.7.

5.1.1 Extensions of the existing models for Greater Beijing

The proposed new Greater Beijing LUTI Model is developed based on the existing models developed in the Martin Centre at the University of Cambridge, including the Beijing-Tianjin-Hebei City Region Model (Wan 2016) and The Greater Beijing Strategic Transport Model (Deng 2015). This new model is more complete compared to the existing models in the following aspects:

1) This model links the land use and transport simulations to an equilibrium status and establishes feedback loops between the two markets. The transport inputs in terms of zone to zone travel times, costs and distances are endogenously generated from the

transport model to the land use model, while the employment-residence location inputs as travel demands are endogenously generated from the land use model to the transport model.

2) This model extends the urban activities from only commuting related employment-residence locational choices to all urban activities.

3) This model makes incremental changes to the transport network and allows the modellers to study scenario variances in the network, by adding a built-form component.

4) Compared to the existing models, this model is well-calibrated using newly published data (Beijing Transportation Research Centre 2016), in terms of travel speed, distance, trip range distribution and travel mode share.

5) This model extends the temporal dimensions of the existing Greater Beijing models. It adds a cross-sectional year 1990, so that a pre-greenbelt year can be modelled and compared with later modelling years after the greenbelt policies were launched.

5.1.2 Geographical extent and zoning

The Greater Beijing in this research is defined as the region that covers the whole Beijing Municipality, Tianjin Municipality and Hebei Province (Jing-Jin-Ji Area). The central government has announced the Master Plan of Jing-Jin-Ji Integrated Development in 2015 (Central Political Bureau of China 2015), which emphasises that regional integration is crucial for solving the overcrowding and environmental challenges in Beijing and enhancing sustainable development in the whole region.

	Beijing	Tianjin	Hebei	JJJ Regional Total
Population (million)	21.5	15.2	73.8	110.5
Percentage of regional total	19%	14%	67%	100%
Gross regional product (billion yuan)	2133.1	1572.7	2942.1	6647.9
Percentage of regional total	32%	24%	44%	100%

Table 5-1 Population and GRP in 2014 Source:(National Bureau of Statistics of China 2016)

Major cities in the region are connected by high-speed railways. For example, the two municipalities are connected by a 161 km long inter-city high-speed rail line which shortens the travel time between the two city centres to 30 minutes. There are also other high-speed railways which have been built or under construction. The high speed railways connect Beijing to other major cities in Hebei Province (Baoding, Langfang, Cangzhou, Shijiazhuang, Zhangjiakou, Chengde), which are expected to promote inter-city commuting and accelerate economic integration. However, in the foreseeable future, Beijing, as the capital of China, is still the dominant city of the region. Therefore, the Greater Beijing LUTI model narrates Beijing in a finer granularity, subject to data availability.

The whole model consists of 209 zones according to the existing administrative boundaries and transport links.

Beijing Municipality is divided into 130 zones with detailed road network. They are *core zones* in the modelled area, which means these zones are divided into fine geographic granularity based on the smallest administrative boundaries subject to data availability. The core zones are spatially close the greenbelt and they are where the greenbelt has direct impacts on.

There are 28 zones at Beijing's urban fringe selected out of core zones as *greenbelt zones* for policy test purposes. The zone sizes are relatively large compared to the most core zones due to data availability, but the intra-zonal scale policy variances are allowed to be tested, through the built-form component.

Tianjin Municipality is divided into 22 zones mainly based on the administrative boundary. Hebei Province is divided into 57 zones. The major regional hubs in Hebei Province are extracted as independent zones, while other zones in Hebei are highly aggregated. The Tianjin and Hebei zones are *peripheral zones*. Although they exchange population and traffic with core zones and greenbelt zones, but the peripheral zones are not where the main exchange happens. They are included in order to represent the impacts of the greenbelt on the Greater Beijing regional scale, and to test if the greenbelt facilitates the cross city boundary movement of population and employment.

All the four sub-models share the same zoning, so that simulation results from any sub-model can be used directly as inputs/outputs for the others without discrepancy.

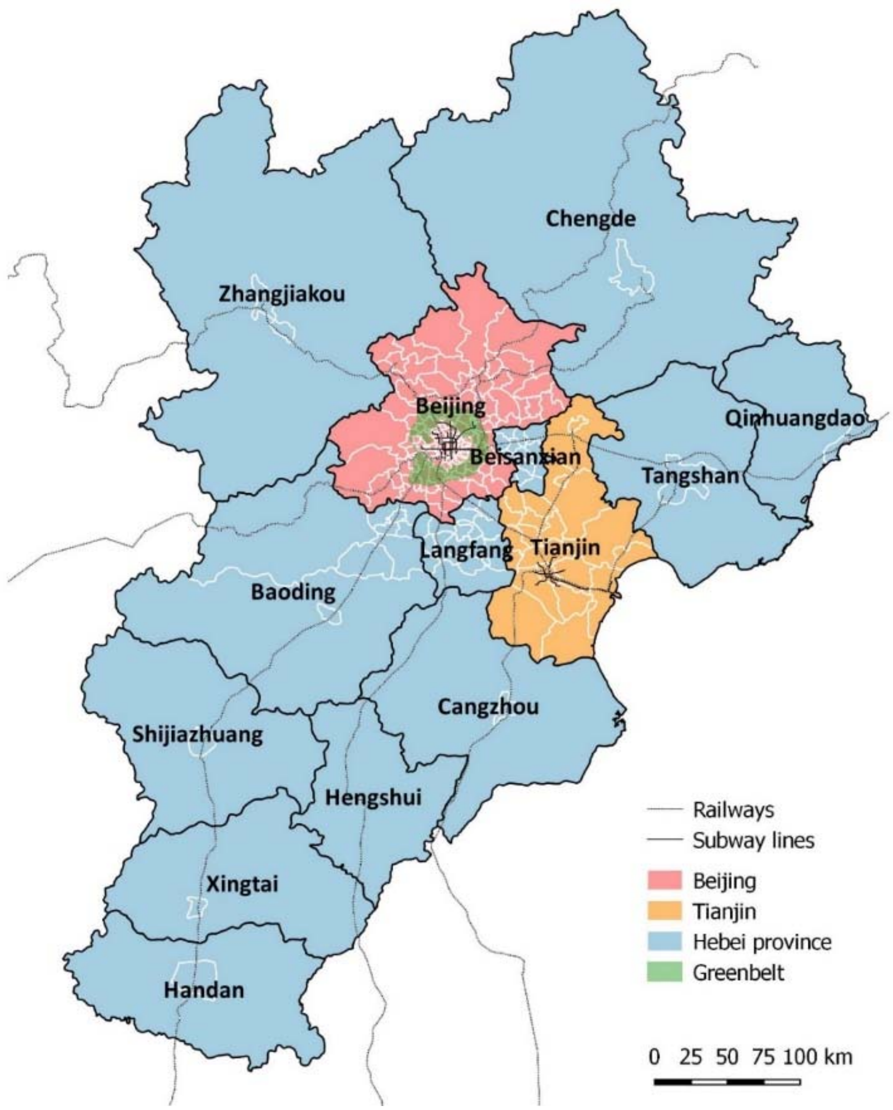


Figure 5-1 Zones, railways and metro lines in 2010

5.1.3 Temporal dimension of the model

The purpose of building this Greater Beijing LUTI Model is to understand the effects of the greenbelt, by reviewing the policy historically and testing alternative configurations for future. The first greenbelt policy was introduced in 1994, followed by the second greenbelt policy in 2003. Therefore, it is necessary to start the model with a year before the first greenbelt policy, so that the effects of the first greenbelt can be captured. A cross-sectional year 1990 is therefore introduced. The model starts from 1990 and covers 4 decades till 2030. It is divided into two time periods, and year 2010 is the threshold.

The first period of the model covers 3 time horizons: years 1990, 2000 and 2010. The purpose of running the model from 1990 to 2010 is to review the two historic greenbelts policies (launched in 1994 and 2003). Such a retrospective simulation from the modelling perspective has not been done in Beijing. It will provide a better understanding for designing future greenbelts. Due to the data availability for this time period, we simplify this model to represent only Beijing Municipality with only one socio-economic group. We only apply the Spatial Equilibrium Model for this time period. The impacts of the two greenbelts on population and job distribution, rents and utility can be quantified through SE.

The second period of the model covers 3 time horizons: years 2010, 2020 and 2030. The purpose of this simulation is to predict the performance of future greenbelts and assess alternative configurations. This period of the model covers the Greater Beijing area with 3 socio-economic groups and 3 types of housing. We do not extend the model beyond year 2030, because the official infrastructure plan only predicts that far. Beyond 2030, there is no information to update the transport network for the transport model. All the 4 sub-models are applied to this time period, so that a more complete investigation of the greenbelt's impacts can be carried out.

For the first period, year 1990 is the base year for the simplified retrospective model. However, the data for year 1990 are not well-documented enough for running all the four sub-models in prediction mode. For the model predictions to be valid and accurate, when running the second model period from 2010 to 2030, we use year 2010 as the base year.

	Model period 1990 - 2010	**Model period 2010 - 2030**
Modelling area	Beijing	Beijing, Tianjin, Hebei
Socio-economic groups	1	3
Housing types	1	3
Transport network	Static	Update every ten years
Sub-models applied	SE	SE, NCTD, ST, RD

Table 5-2 Modelling periods

5.2 The Spatial Equilibrium Model (SE) settings

Boundary conditions need to be set for the Spatial Equilibrium Model. These include the total number of residents and workers, the floorspace constraints, and the wage levels. There is one type of residents and workers before 2010 and from 2010, the socio-economic groups are extended to 3 types. Similarly, there is only one type of floorspace before 2010, and the types are extended to 3 types after 2010. There is always only one type of composite goods and services.

5.2.1 Residents and workers 1990-2010

For the years 1990, 2000 and 2010, the zonal numbers of employed residents and workers are required for calibration purpose. Zonal data for the year 1990 are derived based on the census and database in the Beijing 60 Years Development Report 1949-2009 (Beijing Bureau of Statistics & NBS Survey office in Beijing 2009). The derivation algorithm and the data verification method for the 1990 zonal data will be presented in section 6.2.2 in detail. Data for 2000 and 2010 are from Rong (2016). Rong compared various sources to eliminate possible biases caused by different statistical calibres.

Year 2010 is the ending year for the 1990 – 2010 retrospective simulation. It is also the starting year for the future policy tests. Therefore, the 2010 data are extended to the whole Greater Beijing region in a finer granularity. According to the income level, education level and occupation, Rong (2016) differentiated the employed population into three socio-economic groups for year 2010 for Beijing, namely high, middle and low. Tianjin and Hebei have only one type of composite socio-economic group, who shares the same behavioural preferences as the middle group in Beijing. This classification has been used in the existing models for Greater Beijing, including Deng (2015) and Wan (2016). Therefore, we follow the same socio-economic group stratification.

The total numbers of employed residents and workers are summarised in the table below. Please note that we collect the number of workers in units of people, not in units of jobs. The total number of employed residents equals the total number of workers.

	Beijing			**Tianjin**	**Hebei**	**Total**
1990	6,271,000			/	/	/
2000	7,116,587			/	/	/
2010	11,805,556			7,287,000	38,651,400	57,743,956
	high	middle	low			
	1,865,939	6,678,491	3,261,127			

Table 5-3 Numbers of employed residents and workers 1990 – 2010

Non-employed households are not modelled before 2010. For 2010, the zonal number of non-employed households can be found in census. For each non-employed household, there are constantly 2.33 non-employed people. This number is derived from the long sheet data in census. For those people who are not employed but in an employed household, they will be modelled in NCTD. The locational choice of non-employed household is modelled in RD. The composition of the 2.33 non-employed people in non-employed households and their travel behaviour will be explained later in the NCTD model.

	Beijing	**Tianjin**	**Hebei**	**Total**
Number of household	950,089	1,568,320	3,210,214	5,728,623
Number of people	2,213,707	3,654,186	7,479,799	13,347,692

Table 5-4 Numbers of non-employed households/people

5.2.2 Floorspace stocks 1990-2010

For year 1990 and 2000, the types of housing floorspace are not classified. For the year 2010, housing floorspace in Beijing are classified into 3 types: large, medium and small, according to their sizes. The zonal floorspace stock by type for 2000 and 2010 is calculated based on the average housing space per household from the long sheet data in census (see Rong 2016 for the detailed calculation method). For the 1990 floorspace data, we use historic maps and building permit data from 1953-2003 from the Beijing Planning Institute to estimate them.

Housing floorspace stock (million m^2)		Beijing		Tianjin	Hebei	Total
1990		169.7		/	/	/
2000		284.8		/	/	/
2010		575.3		547.1	2436.0	3558.4
	large	medium	small			
	43.2	460.4	71.7			

Table 5-5 Housing floorspace stocks1990 - 2010

We do not classify business floorspace types, so there is always one type of building floorspace for any cross-sectional year. There are no explicit data showing the actual number of business floorspace in Beijing. In the existing models, this number was derived from the number of workers, by assuming each worker occupies 20 m^2 working floorspace. Hereby we follow this method and obtain the business floorspace in 1990.

Business floorspace stock (million m^2)	Beijing	Tianjin	Hebei	Total
1990	125.4	/	/	/
2000	142.3	/	/	/
2010	237.6	146.6	773.0	1157.2

Table 5-6 Business floorspace stock 1990 - 2010

5.2.3 Average income 1990-2010

Average income level defines the total amount of spendable money in the modelled area. This is the income per modelled resident, which includes the employed residents and non-employed residents (only in non-employed households). The income per worker and the disposable income (wage and non-wage) on the municipal or provincial level is accessible in the statistical yearbook. We then calculate the weighted average income per resident for Beijing (1990 - 2010) or for the Greater Beijing area (2010). Price levels are converted to 2010.

Year	Average income (Yuan)
1990	3,871
2000	8,641
2010	22,246 (Beijing)
	14,251(Greater Beijing)

Table 5-7 Average income level 1990 – 2010

The Spatial Equilibrium Model has been calibrated and validated in the existing Beijing-Tianjin-Hebei City Region Model (Wan 2016). The modelling year 2010 in the new Greater Beijing LUTI Model can borrow the parameters from the existing model, regarding the consumption and production input shares, the locational choice preferences and the elasticities of substitutions. The 1990 model also borrows most of the parameters with some changes in consumption structure (Ma & Jin 2015). We highlight the key parameters used in SE in Appendix A.

5.3 The Non-commuting Travel Demand Model (NCTD) settings

The NCTD model first converts employed individuals from the SE model to households. Then it generates non-employed individuals from households into the categories that are directly linked to travel demand segments. We first describe the matrix used to compose a household. Then we explain how the non-employed individuals and non-commuting activities are generated based on the travel demand segments in Beijing.

5.3.1 Household composition and individual generation

Households are modelled as the combination of persons. The household composition matrix a^{hf} in 4.3.1 defines the number of different types of employed residents in each employed household type. The a^{hf} matrix is defined at the provincial/municipal level. The differences of composition among zones in the same province or municipality are ignored. The household composition matrix can be derived from the long-sheet sample data in census and statistical yearbooks.

Households type	Employed resident-High	Employed resident Middle	Employed resident -Low
		Beijing	
High	1.67	0.43	0.06
Middle	-	1.76	0.20
Low	-	-	1.41
		Tianjin	
Composite	-	1.88	-
		Hebei	
Composite	-	2.02	-

Table 5-8 Household composition matrix a^{hf} for employed residents in employed household in 2010

Employed households together with exogenous non-employed households generate non-employed individuals in the following types: children aged 0-5, children aged 6-17, retired and unemployed population. The coefficients are derived from census data and the statistical yearbook for Beijing (see Table 5-9). For Tianjin and Hebei, we currently do not have the composition of non-employed individuals in different types of households. We assume that the composition of non-employed individuals of Tianjin would be similar to that of the middle income group in Beijing; the composition of non-employed individuals of Hebei would be between Beijing's middle and low income groups. In this model version, we borrow the coefficients of Beijing's middle socio-economic group for both Tianjin and Hebei. The coefficients can be changed when more data are available. Hebei's composition of non-employed individuals will not affect the main testing results regarding the greenbelt impacts, because (1) the model allows for specific zonal adaptions of the model parameters; (2) zones in Hebei are large, there are few inter-zonal non-commuting trips.

Households type	Children aged 0-5	Children aged 6-17	Retired	Unemployed	Total
High	0.067	0.132	0.333	0.129	0.66
Middle	0.068	0.134	0.338	0.132	0.67
Low	0.106	0.210	0.530	0.206	1.05
Non-employed	0.019	0.382	1.580	0.352	2.33

Table 5-9 Non-employed individual generation matrix a^{cf} in 2010

Apart from the individuals generated by the households, there are also individuals considered as exogenous individual inputs: college students and floating population. Beijing is the capital city where top universities concentrate. It also attracts many visitors for business or tourism purposes, which are a non-negligible part of travel demand estimation. Data regarding college students are recorded in the census. Floating population is estimated based on the statistical reports from the public security department.

5.3.2 Travel demands segments

According to the Beijing Travel Surveys carried out in 2012 and 2016, travel demands are segmented into 4 major parts: going to work, going to school, business travel, and other personal trips (shopping, visiting friends, visiting family, etc.). Following the travel demands segments, trips are classified into 4 broad *flows*, in line with the BTRC reports (Beijing Transportation Research Centre 2012; Beijing Transportation Research Centre 2016): commuting trips, education trips, business trips and other trips (including shopping trips and personal trips). Commuting trips are generated from SE given the employment-residence locations. Non-commuting trips are generated from NCTD. Trips are generated independently at the origins and have no interactions between flows. For each travel purpose, trips are further divided into 3 socio-economic groups. In total, 12 flows are generated by travel purpose and socio-economic group. For Tianjin and Hebei, there is no further classification of socio-economic groups. The one composite socio-economic group shares the same behavioural preference as Beijing's middle group. College students and floating population do not belong to any household, so they are treated as exogenous inputs. The generation flowchart is summarised in Figure 5-2.

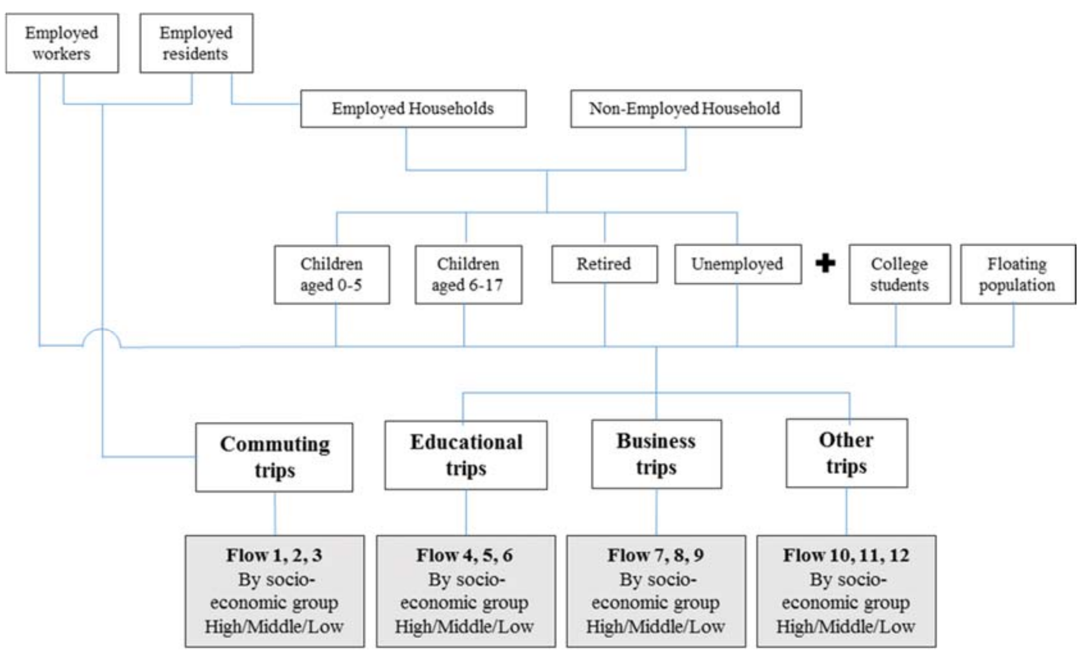


Figure 5-2 Flowchart of flow generation

5.3.3 Non-commuting trade generation

The trade generation coefficient matrix a^{tc} is calculated from observed data. Here we unify the socio-economic groups and use one set of coefficients to describe children, retired people and the unemployed from different socio-economic backgrounds. It is understandable that their behaviour will not be much different across socio-economic groups.

Individual type	School trip	Business trip	Other trip
Employed worker	0	4.35	0*
Children aged 0-5	0	0	0
Children aged 6-17	49.1	0.2*	7.9
Retired	0	0.4	58.4
unemployed	0	0.6	53.1
College student	49.1	0.2	7.9
Floating population	0.1	6.1	25.3

*We do not have data showing the number of other trips generated by employed workers. However, we believe the number of such trips in morning peak is few.

*The age limit for employment in China is 16. The 0.2 trip/month is from employees aged 16-17.

Table 5-10 Trip generation matrix a^{tc} (unit: number of trips per month)

The non-commuting trip concentration parameters λ^t [Equation 4-19] are calibrated based on the observed average journey length in Beijing. Table 5-11 summarises the trip concentration parameters for each flow.

Flow number	Description	Concentration parameter λ^t
4	Journeys to school (high socio-economic group)	2.55
5	Journeys to school (middle socio-economic group)	2.55
6	Journeys to school (low socio-economic group)	2.55
7	Business trips (high socio-economic group)	1.80
8	Business trips (middle socio-economic group)	1.80
9	Business trips (low socio-economic group)	1.80
10	Other personal trips (high socio-economic group)	2.05
11	Other personal trips (middle socio-economic group)	2.05
12	Other personal trips (low socio-economic group)	2.05
Source	Own calibration using observed trip distance	

Table 5-11 Non-commuting trips distribution parameter λ^t

5.4 The Strategic Transport Model (ST) settings

ST is different from the existing Greater Beijing Strategic Transport Model (Deng, 2015) in the following aspects: 1) Deng's model had a systematic error in measuring road lengths, which caused the road lengths to be 26% more than the actual distance. ST corrects this error caused by the projected coordinate system in ArcGIS. 2) ST confines the travel modes allowed on certain roads, rails and access links. This eliminates the chance that the model chooses a short-cut route. Before this confinement, for example, a traveller could drive a car through an access link built for a metro station. 3) ST calibrates the modal choice and bands choice based on the newly released data from the 5th Beijing Transport Survey Report (Beijing Transportation Research Centre 2016). It also calibrates the trip distance of Tianjin and Hebei.

Although there are transport models for Beijing based on numerous small zones with finer networks, for example models built on traffic analysis zones (Long & Shen 2015), ST has the same zoning system as SE and NCTD. Adopting relatively aggregated zoning in the transport model avoids the data needs that cannot be met currently and makes the model computation times relatively short, so that the modelling work can be completed within the timeline. The problem of a much higher share of intra-zonal trips is mitigated through the differentiation of intra-zonal distance bands for all modes. Of course, this large zoning system sacrifices some spatial detail and so it has a limited capability for testing small scale local network improvements. This is an area where future improvement will be required when data availability becomes better.

5.4.1 Inter-zonal network

The base year 2010 network is built upon Open Street Map. Inter-zonal networks are classified into road, metro and rail. For each type of network there are different subtypes to represent speed and capacity on each link. Obtaining network speed is always a challenge for transport modellers. The method used to estimate the congestion network speed from low-frequency GPS taxi traces of Beijing can be found in Deng, Denman and Zachariadis (2015).

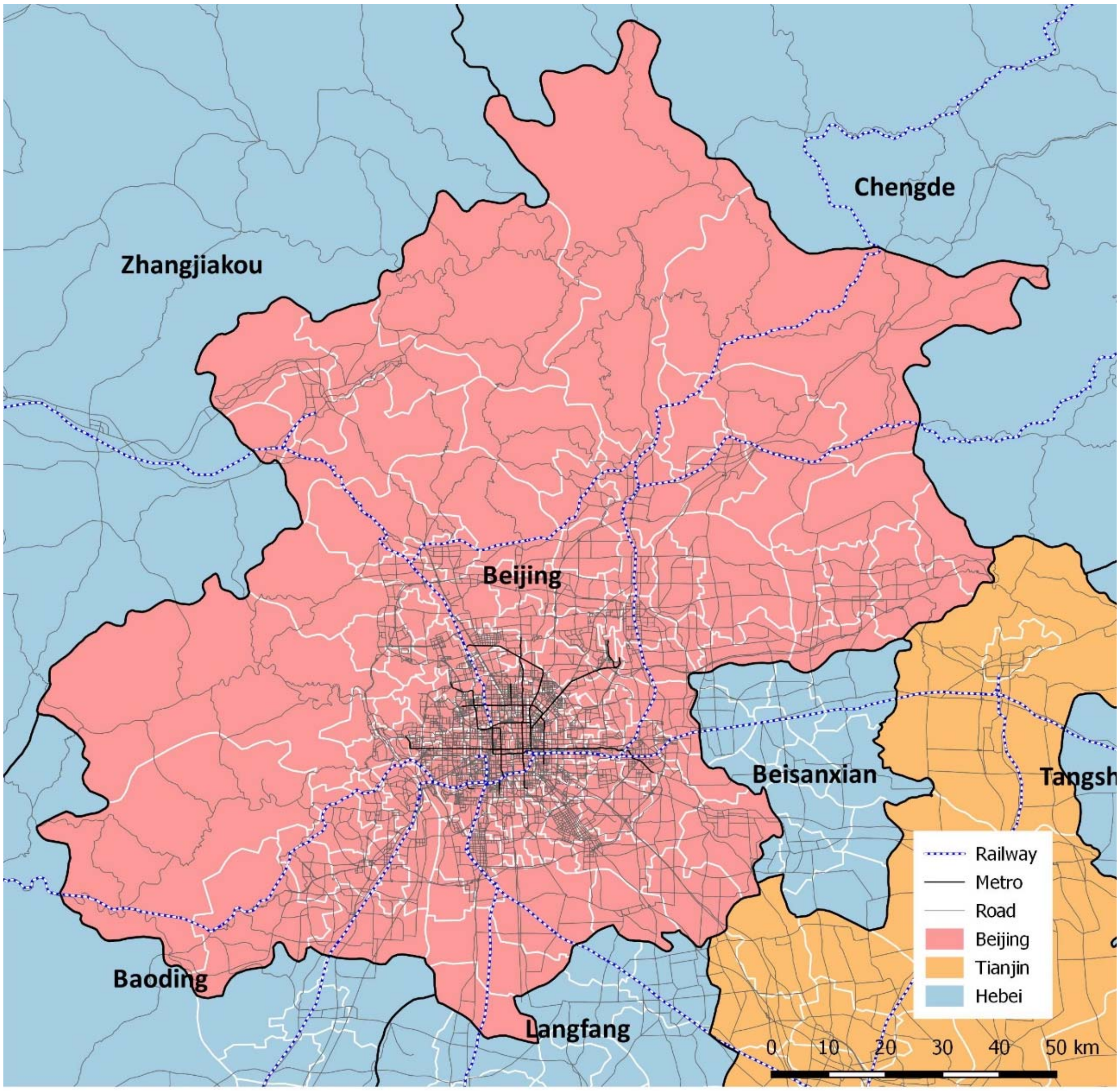


Figure 5-3 Inter-zonal network 2010

5.4.2 Intra-zonal network

As the zone sizes in the transport model are relatively large, there are a large number of trips happening inside the zone. However, traffic flows on the intra-zonal level are not represented on the conventional inter-zonal networks. That is to say that the traffic demand is underestimated if we only consider the inter-zonal networks. The intra-zonal transport times and costs might be of little practical significance to conventional transport models, but for LUTI models, they are of equal importance to inter-zonal transport times and costs. So the supplementary intra-zonal network is used to improve the representation of the entire network.

Intra-zonal trips vary according to zone sizes, flow types, and modal availabilities. Therefore, a proper intra-zonal network should be able to represent the correct travel distances and travel modes.

Here we draw upon the method structured in 4.4.2. The logit based hierarchical discrete choice model was first reported in Jin and Williams (2002) to represent the intra-zonal network. This method was later implemented in part of the UK National Transport Model. The intra-zonal transport network follows the principle that the mode choices are differentiated by appropriate distance ranges. They are coded by distance band according to the characteristics of the zones. For each band, certain travel modes are allowed. For example, for shorter distance bands, walking and cycling are assigned to the link as available travel modes, but for longer distance bands, they are not assigned. Larger zones normally have longer distance bands. However, highly aggregated zones in Hebei province with lower income level do not have long bands. Although these zones are large, people have lower mobility and are unlikely to travel for more than 20km within the zone.

Distance band	Distance (km)	Modes allowed	Areas allowed
1	0-1	Car, bus, walk, cycle, metro/rail	Beijing, Tianjin, Hebei
2	1-2	Car, bus, walk, cycle, metro/rail	Beijing, Tianjin, Hebei
3	2-5	Car, bus, walk, cycle, metro/rail	Beijing, Tianjin, Hebei
4	5-10	Car, bus, cycle, metro/rail	Beijing, Tianjin, Hebei
5	10-15	Car, bus, cycle, metro/rail	Beijing, Tianjin, Hebei
6	15-20	Car, bus, metro/rail	Beijing, Tianjin, Hebei
7	20-25	Car, bus, metro/rail	Beijing, Tianjin
8	25-50	Car, bus, metro/rail	Beijing, Tianjin
9	50+	Car, bus, metro/rail	Beijing, Tianjin

Table 5-12 Intra-zonal network design

5.4.3 Inter-modal network and built-form

Inter-modal network establishes the links between different travel modes so that an integrated multi-modal transport network can be modelled. It represents the interchanges between modes, for example, transferring from one metro line to another metro line, driving to the train station, and joining the network from zonal centroids. There are 7 link types serving 7 inter-modal travel purposes as shown in the figure and table below.

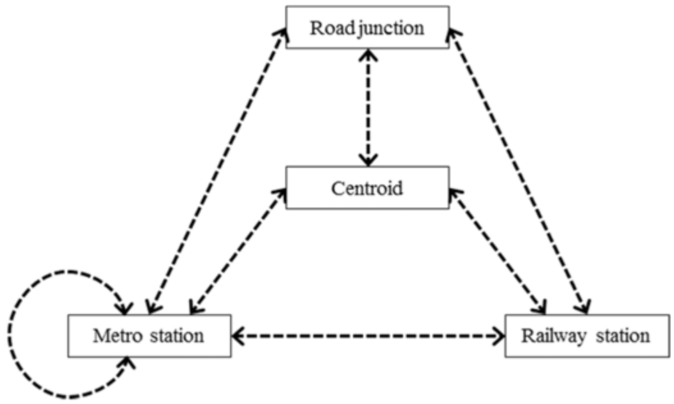


Figure 5-4 Inter-modal network structure

Type	Description	Modes allowed on the link
1	Access between zonal centroids and road junctions	walking, cycling, car, bus
2	Access between zonal centroids and railway stations	walking, cycling, feeder car*, bus
3	Access between zonal centroids and metro stations	walking, cycling, feeder car*, bus
4	Link between railway stations and metro stations	walking
5	Link between railway stations to road junctions	walking, cycling, car, bus
6	Link between metro stations to road junctions	walking, cycling, car, bus
7	Transfer link between the metro stations at the same stop on different lines	walking

* Feeder car is a mode that travelling by car to or from metro/rail stations. Travelling by car as the main mode is not an option on the links where only feeder car is allowed.

Table 5-13 Description of inter-modal network

Inter-modal network type 1-3 from Table 5-13 are the access links from the centroids to the physical network. Theses links are conceptual (see Figure 5-5 as an example). Using the method we proposed in 4.4.3, a ratio is assigned to gauge the length of the links. We only apply this method to the 28 greenbelt zones in the Greater Beijing LUTI Model for forecasting simulations. These zones are at the fringe of a city, where activities are dispersed and the sizes are large.

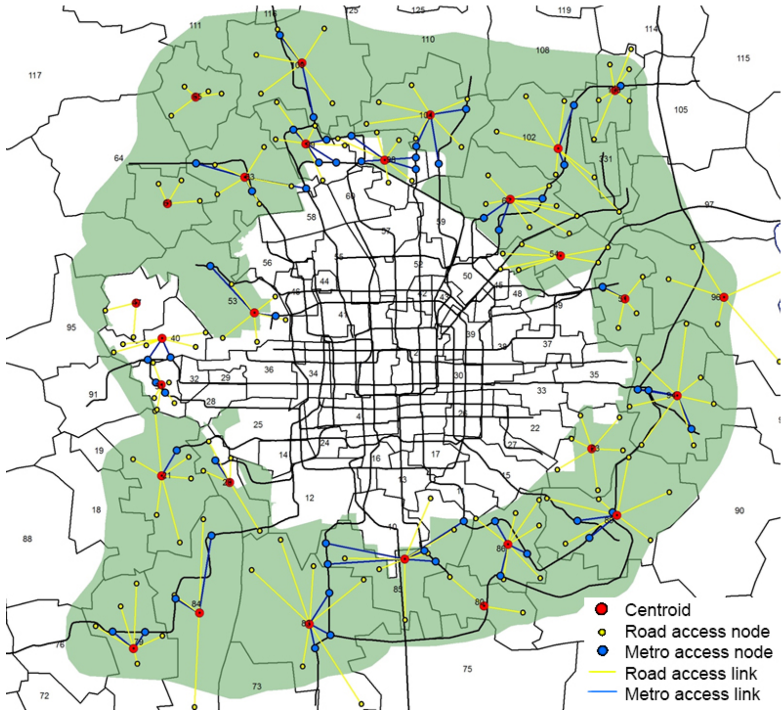
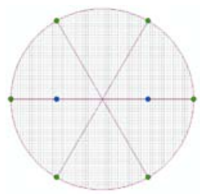
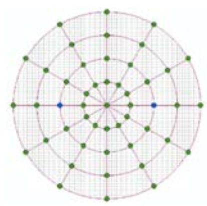
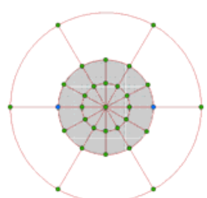


Figure 5-5 Example of access links

We categorise the greenbelt zones into 3 built-forms: 1) greenfield: low density rural houses with sparse road; 2) built-up towns: ubiquitously built-up in medium to high density with homogenous road provision; 3) Transit-Oriented Development (TOD) nodes: relatively densely built-up only around stations while roads are sparse elsewhere. The 3 built-forms stand for 3 configurations of greenbelts: built-form 1 can be commonly found in the traditional ring-shaped greenbelt. Built-form 2 is the "no greenbelt" scenario, which means roads and constructions spread ubiquitously and homogeneously without policy intervention. Built-form 3 stands for the "green-wedges" scenario, which means construction is allowed in some designated greenbelt areas (built-up wedges), but concentrates around transport nodes densely. The remaining land is still maintained as greenfield.

For each type of built-form, a ratio is assigned to represent the relations between the zonal radius and access link length. This ratio is first calculated using a generic shape (Holroyd 1966) (see Table 5-14 and Figure 5-6). Then it is verified by tracing the built-up patches (Figure 5-7) and measuring the average access distances to the selected stations and road junctions (Figure 5-8) of several greenbelt zones in Beijing. The detailed calculation and verification method can be found in the Appendix B.

Type	Generic type	Example	Road access link length	Station access link length
1 greenfield			100% r*	114% r
2 built-up towns			93% r	86% r
3 TOD nodes			96% r	58% r

*r is the zonal radius, which is the arithmetic average distance from the centroid to all the perimeter vertices.

Table 5-14 Built forms and access link length estimation

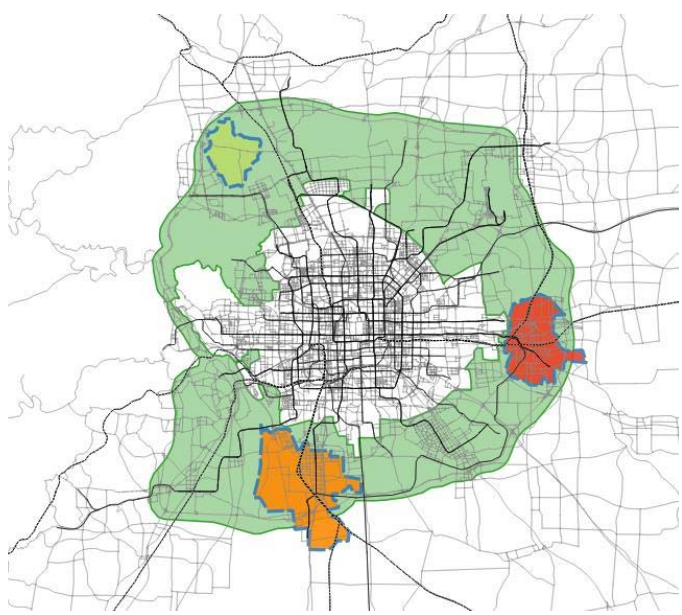


Figure 5-6 Location of the built-form examples in the greenbelt

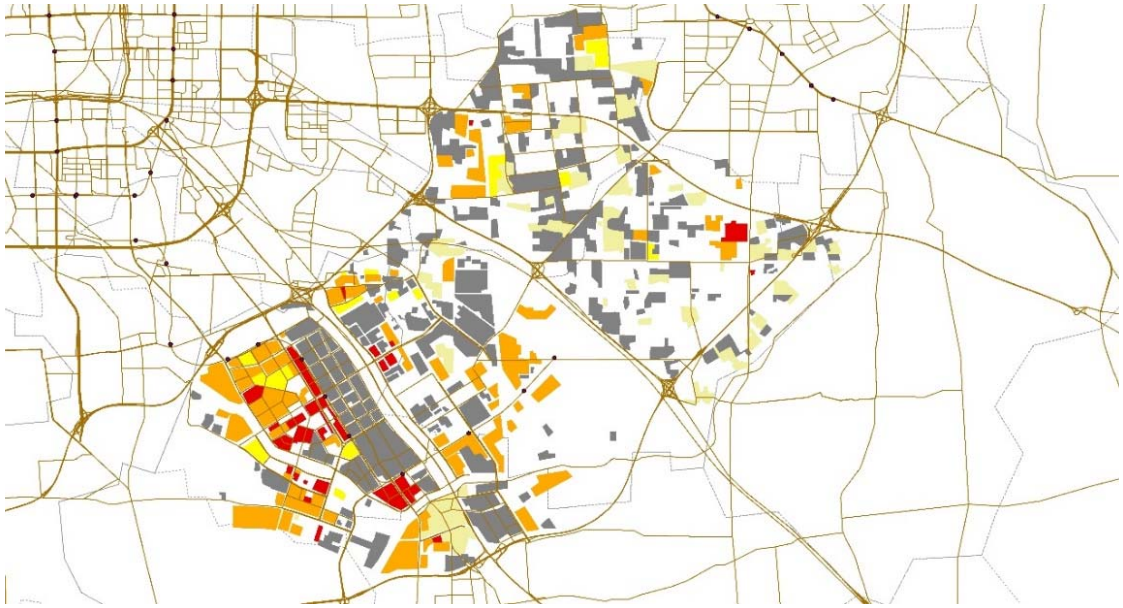


Figure 5-7 An example of tracing built-up patches in the greenbelt by land use types in order to obtain the access link length ratio

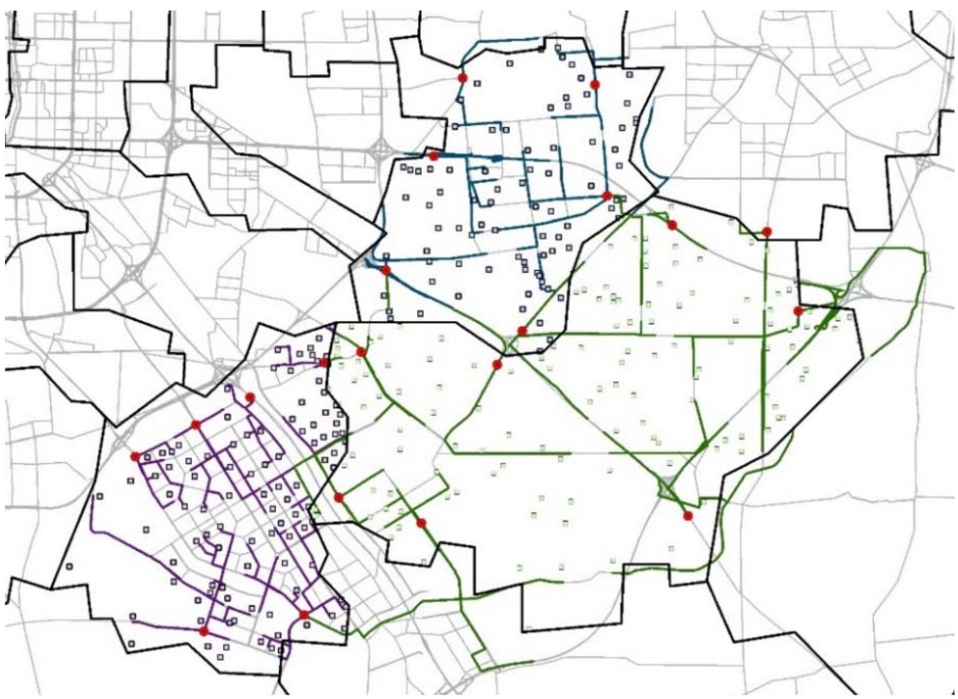


Figure 5-8 An example of measuring the average distances to road junctions types in order to obtain the access link length ratio

The access link length change stands for the proximity between the built-up areas and the transport network. This proximity will subsequently affect people's preference to travel on different intra-zonal distance bands. It is understandable that people in the sparsely built-up greenfield tend to travel in longer distance bands, while people in the densely built-up TOD nodes are inclined to travel in the shorter distance bands. We specify a disutility to represent the preference of travelling in the shorter distance bands (band 1-3).

The built-form variations will also affect the off-network travel time (eg. people spend longer times waiting for a lift if they live in a densely-built environment). As large gated compounds are the main residential type at Beijing's urban fringe, this off-network travel time is essentially the time spent on moving from the flat door to the compound gate. A traveller may take the lift to the underground garage and then drive to the neighbourhood gate, if travelling by car. Alternatively, he/she may take the lift to the ground floor and then walk to the compound gate, if taking the metro. The built-form of the compound does affect such a time. The off-network times applied for different built-forms are summarised in the table below. These times are calculated based on a generic model of the geometry of the compound, which is documented in Appendix C.

Type	Shorter distance bands* disutility	Off-network origin time for metro	Off-network destination time for metro	Off-network origin time for car	Off-network destination time for car
1 greenfield	+20	22.8	11.4	6.6	5.5
2 built-up towns	+0	21.5	10.3	6.3	5.3
3 TOD nodes	-20	15	9.8	9.5	8.0
* shorter distance bands are bands 1 - 3 in the Greater Beijing LUTI Model, refer to Table 5-12					

Table 5-15 Disutility for choosing a shorter distance band and off-network time

5.4.4 Modal hierarchy and mode choice

There are two definitions of travel modes in the Strategic Transport Model: user-mode and network-mode. A user-mode may include several distinct stages of network-mode. For example, taking the metro as a user-mode may involve network-modes such as: cycling from the trip origin to the station, waiting at the platform, riding the train, and walking from the station to the destination. The network-mode is a representation of the characteristic of each link while user-mode is the behavioural depiction of the discrete choice of travel mode. Therefore, travel mode choice refers to user-mode choice.

The user-mode choice is built upon the comprehensive representation of the multimodal transport network as presented above. The mode choice is simulated by a hierarchical multinomial logit model (Figure 5-9). The inter-zonal and intra-zonal modes are defined separately. The modelled time is a typical working day morning peak between 6:30 – 9:30 am, and the network speed is calibrated to this congestion level. Travel modes are in line with the main modes reported in Beijing Transport Survey 2012 and 2016, which include car, bus, walking, cycling, metro, rail and high-speed rail. In the survey, there are additional modes like taxi, company bus and school bus. We merge them into the main travel modes (taxi into car mode, company bus and school bus into bus mode). Car ownership in Beijing closely correlates with income level and we have already classified the travel demand according to socio-economic level. Therefore, no further car ownership segmentation is required.

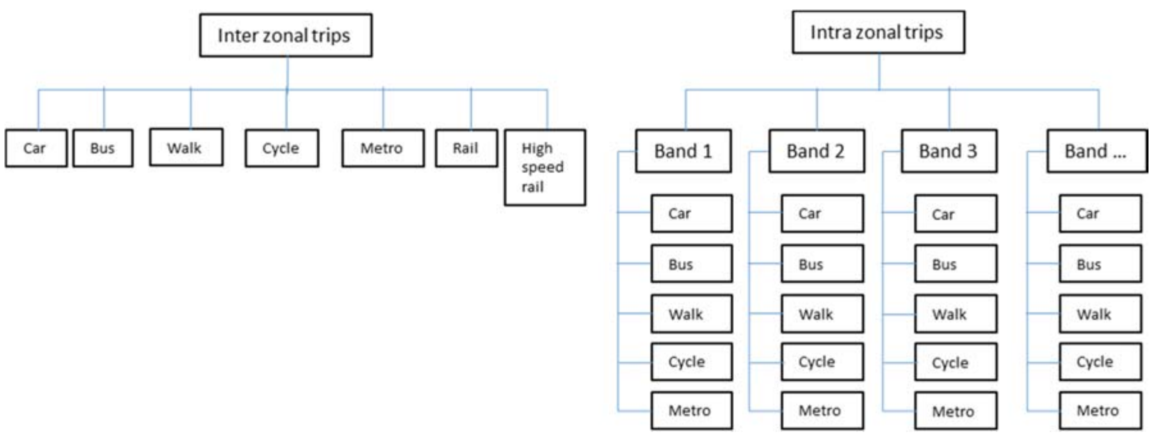


Figure 5-9 Modal hierarchy

Concentration parameters vary by flow type. Within each type, the concentration parameters for choosing between inter-zonal modes differ from the intra-zonal ones. The marginal utility of money ϕ^t (the reciprocal of value of time) is a measure to show how sensitive travellers are to monetary cost (see [Equation 4-24]). It therefore increases from richer socio-economic groups to poorer ones. The concentration parameters for modal choice and marginal utility of money are listed in Table 5-16.

Flow	Flow description		Inter-zonal mode choice concentration parameters λ_m^t	Intra-zonal mode choice concentration parameters $\lambda_{m\|B}^t$	Marginal utility of money (minute/cent) ϕ^t
	Trip purpose	Socio-economic group			
1	Commuting trips	high	0.06	0.10	0.046877
2		middle	0.07	0.11	0.095804
3		low	0.08	0.12	0.174834
4	Education trips	high	0.06	0.10	0.046877
5		middle	0.07	0.11	0.095804
6		low	0.08	0.12	0.174834
7	Business trips	high	0.04	0.08	0.023439
8		middle	0.05	0.09	0.047902
9		low	0.06	0.10	0.087417
10	Other personal trips	high	0.06	0.10	0.046877
11		middle	0.07	0.11	0.095804
12		low	0.08	0.12	0.174834
Source			LASER 3.0, Department of Transport & ME&P 2002		Own calibration from income level

Table 5-16 Parameters for modal choice

5.5 The Recursive Dynamic Model (RD) settings

The time interval selected for the RD model is 10 years between two horizons for our study area. This is because 10 years is the distinct policy cycle period in China and it is suitable to represent the slow urban development. Moreover, Jin (2013) suggests that ten or more years may be required for development and restructuring effects to work through producer and consumer choices. From the data availability perspective, a time interval of 10 years fits the cycle period for census and master plan revision.

5.5.1 Parameters for updating floorspace stock and non-employed household relocation

Here we follow the selected formula forms in 4.5.1 and 4.5.2 to update the floorspace stock and zonal non-employed households. These formula forms have been validated in the Beijing-Tianjin-Hebei City Region Model (Wan 2016) and the parameters are also calibrated. Therefore, we keep them for the Greater Beijing LUTI Model. The key parameters are listed in Appendix A.

5.5.2 Network updates

The transport network is updated manually in future model years 2020 and 2030, according to the infrastructure development plan of Greater Beijing. New metro lines, high speed railways and roads are added. The road network speeds are kept the same as the congestion speed in 2010 through adjustments in infrastructure, operations investment, relocation of jobs and households, pricing and regulation. This assumption is made based on the observations so far in Beijing. Although particular stretches of roads are more congested, the average road speed in 2006 stayed stable compared to previous years (Beijing Transportation Research Centre 2007). From 2006 onwards, the morning peak hour arterial road speed are 22.5 km/h in 2006, 22.2 km/h in 2010, 23.3 km/h in 2012, 23.2 km/h in 2014 (Beijing Transportation Research Centre 2007; Beijing Transportation Research Centre 2011; Beijing Transportation Research Centre 2013; Beijing Transportation Research Centre 2015). The variation across years indicates a relatively constant congestion level. It is worth mentioning that in 2011, the Beijing government put forward 28 road regulations to relieve congestion. For a short term, the congestion was relieved, but it bounced back to the original congestion level after 2012 (Beijing Transportation Research Centre 2016). This assumption is a starting point of gauging travel demand change due to land supply constraint and built-form change, because it excludes the impact of road speed change on people travel behaviour. Thus it makes the impact of built-form change and access link change on travel behaviour clearer. This assumption does not preclude changing road speeds when there is better road capacity data.

The access links, as part of the network, are subject to change in accordance with the built-form in the greenbelt. The access link change is scenario-specified. We will discuss this in the scenario design section 6.3 in Chapter 6.

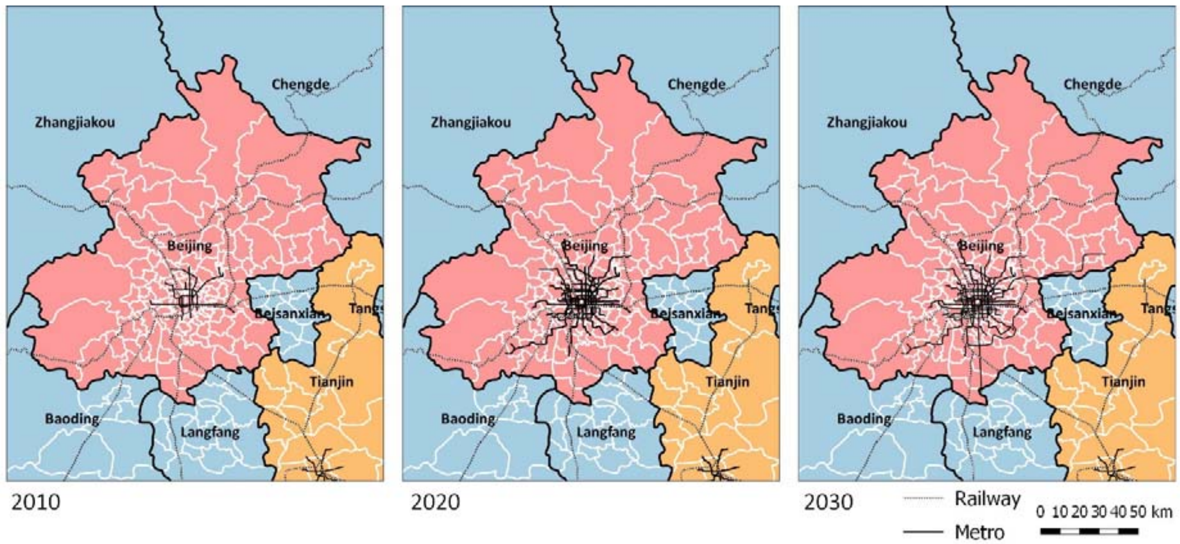


Figure 5-10 Metro lines and railways development from 2010 to 2030

5.6 LUTI model calibration through synthesising modal travel demand matrices

5.6.1 Calibration overview

A well-calibrated base year[7] is fundamental for the accuracy of future predictions. In the existing Beijing-Tianjin-Hebei Model (Wan 2016) and Greater Beijing Strategic Transport Model (Deng 2015), calibrations for year 2010 were carried out within the land use simulation loop or the transport simulation loop. They have provided the majority of parameters for the Greater Beijing LUTI Model.

However, the two models were not connected to reach an equilibrium and a full LUTI run was not established in the commuting related urban activities. That is to say, the commuting travel matrices output from the Greater Beijing Strategic Transport Model are not identical to the travel matrices input for the Beijing-Tianjin-Hebei Model. The predicted OD pairs from the

[7] In this section, the base year refers to year 2010. Year 1990 is also used as the base year for the retrospective simulations. The calibration for year 1990 will be presented later in section 6.2.2.

Beijing-Tianjin-Hebei Model are not identical to the travel demand input for the Greater Beijing Strategic Transport Model either. Moreover, the parameters for trip ranges distribution and mode share were not calibrated in Deng's model. The newly released data (Beijing Transportation Research Centre 2016) allow us to calibrate the base year network in a better quality.

The calibration carried out in this section aims to connect the two models so that the aforementioned discrepancies are eliminated within commuting related activities. The calibration also provides a well-calibrated multi-modal network for base year 2010, in terms of travel distance, time, trip range distribution and mode share.

5.6.2 Calibration method

This calibration is based on incomplete information, as the zone-to-zone travel demand matrices do not exist in Beijing. Therefore, we keep the majority of the parameters from the existing models unchanged. They are the parameters which were calibrated within the Spatial Equilibrium Model or the Strategic Transport Model independently, and do not have direct effect on the full LUTI interactive run. Then we change three sets of parameters in two calibration stages: the off-network travel times, inter-zonal travel band constants, and modal specific constants (see Figure 5-11), which are either uncalibrated in the existing model or required re-calibration to fit the full LUTI run.

Stage 1: Linking the land use model and transport model for commuting trips

The purpose of this step is to obtain a connected land use and transport interaction model for commuting related activities and to eliminate discrepancies in the OD matrices and travel cost matrices, although the model may not be well-calibrated in detail after this stage. The rationale is that given the initial travel matrices from the Strategic Transport Model, the Spatial Equilibrium model will produce a commuting OD and general commuting statistics (commuting trip length, time, percentage of intra-zonal trips). If they do not match the observed BTRC survey statistics, we adjust the intra-zonal off-network travel time. Then the ST model will generate updated travel matrices for SE and eventually, the observed commuting trip length and time can be met.

There are internal convergence criteria within the SE model. The SE model will try to fit the modelled OD with the observed zonal population and job numbers by adjusting the zonal attractiveness $E_{fi|j}$ and E_{fj} (see [Equation 4-8] [Equation 4-10]). The iterations within SE will stop when $\left|\frac{modelled\ zonal\ population\ and\ job - observed\ zonal\ population\ and\ job}{observed\ zonal\ population\ and\ job}\right| \leq 0.001$. Then SE outputs the modelled commuting statistics for comparison. We keep adjusting the off-network travel time until $\left|\frac{modelled\ commuting\ statistics - observed\ commuting\ statistics}{observed\ \ commuting\ statistics}\right| \leq 0.01$.

The set of parameters subject to change is the off-network travel time (included in the destination disutility p_{jm}^{t}, see [Equation 4-24]). This travel time was not calibrated in the existing models. It has a profound effect on the overall intra-zonal travel times and consequently affects the intra-inter trip split and general travel statistics.

Stage 2: Calibrating trip range distribution and travel mode share

The purpose of this step is to obtain a well-calibrated Strategic Transport Model, in terms of the trip range distribution and travel mode share. In the last stage, only commuting trips are considered, while in this stage, education, business and other trips are added from NCTD to ST.

There are two sets of parameters subject to change: the intra-zonal band constants Ω^{Bt} (see [Equation 4-25]) and modal specific constants Ω_{m}^{t} (see [Equation 4-24]). By adjusting them and running ST iteratively with updated off-network travel time from Stage 1, the model will eventually produce the distance range distribution and mode share that match the data for all travel purposes. There are two convergence criterion for this calibration stage: $\left|\frac{modelled\ trip\ range\ distribution - observed\ trip\ range\ distribution}{observed\ trip\ range\ distribution}\right| \leq 0.03$ and $\left|\frac{modelled\ mode\ share - observed\ mode\ share}{observed\ mode\ share}\right| \leq 0.01$.

It is worth noting that the intra-zonal modal split step in ST is a nested logit model, which means the model chooses trip range first, and then within the range, it splits the trips into travel modes. Therefore, it is necessary to make the trip range distribution correct before carrying out the modal split. This will help the Matlab F-solve function[8] to find the modal specific constants more easily.

After this step, the ST model outputs band constants and modal specific constants for the Greater Beijing LUTI Model and outputs updated travel matrices for further SE runs in stage 3.

Stage 3: Running stage 1 and 2 iteratively

Given the new parameters and travel matrices from the first iteration, Stage 1 and 2 need to be repeated iteratively. The iterations will stop when all the convergence criteria are satisfied. The calibration gives three sets of parameters: the off-network travel times, band constants, and modal specific constants.

[8] Matlab F-solve function solves systems for nonlinear equations of several variables. We set the band constants and modal specific constants as variables, input the target band distribution and modal split ratio from BTRC data and run the F-solve function to find the solutions.

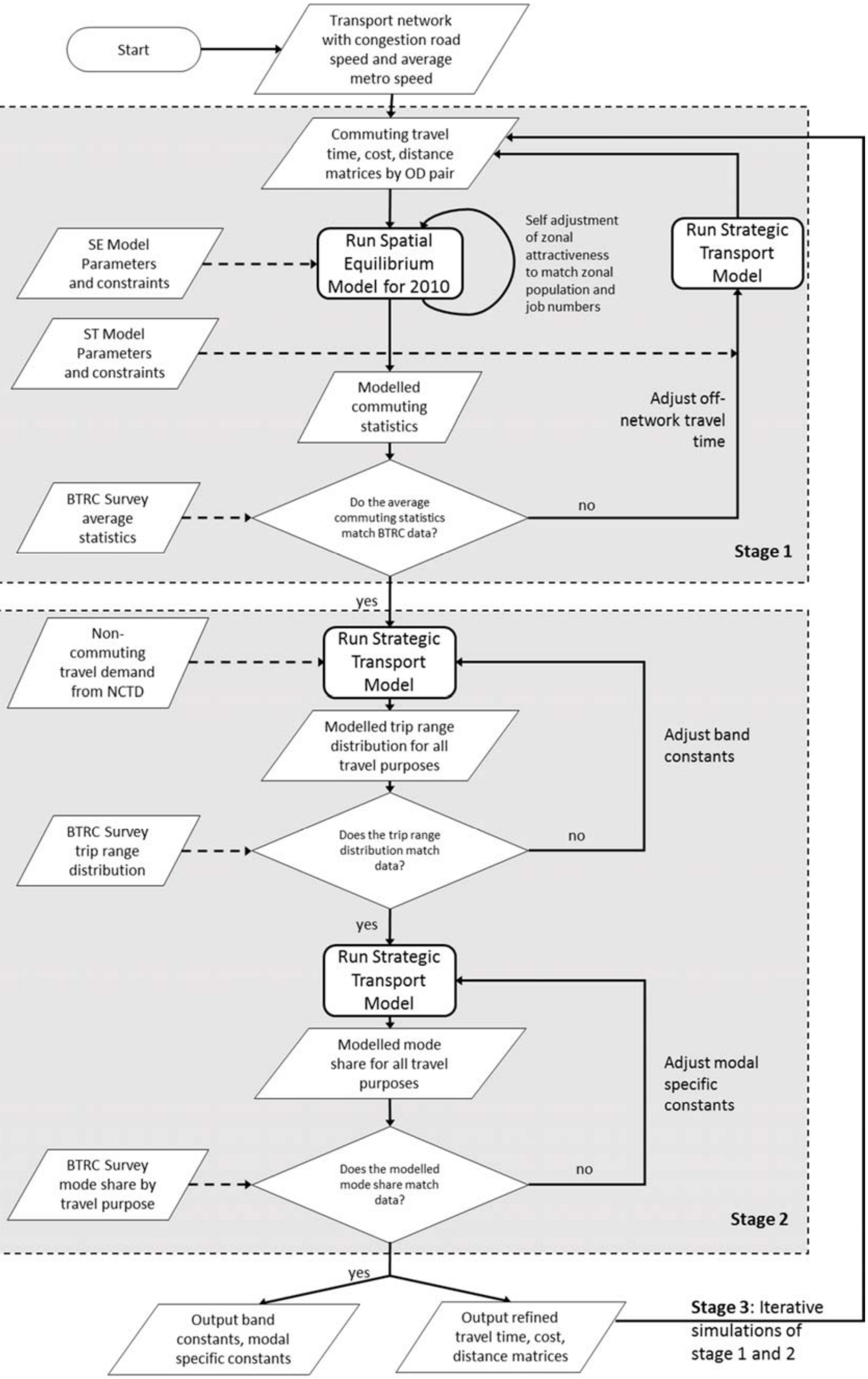


Figure 5-11 Calibration flowchart

After the calibration, both the land use model and the transport model converge to the same spatial pattern: they share the same travel time, cost and distance matrices and the same ODs for all trip purposes. The calibration results are listed in the following section 5.6.3. The calibrated off-network travel times, band constants, and modal specific constants are listed in Appendix D and E.

5.6.3 Calibration results

5.6.3.1 General statistics for commuting trips

Because there are no well-documented data of Beijing with detailed number of people and jobs arranged by OD pair, we only carry out the calibration to match the general statistics (average commuting distance and time) and to generate a reasonable spatial pattern. The reasonable pattern means that first of all, the ratio of intra zonal trips to total trips should decrease from poorer areas to richer areas, and from the poorer socio-economic group to the richer socio-economic group. Secondly, the travel distances and times should decrease from poorer areas to richer areas, and from the poorer socio-economic group to the richer socio-economic group.

Table 5-17 and Table 5-18 summarise the commuting general statistics. The results show a pattern that people in Beijing have the longest travel distance and time in general, followed by Tianjin and then Hebei. Within Beijing, high income people’s travel distances are the longest, as they can afford the cost of faster travel modes. The ratio of intra-zonal trips is highest in Hebei, as the zones are big and the average income level is lower, so people only travel within the zone. In Beijing, the mobility is high and the zones are small, so less people travel within the zone. This ratio also goes higher as people become poorer and have lower mobility.

	Beijing	Beijing within the 6th ring-road	Tianjin	Hebei	Region
Modelled average commuting distance (km)	10.0	9.6	8.8	5.5	6.8
Observed average commuting distance (km)		9.5			
Modelled average commuting time (min)	43.1	43.9	35.2	30.6	33.7
Observed average commuting time (min)		43.3			
Ratio of intra-zonal trips	39%	35%	79%	97%	84%

Table 5-17 Commuting trip statistics after calibration. Observed distance and time from The 5th Beijing Transport Survey Report (Beijing Transportation Research Centre 2016)

OD general statistics	Beijing high	Beijing middle	Beijing low
average commuting distance (km)	13.2	9.5	7.3
average commuting time (min)	47.2	44.6	39.9
average commuting speed (km/h)	16.8	12.7	11.0
ratio of intra-zonal trips	12%	31%	62%

Table 5-18 Commuting trip statistics within the 6th ring-road by social economic group

After we are confident that SE and ST are converged to the same commuting spatial pattern, we expand the model to cover non-commuting trips.

5.6.3.2 Trip range distribution and travel mode share for all travel purposes

Taking the modelled employment-residence pattern in Stage 1 as inputs, the NCTD model generates the non-commuting travel demand using the existing parameters. The commuting and non-commuting travel demands are both inputs for the ST model. Then the ST model is able to generate the trip range distribution and mode share for all travel purposes, given the well-calibrated band constants and modal specific constants.

Figure 5-12 is the calibration results regarding the trip distance range for all travel purposes. Figure 5-13 is the modelled mode share compared to the observed data within the 6th ring-road area. Both of them present a high calibration quality.

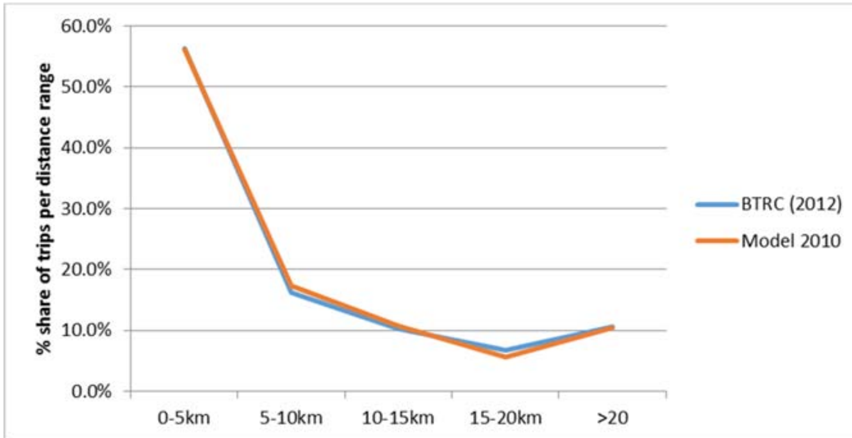


Figure 5-12 Trip range distribution. Modelled vs. Data (Beijing Transportation Research Centre 2012)

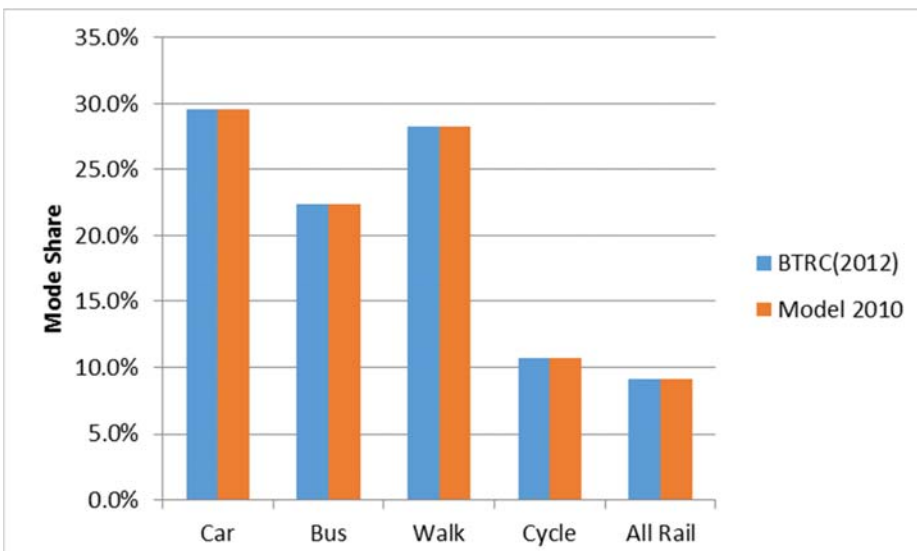


Figure 5-13 Mode share. Modelled vs. Data (Beijing Transportation Research Centre 2012)

We disassemble the overall trip range distribution and mode share into the matrix below. This multi-modal network in 2010 works well in term of doing the modal split and distance range assignment.

Mode \ Distance		0-5km	6-10km	11-15km	16-20km	>20km	Total
Car	Modelled	11.6%	7.3%	4.7%	2.6%	3.0%	29.3%
	Survey	10.9%	6.7%	4.3%	3.0%	4.6%	29.6%
Bus	Modelled	10.4%	5.1%	3.7%	1.3%	2.4%	22.9%
	Survey	8.3%	5.9%	3.3%	1.9%	2.9%	22.4%
Walk	Modelled	27.2%	0.7%	0.0%	0.0%	0.0%	27.9%
	Survey	27.6%	0.3%	0.1%	0.1%	0.1%	28.2%
Cycle	Modelled	6.6%	2.7%	1.0%	0.2%	0.1%	10.6%
	Survey	8.8%	1.5%	0.3%	0.1%	0.1%	10.7%
Metro/rail	Modelled	0.3%	1.4%	1.2%	1.4%	4.9%	9.3%
	Survey	0.7%	1.7%	2.1%	1.6%	2.9%	9.1%
Total	Modelled	56.1%	17.3%	10.7%	5.6%	10.3%	100.0%
	Survey	56.3%	16.2%	10.2%	6.7%	10.6%	100.0%

Table 5-19 Percentage of trips by mode and distance band after calibration for all travel purposes

5.6.3.3 Travel distance and mode share by travel purpose

Following the demand segments set in the BTRC survey, we calibrate the 12 travel flows (4 travel purposes by 3 socio-economic groups in each purpose) one by one. There are well-documented data showing the mode share in each travel purpose. This enables us to calibrate the modal specific constants for each travel purpose in high accuracy (see Table 5-20). In general, in business trips, car is the most common travel mode; for educational or shopping trips, people incline to walk. The modal specific constants in Appendix E have represented such a preference.

	Commuting		Education		Business		Other		Total	
	Modelled	Survey	Modelled	Survey	Modelled	Survey	Modelled	Survey	Modelled	Survey
Car	26.5%	26.2%	16.9%	16.3%	71.3%	72.0%	33.2%	34.0%	29.3%	29.6%
Bus	25.2%	25.7%	31.0%	32.0%	12.0%	11.0%	19.4%	18.0%	22.9%	22.4%
Walk	19.9%	19.4%	32.8%	32.6%	3.3%	3.0%	35.1%	36.0%	27.9%	28.2%
Cycle	14.4%	14.8%	14.0%	13.7%	3.3%	3.0%	6.7%	6.0%	10.6%	10.7%
Metro/ rail	14.0%	13.9%	5.3%	5.4%	10.2%	11.0%	5.7%	6.0%	9.3%	9.1%

Table 5-20 Mode share by travel purpose

However, there are no data recording the distance range distribution for each travel purpose. Therefore, for the band constant calibration, we aim to create a reasonable pattern for each travel purpose (see Figure 5-14), and to match the overall travel distance distribution with data.

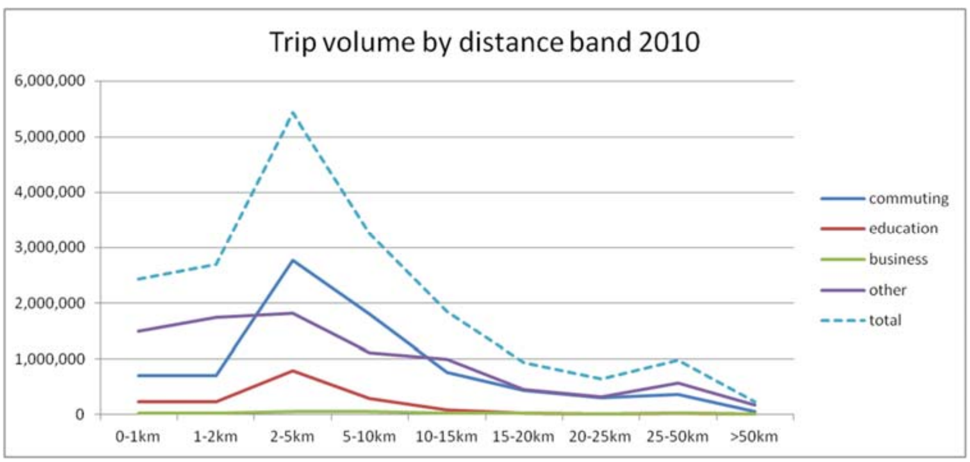


Figure 5-14 Distance range distribution by travel purpose

There are data showing the overall travel time and distance for commuting and educational travels in Beijing, but there are no data showing the travel statistics by socio-economic group. Therefore, we only guarantee that the travel times, distances and speeds decrease from high to low socio-economic groups. On average, educational trips are relatively short. Business trips are relatively long.

Purpose	Socio-economic group	Average travel time (min)		Average travel distance (km)		Average travel speed (km/h)
		Modelled	Survey	Modelled	Survey	Modelled
Commuting	**high**	47.2		13.2		16.8
	middle	44.6		9.5		12.7
	low	39.9		7.3		11.0
	average	43.9	43.3	9.6	9.5	13.1
Education	**high**	34.8		6.1		10.5
	middle	32.2		4.7		8.8
	low	30.4		4.1		8.0
	average	32.3	32	4.8	4.8	9.0
Business	**high**	53.4		28.3		31.8
	middle	42.0		13.5		19.2
	low	39.7		10.0		15.1
	average	43.4		15.2		21.0
Other	**high**	35.0		9.1		15.6
	middle	31.9		7.4		14.0
	low	29.0		5.5		11.3
	average	31.9		7.3		13.8
All purposes		37.2	38	8.2	7.6 [9]	13.2

Table 5-21 Travel times, distances and speeds by trip purpose and social-economic group, within the 6th ring-road

[9] The data for commuting and educational trips are from the 5th survey (Beijing Transportation Research Centre 2016), while the data for all purposes are from the 4th survey (Beijing Transportation Research Centre 2012). The 5th survey has more samples than the 4th survey and improves the 2010 data base. Our model uses the 5th survey as the primary dataset. In this dataset, the travel distance tends to be longer. Therefore, our modelled travel distance (8.2 km) is reasonably longer than the number (7.6 km) in the 4th survey.

5.7 Sensitivity tests

Model validation is a logical step after calibration, in order to see how the model behaves given the calibrated parameters. The validations for individual sub-models have been carried out in the existing model applications in Greater Beijing, through using the parameters calibrated for 2010 to reproduce the spatial pattern for 2000 (Wan 2016), or using the 2000 parameters to reproduce the spatial pattern for 2010 (Deng 2015). However, for the newly-assembled LUTI model, validation is still required in order to find out the overall response to variations from one side (land use or transport side) of the model. These are carried out through the sensitivity tests.

The sensitivity tests aim to investigate how the model responds to variations given the parameter values listed in sections 5.2 - 5.6. Such sensitivity tests are particularly relevant in situations where the data available for parameter estimation are limited. They will provide a firmer platform for the subsequent real world scenario tests and give a more confident interpretation of the policy findings.

We carry out three sensitivity tests in sections 5.7.1- 5.7.3. Firstly, the short-term travel demand elasticity test investigates how the transport model responds to travel time and cost variations, provided the newly calibrated parameter values. Secondly, the long-term travel demand elasticity test investigates how the land use model responds to the changes from the transport model, and vice versa. Thirdly, the built-form component sensitivity test investigates how well this component can represent the impact of built-form on travel mode choice.

Zones are grouped into 10 types in the sensitivity tests (refer to Figure 5-15). The results are reported in line with the same grouping scheme. We use this grouping scheme because it not only corresponds to the broad income level and transport supply level, but also correlates to the zone size. Such zone groups will make the causalities clearer and easier to follow. The 10 types are: Beijing central 4 districts, Beijing suburban 4 districts, other Beijing zones within 6th ring-road, the rest of Beijing, Tianjin central zones, Tianjin suburban zones, the rest of Tianjin, Hebei zones nearby Beijing, Hebei zones around Beijing, and the rest of Hebei.

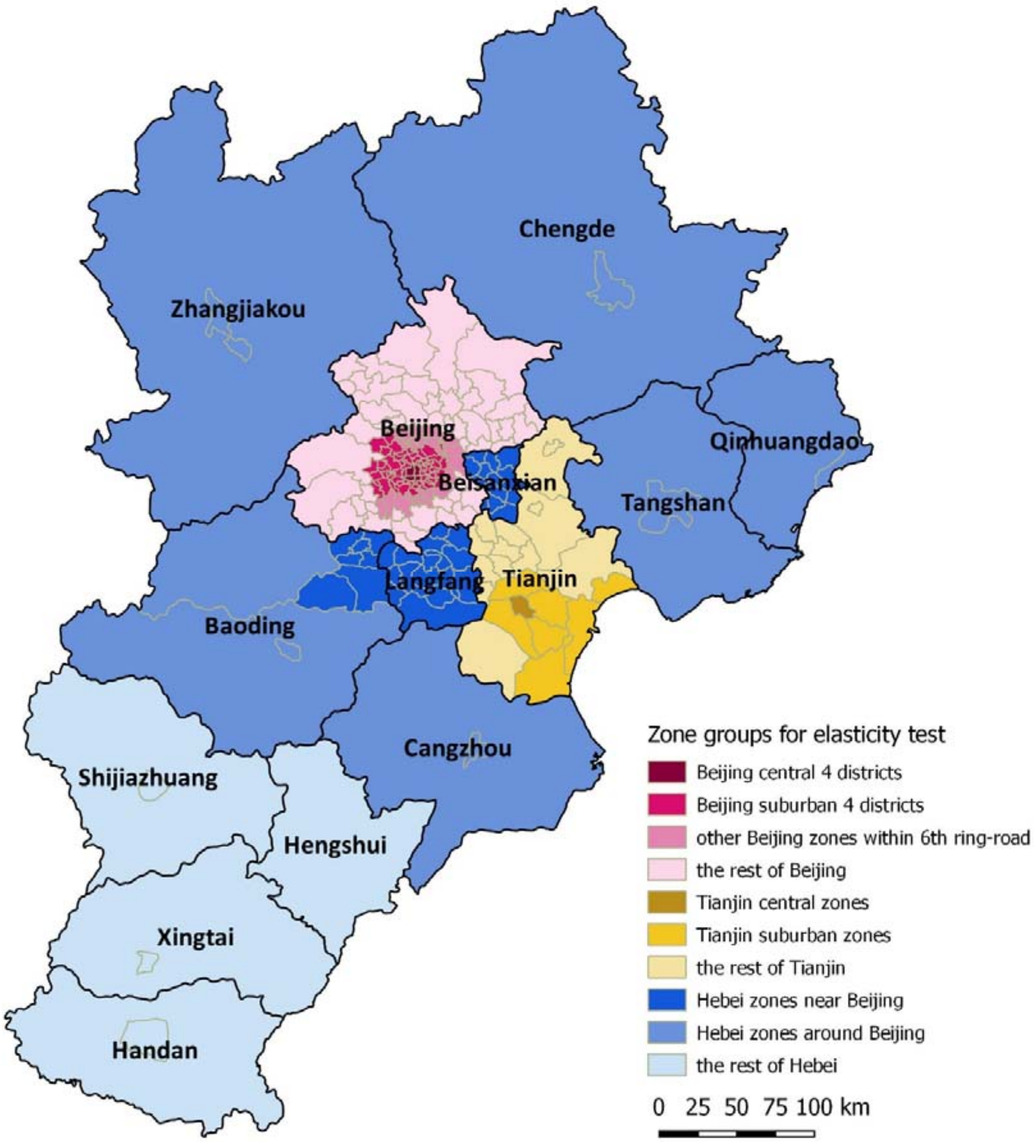


Figure 5-15 Zone groups for showing elasticity test results

5.7.1 Short term travel demand elasticity test

The purpose of this test is to examine how the transport model behaves to travel time changes given the new intra-zonal trip off-network travel times, band constants and modal specific constants we obtained through calibration in section 5.6.3. We fix the total trips in each OD for each trip purpose. Then we increase the travel time for car by 20% and see the changes of passenger-km by mode in different areas in Greater Beijing.

However, it is worth noting that the change of land use is not completely precluded from this test. Although the trip origins and destinations are fixed, the change of car travel time will trigger the shifts between intra-zonal distance bands. Such shifts can be seen as land use change. Therefore, apart from fixing OD pairs, we also exclude the band shift effects in the test, by only looking at inter-zonal travels.

The absolute value of car time elasticity is less than 1, which means with a 20% increase in car travel time, the usage of cars in term of passenger-km will drop by less than 20%. In the central areas where car is the main travel mode, people seem to be more sensitive to the change of car time. In the remote areas where car is not the major travel mode, the change of car time will not result in a big decrease of car usage. We have noticed that the elasticities for some modes in the remote zones are disproportionally high. Such drastic changes happen in the zones where the network is highly aggregate. Such a network is not a suitable representation for travel modes such as cycle and bus.

	Car	Bus	Walk	Cycle	Metro/rail	All modes
Beijing central 4 districts	-0.69	0.38	0.33	0.40	0.29	-0.01
Beijing suburban 4 districts	-0.61	0.42	0.29	0.39	0.40	0.00
other Beijing zones within 6th ring-road	-0.57	0.30	0.44	0.48	0.25	0.00
the rest of Beijing	-0.35	0.38	0.37	0.65	0.05	0.00
All Beijing Zones	-0.57	0.38	0.31	0.41	0.28	0.01
Tianjin central zones	-0.37	0.53	0.95	0.89	0.37	0.00
Tianjin suburban zones	-0.24	1.41	0.95	1.14	0.46	0.03
the rest of Tianjin	-0.34	0.98	1.77	1.46	0.13	0.03
All Tianjin Zones	-0.29	1.08	1.04	1.14	0.34	0.03
Hebei zones near Beijing	-0.25	0.92	0.93	1.08	0.16	0.01
Hebei zones around Beijing	-0.23	2.55	/	4.58	0.07	0.01
the rest of Hebei	-0.30	1.79	/	1.84	1.53	0.03
All Hebei Zones	-0.27	1.30	0.93	1.20	0.24	0.04
All zones	-0.44	0.52	0.31	0.43	0.28	0.02

Table 5-22 Short-term car time elasticities by travel mode and area

Then we repeat the same method, but increasing car cost by 20%. The results are listed in Table 5-23. The car cost elasticity is more than 1 in general, which indicates that with an increase of 20% car cost, the usage of cars in term of passenger-km will drop by more than 20%. The results show that in general, the urban areas have lower car elasticities, while the poorer rural areas have higher ones. This is because the marginal utility of money for richer travellers is low, so they care less about the increase of monetary costs. However, poorer travellers are more sensitive to the increase of monetary costs.

	Car	Bus	Walk	Cycle	Metro/rail	All modes
Beijing central 4 districts	-1.19	0.69	0.65	0.78	0.47	0.01
Beijing suburban 4 districts	-1.19	0.90	0.67	0.89	0.70	0.02
other Beijing zones within 6th ring-road	-1.30	0.74	1.20	1.38	0.48	0.03
the rest of Beijing	-0.91	1.12	1.13	2.16	0.10	0.03
All Beijing Zones	-1.17	0.87	0.69	1.00	0.49	0.02
Tianjin central zones	-1.09	1.64	3.06	2.99	1.08	0.06
Tianjin suburban zones	-0.77	5.42	3.10	4.00	1.33	0.12
the rest of Tianjin	-1.11	3.52	4.62	4.60	0.36	0.10
All Tianjin Zones	-0.91	3.98	3.24	3.84	0.99	0.10
Hebei zones near Beijing	-0.72	2.82	1.74	3.36	0.41	0.06
Hebei zones around Beijing	-0.80	11.00	/	20.67	0.17	0.19
the rest of Hebei	-0.96	6.00	/	6.31	4.87	0.28
All Hebei Zones	-0.83	4.31	1.74	3.84	0.70	0.15
All zones	-1.04	1.44	0.69	1.08	0.59	0.06

Table 5-23 Short-term car cost elasticities by travel mode and area

5.7.2 Long term travel demand elasticity test

The Greater Beijing LUTI Model bridges the land use and transport sub-models in a full LUTI run. It is therefore necessary to test how the land use sub-model responds to the changes from the transport sub-model, and vice versa. Therefore, in this long term elasticity test, we do not fix trip origins and destinations any more. We carry out the test by increasing the overall travel time by 20% and see the changes of passenger-km in different areas in Greater Beijing. Because ODs are allowed to adapt to the new travel time, the changes of passenger-km are not only caused by the shifts amongst modals and bands, but also by the re-distribution of population.

Table 5-24 summarises the long-term travel time elasticities by trip purpose and area due to the increase of travel time. Commuting trips show a more rigid spatial pattern as they are less affected by the time increase. This is reasonable because travel disutility is not the only factor to decide where to live and work. The consumption utility and zonal attractiveness are just as important in employment-residence locational choices [Equation 4-8]. On the contrary, educational and other personal trips are more sensitive to travel disutility change [Equation 4-19] and consequently travellers adapt to the change by choosing closer destinations.

In the central urban areas, passenger-km show less radical decrease to the increase of travel time, while in the rural areas, the decrease is more obvious. This is to do with the zone size. In large zones, the intra-zonal travel time is much less than the inter-zonal travel time. The added 20% time enlarged this difference and triggers the shift from inter-zonal travels to intra-zonal travels. As more people choose to travel within the rural zones, trip distance decreases. On the contrary, in central zones which are normally small, the time differences between intra-zonal travel and inter-zonal travel are not as obvious as large rural zones. The added 20% time increase will not enlarge the differences significantly and will not trigger many inter to intra shifts.

	Work	Education	Business	Other	All flows
Beijing central 4 districts	-0.17	-0.64	-0.40	-0.60	-0.39
Beijing suburban 4 districts	-0.20	-0.60	-0.42	-0.57	-0.38
other Beijing zones within 6th ring-road	-0.31	-0.70	-0.57	-0.69	-0.49
the rest of Beijing	-0.46	-0.70	-0.69	-0.88	-0.65
All Beijing zones	-0.28	-0.64	-0.47	-0.67	-0.47
Tianjin central zones	-0.25	-0.56	-0.77	-0.72	-0.56
Tianjin suburban zones	-0.42	-0.68	-0.80	-0.96	-0.74
the rest of Tianjin	-0.68	-0.72	-0.83	-1.01	-0.87
All Tianjin zones	-0.46	-0.64	-0.80	-0.91	-0.73
Hebei zones near Beijing	-0.31	-0.63	-0.73	-0.75	-0.57
Hebei zones around Beijing	-0.40	-0.52	-0.58	-0.62	-0.54
the rest of Hebei	-0.83	-0.60	-0.57	-0.78	-0.78
All Hebei zones	-0.61	-0.57	-0.59	-0.71	-0.67
All zones	-0.49	-0.60	-0.58	-0.74	-0.63

Table 5-24 Long-term travel time elasticities by trip purpose and area

Following the same method, we increase overall travel cost by 20% and investigate the passenger-km change by travel purpose by area. The results are listed in Table 5-25. Compared to the elasticities in travel time, travellers are less sensitive to the cost increase. Commuting travellers are the most indifferent to the increase of travel cost. This can be explained through the way we design the model. For employment locational choices, monetary cost is not one of the concerns in the travel disutility function [Equation 4-7]. For non-commuting locational choices, costs are converted through the marginal utility of money into time unit, and the converted costs only make up a small term in the disutility function compared to other terms, for example, travel time, off-network disutility and modal specific constants [Equation 4-24].

	Work	Education	Business	Other	All flows
Beijing central 4 districts	-0.06	-0.37	-0.34	-0.40	-0.24
Beijing suburban 4 districts	-0.04	-0.36	-0.31	-0.43	-0.23
other Beijing zones within 6th ring-road	-0.03	-0.34	0.10	-0.42	-0.20
the rest of Beijing	-0.07	-0.28	-0.29	-0.37	-0.21
All Beijing zones	-0.05	-0.34	-0.25	-0.41	-0.22
Tianjin central zones	-0.08	-0.22	-0.36	-0.30	-0.23
Tianjin suburban zones	-0.11	-0.18	-0.26	-0.26	-0.20
the rest of Tianjin	-0.18	-0.19	-0.33	-0.27	-0.24
All Tianjin zones	-0.12	-0.20	-0.31	-0.27	-0.22
Hebei zones near Beijing	-0.09	-0.17	-0.52	-0.29	-0.20
Hebei zones around Beijing	-0.13	-0.13	-0.26	-0.19	-0.17
the rest of Hebei	-0.21	-0.11	-0.10	-0.17	-0.18
All Hebei zones	-0.17	-0.12	-0.21	-0.19	-0.18
All zones	-0.12	-0.18	-0.24	-0.24	-0.19

Table 5-25 Long-term travel cost elasticities by trip purpose and area

5.7.3 Built-form component sensitivity test

The settings in section 5.4.3 regarding the built-form component need to be tested and validated. In order to do this, we fix the trip origins and destinations and examine how different built-form settings will lead to distinct travel mode choices in the 28 urban fringe zones.

First of all, we only allow one change to happen in the built-form component, which is the access link length. Table 5-26 shows that if a certain type of access link length increases, the respective travel mode share decrease, and vice versa. The changes are trade-offs only between car mode share and metro/rail mode share, which shows that the modes allowed on the access links are reasonably designed in Table 5-13. The trend of change is reasonable, but the absolute change in mode share is minor. This is understandable because access links only contribute to a very limited amount of the total network length.

Built-forms	Car	Bus	Walk	Cycle	Metro/Rail	Total
1 Greenfield	40.1%	30.2%	19.7%	4.5%	5.6%	100.0%
2 Built-up towns	40.6%	30.2%	19.7%	4.5%	5.1%	100.0%
3 TOD nodes	39.6%	30.2%	19.7%	4.5%	6.1%	100.0%

Table 5-26 Mode share change due to access link length change for all trip purposes

We then launch the full function of the built-form components. The variations in the built-form components are extended to cover 1) the access link length, 2) the off-network time at trip origin and destination, 3) the disutility for choosing shorter intra-zonal band. Table 5-27 summarises the mode share changes resulting from different built-forms.

Built-forms	Car	Bus	Walk	Cycle	Metro/Rail	Total
1 Greenfield	40.1%	30.2%	19.7%	4.5%	5.6%	100.0%
2 Built-up towns	42.3%	34.3%	14.5%	3.5%	5.4%	100.0%
3 TOD nodes	37.4%	27.2%	22.6%	5.0%	7.8%	100.0%

Table 5-27 Mode share change due by built-form change for all trip purposes

As we expected, built-form 1 and 2 are the are car oriented scenarios while built-form 3 promotes rail/metro transit. The proximity to the network in built-form 3 also promotes walking and cycling. The full package of built-form components is able to convey the variations in proximity to network, built-up density and network provision into the divergences in the travel mode choice.

To sum up, this chapter specifies the spatial and temporal dimensions of the Greater Beijing LUTI Model. It also sets the constraints and parameters used in the four sub-models. More importantly, the four sub-models are now calibrated to match the same price level, the same observed OD and the same transport statistics, so that demand and supply flows can move within the four sub-models without discrepencies. This LUTI model responds reasonably to time and cost changes given the parameter values. Therefore, we are confident to apply this model to test real-world scenarios in the next chapter.

CHAPTER 6 MODELLING BEIJING'S GREENBELT

6.1 Overview

The newly assembled Greater Beijing LUTI Model will be applied to real-world scenario tests in this chapter.

As reviewed in Chapter 2, Beijing's first greenbelt policy was implemented in 1994, followed by the second in 2003. The two greenbelt policies were challenged by the development pressure from urban expansion and implemented with difficulties since they were launched. Therefore, we firstly apply the Greater Beijing LUTI Model from a retrospective viewpoint and test the counter-factual scenarios in the past from 1990 to 2010 in section 6.2. This application intends to answer the question of where a greenbelt should initially be implemented in a fast growing city. It also verifies the data used in 1990 and validates model parameters.

Then we take the insights from the retrospective simulation and carefully design the alternative future configurations of green spaces from 2010 to 2030 in section 6.3. The alternatives include: the concentric expansion, the greenbelt, the greenbelt with intensive new town development, and the green-wedges. These alternatives will be tested through the Greater Beijing LUTI Model subsequently, using the well-calibrated 2010 model from the last chapter as the base year. The simulation results in section 6.4 and 6.5 will reveal the impacts of different green spaces on the labour market, the production market, the real estate market and the transport market.

Section 6.6 offers a parallel study to investigate how the urban centre densification affects the aforementioned greenbelt variations.

6.2 Greenbelts in retrospect from 1990 to 2010

The ultimate purposes of the Greater Beijing LUTI Model is to answer what-if questions about the future greenbelt policy interventions. However, there is an often omitted stage which is to take a retrospective viewpoint and review the greenbelt by testing historical-what-if scenarios. Such a retrospective simulation is beneficial in policy analysis, because it is free of the uncertainties in the background socio-economic and macroeconomic development, and can be compared with an observed development trend. From the modelling perspective, it also has the potential to offer an appropriate model calibration and validation for future forecast. Therefore, the retrospective simulation is a logical step towards building valid prediction models for future scenarios.

The accumulation of the datasets in Beijing from 1990 to 2010 have made the retrospective tests through the LUTI model feasible. We first establish, calibrate and validate the 1990 base year in section 6.2.2. Then we analyse the impacts of the two greenbelts through establishing historic-what-if scenarios in 2000 and 2010, and compare them with what actually happened in section 6.2.3. We would like to question: what if there had been no first and/or second greenbelt at all? Or what if the two greenbelts had been successfully implemented? The key variables of such historic-what-if assumptions to be tested are the size and location of the greenbelts.

The retrospective simulation aims to 1) re-evaluate the historic policies quantitatively; 2) provide insights for designing the future configurations of greenbelts; 3) give better understanding of how the model works across several time sections, by adding a cross-sectional modelling year 1990.

6.2.1 Zone categories of Beijing 1990-2000-2010

The 130 zones in Beijing Municipality are classified into 7 broad types in order to represent the two greenbelts' effects. The types are: 1) the central city encircled by the first greenbelt, 2) the first greenbelt (GB1), 3) the settlements beyond GB1, 4) the second greenbelt (GB2), 5) the new towns beyond GB2, 6) the far suburb, and 7) the ecological protection area (EPA).

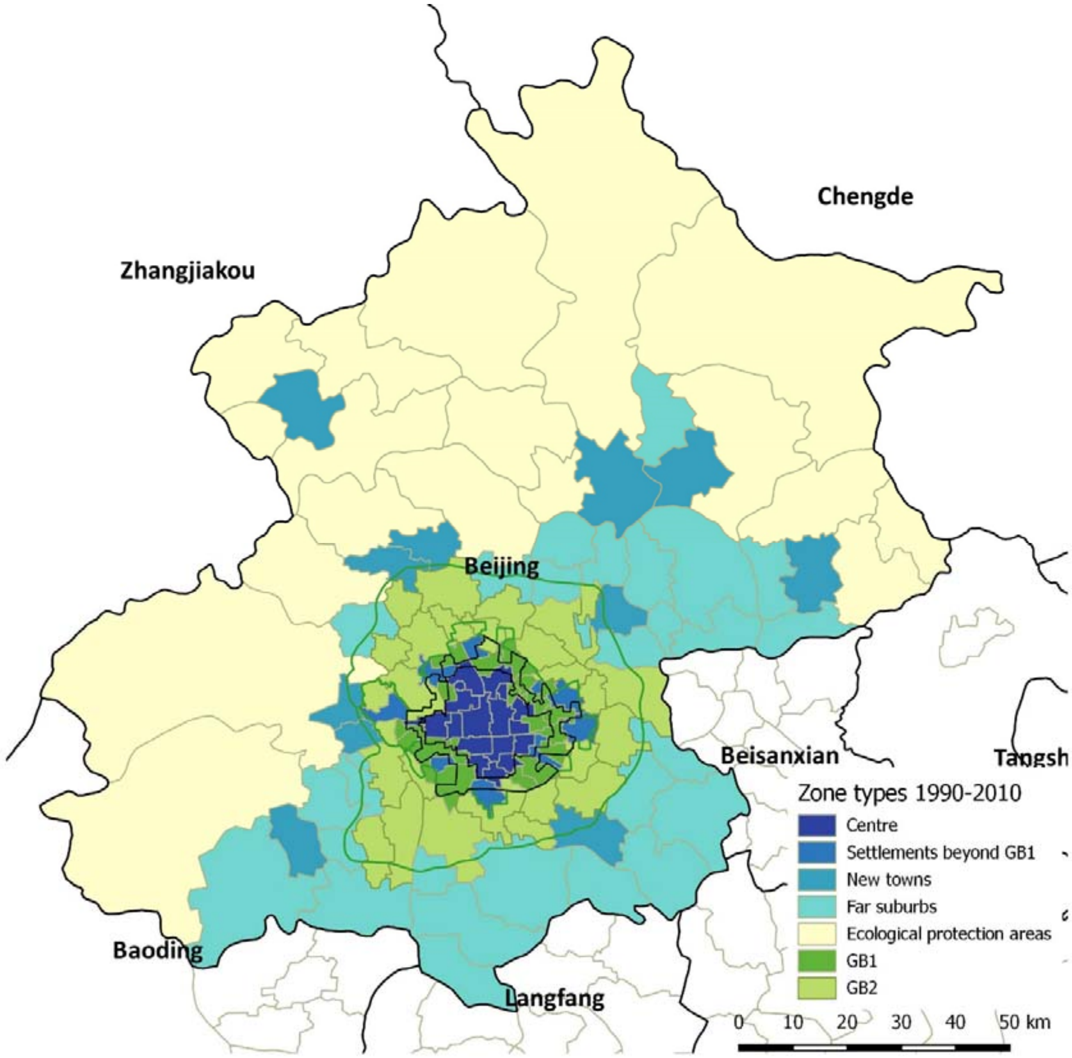


Figure 6-1 Zone categories in Beijing Municipality in 1990

There are 20 zones categorised as GB1 and 27 zones as GB2. Boundaries do not 100% comply with the greenbelt policies, because zones are defined by transport networks and administrative boundaries, not by greenbelt policy boundaries. However, this zoning is able to show the ring shapes of the two greenbelts.

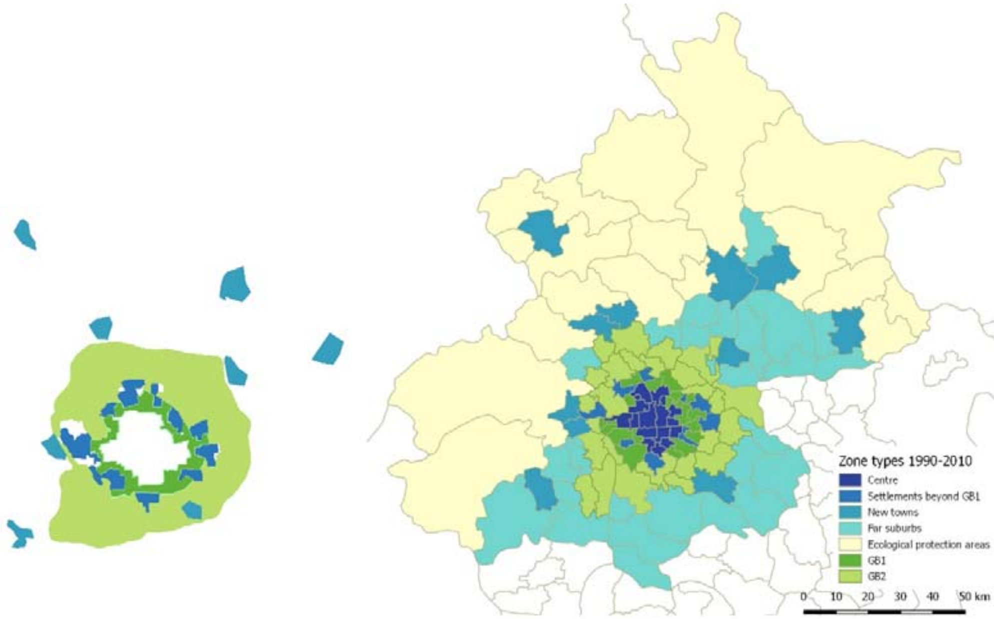


Figure 6-2 Left: GB1 and its fringe settlements, GB2 and new towns in the master plan. Right: zone classifications in the 1990 model

6.2.2 The 1990 greenbelt model

In order to model the greenbelt policies in retrospect, a starting year before the existence of the first greenbelt is needed. Year 1990 is selected for this purpose. The 1990 model is built on a relatively aggregate dataset. Due to the data availability, we make several simplifications for the 1990 simulation: 1) we only run the Spatial Equilibrium Model for the 130 Beijing zones. Tianjin and Hebei zones are not modelled. This is a reasonable simplification because before 2010, the chance of commuting cross-cities is very slim. The NCTD, ST and RD models are not applied yet to 1990, but they can be added when more data are available. 2) We do not distinguish labour types and floorspace types. 3) We borrow the 2000 transport network built by Deng (2015) to represent the network in 1990. From 1990 to 2000, road network had no substantial changes and there were no new metro lines constructed in the decade.

There are three steps towards building a valid 1990 model as the base year. Firstly, we develop a method to estimate and verify the data used for the 1990 simulation. This is a method to estimate the 1990 data through interactive and iterative simulations among the 1990, 2000 and 2010 cross-sectional models. Secondly, we calibrate the 1990 model and present the calibration results for 1990 together with the calibration results from the 2000 and 2010 simplified model.

Thirdly, we validate the 1990 model by running it in prediction mode to reproduce the observed 2000 and 2010 data.

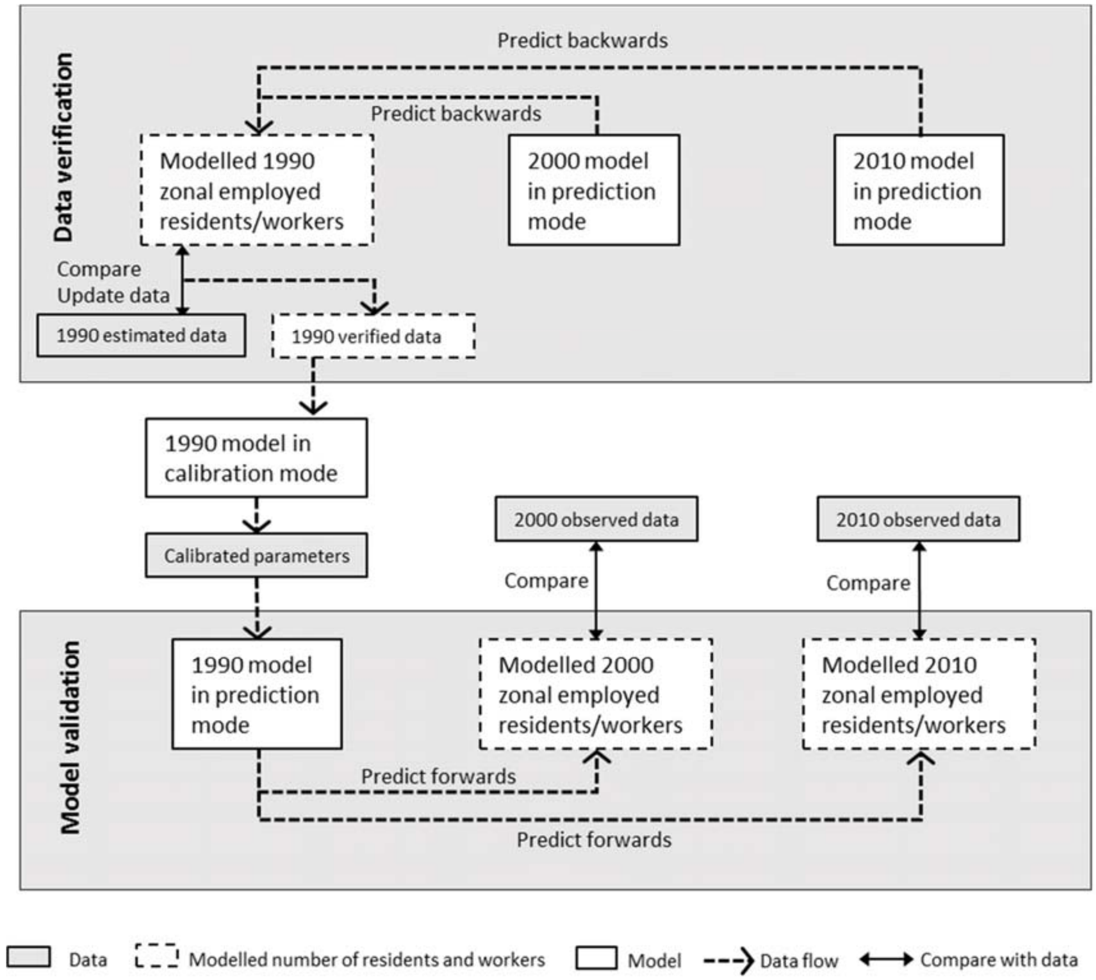


Figure 6-3 Data verification and model validation process

6.2.2.1 Data estimation and verification for 1990

The data needed for calibrating the simplified cross-sectional 1990, 2000 and 2010 models include the zonal number of employed residents, zonal number of employed workers, zonal floorspace stock, and income level.

The data for year 2000 and 2010, and the income level for 1990 can be found in censuses and statistical yearbooks. The 1990 zonal floorspace stock can be derived from the building permit dataset (Ma & Jin 2015). However, the 1990 population and job numbers only exist on the district level, which is geographically larger than the model zones. An estimation is required to distribute the district level data into zones for 1990. The estimation steps are described as follows:

1) We calculate the population (employed residents or workers) growth rates at district level from 1990 to 2000 and apply these growth rates as the average growth rates to individual zones in different districts.
2) We calculate the zonal population growth rate from 2000 to 2010. This growth rate highlights the zonal differences, as within one district, urbanised areas may have higher growth rates while rural areas may have lower growth rates. We assume the zonal differences from 1990 to 2000 are the same as from 2000 to 2010.
3) We adjust the district average growth rate proportionally to the zonal differences so that the zonal population growth rates from 1990 to 2000 are obtained. Zonal population can be calculated by dividing the 2000 zonal data by the zonal growth rate.
4) We apply the 1990 district level data as constraints to the estimated zonal population from step 3, and scale them according to the district total. In this way, we obtain the first round zonal population number for 1990.

The estimated zonal resident and job numbers need to be verified through an iterative simulation process, using the two cross-sectional models for year 2000 and 2010 (see the top half in Figure 6-3). We first calibrate the 2000 model and 2010 model independently, according to the observed zonal numbers of employed workers and residents (calibration results listed in 6.2.2.2). Price levels are all converted to the year 2010. The models are calibrated through adjusting the zonal attractiveness to fit the observed data of zonal numbers of employed workers and residents. Then we run the 2000 and 2010 models separately in forecasting mode to "predict backwards" to year 1990, and compare if the modelled zonal population numbers are close enough to the estimated zonal population numbers. Such a data verification method is valid due to the independency of the cross-sectional equilibrium models. The Spatial Equilibrium Model can predict forwards (from 1990-2000-2010) or backwards (2010-2000-1990). This characteristic gives us a tool to verify the zonal data of 1990.

We first run the 2000 model in forecast mode, predicting back to year 1990. Secondly we run the 2010 model in forecast mode, predicting back to 1990 as well. The third step is to compare the two groups of modelling results of employed workers and residents with the 1990 estimation. If the differences between the estimation and two modelling results are less than 10%, we keep the estimated number. If the differences are higher than 10% but less than 30%, we update the 1990 number by averaging the three numbers. If the differences are higher than 30%, we look for policy interpretations. For example, the growth rate between 1990-2000 for a specific zone may be overestimated because a science park plan was carried out after 2000, which caused a sheer increase of population in 2000-2010, but not in the 1990s. Such zonal numbers of population need to be adjusted case by case, by comparing with other data sources, for example local government reports.

The zonal employed residents and workers changes are plotted after we get a confident result from the verification. As shown in the figure below, a ring effect can be witnessed in the demographic patterns: residents intended to move outwards to the first greenbelt from 1990-2000 and then spread into the second greenbelt in the following decade. Jobs show a more centralised pattern as most new jobs stayed in the centre from 1990-2000 and spread to the east during 2000-2010.

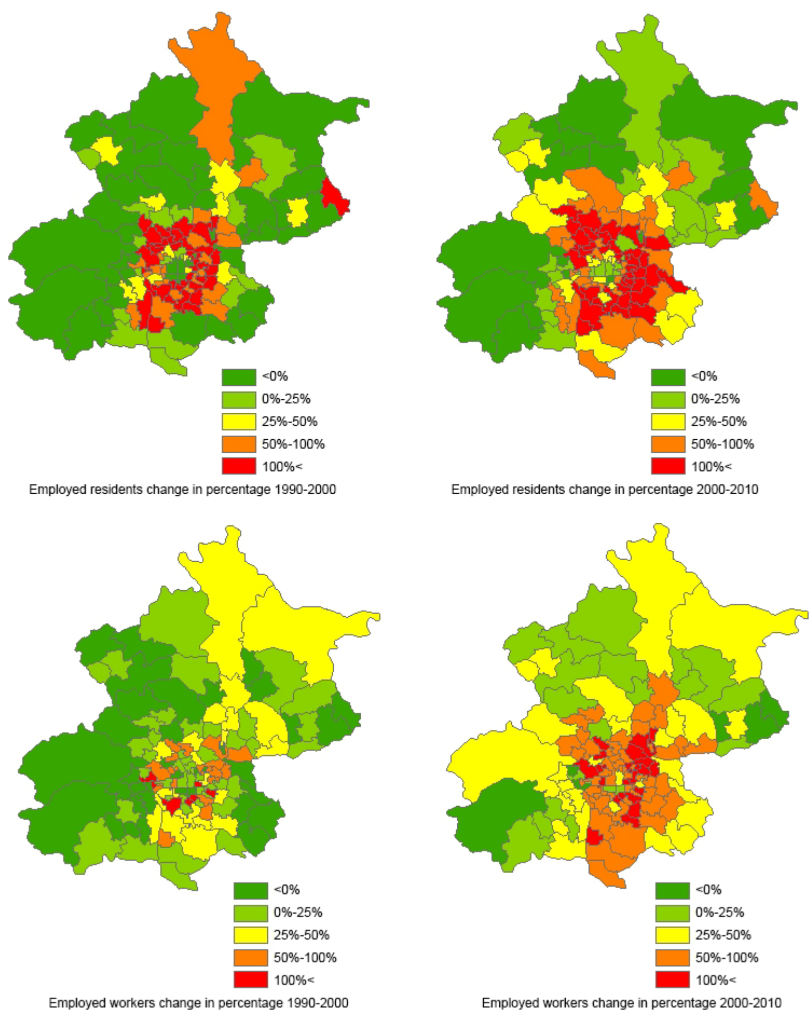


Figure 6-4 Employed residents and employed workers change in percentage 1990-2000, 2000-2010

6.2.2.2 1990 model calibration

We carry out the same calibration method for the 1990 model as the one we used to the 2000 and 2010 simplified models, by adjusting the zonal attractiveness to fit the observed data of zonal numbers of employed workers and residents. It is valuable to go through the results of the three cross-sectional runs briefly, because they reproduce the historic patterns and reveal some unknown information. For example, the information of prices, rents and wages from 1990 to 2010 for the greenbelt areas were unknown in data, but the cross-sectional runs have modelled them specifically for this geographical scope.

After calibration, the solutions in terms of the zonal employed workers and residents match the observed census data input into the calibration procedure as shown in Figure 6-5.

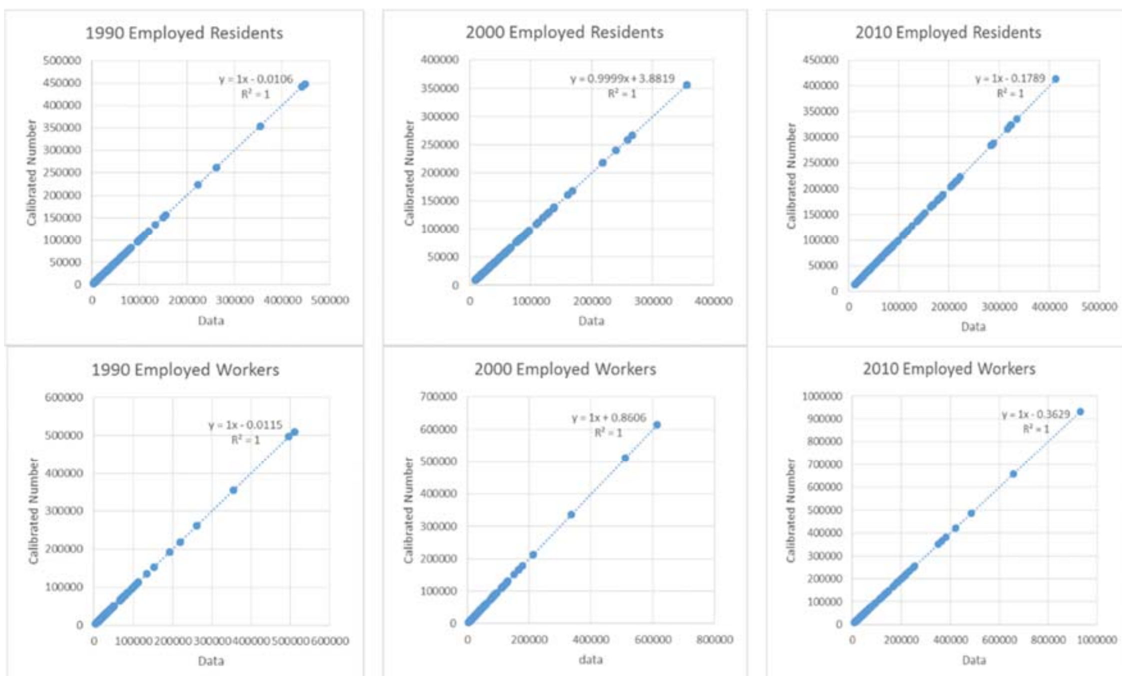


Figure 6-5 Fitness of zonal calibrated population to data after calibration

The calibrated model runs provide insight into the spatial variations in prices, wages, rents, household utilities and production levels over two decades. They also reveal the effects of the greenbelt interventions. The restrictions of land supply have led to an increase in rent: In 1990, wages, prices and rents in GB1 stayed similar to the municipal average, but from 2000, the price related index transcended the municipal average. GB1 became an expensive and popular area when the city expanded. In year 2010, GB1 remained expensive while the effect of land supply constraint had not shown in GB2.

	1990			2000			2010		
	Municipal average	GB1 area	GB2 area	Municipal average	GB1 area	GB2 area	Municipal average	GB1 area	GB2 area
Average office rent (¥/m^2/year)	61.1	61.2	52.5	136.4	139.2	117.8	350.2	359.2	301.6
Average product price (¥/unit)	8.02	8.02	7.21	17.70	17.78	15.76	45.22	45.47	39.89
Average wages (¥/household/hour)	2.01	2.04	1.86	4.43	4.49	4.04	11.32	11.44	10.18
Average housing rent (¥/sqm/year)	77.6	75.1	67.9	116.3	127.8	104.9	244.4	270.8	227.1

Table 6-1 Summary of main model results by geographical greenbelt boundaries

6.2.2.3 1990 model validation

Given the calibrated 1990 model, we run the model forward from 1990 to 2000 and from 1990 to 2010 for validation (see the bottom half of Figure 6-3). The modelled zonal number of residents and workers is compared with observed 2000 and 2010 data, in order to test how well-behaved the calibrated 1990 model is.

For those zones that have a substantial difference in the number of employed residents and workers in the 2010 validation results, we look back to policy variations to interpret them. For example, in the third chart in Figure 6-6, the predicted employed residents in Zone 7(Huaxiang), Zone 12 (Fangzhuang), Zong 29 (Ganjiakou), Zone 37 (Hepingjie), Zone 38 (Taiyanggong) are higher than the observed values. These zones were new suburban residential areas which are promoted by the local government in the 1990s. However, they did not develop as quickly as the government expected. When calibrating the resident numbers in 1990 for these zones, their attractivenesses are overestimated. This causes an over-estimation of zonal residents when the model predicts from 1990 to 2010. A possible solution to this problem is to make corrections to the zonal resident numbers in these zones in 1990, ideally based on more detailed physical and socio-economic attributes of the areas. This will have to be left as future work.

Apart from these new suburban residential zones, as shown in Figure 6-6, most of the observed numbers of employed workers and residents fit the number predicted from 1990. Therefore, we are confident to use this 1990 model as base year to predicted counter-factual scenarios in 2000 and 2010.

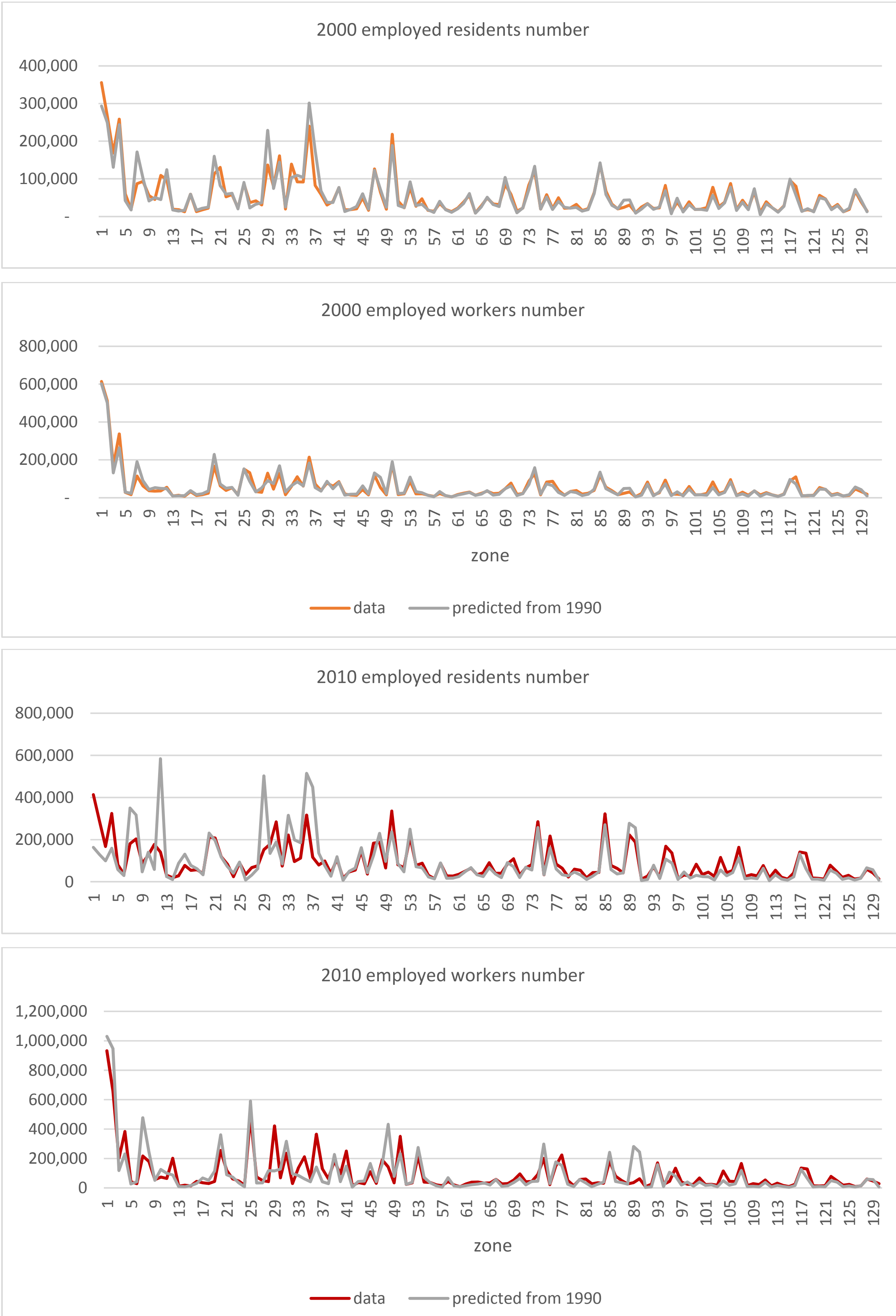


Figure 6-6 Comparison of employed residents and workers numbers: observed and predicted

6.2.3 Historic-what-if scenarios

6.2.3.1 Simulation structure

Starting from a "no-greenbelt" base year 1990, the model will run through two decades till 2010. The policy variations are solely the existence of the greenbelts. We push the variations to the extremes by assuming the greenbelt as either fully accomplished or never existed.

From year 1990 to year 2000, GB1 is the policy variable. There are two scenarios which are 1) a stringent GB1 or 2) no GB1. From year 2000 to year 2010, GB2 is the policy variable. There are four scenarios stemming from the previous decade:

Scenario 1-1) is to implement a second stringent greenbelt in addition to the first one, so that the city will have an expanded green system;

Scenario 1-2) is to keep the first stringent greenbelt, but no further action of the second greenbelt will be put forward;

Scenario 2-1) is to implement a stringent GB2 based on the condition that no GB1 has been designed;

Scenario 2-2) follows the "no greenbelt" policy and still does nothing to control expansion.

The purposes of designing the four scenarios in such an order are to reveal the impacts of 2 variables: the locations and sizes of the greenbelts. Scenario 1-1 stands for the compact and stringent development rationale. Scenario 1-2 represents the spatial structure of a small greenbelt implemented at an early development age right next to the urban built-up area. Scenario 2-1 represents the spatial structure of a large greenbelt implemented before the development actually reaches the urban fringe. Scenario 2-2 represents the no intervention concept.

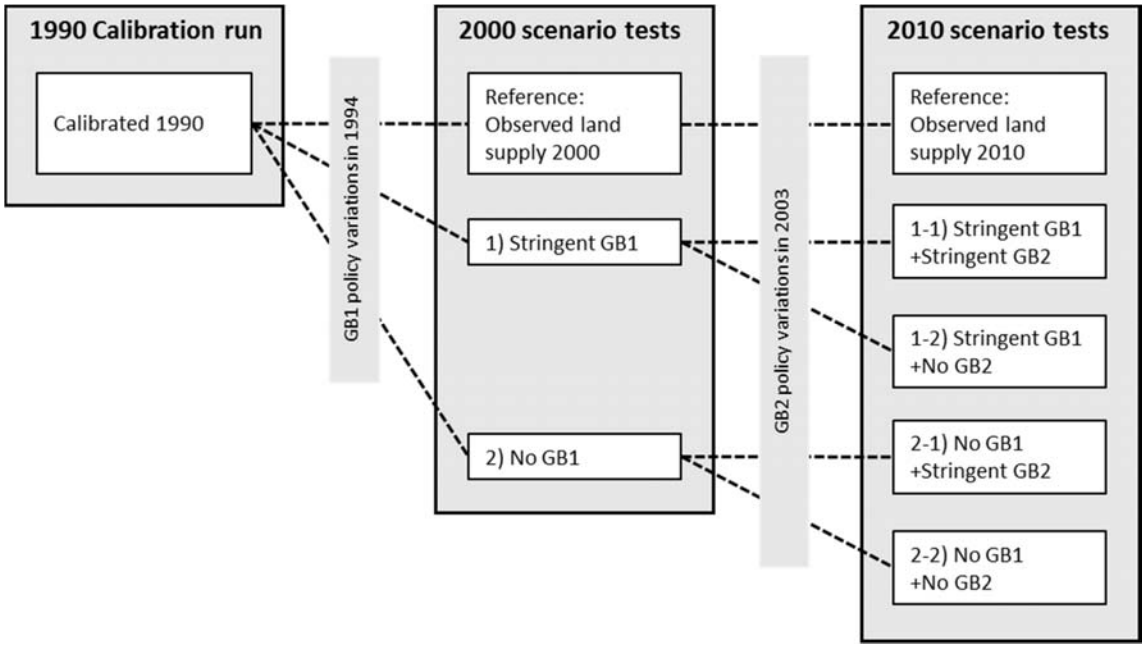


Figure 6-7 Simulation structure

Scenarios will be compared with the references. References are predicted from the 1990 model subject to the observed floorspace supplies. Scenarios are predicted from the 1990 model subject to the user-specified floorspace supplies.

6.2.3.2 Scenario inputs

The scenarios in the same year have the same demographic settings: the same number of households and jobs, the same family size and income. The total floorspace stocks across scenarios are the same. Differences are represented only in the location of floorspace supply.

Year	1990	2000	2010
Total number of residents (thousands)	6271	7116	11805
Total number of jobs (thousands)	6271	7116	11805
Income per person per year (RMB)	3871	8641	22246
Household size (persons per household)	3.20	2.90	2.45

Table 6-2 Inputs for year 1990, 2000 and 2010

There are 7 zone categories defined in 6.2.1. For each category in each scenario, we define a specific growth rate for business and housing floorspace from base year 1990. Before 2010, the far suburb and the EPA are essentially not too different from each other. Therefore, they are merged into one category in Table 6-3.

For year 2000, Scenario 1 represents a stringent greenbelt plan with intensively developed fringe settlements, which means only 2% growth is allowed in GB1 from 1990 to 2000 according to the first greenbelt policy (Beijing Municipal Government 1994). Scenario 2 represents a "no greenbelt" pattern, in which we deliberately eliminate the growth control in the designated GB1 area. For the rural zones beyond GB1 in both scenarios, a natural growth rate of 5% will be applied.

The floorspace constraints of the 2010 scenarios are also user-specified. Based on the inputs from the previous decade, a 2% growth for the greenbelts in the stringent growth scenarios is applied. For the zones outside GB2, a natural growth rate of 5% will be applied.

For the zones which are not specified above, the floorspace increases proportionally according to the stock sizes in the previous decade. That is to say that except for the greenbelts and rural areas, we distribute the floorspace growth proportionally to zones based on the existing zonal stock size. In this way the total floorspace stocks are kept identical across scenarios. This proportional distribution reflects the development inertia. Development is more likely to happen in the places which are already partially built-up. Figure 6-8 shows the observed floorspace provisions chronologically. Table 6-3 summarises the floorspace variables in scenarios.

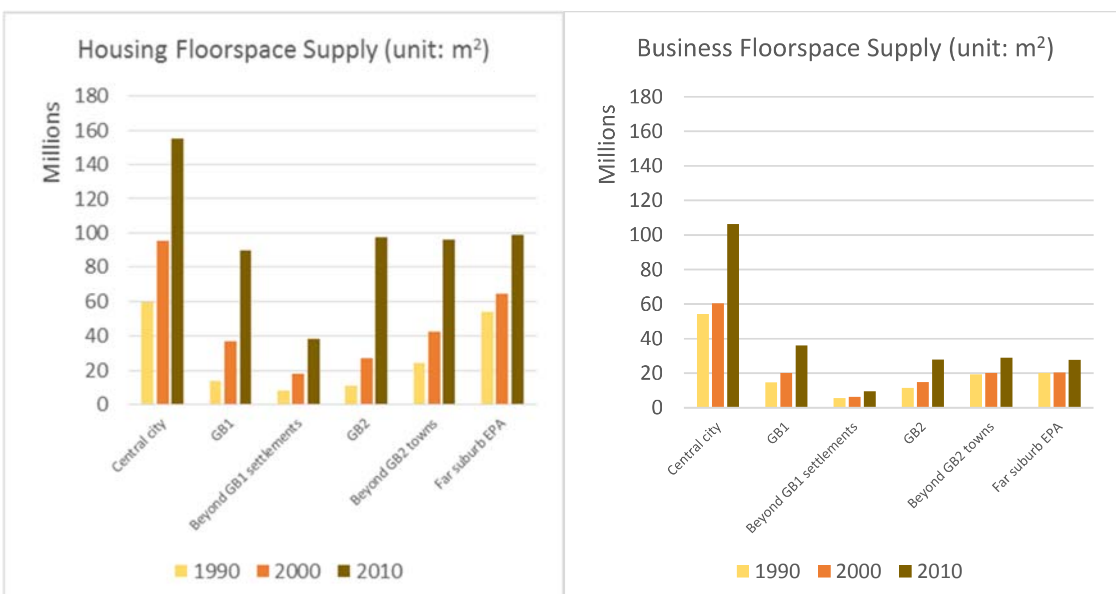


Figure 6-8 Total floorspace constraints 1990-2000-2010

		Central city	**Greenbelt1**	**Beyond GB1 Settlements**	**Greenbelt2**	**Beyond GB2 New Towns**	**Far suburb + ecological protection area**
	Subscript	C	G1	S	G2	T	R
Year	**Scenarios**						
1990	**Base year: Observed land supply**	$F_{C-1990-o}$	$F_{G1-1990-o}$	$F_{S-1990-o}$	$F_{G2-1990-o}$	$F_{T-1990-o}$	$F_{R-1990-o}$
	Reference: Observed land supply	$F_{C-2000-o}$	$F_{G1-2000-o}$	$F_{S-2000-o}$	$F_{G2-2000-o}$	$F_{T-2000-o}$	$F_{R-2000-o}$
2000	**1) Stringent GB1**		1.02 $F_{G1-1990-o}$		1.05 $F_{G2-1990-o}$	1.05 $F_{T-1990-o}$	1.05 $F_{T-1990-o}$
	2)No GB1				1.05 $F_{G2-1990-o}$	1.05 $F_{T-1990-o}$	1.05 $F_{T-1990-o}$
	Reference: Observed land supply	$F_{C-2010-o}$	$F_{G1-2010-o}$	$F_{S-2010-o}$	$F_{G2-2010-o}$	$F_{T-2010-o}$	$F_{R-2010-o}$
	1-1) Stringent GB1+ Stringent GB2		1.02 $F_{G1-2000-str}$		1.02 $F_{G2-2000-str}$		1.05 $F_{R-2000-str}$
2010	**1-2) Stringent GB1+ No GB2**		1.02 $F_{G1-2000-str}$				1.05 $F_{R-2000-str}$
	2-1) No GB1 + Stringent GB2				1.02 $F_{G2-2000-No}$		1.05 $F_{R-2000-No}$
	2-2) No GB1 + No GB2						1.05 $F_{R-2000-No}$

Note: the cells left blank mean increasing the amount of floorspace proportionally from base year.

The subscripts of F are in the sequence of "zone category- year- scenario name" (o=observed land supply; str=stringent; No=no greenbelt) respectively.

Table 6-3 Floorspace input in historic-what-if scenarios

The same amount of total floorspace is distributed to zones according to the scenario specifications. Figure 6-9 shows the variations in floorspace constraints across scenarios by zone category.

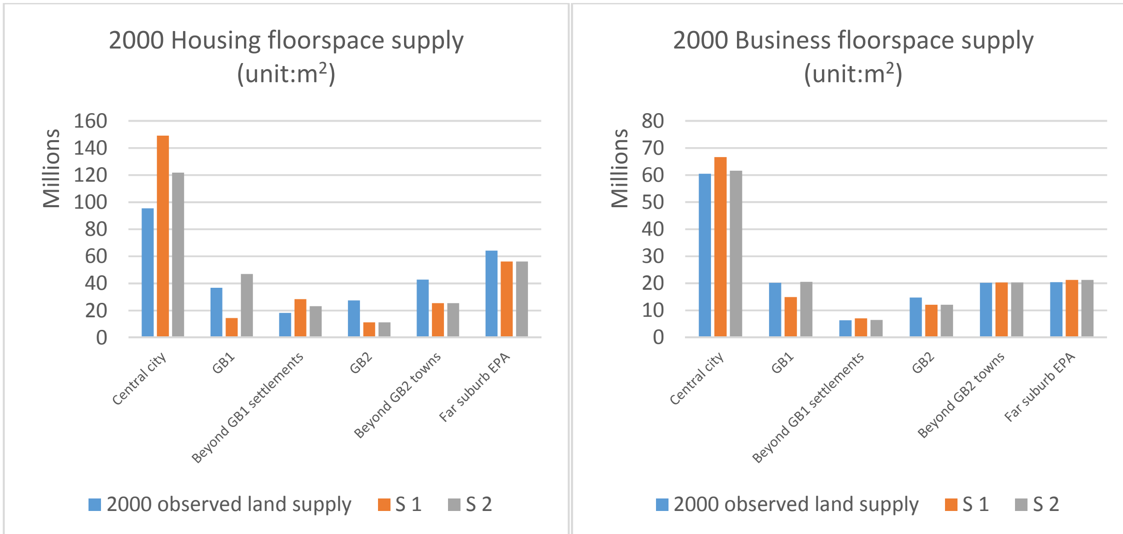


Figure 6-9 Floorspace supply 2000 by zone category

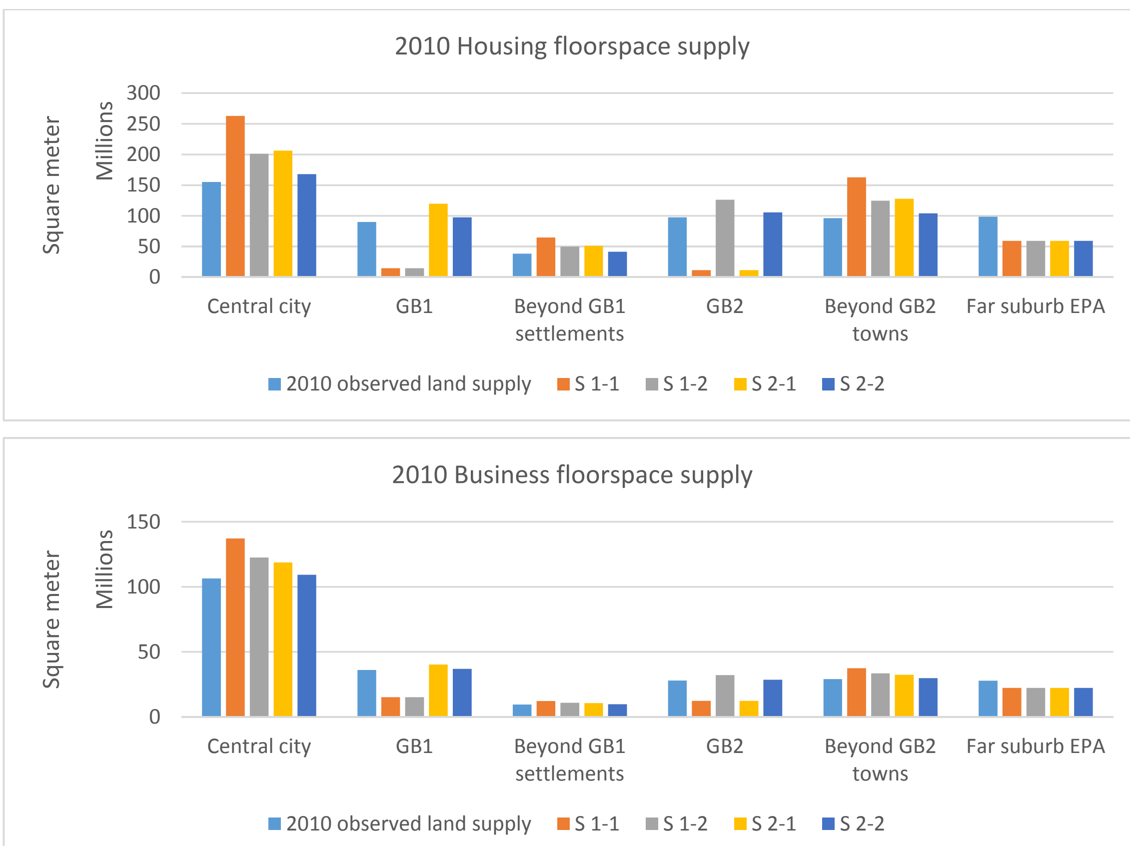


Figure 6-10 Floorspace supply 2010 by zone category

6.2.4 Modelling results and discussions

We input the parameters and zonal attractiveness of the calibrated 1990 model in section 6.2.2 to predict the 2 historic-what-if scenarios in year 2000 and the 4 historic-what-if scenarios in year 2010, subject to the floorspace constraints. The model will reveal differences in prices, wages, rents, household utilities and industry productivities across scenarios. It will also show the counter-factual locational distribution of residents and jobs. Figure 6-11 lists resident and job distributions in different scenarios.

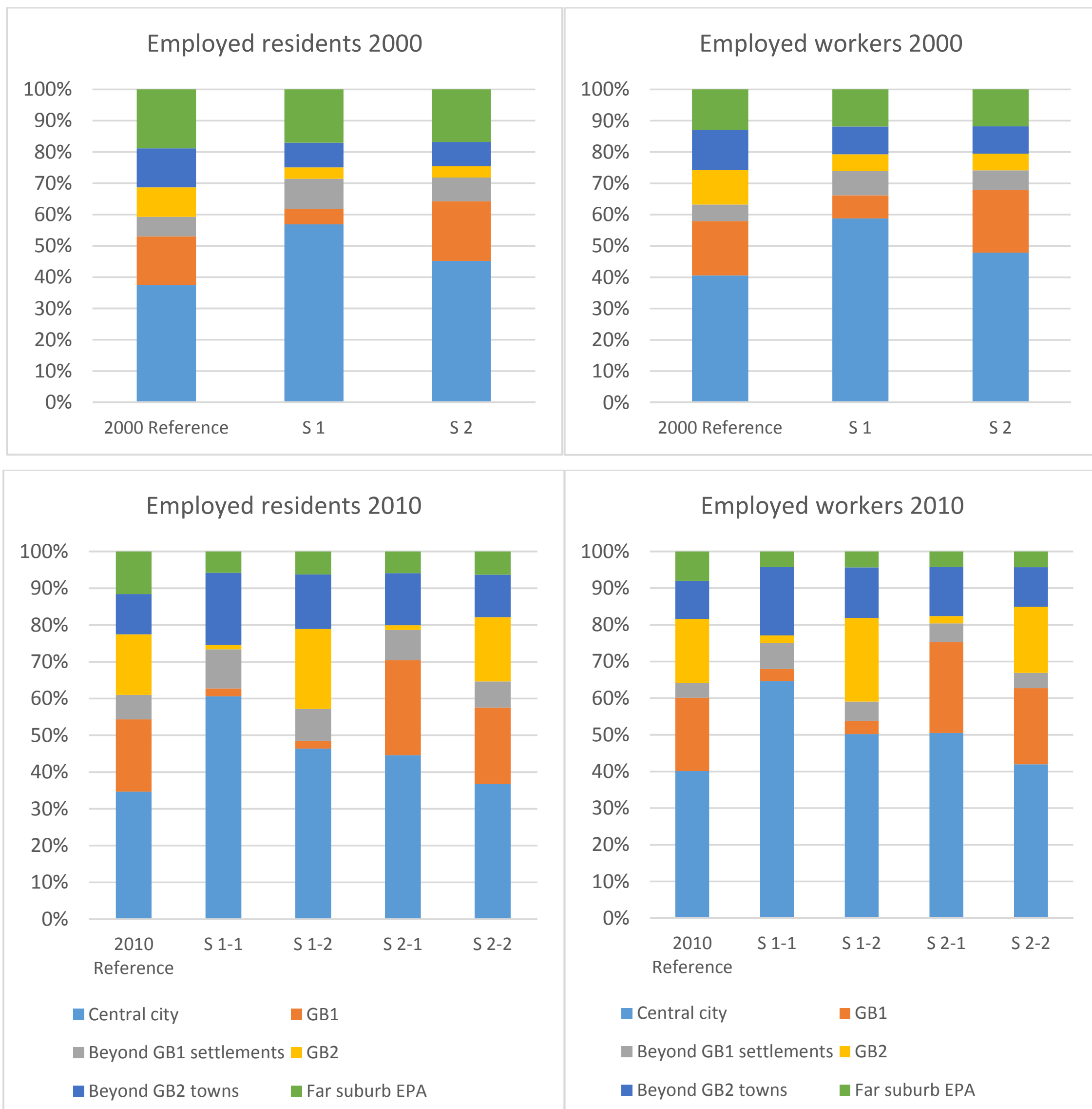


Figure 6-11 Modelled employed residents and workers in 2000 (top) and in 2010 (bottom)

Table 6-4 lists the main modelling outputs regarding price indices.

	1990	2000 Scenarios			2010 Scenarios				
Scenarios	**Ref**	**Ref**	**1**	**2**	**Ref**	**1-1**	**1-2**	**2-1**	**2-2**
Total production (million units)	3985	4545	4521	4528	7419	7446	7377	7451	7407
Average office rent(￥/sqm/year)	61.1	136.4	136.4	136.4	350.2	350.2	350.2	350.2	350.2
Average product price (￥/unit)	8.02	17.80	17.90	17.87	46.58	46.41	46.84	46.38	46.66
Average wages (￥/household/hour)	2.01	4.42	4.41	4.41	11.30	11.28	11.29	11.27	11.28
Average housing rent(￥/sqm/year)	77.61	116.3	116.0	116.1	243.9	243.3	243.6	243.4	243.6
Average household utility	7.907	7.972	7.972	7.971	7.974	7.968	7.969	7.973	7.973
Consumer surplus as percentage of money income %	-	0	-0.4%	-0.3%	0	-2.5%	-2.1%	-0.4%	-0.4%

Table 6-4 Summary of main modelling results 1990-2010

The average rents are not dissimilar across scenarios. This is understandable, because the total floorspace constraints are the same, and the total employed residents are the same as well. The differences are represented at zone level.

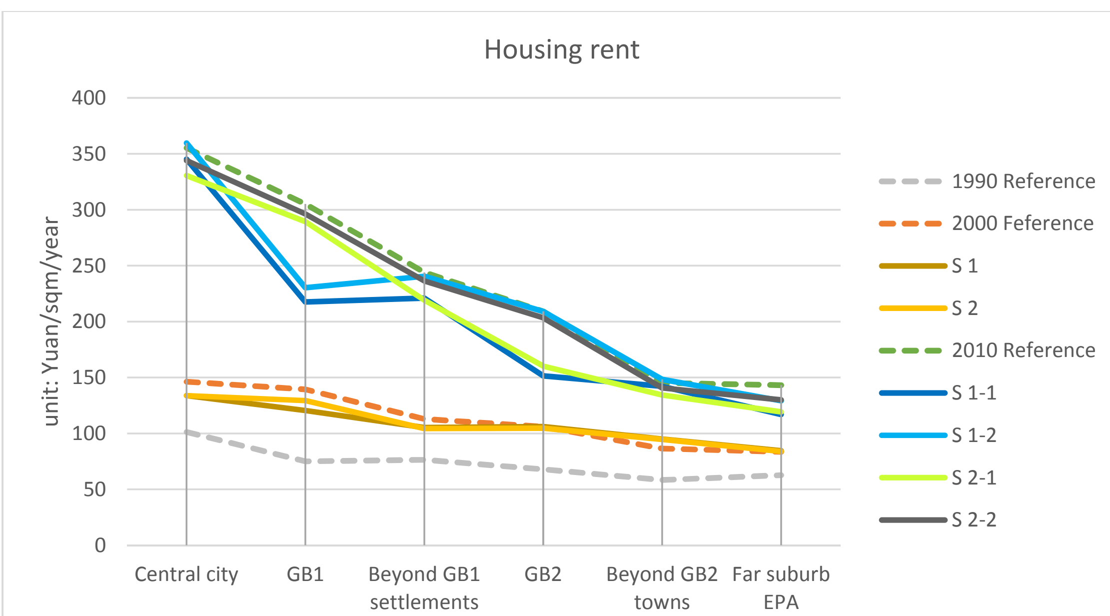


Figure 6-12 Housing floorspace rent by zone category 1990 -2010

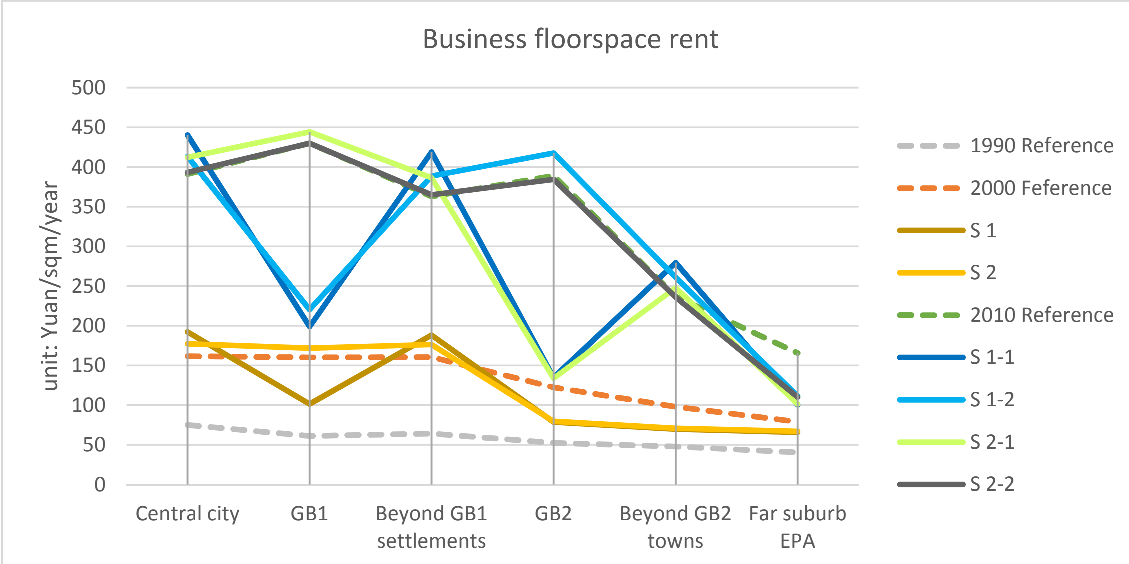


Figure 6-13 Business floorspace rent by zone category 1990 – 2010

At the zonal level, rents respond sensitively to floorspace supply. For the free market scenarios (i.e. references and no-greenbelt scenarios), rent level reflects the direct market effects and drops from the centre to the hinterland. For various greenbelt scenarios, the development control has made the greenbelt areas less attractive, which in turn suppresses the rent levels. In the model, housing rent is basically determined by housing floorspace supply and the numbers of residents who locate in the zone and demand housing. Housing floorspace is measured by square metres and employed residents choose how many square metres to consume. Taking S1-1 as an example, the total housing floorspace supply drops by 84% in GB1 compared to the observed housing supply (from 90 million m^2 to 15 million m^2). Meanwhile, the total residents in GB1 drops by 89% compared to the observed number of residents (from 2.3 million to 250 thousand). As a result, the rent in GB1 area become lower than the observed rent, because housing demand decreases more severely than housing supply.

Furthermore, the 1990 model is a geographically closed system for floorspace supply. This is to say, the greenbelt restrictions will only divert the housing and business floorspace from the greenbelts to other places with Beijing's geographical boundary. The city centre obtains most of the diverted floorspace, because the floorspace is added proportionally based on the existing floorspace stock in the previous decade. GB1 cannot compete with the city centre to attract residents and jobs. In S1-1, jobs in GB1 decreases by 83%. Because there is no transport improvement from 1990 to 2010 in the model settings, it is not convenient to live in GB1 while working in the city centre. Therefore, residents move out of the greenbelt, which in turn decreases housing demand and depresses housing rent. This is different from the usual scenarios where suburban and rural transport supply continues to improve after the designation of the greenbelt (e.g. around London).

The modelling results show that the location of floorspace supply as a result of different greenbelt interventions could greatly affect household welfare and impact upon the economic performance of the city. Restricted floorspace supply has substantial effects on rents and household locational choices.

The spatial patterns of 2000 and 2010 with observed land supply are similar to the two No-Greenbelt scenarios (Scenario 2 and Scenario 2-2) in Figure 6-11. In the 2000 Reference and Scenario 2, GB1 contains some 20% population and jobs. In the 2010 Reference and Scenario 2-2, the two greenbelts together contain some 40% population and jobs. It suggests that the existing greenbelts in Beijing as they stand have not reached the goal of reshaping urban spatial structure and preserving greenfield land. The successive development over the two decades has effectively been a continuation of the pancake-like expansion.

A stringent realisation of GB1 in 2000 would engender further concentration of population and jobs in the city centre (Scenario 1). The establishment of GB2 in 2010 reinforced such effects, as more than 60% of the jobs and residents remain in the city centre (Scenario 1-1). The two stringent scenarios fulfil the aim of preserving greenfield sites at the urban fringe, as the number of jobs and population in greenbelts are controlled at a low level. Accordingly, rents in the centre, fringe settlements and towns increase, because the stringent greenbelts propel people and jobs to the expensive central zones and fringe settlements. Meanwhile, the restriction in the greenbelt area causes a drastic drop in rent. The overall consumer surplus drops 2.5% in Scenario 1-1, which is the largest among 2010 scenarios. The stringent greenbelt city may turn out to be a costly scenario, which may explain why the greenbelt plans encountered so many difficulties in implementation in Beijing.

The two hybrid scenarios (Scenario 1-2 and Scenario 2-1) in 2010 show distinctive spatial patterns due to different locations and scales of greenbelts. Scenario 1-2 represents a greenbelt in smaller size and close to the city centre. Consequently, people tend to live beyond GB1, seeking lower rent, price and bigger properties. In 1994 when the first greenbelt was established, Beijing had not yet reached the rapid development period. This can be seen from the total increase of floorspace supply from 1990 to 2010 in Figure 6-8. When urban expansion started after 2000, people began to locate beyond the first greenbelt, because the limited land supply in the city centre is far from enough. Scenario 2-1 represents a wide greenbelt in rapid urban expansion. Consequently, development spread into the first greenbelt but did not go beyond the second greenbelt.

6.2.5 Summary of greenbelts in retrospect

To sum up, this retrospective model quantifies impacts of land use control through three cross-sections over two decades. The model is successful in reproducing the historic patterns of urban growth and encroachment of the planned greenbelts. The model provides a unique set of insights to understand the past patterns of development and to design the alternative configurations for future's greenbelt.

Firstly, in terms of size, S1 and S1-2 show that a small and narrow greenbelt did not fulfil the aim of urban containment, as people can easily cross it and built beyond the greenbelt.

Secondly, in terms of location, a greenbelt should be placed in a distance to the urban built-up edge and give development a buffer area to contain the growth in the near future. S1-2 shows that a greenbelt right next to the immediate urban built-up boundary is harmful. It leaves no buffer zone for future development to take place and causes a substantial decrease of consumer surplus. On the contrary, S2-1 shows that a greenbelt which gives a development buffer zone in advance performs better in term of consumer's well-being.

Thirdly, the similarities between the two reference cases and the no-greenbelt scenarios have implied that the two ring-shaped greenbelts have failed in Beijing. In fact, Beijing's development from 1990 to 2010 followed the no-containment rationale. As the urban expansion of Beijing has sped up after 2010, which indicates that the greenbelt implementations are under even greater pressure, the existing greenbelt policies are unlikely to be suitable.

Fourthly, in future scenario designs from 2010 to 2030, we should consider not only the extreme scenarios of no-greenbelt and a ring-shaped greenbelt, but also the in-between configurations.

When designing the future configurations, we need to bear in mind that development constraint should be carefully placed not at the immediate urban fringe, but at the areas with less development pressure. The possible configurations will be reported in section 6.3.

From the LUTI model perspective, the ultimate aim of this model is to answer what-if questions about future greenbelt policy interventions. However, it is necessary to have an often omitted stage of model calibration and validation. This is carried out here through testing the 1990 model in reproducing the observed growth in 2000 and 2010. The parameters (see Appendix A) used in this test are defined in section 5.2. The fact that the 1990 model is capable of reproducing the observed spatial pattern under such parameters gives us confidence in the prediction capability and the validity of the model. The parameters are verified through the 3 cross-sections over 2 decades, which gives a firmer platform for testing real-world scenarios.

The 1990 greenbelt model can be spatially extended to cover Greater Beijing, and it can also be developed in finer granularity to represent socio-economic and transport variables, when more data are available. In the following section, the retrospective model will be developed from 2010 into a prospective model. It will be extended to reflect a more precise socio-economic, land use and transport context of Greater Beijing in greater granularity.

6.3 Scenario design for future configurations 2010-2020-2030

Analyses in section 6.2 have shown that the two greenbelts did not stop urban expansion successfully. The first greenbelt was built-over[10]. Although there are still green spaces in the second greenbelt, they are also under the threat of being built over. After 2010, the development of Beijing has sped up drastically, the second greenbelt is under greater threat of being completely built-over. Therefore, for the model period 2010-2030, we pay close attention to how to design the future configurations of the second greenbelt. Moreover, as the regional integration plan has been carried out in Greater Beijing, the geographical extent of the model is extended to the Greater Beijing region from 2010. This section is structured as follows:

[10] Less than 11% of the GB1 land is still green (Wang, 2015).

Section 6.3.1 introduces the zoning of the 2010-2030 prospective model. Then we specify the scenarios in section 6.3.2. The macroeconomic background and socio-economic development trend for scenarios are defined in section 6.3.3.

6.3.1 Zone categories of Beijing 2010-2020-2030

The prospective model covers the Greater Beijing region (see Figure 5-1 on page 98). Zoning in the prospective model complies with that in the retrospective model. However, the zone categories are slightly different from the retrospective model. The 130 zones in Beijing Municipality is classified into 6 broad categories: 1) the central city, 2) the inner city, 3) the (second) greenbelt, 4) the new towns, 5) the far suburb and 6) the ecological protection area (EPA). The first greenbelt is no longer an explicit category but merged into the inner city. Land use variables in term of floorspace constraints are specified on the zone-categorical scale.

There are 28 zones categorised as greenbelt, based on the designated greenbelt boundaries and the remnants of green spaces. Transport provisions in term of the built-form variations are only presented to the greenbelt zones in a case by case manner. In compliance with the built-form variations in section 5.4.3, a greenbelt zone can be designed as 1) greenfield, 2) built-up towns, or 3) TOD nodes. Whether a zone is specified as a greenfield zone, a built-up zone or a TOD node is a user-defined policy specification, which reflects the density, transport provision and the proximity of built-up areas in relation to the transport network. A zone with metro stations is not necessarily a TOD node; nevertheless, a TOD node must be a zone with metro stations in.

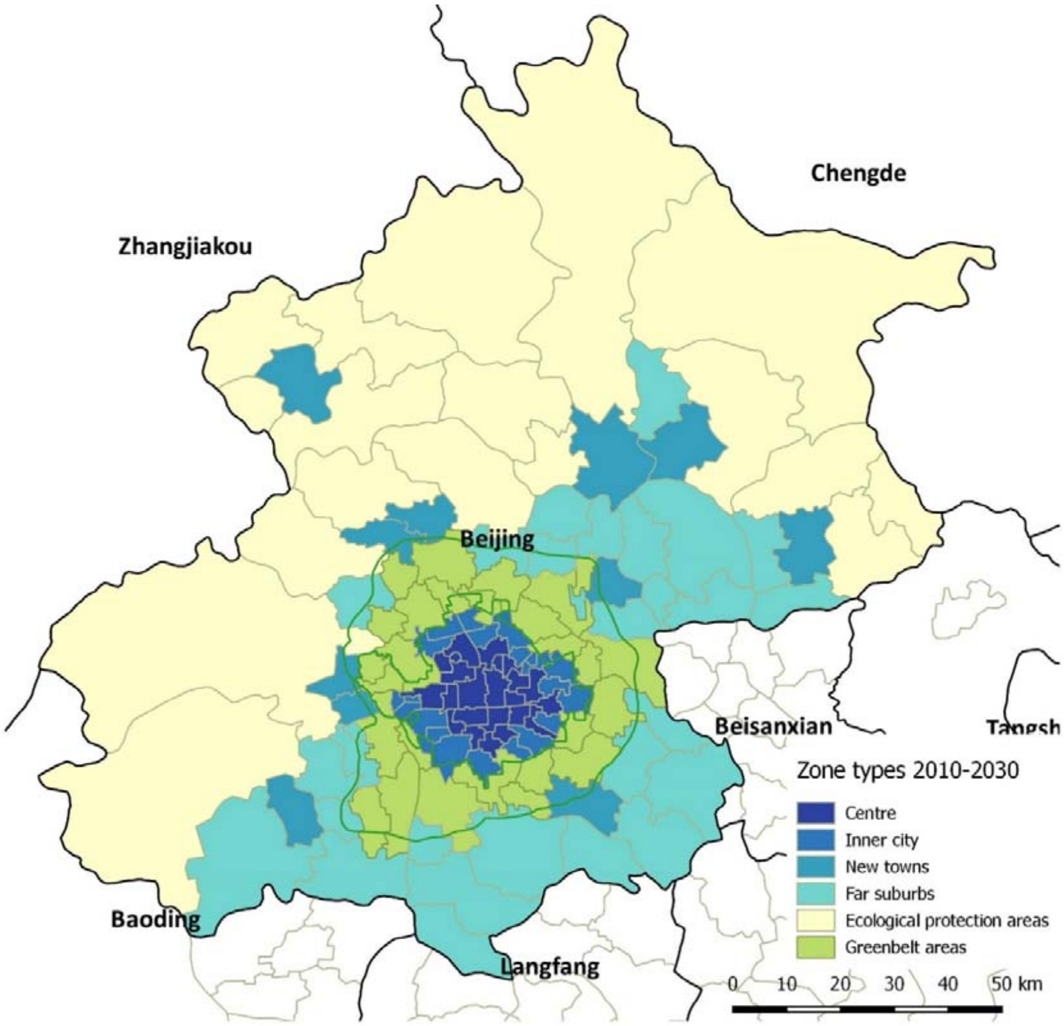


Figure 6-14 Zone categories in Beijing Municipality 2010

6.3.2 Scenario specifications

The aim for scenario test is to explore how different configurations of green spaces trigger distinct development outcomes. Configurations of green spaces are interpreted into measurable policy variables. The first policy variable is the location of floorspace growth, because as an urban containment policy, large scale green spaces will have a direct impact on zonal floorspace supply. The second policy variable is the transport supply variable, which is represented as the built-form variations in the greenbelt.

For the *floorspace growth location variable*, we specify where housing and business floorspace would be provided or restrained. For the scenarios to be realistic, we differentiate two types of floorspace growth: natural growth and discretionary growth. Natural growth happens in a spontaneous manner. It can be witnessed as the increase of floorspace through extension of the existing buildings, or infilling development in built-up areas. Discretionary growth is designed to reflect the policy interventions. We assume that for all scenarios, the natural growth accounts for 50% of the projected total floorspace growth. Natural growth is distributed proportionally to the existing stock size everywhere, unless specified as 0 in the greenbelt. The discretionary growth accounts for the other 50% of the total growth. The distribution of discretionary growth is subject to scenario specifications.

For the *transport supply variable*, we differentiate the transport provisions in greenbelt zones in cross-sectional simulations, according to the built-form in scenario specification. A greenbelt zone can shift into one out of the three built-forms in a cross-sectional year. For example, a zone can be preserved from 2010 to 2020 as *Type 1 greenfield*, then developed into *Type 3 TOD nodes* from 2020 to 2030. The transport supply changes accordingly. The changes include the changes in the access link length, the changes in off-network travel time, and the changes of the preference to choose shorter intra-zonal distance bands. For other zones, the transport network remains the same across scenarios in the same modelling period. Of course, the network updates every decade according to the government's medium to long term infrastructure plan. We keep the transport supply identical (except for the greenbelt zones) across scenarios in the same cross-sectional simulation year, which provides a comparable platform to reveal solely the impacts of green space configurations on transport.

For the scenarios to be realistic, we first classify three broad development types in Greater Beijing. 1) As concluded in the last section, historical review has pointed to the uncontrolled concentric growth as the default development trend. Therefore, concentric growth is selected as one development type. 2) Despite the fragmented remaining green spaces, there are still planners and authorities blindly claiming that greenbelt policies are beneficial and suitable for Beijing for political reasons (Beijing Municipal Government 2008; Beijing Municipal Commission of Urban Planning 2012). They advocate no more development in the designated greenbelt boundary. So the greenbelt scenario will definitely be included as one development type. 3) As tested in the last section, the stringent greenbelt is not a promising solution for future development, and the remnant green spaces have pointed to a hybrid configuration. As the green-wedges configuration has been proposed in some development studies in Beijing, we will also include green-wedges as a development type.

We then expand the three development types into four scenarios. All the scenarios are based on the same projections of regional macroeconomic and demographic growth. Differences are presented in the *floorspace growth location variable* and *transport supply variable*. The variable specifications are summarised in Table 6-5. The changes of built-forms by decade are summarised in Figure 6-15. The four scenarios are:

1) The Reference Scenario (Ref) is an extrapolation of the development trend in Beijing from 1990 to 2010. It reflects a concentric expansion typology. There is no fringe development control, so that housing and business floorspace can build over the greenbelt. However, the development in the city centre is controlled, which is in accordance with the current master plan (Beijing Municipal Commission of Urban Planning 2004). Therefore, in Ref, the discretionary growth of floorspace is prohibited in the city centre and EPA zones. The 28 greenbelt zones are denoted with *Type 2 built-up towns* built-form, which will be interpreted as medium to high built-up density, comparatively shorter distance to road junctions and moderate distance to metro stations.

The greenbelt development type split into 2 scenarios: the Greenbelt Scenario (GB) and the Greenbelt - New Town Scenario (GB-NT).

2) The Greenbelt Scenario (GB) is proposed to represent the stringent urban containment concept. Although there have been many built-up patches in the greenbelt in 2010, a strict development control is implemented onwards to the greenbelt zones, which means no further growth of floorspace any more (neither natural growth nor discretionary growth). Similarly to Ref, discretionary growth in the city centre and EPA zones are suppressed. 24 (out of 28) greenbelt zones are specified as *Type 1 greenfield* built-form, which is interpreted as lower built-up density, sparse road layout, comparatively longer distance to road junctions and to metro stations. The remaining 4 greenbelt zones are denoted with *Type 2 built-up towns*, because they were already partly built-up in 2010 and could not be turned back to greenfield.

3) The Greenbelt - New Town Scenario (GB-NT) is the same to GB in every way, except the intensive development scheme in the new towns. It represents a strong policy-oriented decentralization from the main city to the new towns. New town development is normally put forward with greenbelt policies to decentralise overspilled population. Such a development typology can be seen in many cities with greenbelts, for example in London and Seoul. Beijing Municipal Government has also proposed the new town plan to support the greenbelt (Beijing Municipal Commission of Urban Planning 2012). Here we test whether the greenbelt will perform better with the supplementary new town movement. The transport network and built-forms are the same as GB.

4) The Green-Wedges Scenario (GW) considers the factual remnants of green spaces and proposes a hybrid greenbelt-TOD configuration. Part of the greenbelt zones are strictly preserved as *Type 1 greenfield*, and no growth is permitted at all. Meanwhile, the rest of the greenbelt zones are designated as *Type 3 TOD nodes*, which means development is not only permitted, but also promoted in such zones. However, this does not mean that the development will spread across such zones. It is only promoted around metro stations within a certain radius. Similar to the other 3 scenarios, the discretionary development in the city centre and EPA zones are banned.

Scenarios			Land Use Supply Specifications									Transport Supply Specifications
			Beijing							Tianjin	Hebei	
			Centre	Near Suburb	Greenbelt	TOD Nodes	New Towns	Far Suburb	EPA			
Reference	**Ref**	Concentric growth (controlled development in the centre)	×	√	√	N/A	√	√	×	√	√	Network updates by decades Greenbelt zones built-form type 2
Greenbelt	**GB**	No growth in Greenbelt	×	√	O	N/A	√	√	×	√	√	Network same as Ref, except: 24 greenbelt zones built-form type 1
	GB-NT	GB + additional new town development	×	√	O	N/A	√+	√	×	√	√	Network same as GB
Green-Wedges	**GW**	Additional growth in the TOD nodes in the built-up wedges	×	√	O	√+	√	√	×	√	√	Network same as Ref, except: Greenfield zones built-form type 1 TOD zones built-form type 3
Note	√ denotes both natural growth and discretionary growth are allowed. √+ denotes development is promoted with special policy support. × denotes natural growth is allowed, but no discretionary growth. O denotes no growth at all											

Table 6-5 Scenario variables overview

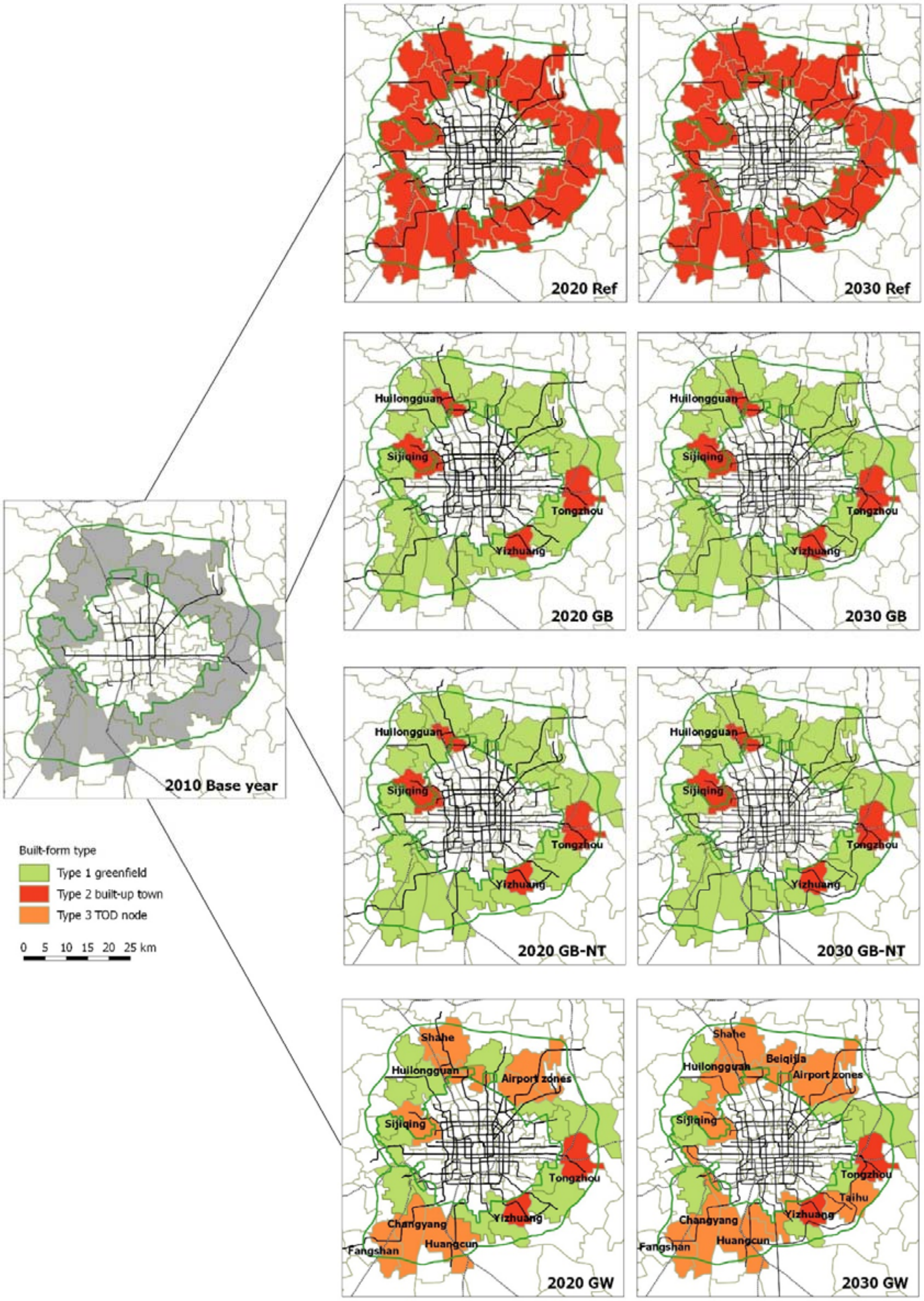


Figure 6-15 Transport variable and built-form changes

6.3.3 Background constraint projection

All the scenarios share the same socio-economic and macroeconomic background, which provide a uniform basis for scenario comparisons. Under the same background trend, scenario-specific policy settings can generate distinct urban development patterns. The overall socio-demographic and macroeconomic changes are not modelled endogenously, but defined by the user. We refer to exogenous forecasts and projections from various sources to define these constraints. The references include the governmental economic and demographic projections, projections from other research institutes and NGOs, and historic data from other city regions which are comparable to Greater Beijing.

The background constraints include the socio-demographic changes, the building floorspace stock changes and income level changes. They are estimated exogenously, because such constraints are contingent on the external government plans, planning regulations and wider economic climate. User-defined background trend and constraints are likely to be the most appropriate in terms of reflecting policy targets and background changes.

6.3.3.1 Population projection

The population inputs needed for model simulation are the total employed population by socio-economic groups for the Greater Beijing region. There has not been such a specific prediction for this geographical scope. Therefore, we start the estimation from the municipal/provincial level to the regional level, and from the total population to the segmented employed population.

Wu & Wu (2012)'s research has forecasted the demographic change in Beijing to 2049, and this projection has been widely accepted by authorities. In Wu's research, the population size of Beijing will double to 40 million in 2049, compared to 2010. We interpolate this 40 million population in 2049 cross the 40 years and then obtain the population projection in 2030. For Tianjin and Hebei, there is no official population projection. The Master Plan of Jing-Jin-Ji Integrated Development (Central Political Bureau of China 2015) has emphasised that Hebei will be the third development pole after Beijing Municipality and Tianjin Municipality. Although there is some uncertainty regarding the population growth rates in the scenarios we have tested, we consider it as a representative scenario to maintain a uniformly high growth rate for all three areas.

Given the total population projection, we assume that the employed population accounts for 50% of the total population. This percentage is selected based on the research of China's future employment size projection carried out by Qi (2010). We also refer to the case of London, where, in 2014, the percentage of employed population to the total is about 50%[11]. This could be an indicator for Beijing in 2050, given the development lag between the two cities.

The next step is to divide the employed population into socio-economic groups. This was done by Rong (2016). In order to derive a reasonable prediction for Beijing's socio-economic segmentation, Rong compared several socio-economic growth projections from various sources, including the prospects published officially by United Nations, and the studies in China, US, the EU, and Brazil. The EU style socio-economic change is adopted as the development trend for Greater Beijing, which is characterized by the rise of the middle group, a continuous reduction of the low group and a modest growth of the high group. Population in Tianjin and Hebei are not segmented. They are assumed to have the same socio-economic characteristics as Beijing's middle group.

Table 6-6 summarises the segmented employed population as model inputs. In theory, they can move cross administrative boundaries. However, because population classified into low and high socio-economic groups only exists in Beijing due to the data availability issue, such groups can only move within Beijing's municipal boundary. This seems to be a reasonable model specification, because high profile jobs and households mainly concentrate in Beijing, while low income population has lower mobility and is less likely to accomplish cross-boundary movement.

[11] https://www.nomisweb.co.uk/reports/lmp/gor/2013265927/report.aspx

Employed population (person)	Beijing			Tianjin	Hebei	Total
2010		11,805,556		7,287,000	38,651,400	57,743,956
	high	middle	low			
	1,865,939	6,678,491	3,261,127			
2020 projection		13,850,000		8,900,000	47,200,000	69,950,000
	high	middle	low			
	2,650,000	8,250,000	2,950,000			
2030 projection		15,900,000		10,510,000	55,750,000	82,160,000
	high	middle	low			
	3,430,000	9,840,000	2,630,000			

Table 6-6 Employed population projection

The increase of non-employed households in total remains as exogenous input (Rong 2016). The household size remains constant from 2010 to 2030.

	2010	2020	2030
Number of household	5,728,623	10,763,948	15,802,575
Number of people	13,347,692	25,080,000	36,820,000

Table 6-7 Projection of non-employed households

The upgrade of socio-economic groups is witnessed in the household composition for 2030, compared to the matrix presented in Table 5-8 for 2010. The percentage of individuals in low socio-economic group decreases.

Households type	Employed resident-High	Employed resident Middle	Employed resident -Low
		Beijing	
High	1.67	0.43	0.06
Middle	-	1.96	-
Low	-	-	1.41
		Tianjin	
Composite	-	1.96	-
		Hebei	
Composite	-	1.96	-

Table 6-8 Household composition 2030

6.3.3.2 Floorspace stock projection

The model forecast requires the projection of total regional floorspace as input constraints. The floorspace constraints include the housing floorspace by type and the business floorspace.

The projection of total housing floorspace is from the estimation of average housing floorspace per household. By referring to the historic trend and literatures (Chen & Chen 2013; Sun 2011), we assume the average housing floorspace per household will increase from 50 m^2 in 2010 to 67 m^2 in 2030. This gives us an indicator of calculating the total floorspace supply.

In terms of housing varieties, we further assume that among the total housing floorspace growth, 10% comes from small-size housing, 60% comes from medium-size housing and 30% comes from large-size housing. This subdivision represents the fact that small houses/flats are likely to be upgraded slowly, because most of them are in the city centre and will be renovated or enlarged through the historical city centre regeneration plan. The medium-size and large-size housing will make up the majority of the housing provision. Due to data availability, we only differentiate the housing varieties for Beijing, and assume housing type in Tianjin and Hebei shares the same characteristics as the medium-size housing in Beijing. Table 6-9 summarises the housing floorspace constraints used in the model.

Housing floorspace stock (million sqm)		Beijing		Tianjin	Hebei	Total
2010		575.3		547.1	2436.0	3558.4
	large	medium	small			
	43.2	460.4	71.7			
2020 projection		962.5		923.7	3874.8	5761.0
	large	medium	small			
	288.8	577.5	96.2			
2030 projection		1364.1		1309.4	5290.1	7963.6
	large	medium	small			
	409.2	818.5	136.4			

Table 6-9 Housing floorspace projection

For business floorspace, we follow the assumption that every employed worker occupies 20 m^2. Thus the growth of business floorspace is in proportion to the growth of the number of employed workers.

Business floorspace stock (million sqm)	Beijing	Tianjin	Hebei	Total
2010	237.6	146.6	773.0	1157.2
2020 projection	318.3	182.9	897.8	1399.0
2030 projection	414.6	216.1	1012.5	1643.2

Table 6-10 Business floorspace projection

Although the regional floorspace constraints are user-defined through exogenous projections, the zonal floorspace constraints are simulated in the Recursive Dynamic Model, which provides boundary conditions for the cross-sectional Spatial Equilibrium Model and Non-Commuting Travel Demand Model.

6.3.3.3 Income level and value of time projection

For economic development, we adopt the OECD's GDP projection (OECD 2012) for China, which predicts that China's GDP in 2050 will be 7.4 times as that of 2010. This is equivalent to an annual GDP growth rate of 5.1% up to year of 2050, which is in line with the current government targets. We interpolate the total GDP growth across 2010-2050, but considering the slowing down of growth rate by time.

The GDP growth rate provides us a reference for the income growth projection. Specifically we assume that the average wage income per resident would grow at the same rate as the GDP per capita projection. This assumption reflects the government's initiative to share the national development outcome with households and to promote domestic consumption.

	Regional average income per person (Yuan)	Implied annual growth rate
2010	14,251	
2020 projection	36,744	9.9%
2030 projection	59,236	4.9%
2040 projection	81,729	3.3%
2050 projection	104,221	2.5%

Table 6-11 Regional income level projection

Marginal utility of money measures how sensitive people are to monetary costs in travel. The value therefore decreases proportionally as the income grows. The model does not distinguish the marginal utility of money by geographical boundaries, but only by socio-economic groups. Table 6-12 summarises the values used in the Strategic Transport Model.

Flow	Trip purpose	Socio-economic group	Marginal utility of money (minute/cent)		
			2010	2020	2030
1	Commuting	high	0.046877	0.028514	0.017667
2		medium	0.095804	0.0582749	0.036108
3		low	0.174834	0.1063467	0.065893
4	Education	high	0.046877	0.028514	0.017667
5		medium	0.095804	0.0582749	0.036108
6		low	0.174834	0.1063467	0.065893
7	Business	high	0.023439	0.0142573	0.008834
8		medium	0.047902	0.0291375	0.018054
9		low	0.087417	0.0531734	0.032947
10	Other personal	high	0.046877	0.028514	0.017667
11		medium	0.095804	0.0582749	0.036108
12		low	0.174834	0.1063467	0.065893

Table 6-12 Marginal utility of money changes over decades

6.4 Overview of simulation results for 2030

Based on the background constraints from the last section, we carry out the model simulations from the base year 2010 to 2030, and run the four sub-models in the following sequence (refer to Figure 4-7):

1) Run RD to link the base year 2010 to the cross-sectional year 2020.

2) Run the cross-sectional year 2020: start from ST, output the travel matrices into SE; run SE, output the employment-residence locations into NCTD; run NCTD, output the locational choices for commuting and non-commuting activities into ST; run ST.

3) Run RD to link cross-sectional year 2020 to 2030.

4) Repeat the cross-sectional run of 2020 sub-models to 2030 sub-models.

The model will generate distinct spatial patterns for the year 2020 and 2030 under different scenarios. In this section, we offer a comparison of major simulation results among 2030 scenarios on relatively aggregate levels (municipal/provincial or zone categorical levels). The 2030 Ref scenario is the bench mark that is compared against every other scenario.

The simulation results are presented in the following order. First of all, we introduce the results regarding demographic change, in terms of the distribution of residents and jobs. Secondly, we present the modelled building stock provisions across scenarios. Thirdly, indicators regarding the economic performance, including rents, production, and wages are posed on municipal/provincial scale and zone-categorical scale. Finally, transport statistics, including average travel time, distance range distribution, mode share and passenger-km, are compared amongst scenarios.

6.4.1 Socio-demographic analysis

Given the same total population as background assumption, the socio-demographic results focus on 1) revealing the spatial distribution of residents and jobs among Beijing, Tianjin and Hebei, and 2) showing the distribution on zone-categorical level in Beijing.

Table 6-13 and Table 6-14 compare the population distribution of alternative scenarios to the Ref scenario. GB, GB-NT and GW scenarios all stimulate cross-boundary population and employment relocation. Compared to Ref, GB brings about 6% reduction of population and jobs in Beijing, because there is no supporting policy, for example new towns, to absorb over spilled population from the main city of Beijing. Population dissolve into Hebei province. The GW scenario does facilitate cross-boundary movement, but not as obvious as GB and GB-NT. In general, employed worker distribution possesses a very similar pattern to the employed resident distribution.

	2010 base year	2030 scenarios			
		Ref	GB	GB-NT	GW
	Thousand people		Percentage of change compared to Ref		
Beijing	11806	18887	-6%	-4%	-2%
Tianjin	7290	8444	-2%	-4%	1%
Hebei	38649	54829	2%	2%	1%
Regional	57744	82159	0%	0%	0%

Table 6-13 Employed resident distribution at municipal/provincial level

	2010 base year	2030 scenarios			
		Ref	GB	GB-NT	GW
	Person		Percentage of change compared to Ref		
Beijing	11,806	18980	-6%	-4%	-2%
Tianjin	7290	8486	-2%	-4%	1%
Hebei	38649	55994	2%	2%	1%
Regional	57744	82159	1%	0%	0%

Table 6-14 Employed worker distribution at municipal/provincial level

We then zoom into a smaller scale to investigate the employed population distribution in Beijing. According to the zone categories specified in 6.3.1, Figure 6-16 shows the resident distribution among zone categories. Ref shows that if there is no policy intervention, the greenbelt will be a very popular area to settle down. The total employed residents in the greenbelt will double: from 3.2 million in 2010 to 7 million in 2030, even 0.8 million more than the residents in the centre.

Compared to Ref, GB and GB-NT discourage residents to live in the greenbelt and the population is less than 4 million. The city centre gains 0.5 million diverted residents, and the inner city gains 0.6 million diverted residents. If the new town oriented policy is implemented in addition to the greenbelt, more people will relocate and settle in new towns (1.2 million more residents in new towns than that of GB), from elsewhere in Beijing, and from Tianjin and Hebei. However, this does not alter the trend that the city centre and the inner city are the growth poles.

GW shows a distinct pattern to GB and GB-NT, but similar to Ref. The population in the greenbelt increases by a significant amount, from 3.2 million in 2010 to 6.5 million in 2030. This phenomenon represents the popularity of the greenbelt area. The population distribution within the greenbelt boundary cannot be seen at this scale yet.

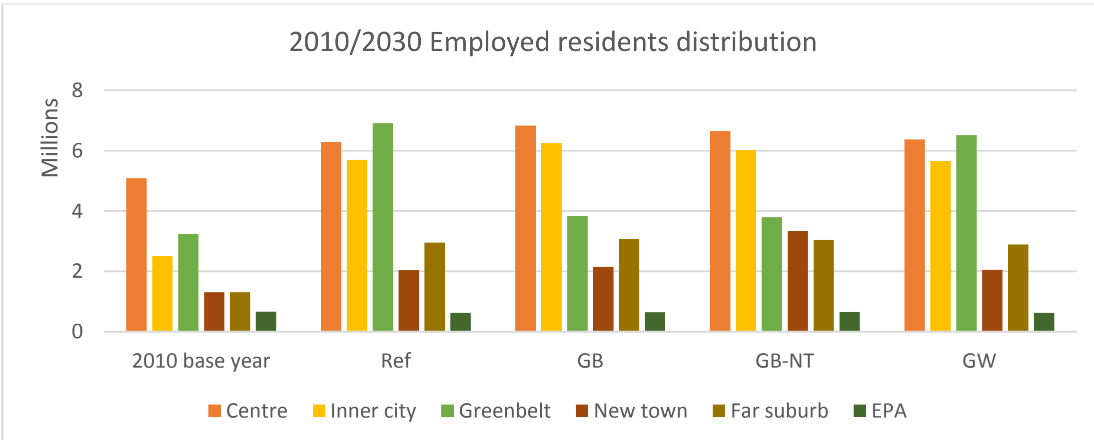


Figure 6-16 Employed resident distribution in Beijing by zone category

Figure 6-17 presents the employed worker distribution through time and across scenarios by zone category. Beijing's city centre is surely the main job centre. However, because the centre has been already very packed since 2010, the inner city becomes the next employment centre in 2030. This is true across the 4 scenarios in 2030: the number of workers in the inner city increases from 1.5 million in 2010 to more than 5 million in 2030. The differences of employed worker distribution mainly exist in the greenbelt zones. Ref and GW share the similar spatial patterns. The employment in greenbelt zones rises significantly from 2 million in 2010 to 4 million in 2030. On this scale, it is hard to tell where the employment locates within the greenbelt area. However, due to the different policy designs, Ref and GW should direct employment to different places within the greenbelt, despite the similar total amounts of employment. This will be discussed later in section 6.5. GB-NT's spatial pattern resembles GB's pattern. The new town oriented policy does help new towns to gain some more job opportunities (0.7 million more than that in GB). However, because new towns are relatively far from the main city, they fail in competing with the city centre and the inner city to become another employment centre.

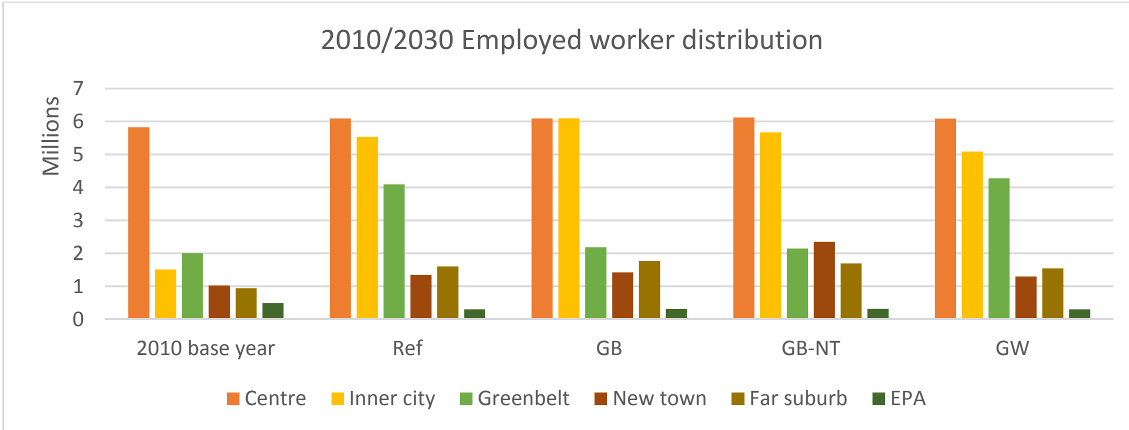


Figure 6-17 Employed worker distribution in Beijing by zone category

6.4.2 Building floorspace analysis

The building floorspace analysis focuses on 1) revealing the spatial distribution of floorspace supply among Beijing, Tianjin and Hebei, and 2) the floorspace supply among zone-categories in Beijing.

Table 6-15 shows the housing floorspace increase from 2010 to 2030 and the variations amongst scenarios in 2030. The GB scenario has the least housing provision in 2030 in Beijing, which is 11% less than the Ref scenario. Subsequently, Tianjin and Hebei gain the channelled housing floorspace from Beijing. GB-NT has a similar tendency of change. The magnitude of the change is less severe (6%), because the complementary new towns accommodate some of the diverted housing floorspace supply. The GW scenario, compared to Ref, does not show any change on the municipal/provincial level. The distribution of housing floorspace on zonal/categorical level will be examined later on.

	2010 base year	2030 scenarios			
		Ref	GB	GB-NT	GW
	Floorspace (million m^2)		Percentage of change compared to Ref		
Beijing	575.4	1169.0	-11%	-6%	0%
Tianjin	547.1	1189.4	2%	1%	0%
Hebei	2436.0	5605.2	2%	1%	0%
Regional	3558.4	7963.6	0%	0%	0%

Table 6-15 Housing floorspace supply at municipal/provincial level

Similarly, the business floorspace supply appears a similar tendency of changes among municipalities and province to the housing floorspace supply. This is summarised in Table 6-16. In the GB scenario, Beijing's business floorspace is 4% less than the reference case. This difference is not as radical as that of the housing floorspace, because business floorspace is more likely to be built in the existing employment centres and the inertia is stronger than housing development. The distributions of business floorspace in GB-NT and GW are respectively similar to the distributions of housing floorspace. The GB and GB-NT scenarios both provoke the redistribution of floorspace development cross administrative boundaries. Beijing's development is restrained while developments in Tianjin and Hebei are promoted.

	2010 base year	2030 scenarios			
		Ref	GB	GB-NT	GW
	Floorspace (million m^2)		Percentage of change compared to Ref		
Beijing	237.7	460.8	-4%	-3%	0%
Tianjin	146.6	197.9	3%	1%	0%
Hebei	773.0	999.3	2%	1%	0%
Regional	1157.3	1643.2	0%	0%	0%

Table 6-16 Business floorspace supply at municipal/provincial level

After the investigation of the floorspace supply at the municipal/provincial level, we summarise the zone-categorical level floorspace provisions.

The result from Ref in Figure 6-18 show that the greenbelt area is the most popular location of housing development if there is no restriction. If urban containment is applied as shown in GB, the development (about 140 million m^2) will be diverted into areas beyond the boundary of Beijing Municipality into Tianjin and Hebei. New towns will gain some additional development (about 60 million m^2), but they are not able to accommodate all of the diverted development from the greenbelt. The housing floorspace pattern of GW still resembles that of Ref at this scale. We need to investigate into a finer granularity to reveal the zonal differences in housing floorspace development between GW and Ref.

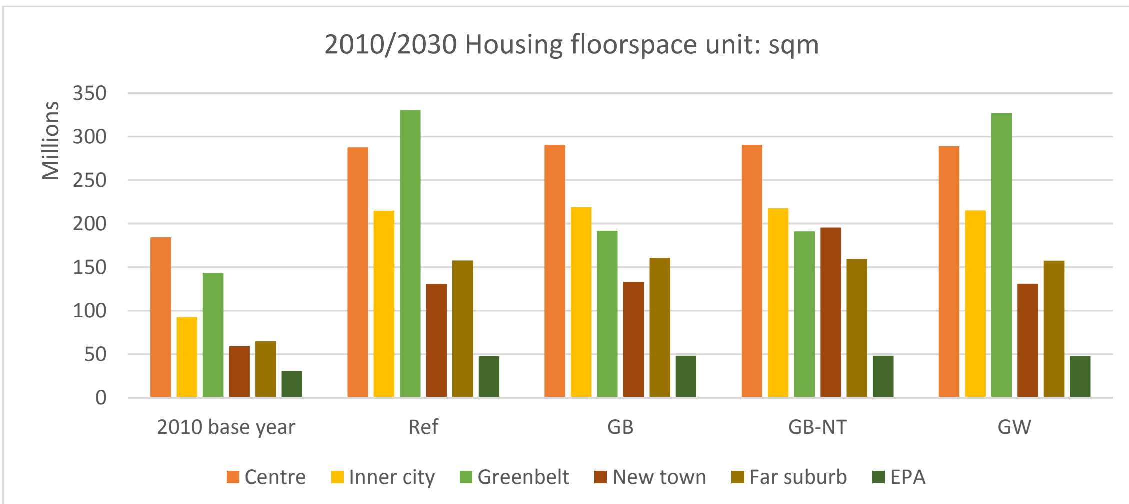


Figure 6-18 Housing floorspace supply in Beijing at zone-categorical level

Unlike housing floorspace, business floorspace development highly concentrates in the city centre and the inner city in all the scenario alternatives. If greenbelt policy is implemented (in GB and GB-NT), some development will be diverted from the greenbelt into the inner city, but more will be diverted into Tianjin and Hebei. With new town policy, new towns grab some development opportunities (20 million m^2), but they are not able to accommodate all the diverted development from the greenbelt (45 million m^2). The amount of business floorspace in greenbelt zones in GW scenario transcend that in Ref by 10 million m^2. We need to investigate later in section 6.5, within the greenbelt boundary, where such a development takes place.

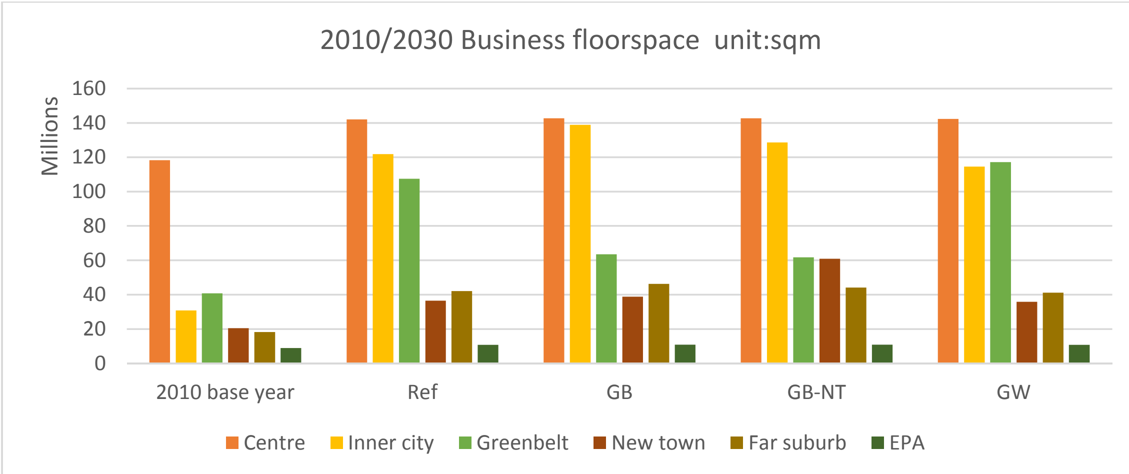


Figure 6-19 Business floorspace supply in Beijing at zone-categorical level

6.4.3 Indicators revealing economic performance

In this section we focus on the indicators related to the economic performance of the city region. We first examine the average rents at municipal/provincial level. Then we compare the total production outputs in different scenarios. Last but not least, we compare the average wage level at municipal/provincial scale.

6.4.3.1 Average rent

Average rent is decided by two factors: floorspace supply and housing/production demand. Plotting the average rent can help to identify which factor plays a dominant role.

As shown in Table 6-17, from 2010 to 2030, the average housing rent in Beijing has doubled (comparing 2010 base year to Ref, from 632 to 1291 Yuan/m^2/year); the rents in Tianjin and Hebei also increase, but not as much as that of Beijing. Recall that income level in 2030 is 4.2 times of that in 2010 (Table 6-11). However, housing rent does not increase proportionally to the income level for two reasons. Firstly, the housing rent in Table 6-17 is the rent per square meter. Referring to Table 6-9, total housing floorspace in 2030 is 2.2 times of that in 2010. This is to say, the rent per square meter in 2030 should be around 1.9 (4.2/2.2) times of that in 2010. The modelling result for the regional average rent increases about 1.6 times. Secondly, the cost shares of housing within each household type stay the same in the model from 2010 to 2030[12], but the proportion of low income household decreases from 2010 to 2030. This indicates that the overall cost share of housing decreases and overall a smaller share of income (by percentage) is spent on housing.

Comparing alternative scenarios to Ref, the decreases of housing development in GB and GB-NT outweigh the reductions of residents in Beijing, which therefore pushes the housing rent up by 7%. Housing rent in Tianjin decreases as a combined result of sufficient housing supply and reduction of residents (refer to Table 6-13 and Table 6-15). Housing supply and resident number both increase in Hebei, and as a result, the rent remains unchanged. At the municipal/provincial level, GB-NT acts as a similar but less radical scenario to GB. The results of GW show that adequate housing supply and a subtle decrease of population in Beijing brings the rent down by 1%. On the contrary, increase of population in Tianjin and Hebei brings the rent up by 1%.

		2030 scenarios			
	2010 base year	**Ref**	**GB**	**GB-NT**	**GW**
	Yuan/m^2/year		Percentage of change compared to Ref		
Beijing	632	1291	7%	3%	-1%
Tianjin	365	545	-3%	-3%	1%
Hebei	334	479	0%	1%	1%
Regional	387	608	0%	0%	0%

Table 6-17 Average housing rent at municipal/provincial level

The change of business floorspace rent in Table 6-18 exhibits a similar pattern to housing rent change. Comparing the Ref to 2010 base year, business floorspace rent shoots up by 267% on regional average. Rent in Beijing goes up slightly in GB and GB-NT (3% and 1% respectively). It points out the fact that in Beijing, the decrease of floorspace supply outweighs the decrease of the production. As a result, the rent rises. In Hebei, the increases of employment and business

[12] Housing cost share for high income group is 0.17, for middle income group is 0.26, and for low income group is 0.35.

floorspace cancel out each other and lead to a stable rent level. On the contrary, GW exhibits a distinct change. Rent in Beijing goes down as a result of sufficient business floorspace and decrease of production.

		2030 scenarios			
	2010 base year	**Ref**	**GB**	**GB-NT**	**GW**
	Yuan/m^2/year		Percentage of change compared to Ref		
Beijing	220	539	3%	1%	-2%
Tianjin	119	242	-5%	-4%	1%
Hebei	71	180	0%	1%	1%
Regional	108	288	0%	0%	0%

Table 6-18 Average business floorspace rent at municipal/provincial level

In 2010, housing rent follows the gradient that falls from the centre to the far suburb in Beijing. In 2030, this gradient is bent. The rent in inner city overtakes that in the central city and becomes the highest. As centre was already packed in 2010, discretionary floorspace development is shifted to the inner city as the second-best location. Residents follow this trend and move to there, which generates high housing demand and thus pushes the housing rent up. The GB and GB-NT policies reinforce this phenomenon, so the rent in the inner city soars by more than 250% from 2010. Ref and GW in general have lower average housing rents, due to the sufficient housing supply in Beijing.

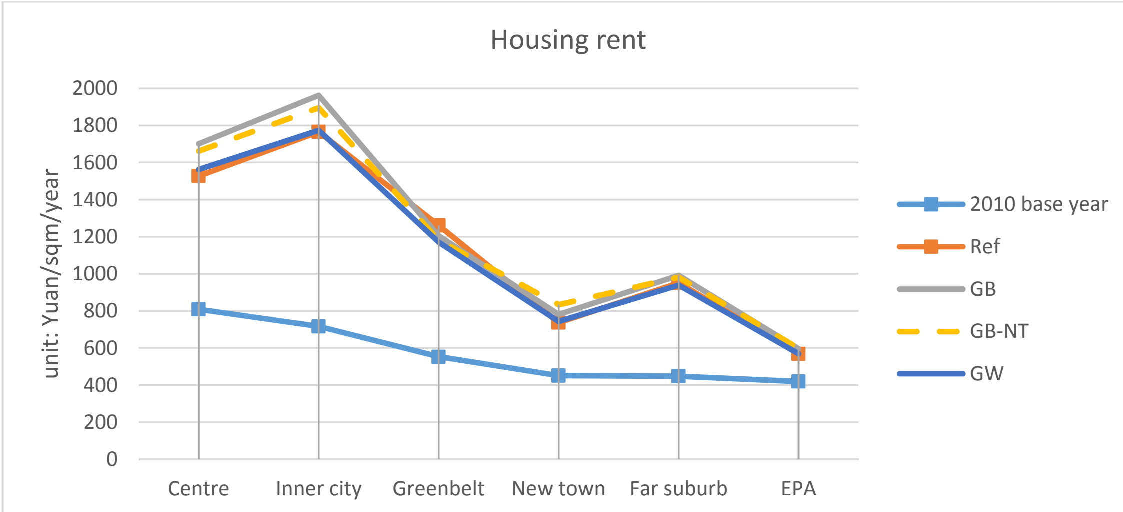


Figure 6-20 Comparison of housing rent in 2010/2030 Beijing

Unlike housing rent gradient, business floorspace rent always follows the gradient that highest rent happens in the centre. Differences among the 4 scenarios can hardly be seen. This is because employment is highly concentrated in the central city which dominates the rent gradient.

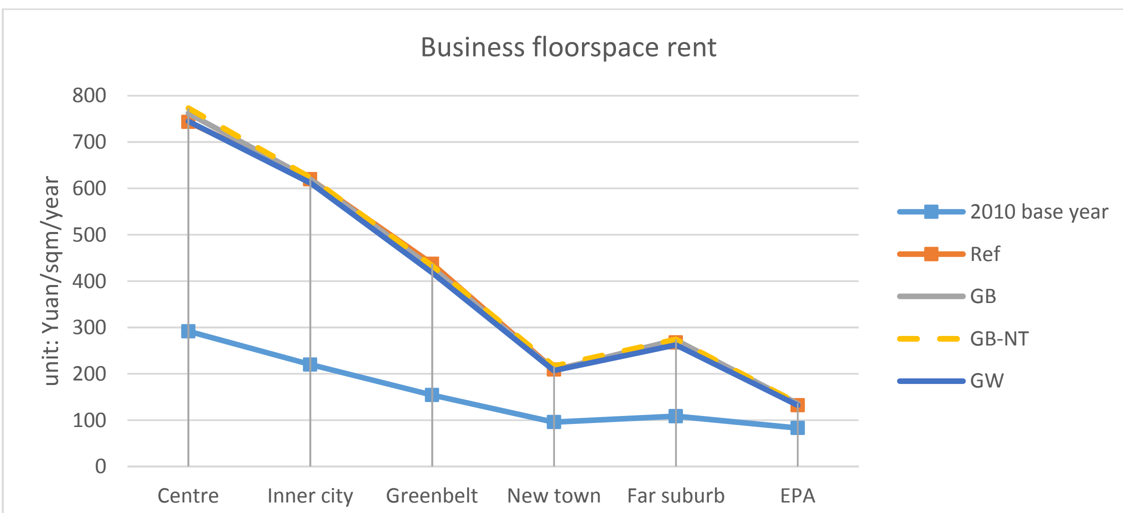


Figure 6-21 Comparison of business floorspace rent in 2010/2030 Beijing

6.4.3.2 Production output

The production output is represented in quantity. It essentially means the unit of composite goods and services produced. It therefore equals the total household demands for composite goods and services. If we analyse the percentage change from the demand side, it is clear that the production output distribution resembles the pattern of resident distribution (see Table 6-13). In GB and GB-NT scenarios, as people move to Hebei from Beijing, production output in Hebei increases accordingly. In GW, production output decreases in Beijing while increases in Tianjin and Hebei.

		2030 scenarios			
	2010 base year	**Ref**	**GB**	**GB-NT**	**GW**
	Quantity (millions)		Percentage of change compared to Ref		
Beijing	3014	5687	-3%	-3%	-2%
Tianjin	6513	8166	-3%	-4%	1%
Hebei	26283	40585	2%	2%	1%
Regional	35810	54438	1%	1%	0%

Table 6-19 Total production volume in quantity of composite goods at municipal/provincial level

Production volumes vary at the zone-categorical level (Figure 6-22). In 2010, the central city dominates the productivity of Beijing, while in 2030, inner city becomes another major production centre. The GB and GB-NT policies supress the productivity in greenbelt zones at a level about 600 million units, while GW policy enhances the productivity in greenbelt to about 1200 million units, even slightly higher than Ref. GB-NT promotes the total production in new towns (500 million units), but the main production still comes from the centre and inner city (3800 million units together).

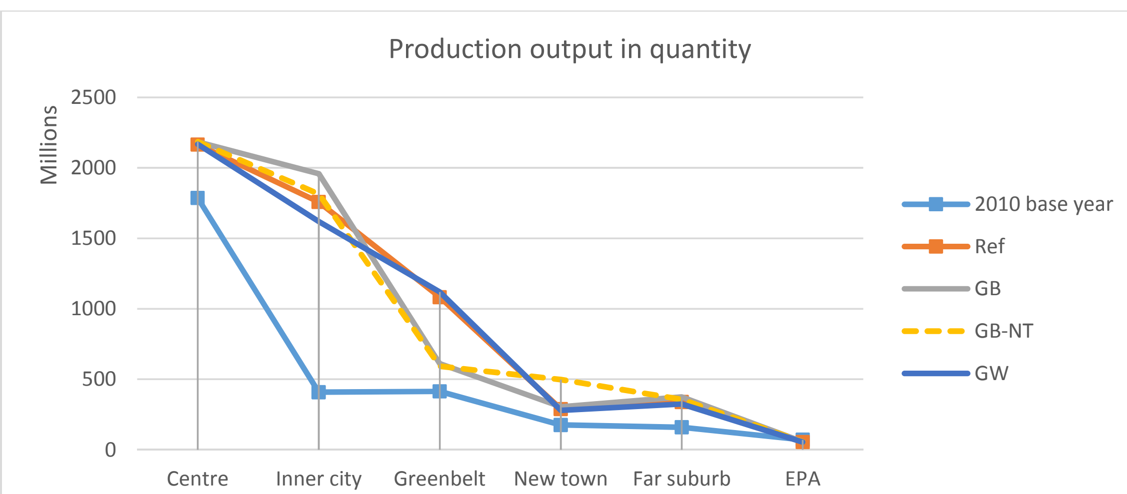


Figure 6-22 Comparison of production output in 2010/2030 Beijing

6.4.3.3 Wage

The average wage at municipal/provincial level is not a trade-off among the administrative boundaries. That is to say, a wage increase in one area does not necessarily result in a decrease in another area. This is because the average wage level mainly depends on two factors: the total production output and labour supply. For example, if the production output rises, more labour is needed. A labour shortage will lead to an increase of wage and vice versa. If the production output and labour supply both go up, the wage level depends on which factor's impact is more significant.

The greenbelt interventions, with or without new town development, cause a shortage of workers in Beijing, meanwhile they also lead to decreases in total production output. The decrease of labour outweighs the decrease of production, and an increase of wage level has been witnessed in Beijing in GB and GB-NT. Green-wedges policy also shows the same trend, but the wage increase is less obvious (only 1%).

		2030 scenarios			
	2010 base year	**Ref**	**GB**	**GB-NT**	**GW**
	Yuan/hour		Percentage of change compared to Ref		
Beijing	16.2	44.5	4%	2%	1%
Tianjin	11.7	26.6	0%	1%	0%
Hebei	9.4	20.1	0%	0%	0%
Regional	11.1	26.4	0%	0%	0%

Table 6-20 Average wage at municipal/provincial level

In general, wage level descends from the city centre to the suburb. However, wage level in new towns across the 2030 scenarios breaks this tendency: it is even lower that the far suburb. This is a combined result of low production output and relatively abundant labour. GB and GB-NT cause labour shortages in the greenbelt zones, which subsequently increase the wage level.

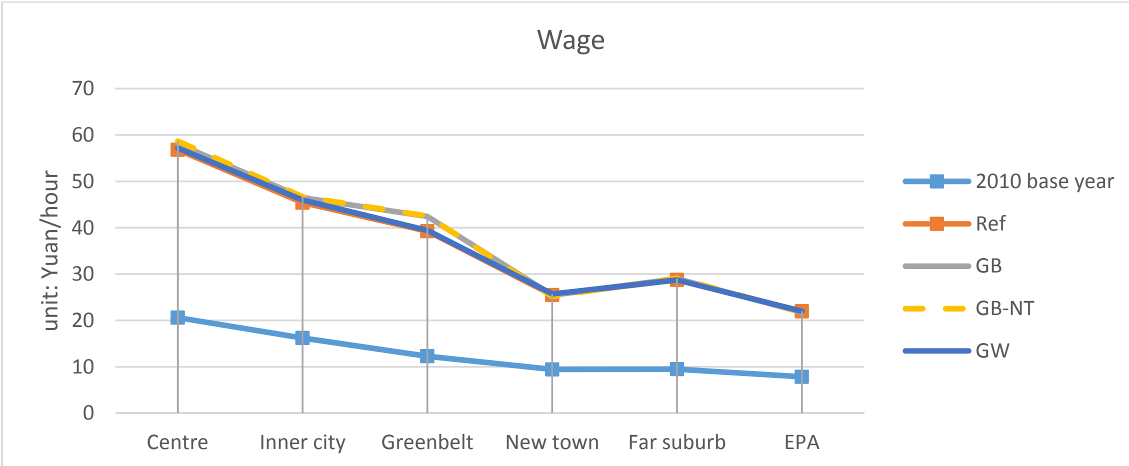


Figure 6-23 Comparison of wage in 2010/2030 Beijing

6.4.4 Transport analysis

Transport analysis focuses on the overall travel statistics mainly in Beijing. This is because the transport model is well-calibrated within Beijing's geographical boundary based on Beijing's travel surveys. Inter-zonal network in Beijing is constructed on a finer granularity while in Tianjin and Hebei they are highly aggregated. We present the results in Beijing, including trip distance range and mode share results, with finer granularity. The Tianjin and Hebei's results are comparable but on only aggregate level.

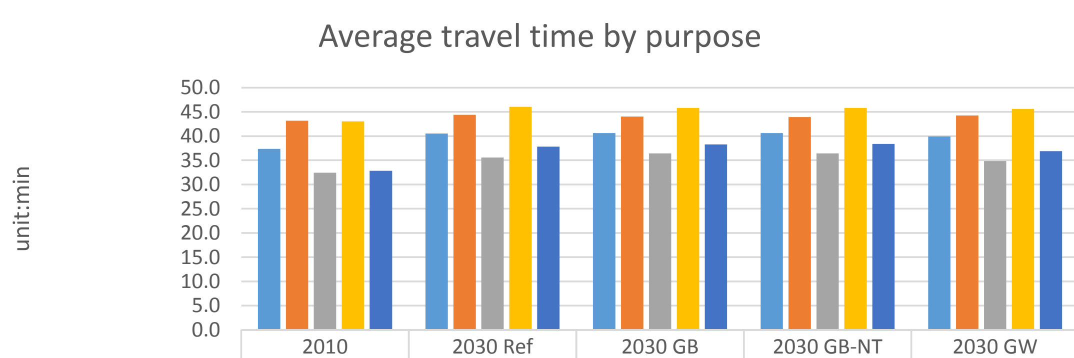
We first examine the average travel times and distances by travel purpose. This is followed by the analyses of trip range distribution and travel mode share. The distances travelled per person per year are presented last.

6.4.4.1 Average travel time and distance

We plot the average travel times and travel distances by travel purpose in Figure 6-24 and Figure 6-25. In general, travel times remain stable with subtle increases from 37.4 minutes in 2010 to 40.5 minutes 2030. The finding of the relatively stable travel times is in line with the empirical findings in Anas (2015), which argued that the improvement of mobility and the employment-residence locational adjustments keep times stable. Amongst 2030 scenarios, the differences of average travel times are not very obvious. This is in line with the findings in

Echenique et al. (2012), which concluded that the influences of urban form policies on travel behaviour are modest.

But generally speaking, Ref has the longest commuting time, followed by GW. GB and GB-NT have slightly shorter commuting time. This contrasts the common sense that the greenbelt policy encourages long distance commuting and increase commuting time. The reason behind such a common sense is that the population and job relocation from city centre to new towns commonly leads to spatial mismatch of employment and residential areas, and it therefore encourages long distance commuting. Nevertheless, GB and GB-NT do not generate such a movement. The GB and GB-NT scenarios either confine residents and jobs in the main city or trigger cross-boundary movement by relocating residents together with employment to Tianjin and Hebei (refer to Table 6-13 and Table 6-14). The two policies therefore do not lead to spatial mismatch and do not encourage long commuting.



	2010	2030 Ref	2030 GB	2030 GB-NT	2030 GW
all trips time	37.4	40.5	40.6	40.6	39.9
commuting time	43.2	44.4	44.0	43.9	44.3
educational trip time	32.4	35.6	36.4	36.4	34.8
business trip time	43.0	46.0	45.8	45.8	45.6
other trip time	32.9	37.8	38.3	38.4	36.9

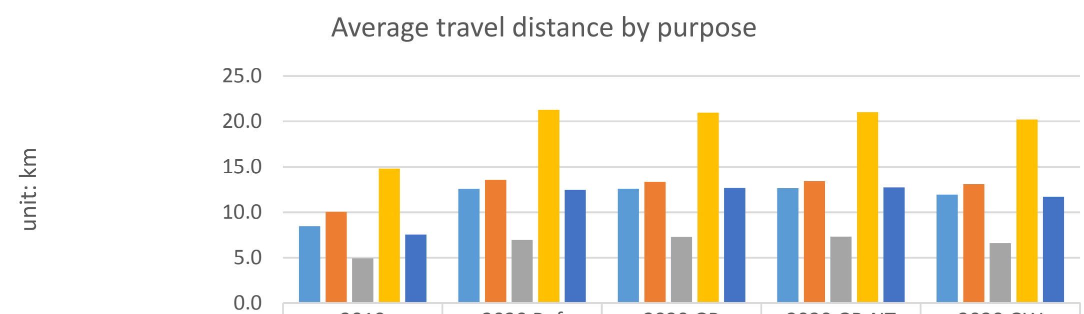
Figure 6-24 Average travel time 2010/2030 in Beijing

Although the average travel time is relatively stable over decades, average travel distance increases by a significant amount. Commuting trip length goes up from 10.0 km in 2010 to about 13 km in 2030 (30% increase). Educational trip length goes up from 4.9 km to about 7 km (42% increase). In order to validate the modelled trip length, we refer to the increase of travel distance from 2010 survey (Beijing Transportation Research Centre 2012) to 2014 survey (Beijing Transportation Research Centre 2016). The commuting distance within the 6th ring-road increases from 9.5 km to 10.1 km over the 4 years. The educational trip distance increases from 4.8 km to 5.6 km over the 4 years. If we extrapolate this growth trend between the two surveys, we will get an even longer travel distance. However, the growth speed will decelerate. Therefore, our modelled trip distances for commuting and educational trips are reasonable.

Business trip length increases by 38% while length for other personal trips increases by 60%. We do not have evidence in Beijing's surveys to refer to so far, and it therefore hard to say if they are under/overestimated. The percentage of business trip length increase is within a reasonable range, as it is similar to the increase of commuting and educational trips. Personal trips are much longer than 2010, but as mobility is enhanced, longer travel distance is possible. Here we refer to external sources by comparing the average travel distance in the UK and the US. The average travel distance reported in National Travel Survey England 2014 is about 11.3 km (Department for Transport 2015), while the London Travel Demand Survey shows that the average distance travelled per person per day in London is about 13.9 km in 2015-2016 (Transport for London 2016) [13]. The average travel distance reported in 2009 National Household Travel Survey in the US is about 15.2 km (U.S. Department of Transport 2015). Our prediction of Beijing's travel distance (11.9-12.6 km) falls in between the two countries in 2030, which is within a reasonable range. However, considering that the income level in Beijing in 2030 is predicted to be still lower than the current levels in the US and England, this travel distance is likely to be overestimated[14].

[13] The England and U.S. average travel distance is in the unit of average distance per trip annually. London's travel distance is by per person per day. Beijing's result is for the average distance per trip in morning peak. Therefore, the external sources can only be used as an approximate guide to compare with the model results for Beijing.

[14] GDP per capita in US in 2009 was 47000 USD (http://data.worldbank.org/indicator/NY.GDP.PCAP.CD); GVA per head in England in 2014 was about 40000 USD (House of Commons Library, SN05795, http://researchbriefings.parliament.uk/ResearchBriefing/Summary/SN05795). GRP per capita in Beijing in 2030 is predicted to be 32000 USD by our model.



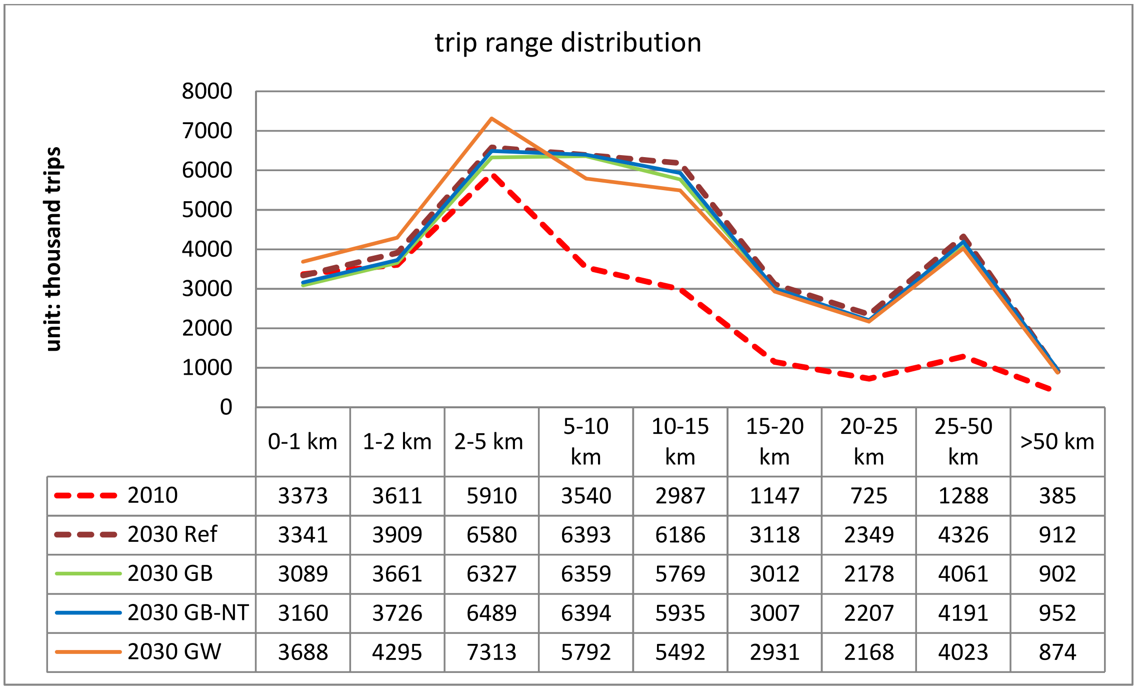
	2010	2030 Ref	2030 GB	2030 GB-NT	2030 GW
all trips distance	8.5	12.6	12.6	12.6	11.9
commuting distance	10.0	13.6	13.3	13.4	13.1
educational trip distance	4.9	7.0	7.3	7.3	6.6
business trip distance	14.8	21.3	21.0	21.0	20.2
other trip distance	7.5	12.5	12.7	12.7	11.7

Figure 6-25 Average travel distance 2010/2030 in Beijing

Figure 6-24 and Figure 6-25 show that in 2030, with similar travel times to 2010, people can reach longer distances, which indicates an improvement of travel speed. As the constant congestion network speed is applied to the Greater Beijing LUTI Model and thus the network speed remains the same from 2010 to 2030, the overall speed improvement is prompted by shifting from slower travel mode to faster travel mode. The mode share change will be discussed later in section 6.4.4.3.

6.4.4.2 Trip range distribution

Compared to the trip range distribution in 2010, trips longer than 5 km happen more frequently in 2030. This complies with the findings in average trip distance. People are likely to travel longer distance as a result of the improvement of mobility. The differences among the 4 scenarios in 2030 mainly exist in trips shorter than 15 km. Ref, GB and GB-NT share similar trip range distributions. Range 2-5 km is always the most frequent region. This is true in every 2030 scenario and in the historic year 2010. Comparatively, GB and GB-NT possess slightly less trips in the longer range (>10 km) than Ref. GW shows a distinctive pattern to the other scenarios. Trips less than 5 km are more common. Trips longer than 5 km are categorically less than those in Ref, GB and GB-NT. This is because in GW scenario, shorter intra-zonal travel bands are promoted in the TOD nodes based on the assumption that people live relatively close to the network.



	0-1 km	1-2 km	2-5 km	5-10 km	10-15 km	15-20 km	20-25 km	25-50 km	>50 km
2010	3373	3611	5910	3540	2987	1147	725	1288	385
2030 Ref	3341	3909	6580	6393	6186	3118	2349	4326	912
2030 GB	3089	3661	6327	6359	5769	3012	2178	4061	902
2030 GB-NT	3160	3726	6489	6394	5935	3007	2207	4191	952
2030 GW	3688	4295	7313	5792	5492	2931	2168	4023	874

Figure 6-26 Trip range distribution for all travel purposes in Beijing

6.4.4.3 Travel mode share

Firstly of all, we explore the mode share of all trips for all travel purposes. Then we investigate the number of trips by mode for each travel purpose. Finally we present the commuting mode share in the greenbelt zones as a result of different built-forms.

Figure 6-27 reveals the overall mode share over decades across scenarios. Compared to the mode share in 2010, car usages prevail in 2030. The increase of value of time (decrease of marginal utility of money) over decades prompts the popularity of car in two ways. Firstly, it directly results in a reduction in the overall car travel cost by reducing the monetary cost term. Secondly, the increase of value of time indirectly causes a reduction in travel disutility in every mode, which encourages people to choose further travel destinations and longer intra-zonal bands. For longer trips, car is an advantageous travel mode, which can be observed in the value of modal specific constants in Appendix E. Unlike car mode share, the shares for bus, cycle and walking see decreases. The share for metro/rail stays the same to that in 2010. Nevertheless, because there are more trips in total in 2030, the actual journeys by metro/rail increase.

Amongst the 4 scenarios in 2030, on this aggregate scale, Ref, GB and GB-NT are indistinguishable. GW shows a slightly different mode share: more metro/rail, cycling and walking trips, less car trips.

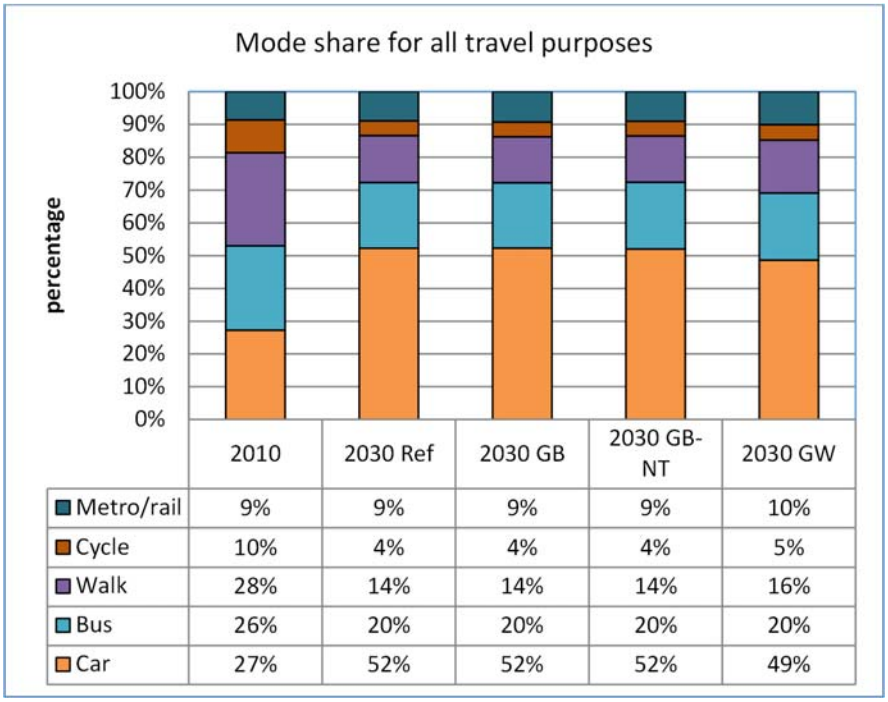
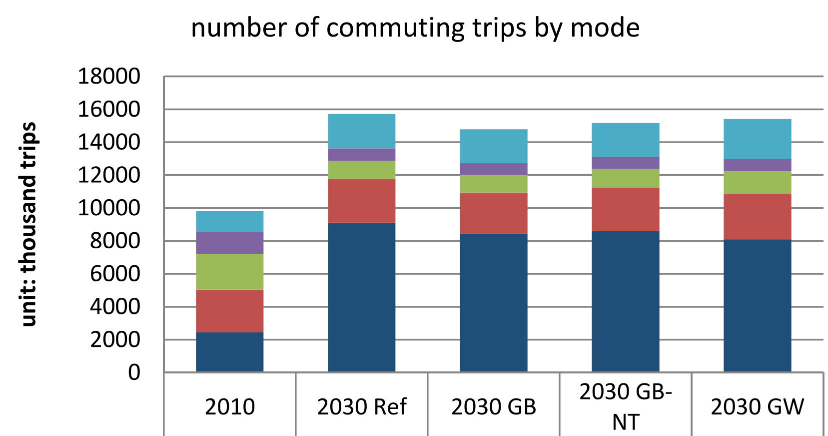


Figure 6-27 Mode share for all travel purposes in Beijing

We then zoom into the mode shares for different travel purposes. Figure 6-28 - Figure 6-31 report the number of trips by mode for commuting, educational, business and other purposes respectively.

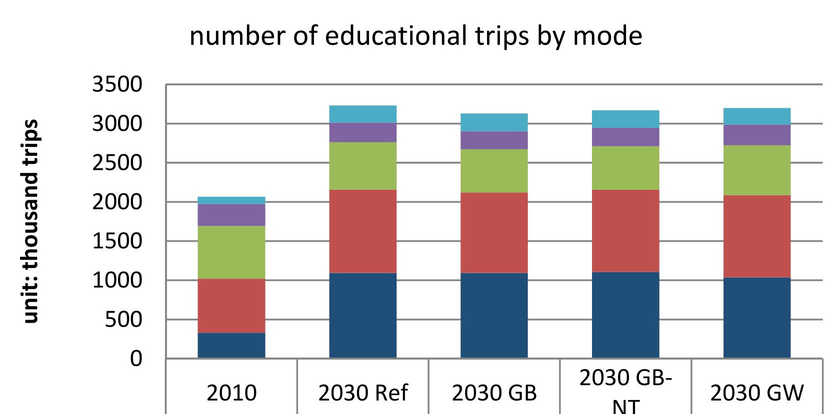
More commuting trips are generated in the Ref scenario which results in the highest car journeys. The population sizes in the GB and GB-NT scenarios are smaller and in return, numbers of trips for each mode is categorically smaller, although the mode shares in percentage are the same as that of Ref. The GW scenario predicts that about half of the commuting trips are done by car. The total number of commuting trips are not too different from Ref, but the car trips are less.



	2010	2030 Ref	2030 GB	2030 GB-NT	2030 GW
Metro/rail	1303	2097	2053	2048	2419
Cycle	1315	757	730	739	762
Walk	2166	1106	1065	1137	1364
Bus	2601	2656	2493	2646	2772
Car	2441	9108	8443	8592	8097

Figure 6-28 Number of commuting trips by mode in Beijing

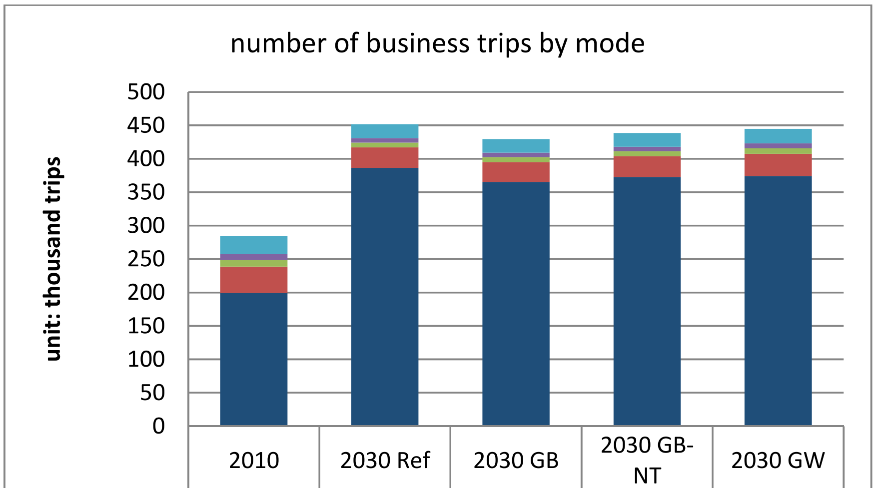
Car is not the major mode for educational trips. Instead, bus and walking together account for more than 50%. Mode share variations amongst the 4 alternatives are indistinct. However, car journeys in GW scenario are comparatively less than other scenarios.



	2010	2030 Ref	2030 GB	2030 GB-NT	2030 GW
Metro/rail	92	219	226	224	212
Cycle	283	251	232	234	262
Walk	672	602	550	557	638
Bus	690	1066	1027	1048	1049
Car	330	1093	1094	1106	1036

Figure 6-29 Number of educational trips by mode in Beijing

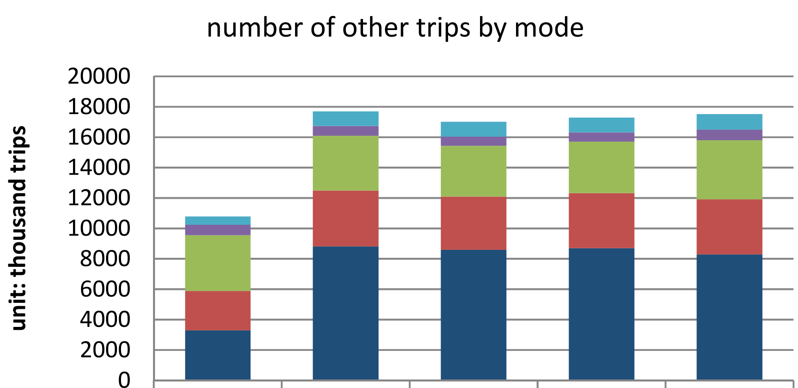
Car travels dominate business trips. Car was already dominant in 2010 and this trend intensifies in 2030. It is understandable that employees are likely to travel by car to meet business partners and clients. To understand it from another perspective, the modal specific constants for Flow 7-9 in Appendix E are very car-oriented for business trips, which indicate the extra benefit from travelling by car. Additionally, as the average distance for business trips are relatively long, car is more preferable, which can also be seen in the calibration of modal specific constants.



	2010	2030 Ref	2030 GB	2030 GB-NT	2030 GW
Metro/rail	27	21	21	20	22
Cycle	9	7	7	7	8
Walk	10	7	7	7	8
Bus	39	30	30	31	33
Car	199	386	366	373	374

Figure 6-30 Number of business trips by mode in Beijing

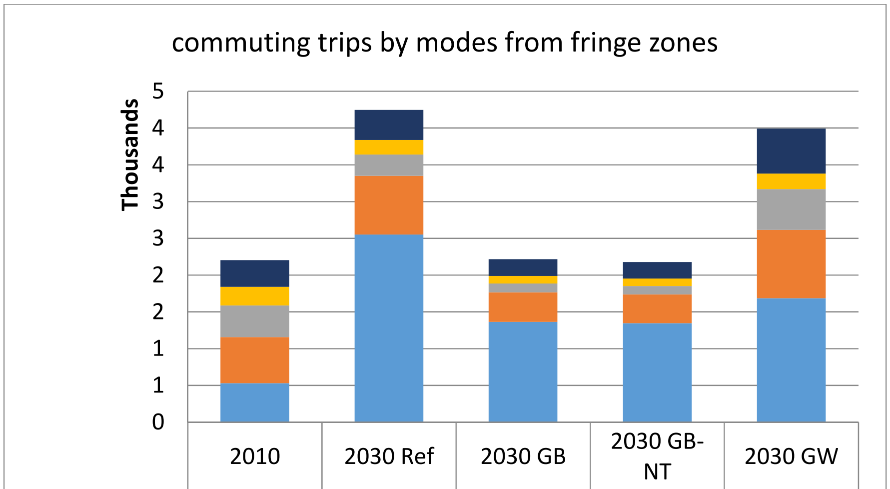
Mode shares of other trips resemble those of commuting trips, but not exactly the same. In 2030, car is still the prevalent mode, but less than half of the trips are done by car. Walking accounts for the second largest share. This is reasonable because for trips like going to grocery, going to parks for leisure, or going to playgrounds to do morning dance (which is a very popular exercise in Beijing), walking is likely to be the most convenient way.



	2010	2030 Ref	2030 GB	2030 GB-NT	2030 GW
Metro/rail	557	961	976	969	1023
Cycle	684	649	611	617	692
Walk	3670	3599	3336	3384	3897
Bus	2581	3676	3492	3626	3612
Car	3296	8820	8600	8696	8296

Figure 6-31 Number of other trips by mode in Beijing

We then pay close attention to the mode share in the greenbelt zones (Figure 6-32). The network supplies in the 2030 scenarios are different from each other due to different built-forms in the greenbelt, which cause the distinct mode shares. The total numbers of commuting trips in the greenbelt are proportional to the number of employed residents (refer to Figure 6-16). In Ref, GB and GB-NT, car journeys take up to 60%. GW shows its competence in promoting sustainable travel modes. Non-vehicle modes (walking and cycling) account for 19%, while public transport (bus and metro/rail) accounts for 39%.



	2010	2030 Ref	2030 GB	2030 GB-NT	2030 GW
Metro/rail	362	407	229	224	612
Cycle	254	198	102	101	211
Walk	429	291	119	114	555
Bus	626	797	402	392	929
Car	531	2552	1365	1346	1686

Figure 6-32 Commuting trip volume from the greenbelt zones by mode

6.4.4.4 Kilometres travelled per person per year

Kilometres travelled per person per year is a common measurement for travel demand. Here we present this measurement for the Greater Beijing region. Compared to the number of trips by mode, Kilometres/person/year is more appropriate to reflect the actual capacity of each mode in the whole region.

In 2030, the total kilometres travelled per person per year on average is predicted to be around 11000 km. Car journeys make up most of the distances, followed by bus. Although journeys travelling by metro/rail are long, but the total trip numbers are limited. For most of the Greater Beijing region, metro/rail has not been an option. Therefore, it contributes about 20% of passenger-km.

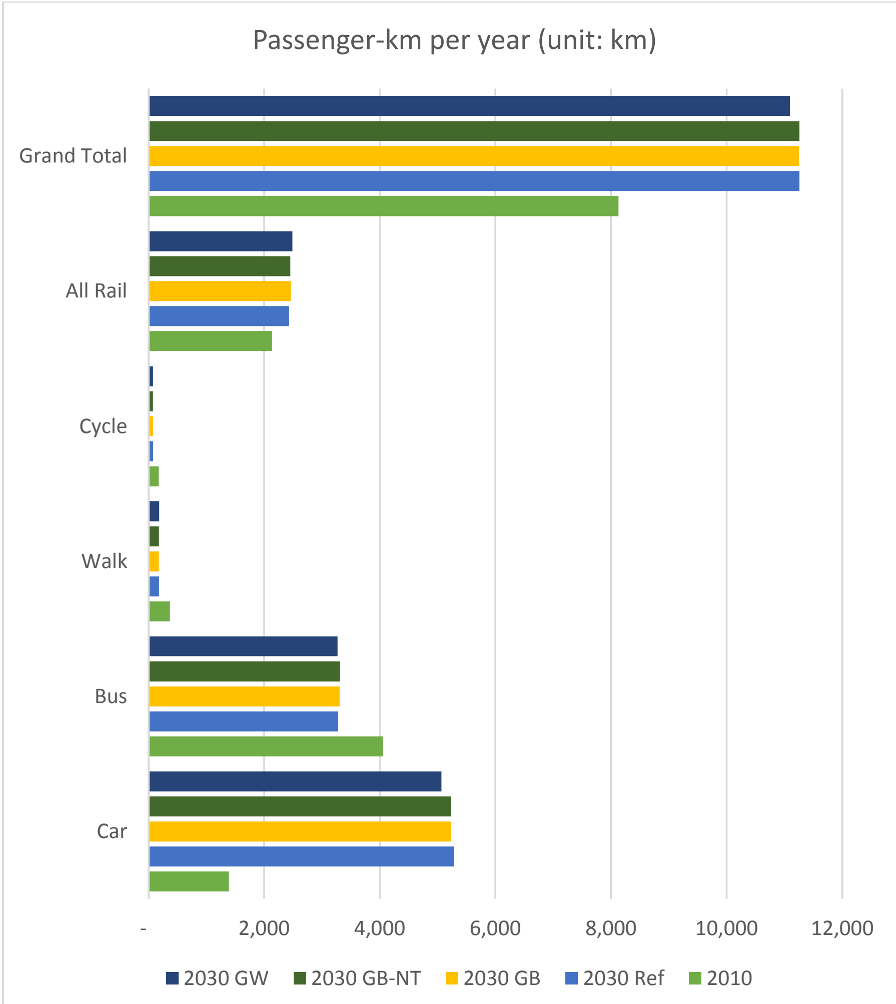


Figure 6-33 Km travelled per person per year in Greater Beijing

6.4.5 Summary of the simulation result overview

This section offers an outline of comparisons between the 2010 base year and 2030 Ref, and also amongst the four 2030 scenarios. All the comparisons are carried out either at the municipal/provincial level or at the zone-categorical level. The zonal differences are not yet demonstrated. Here we summarise several key findings of the result overview.

1) Urban containment policies in Beijing, including GB, GB-NT and GW, will bring about wider impacts on the regional scale in the long run. Compared to Ref, which is a continuation of the current development tendency, all of the other alternatives have triggered cross administrative boundary movement of residents and jobs, and relocation of floorspace development.

Beijing will lose population and jobs to Tianjin and Hebei. However, the outward movements of residents, employment and floorspace development from Beijing due to policy interventions do not mean that Beijing's overcrowding is relieved. The population and job decreases in Beijing mainly happen in the greenbelt area, which does not help to solve the overcrowding issue in the main city. The areas encircled by the greenbelt become more compact due to the implementation of GB and GB-NT.

2) The results shown in Ref suggest that development of Beijing will continue in a concentric manner if there is no intervention. Even though a constraint is added to the city centre, the central Beijing will continue to attract more development of floorspace in its limited space. This is because of the benefit from the agglomeration effects on productivity outweighs the economic costs of overcrowding. Moreover, our model does not simulate the road congestion brought by overcrowding, so that the agglomeration effects are intensified in the model.

3) The GB and GB-NT policy interventions fulfil the aim of preserving Beijing's greenfield in the prices of reducing economic productivity and raising rents in the city centre; however, they are unsuccessful in channelling development to the new towns beyond the greenbelt and forming a poly-centric urban structure[15]. Development is delivered either to Beijing's city centre or outside Beijing Municipality. Even with the complementary policy to support new town development in GB-NT, new towns still fail to compete with the city centre and the inner city to attract employment and business. Without coordinating transport improvements to link the new towns to centre, solely constructing more floorspace would not help to decentralise population.

   In this light, GB and GB-NT may not be the suitable policy interventions for decentralisation purposes for Beijing, but they indeed have wider impacts on redirecting growths to even further places (Hebei or Tianjin) at regional scale. This is the reason that we observe a slightly shorter commuting distance with GB/GB-NT interventions than Ref, which contrasts the common sense that greenbelt policy encourages long distance commuting.

[15] The poly-centric structure of Beijing is identified as "to limit the growth in the main city and to channel new development beyond the greenbelt" (Beijing Municipal Government 2003a; Beijing Municipal Commission of Urban Planning 2012).

4) The GW scenario mitigates the impacts of concentric growth and greenbelt intervention, so that Beijing would not experience an economic loss in terms of employment and floorspace development. Compared to Ref, there is no substantial trade-offs of population, jobs, and floorspace among Beijing, Tianjin and Hebei. Beijing's city centre is still where most productions come from. Nevertheless, the green-wedges policy channels a considerable amount of development from inner city to the greenbelt area. In return, the rents are lower in the central and inner city. At this scale, it is hard to say if the greenbelt area is built over. We need to analyse where the development happens in the greenbelt area in the next section.

   This scenario benefits from the improvement of transport condition. Although the road and rail networks are identical across scenarios, the proximity to network reduces the off-network time and cost. The advantageous transport condition shortens the travel time and distance.

5) A considerable improvement in travel speed from 2010 to 2030 has been spotted, and the improvement comes from adopting to faster travel modes, especially from the prevailing usage of cars. Speed improvement allows people to reach further destinations within the same time period, which enhances the overall mobility, and boosts the suburban development. The rising income level will continuously encourage more people to travel by faster modes, which is seen as beneficial at this modelling stage. However, excessive car journeys might lead to even worse road congestion, but these have not been systematically measured.

   Green-wedges is regarded as an eco-friendly policy, because total annual mileage per person is the shortest among all the scenarios, and the distance travelled by car is the shortest as well. Such advantages originate from the coordination of land use and transport policies. By allocating floorspace development to a limited number of TOD nodes, shorter trips (<5km) are promoted because people work locally. By allocating floorspace to the most convenient places close to the rail network, metro trips are promoted.

6.5 Simulation results by scenario for 2030

In this section, we investigate the zonal level variations in each scenario individually. This section is arranged as follows: firstly, we present the 2030 Reference scenario in section 6.5.1. This reference is considered as a continuation of the current development trend, so the results are reported by comparing them against the 2010 base year. The 2030 Ref will offer us a bench mark for 2030 alternative scenario comparisons. Secondly we present the results of alternative scenarios, namely the Greenbelt, Greenbelt-New Towns, and Green-Wedges, in section 6.5.2 6.5.3, and 6.5.4 respectively, by showing the relative differences to the 2030 Reference case.

For each scenario, we first report demographic changes by socio-economic group. Secondly, we present the building stock changes by floorspace type, along with the change of rent. Thirdly, the price related indicators, including wages, price and consumption utility are reported after rent change. Finally, we present the travel statistics, including the travel times, distances and costs by travel purpose, trip distance range by mode, traffic volume on road and metro networks, and mode shares in the greenbelt zones.

6.5.1 Reference scenario (Ref)

6.5.1.1 Socio-demographic analysis

Figure 6-34 depicts the concentric expansion of Beijing from 2010 to 2030. As city centre has reached a high density in 2010, inner city immediately becomes the next location to settle in for employed residents. The rise of the inner city has been shown and explained in Figure 6-16. Employment density shows a more concentrated pattern. Although the employment also spreads in a concentric manner, the growth takes place mainly in the centre and inner city, sprouting from existing job centres. In terms of regional integration, several Hebei counties to the southeast of Beijing witnesses a strong growth momentum in both population and employment. The main reasons for the fast growth are their adjacent locations to the centre of Beijing and the relatively low cost for real estate development.

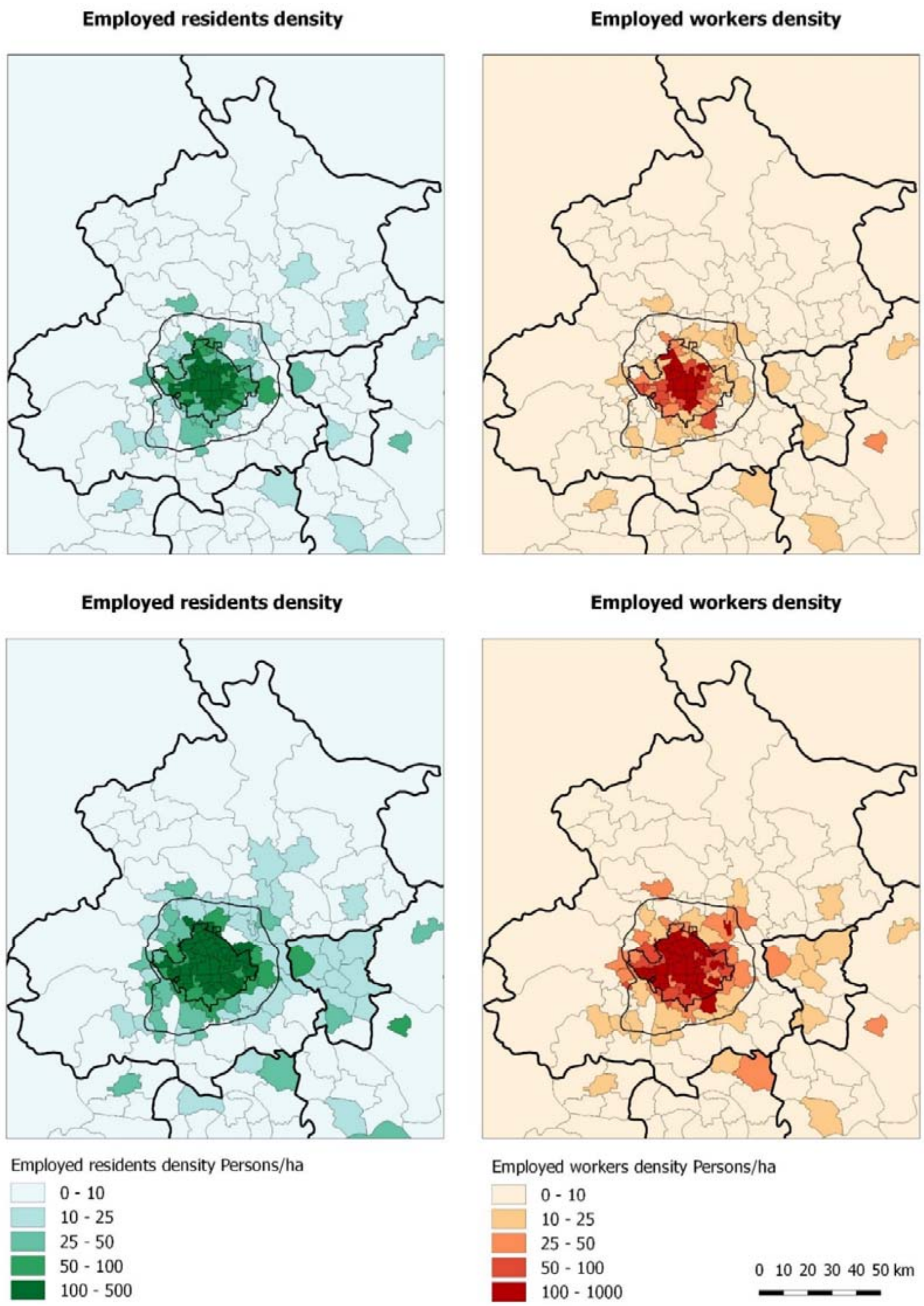


Figure 6-34 Employed residents and workers density. Top: 2010 Bottom: 2030

Historically, richer people live in the north of Beijing. High-paid jobs also concentrate in the north. This trend has not been altered in the 2030 Ref. North of the city is where government sectors, banks, universities and high-tech companies gather. Poorer people used to stay in the central city, but as time goes, they are priced out into the inner city and the centre is replaced by higher socio-economic groups. Middle socio-economic group spontaneously intensify in the main city as well as move outwards. Non-employed households used to live in the centre, but in 2030, their locations are dispersed. Some of them move out of Beijing to the nearby counties.

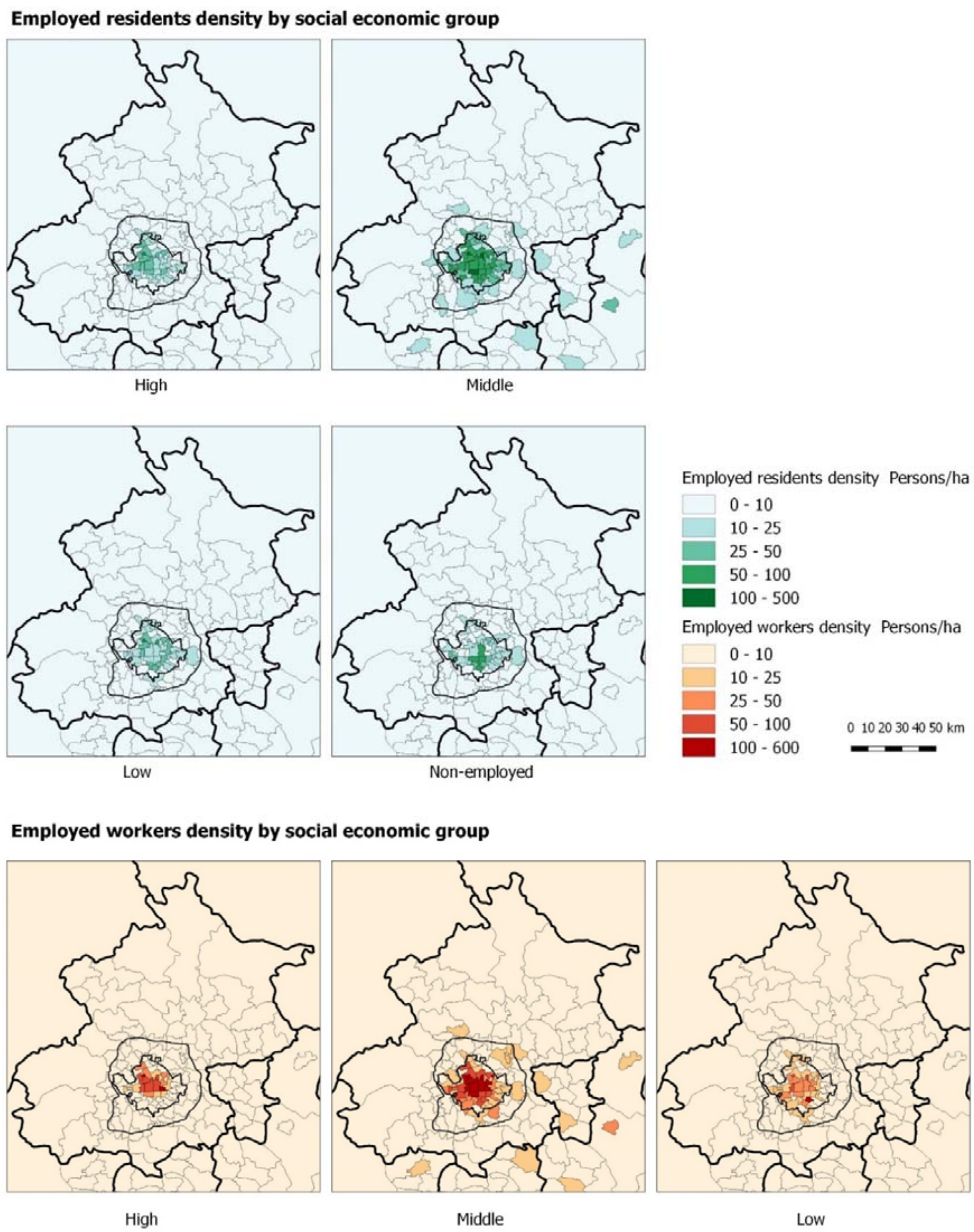


Figure 6-35 Density of employed residents and workers by socio-economic group 2010

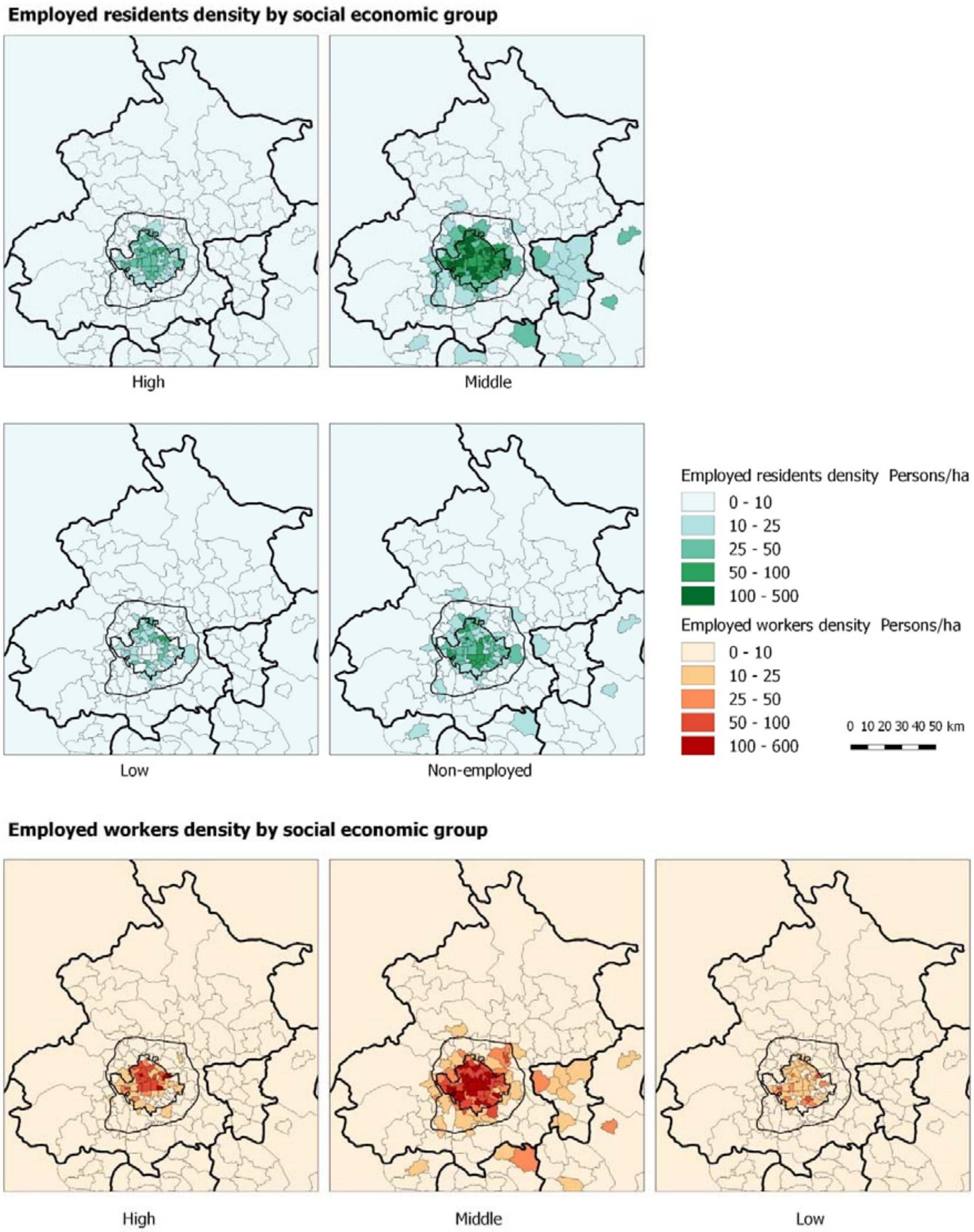


Figure 6-36 Density of employed residents and workers by socio-economic group 2030

6.5.1.2 Building floorspace and rent analysis

The structure of the Recursive Dynamic model has shown that the growth of floorspace is strongly related to the existing building stock size. Without policy intervention, the 2030 floorspace density will be a reinforced version of the 2010 floorspace density. This is demonstrated in Figure 6-37 and Figure 6-38.

The fast housing development in the Hebei counties to the east of Beijing is noticeable. In 2030, Beijing still performs as the regional employment and business centre. However, the soaring housing price propels people to reside in nearby counties, where the rent is lower. With the development of transport links and the faster travel speed, cross administrative boundary commuting has become possible.

Large dwelling units are built in the expensive central and inner city. Medium size dwelling units make up the majority of housing markets. They are predominant in the centre, the inner city, the greenbelt and the new towns. Small dwelling units are developed mainly in the city centre, through the old city regeneration process. In terms of business floorspace development, north of Beijing is the most popular location for office buildings.

Rents increase significantly from 2010 to 2030. Housing rents rise from 632 to 1291 yuan/m^2/year, while business floorspace rents rise from 220 to 539 yuan/m^2/year (Figure 6-39 and Figure 6-40). The escalation of business floorspace rent takes place in the centre, inner city, and parts of the greenbelt. The increase of housing rent displays ubiquitously.

In 2010, central city is the most expensive place to live in. However, in 2030 housing rent in inner city surpasses the rent in the central city. This has been previously captured in Figure 6-20. The north of the inner city is more expensive than the south, because this is where the high income people live. The results also show that the rent of small dwelling unit in the inner city is higher than that of large dwelling unit. This is because the price is presented for per square meter. Renting a large flat is in total more expensive than small flat, but not in the price per square meter.

In 2010, business floorspace rents are higher in the northwest, where banks and high-tech companies locate. In 2030, the rents are disproportionally high in the financial district and high-tech parks in the north. The development of the Central Business District and the airport also boost the rents in the east of Beijing.

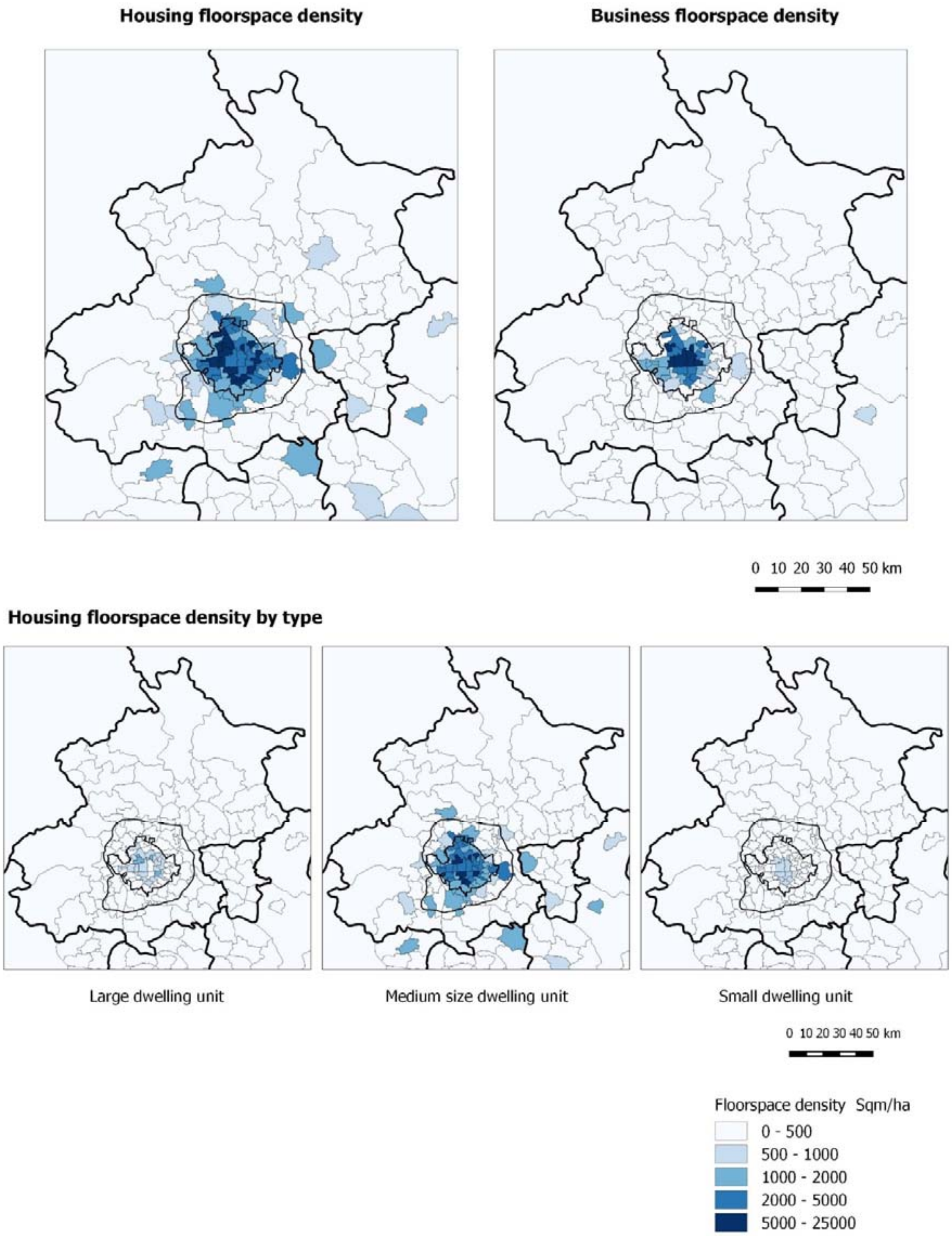


Figure 6-37 Floorspace density 2010

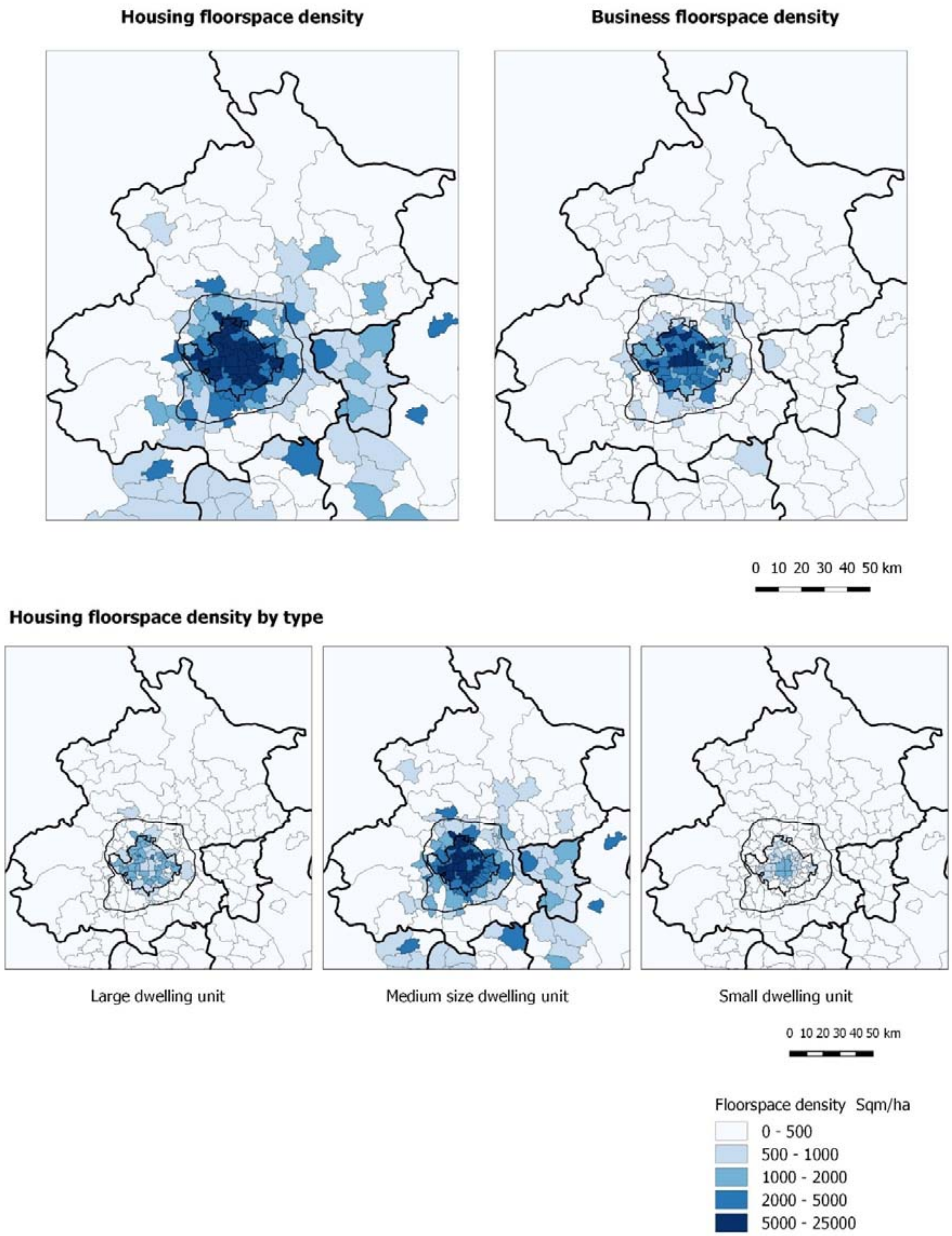


Figure 6-38 Floorspace density 2030

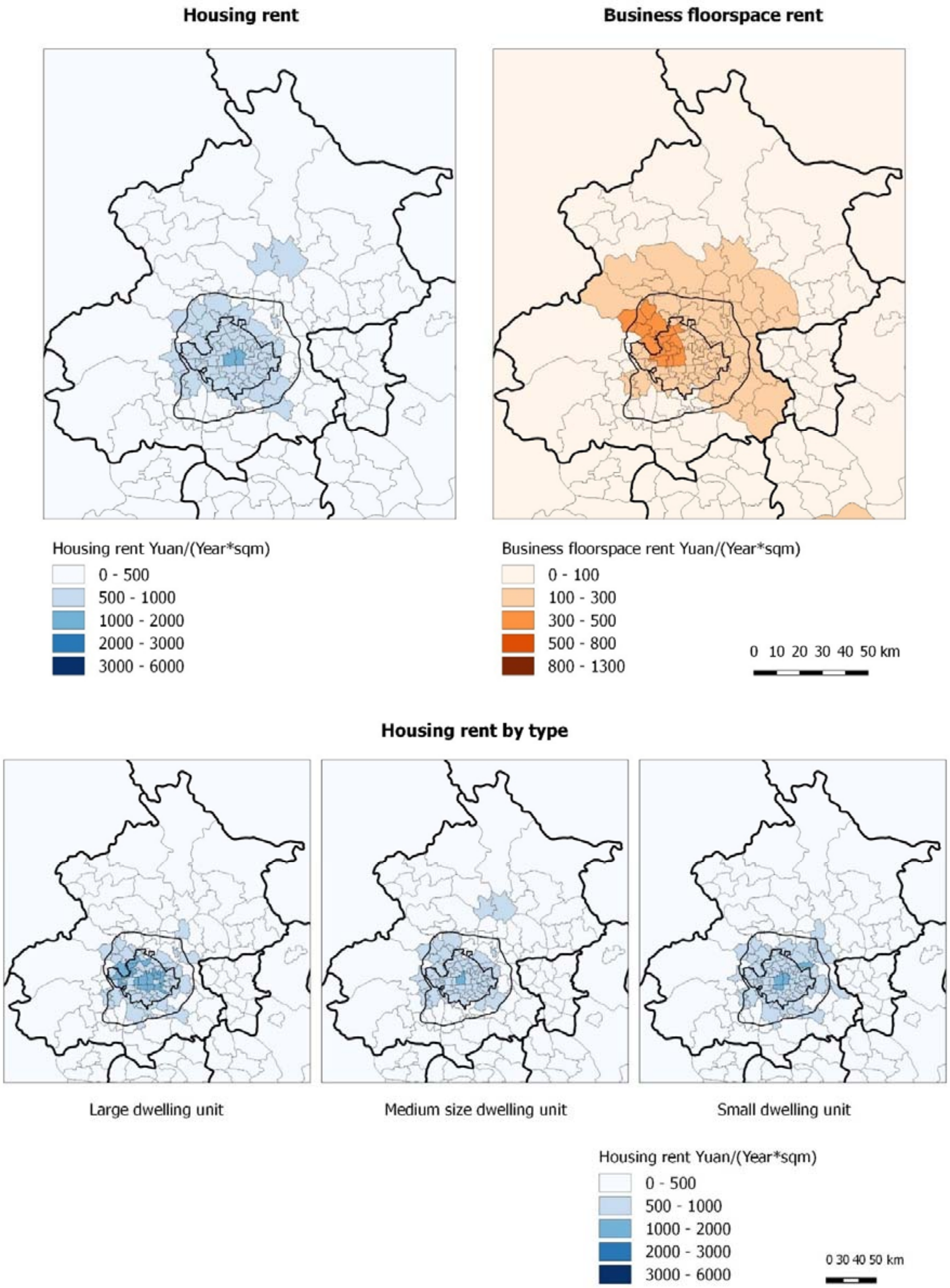


Figure 6-39 Rent 2010

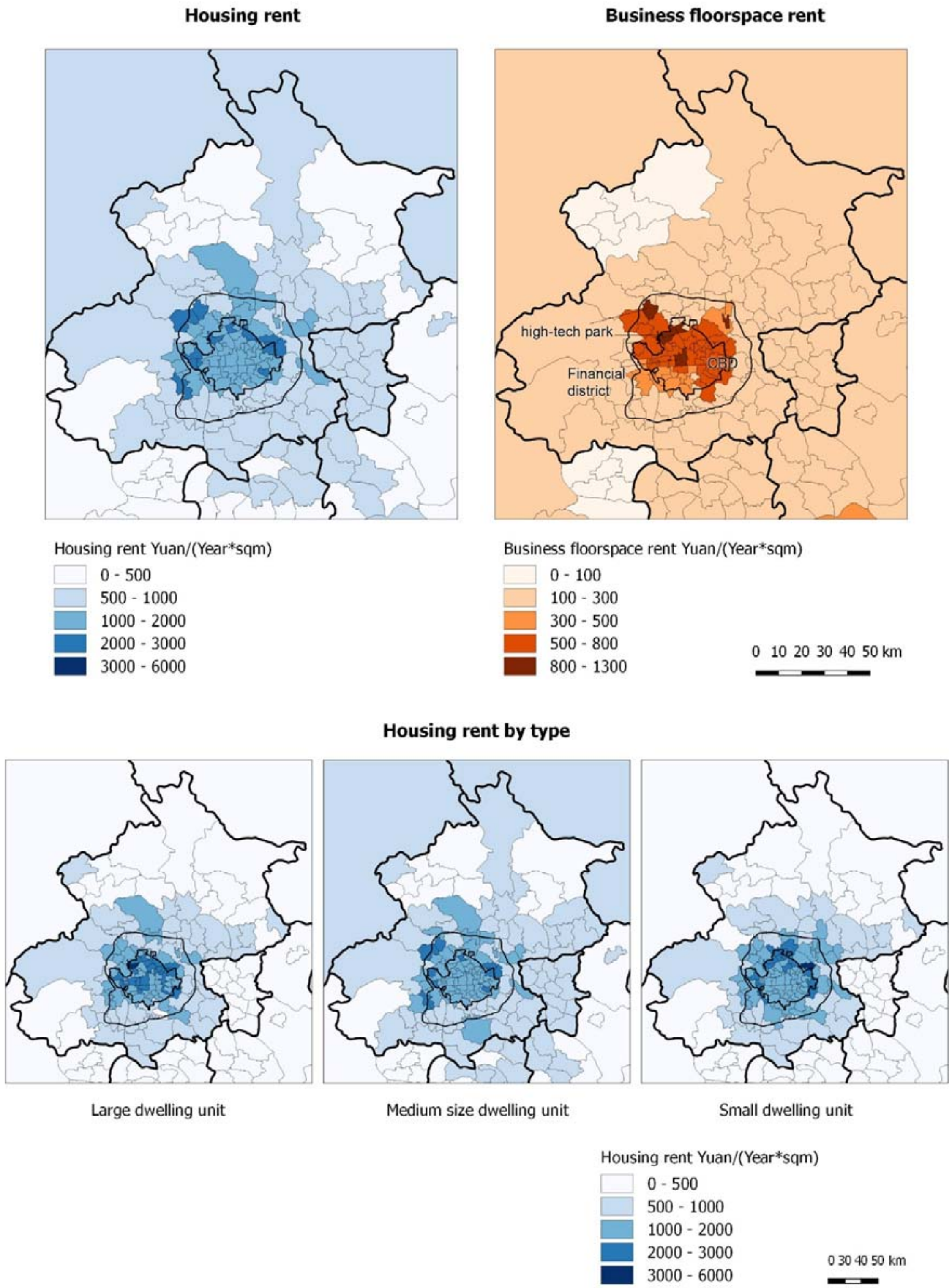


Figure 6-40 Rent 2030

6.5.1.3 Wage, utility and price analysis

Compared to 2010, the wage, utility and price levels witness a global increase in 2030. Consumption utility is determined by two factors, how much floorspace a household can afford and how many goods they can buy. Therefore, the rent level, price level and income level are the three factors that contribute to the consumption utility. In general, it is always relatively low in the city centre, because of the high rent and price. This phenomenon can be observed in the 2010 and 2030 maps. In term of the utility by socio-economic group, richer people are better off by living in the city centre in 2030, because they are able to afford high rent. For middle group, it is better to live beyond the centre. For poorer people, they will benefit from living beyond the greenbelt into the far suburb.

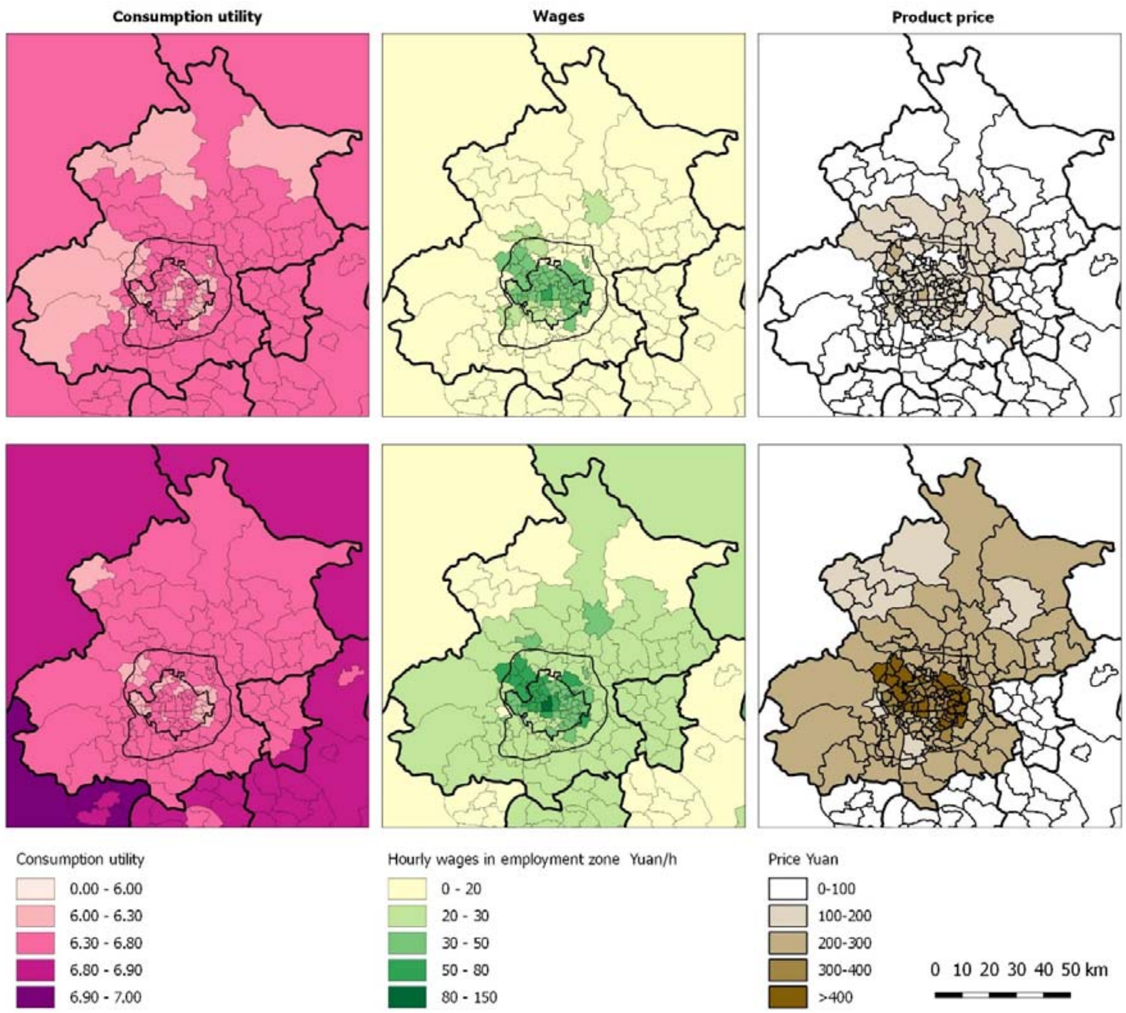


Figure 6-41 Consumption utility, wage and price. Top: 2010, Bottom: 2030

Wage level increases substantially in the north and east within the greenbelt boundary over the two decades. The well-paid job centres in the northwest of the city in 2010 expand further into the greenbelt. Price of the composite goods and service correlates to the wage level. This can be understood from both the consumption side and the production side of the story. From the consumption side, higher wage is needed to compensate high price. From the production side, price is determined by the labour costs and the floorspace costs.

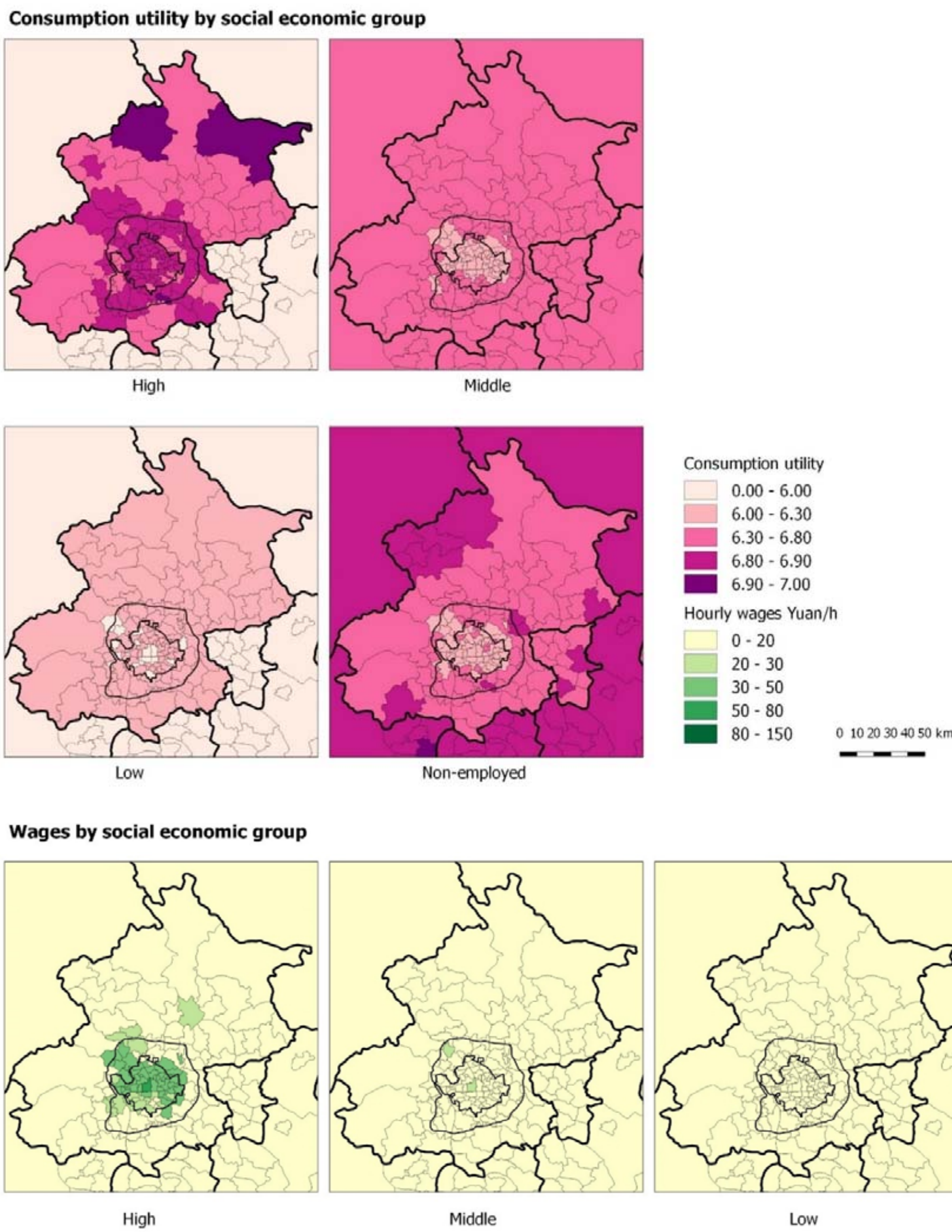


Figure 6-42 Consumption utility by socio-economic group 2010

Figure 6-43 Consumption utility by socio-economic group 2030

6.5.1.4 Transport analysis

The overall transport statistics regarding average travel time and distance, mode share and distance range have been reported in section 6.4.4. Here we elaborate on the travel profiles by presenting them based on travel purposes in Table 6-21. In general, high socio-economic group travels further and spend more money and time on travel. Because of their high mobility (for instance, they are able to afford more expensive transport mode and pay more money to compensate time loss), the speeds are always the highest. On the contrary, low socio-economic group is always the slowest and travels the shortest in any travel purpose.

Commuting trips (Flow 1-3) and other trips (Flow 10-12) have modest length and generate the main passenger-km. Other trips of middle socio-economic group generate the most traffic volumes, which takes up to 35% of the total passenger-km, followed by commuting trips of middle group (31%).

	Flow	Average distance (km)	Average cost (cent)	Average time (min)	Average speed (km/h)	Trip volume (thousand)	Passenger-km/year (million km)	Percentage of total passenger-km/year
1	Commuting High	17.4	719.2	47.3	22.1	2,857	49,760	10.7%
2	Commuting Middle	13.5	479.3	44.4	18.3	10,678	144,519	31.0%
3	Commuting Low	8.8	239.0	40.8	13.0	2,190	19,344	4.1%
4	Educational High	8.8	336.9	37.1	14.3	481	4,252	0.9%
5	Educational Middle	6.7	198.2	35.4	11.4	2,472	16,651	3.6%
6	Educational Low	5.6	115.2	34.4	9.8	277	1,557	0.3%
7	Business High	30.0	1242.0	51.7	34.8	73	2,189	0.5%
8	Business Middle	20.3	895.3	45.5	26.8	327	6,643	1.4%
9	Business Low	15.0	620.5	41.8	21.5	52	778	0.2%
10	Other High	14.4	445.4	39.8	21.7	2,871	41,375	8.9%
11	Other Middle	12.4	281.1	37.7	19.8	13,168	163,274	35.0%
12	Other Low	9.7	169.4	35.5	16.4	1,667	16,197	3.5%
	Total	12.6	378.8	40.5	18.6	37,113	466,538	100%

Table 6-21 Travel profiles by purpose, 2030 Ref scenario

Figure 6-44 shows that the majority of short trips (less than 2 km) are done by walking. In the distance range 2-5 km, bus is the mostly used travel mode while walking and car are also popular. Above 5 km, car surpasses all the other travel mode and becomes the major mode. Metro/rail is barely used when the travel distance is shorter than 5 km, because the off-network travel time (for example, waiting at the platform and queuing to purchase tickets) makes short metro/rail journeys uneconomic. Above this threshold, the number of metro/rail trips rises and reaches its peak when trips are longer than 25 km.

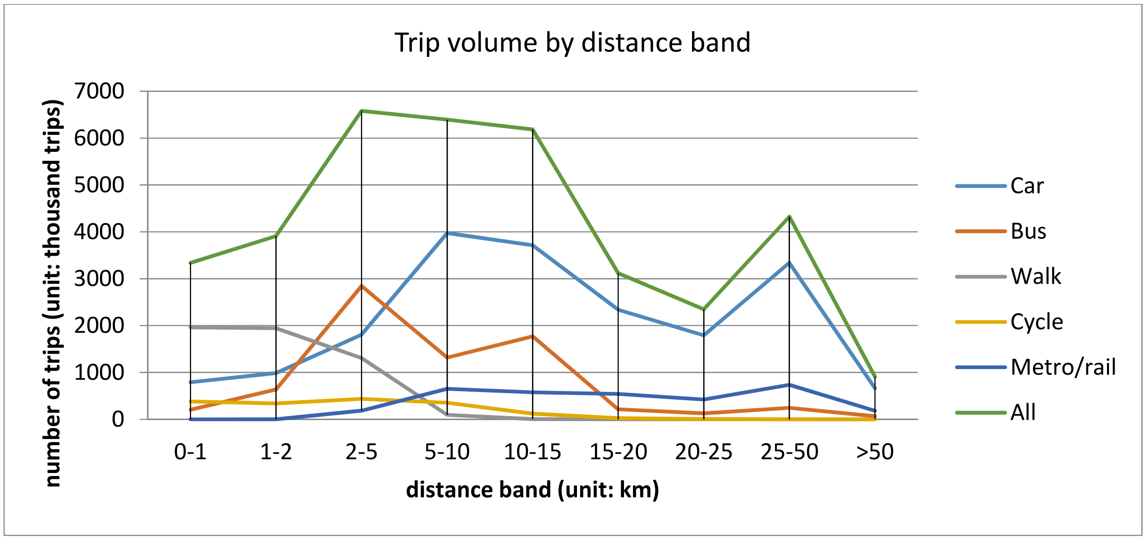


Figure 6-44 Trip volume by distance band by mode, 2030 Ref scenario

We plot the traffic volume in car-km unit on each road, metro line and railway, and then sum the volumes into zones. Figure 6-45 is a section of the morning traffic in Beijing on a typical working day. The left map in Figure 6-45 shows that road traffic presents a more dispersed pattern than metro/rail traffic in the right map. Road traffic in the city centre is high, but not always the highest. Inner city zones and several relatively remote zones where arterial roads go across also have high road traffic volume. This is because the road speed in the centre is low and car trips are therefore discouraged. Unlike road traffic, metro/rail traffic displays a monocentric pattern. Metro traffic crams in the city centre. A limited number of the greenbelt zones and the suburban zones also have higher metro traffic volume. This is because metro/rail trips are confined along metro/rail lines in such zones.

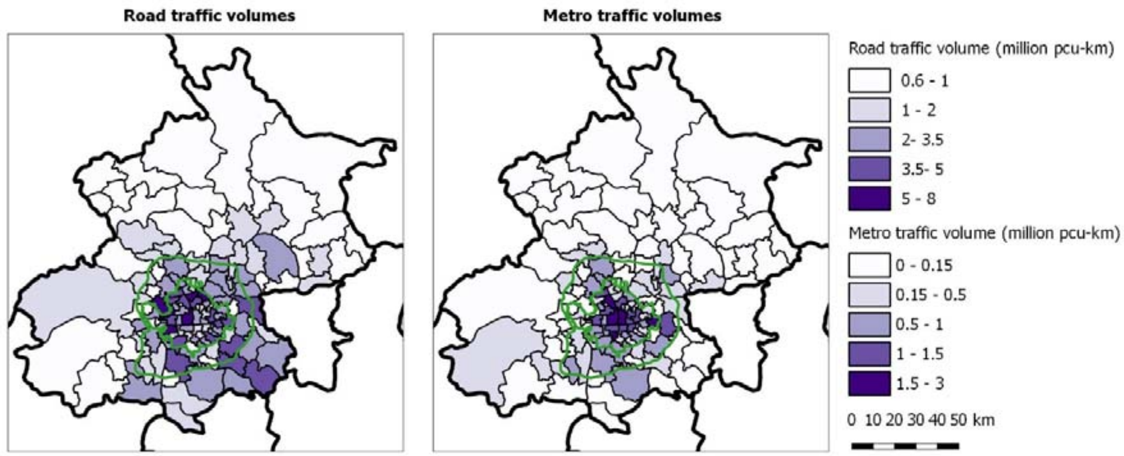


Figure 6-45 Traffic volume by zone, Ref 2030

Last but not least, we examine the impacts of built-form variables. In order to understand the impacts of built-form, we plot the travel mode choice in the greenbelt zones across 3 cross-sectional years. The sizes of the pie charts in Figure 6-46 stand for the total number of trips from the greenbelt zone as trip origins. As the concentric expansion continues from 2010, we assume all the 28 greenbelt zones will be gradually built-up and the distance from buildings to roads are relatively short. Such settings lead to two phenomena: firstly the total trip volumes in greenbelt zones are growing by decade. Secondly, the percentage of car trips triples over two decades.

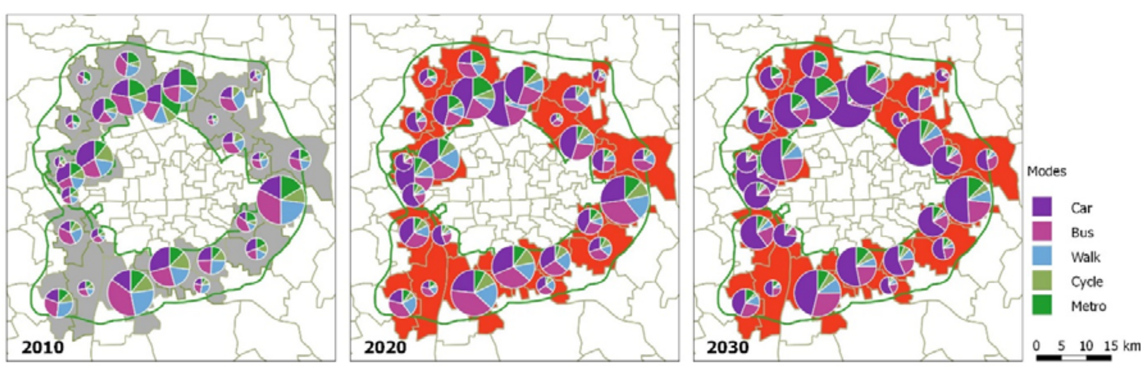


Figure 6-46 Mode share from the greenbelt zones 2010-2030, Ref scenario

To sum up, the Reference scenario is a continuation of the current concentric urban expansion. The main development poles are still the centre and the inner city. The greenbelt is the next for the city to expand into, because of its convenient location and sufficient land supply. Beijing's predominance in regional economy is strengthened under the successive expansion. The northwest of the central Beijing and the CBD in the east become more expensive, because of the increasing population and jobs. Richer people will benefit from the concentric expansion and their consumption utility is the highest in the city centre. Lower socio-economic groups are priced out. Travel demands increase by decade in the fringe zones and car is particularly popular in the ubiquitously built-up urban fringe.

6.5.2 Greenbelt Scenario (GB)

The GB scenario represents a minimal fringe growth concept. With such a policy intervention, Beijing experiences a loss of population and employment to the rest of the region. The aggregate results from section 6.4 have not shown from which zones the loss comes, so this section focuses on presenting the changes at the zonal level, by comparing it with the 2030 Reference case.

6.5.2.1 Socio-demographic analysis

Compared to Ref, the greenbelt loses more than half of the residents and jobs (Figure 6-47). The exceptions are the existing built-up towns in the greenbelt. The loss is a combined result from the floorspace development constraint and the increased travel cost (represented as the inconvenient access link from buildings to the transport network). In the exceptional zones which are defined as *built-form type 2 built-up towns*, zonal floorspace provisions and transport conditions are the same as Ref. Because of the greenbelt restriction in other zones, some residents and jobs move to the built-up towns, which leads to a modest growth (about 10%).

Those who are relocated from the greenbelt are dissolved to almost every other zones. The popular zones are the inner city zones and a limited number of new towns adjacent to the greenbelt (Shunyi, Mentougou, Changping). Nevertheless, the new towns in the far suburb do not stand out as new residential locations. The Hebei county to the east of Beijing (Beisanxian) also see a more than 10% increase in residents, due to the convenient location.

Employment is mainly pushed from the greenbelt zones to the inner city and to the southeast of Beijing, forming a development corridor to Tianjin. Beijing's centre has already become cramped, so the greenbelt policy is unable to transfer jobs to the centre any more.

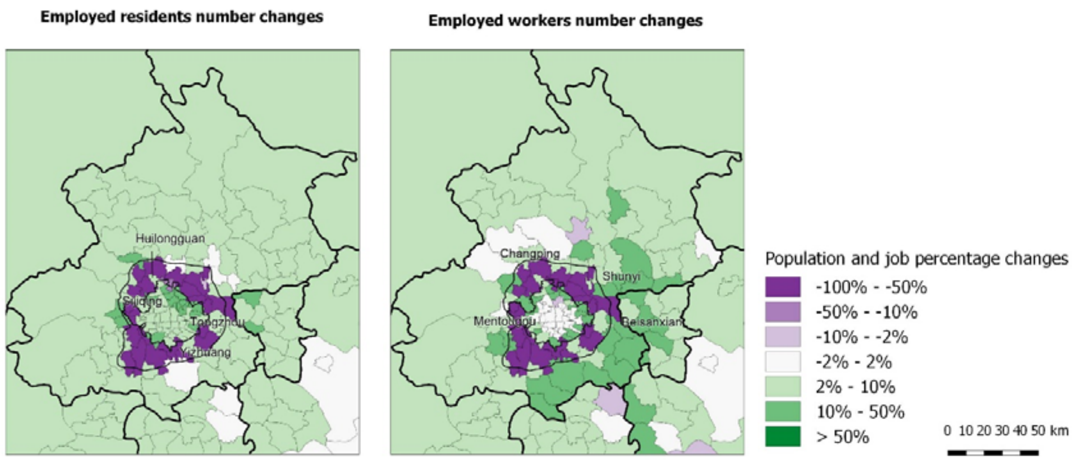


Figure 6-47 Employed residents and workers change, GB compared to Ref 2030

In term of the movement of population and employment by socio-economic group, Figure 6-48 demonstrates that the stringent greenbelt policy affects different socio-economic groups in different ways. Richer people will move outwards beyond the greenbelt due to their high mobility. They will also settle in the centre and the inner city, because they can afford high living cost. The middle class will not move too far from the main city. They live in the zones which are close to job centres, for example, the inner city zones, new towns next to the greenbelt, and Hebei counties to the east of Beijing. The low socio-economic group displays a homogenous relocation pattern: some relocate to the centre because they cannot afford the commuting cost and need to be close to job centre; some move to the far suburb because they are priced out of the main city. Non-employed household will move out of Beijing, because they have no concerns of living close to job locations.

Central Beijing is still a popular place for high profile and low profile jobs under GB intervention, but the number of middle profile jobs decreases in central Beijing. From the modelling perspective, this is because we do not distinguish job variaties outside Beijing. From the empirical perspective, this is because some high profile jobs are less likely to move out of the centre, for example government sectors, banks and headquarters of big companies, and they are able to afford the high business floorspace rent in the centre. Some middle range jobs will choose to relocate to the Hebei and Tianjin counties, due to the high production demand and the increase of business floorspace supply. Low profile jobs are more likely to be close to their residential locations.

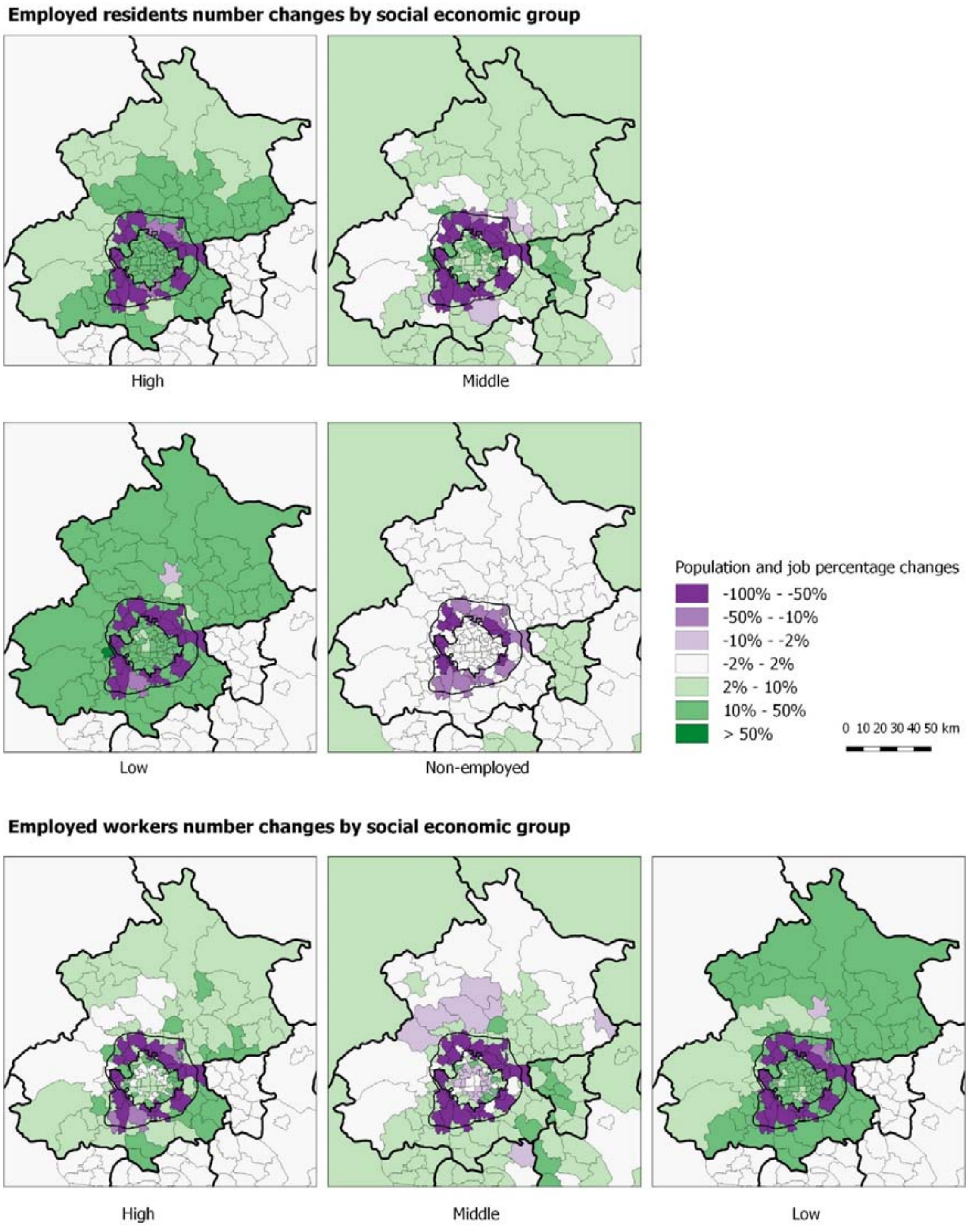


Figure 6-48 Employed residents and workers change by socio-economic group, GB compared to Ref 2030

6.5.2.2 Building floorspace and rent analysis

It is comprehensible that the floorspace supplies in the greenbelt zones are remarkably low. We are more interested in questioning where the diverted floorspace has gone to. As shown in Figure 6-49, the city centre does not gain any shifted development from the greenbelt, because it has been very dense. The northwest suburb of Beijing is restrained as Ecological Protection Area, so the development mainly takes place towards the southeast direction into the wider Greater Beijing region.

Housing floorspace supplies do not move too far from the greenbelt. The inner city and some new towns next to the greenbelt gains additional development. Business floorspace is redirected both outwards and inwards to the zones near the greenbelt. Inner city ring and new towns close to the greenbelt receive about 16% more development.

Large and small housing development is channelled to the far suburb and the inner city of Beijing, while medium size housing development takes place in the Hebei and Tianjin counties beyond Beijing. This result might be biased, because we do not distinguish housing variety in Tianjin and Hebei. However, we are confident in the overall pattern that under GB policy intervention, housing development is channelled towards the wider southeast direction.

Regarding rent, Figure 6-50 shows that the city centre becomes even more expensive to live in due to the stringent greenbelt, as the housing rent increases by about 13%. Apart from the greenbelt area, housing rent in the rest of Beijing also goes up in general. Although the floorspace development is restrained in the greenbelt, the demand is also relatively low. As a result, rent in the greenbelt zones witness a decrease.

Business floorspace rent in the greenbelt also decreases. In the city centre, rent does not shoot up, but stays relatively stable. This is because the increase of business floorspace supplies balances the increasing demand of production output. Nonetheless, the very central districts in the city centre still see a modest increase.

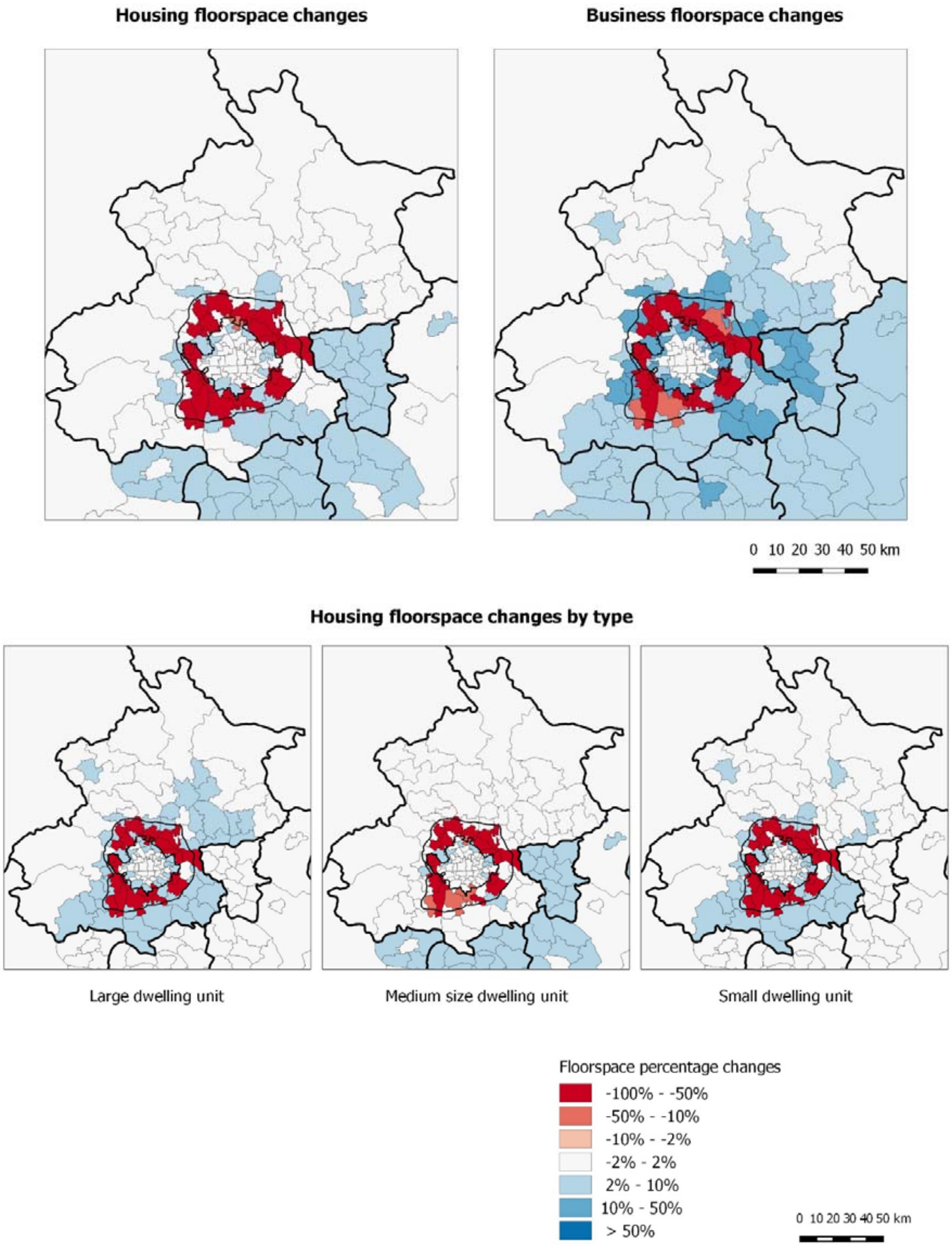


Figure 6-49 Floorspace change by type, GB compared to Ref 2030

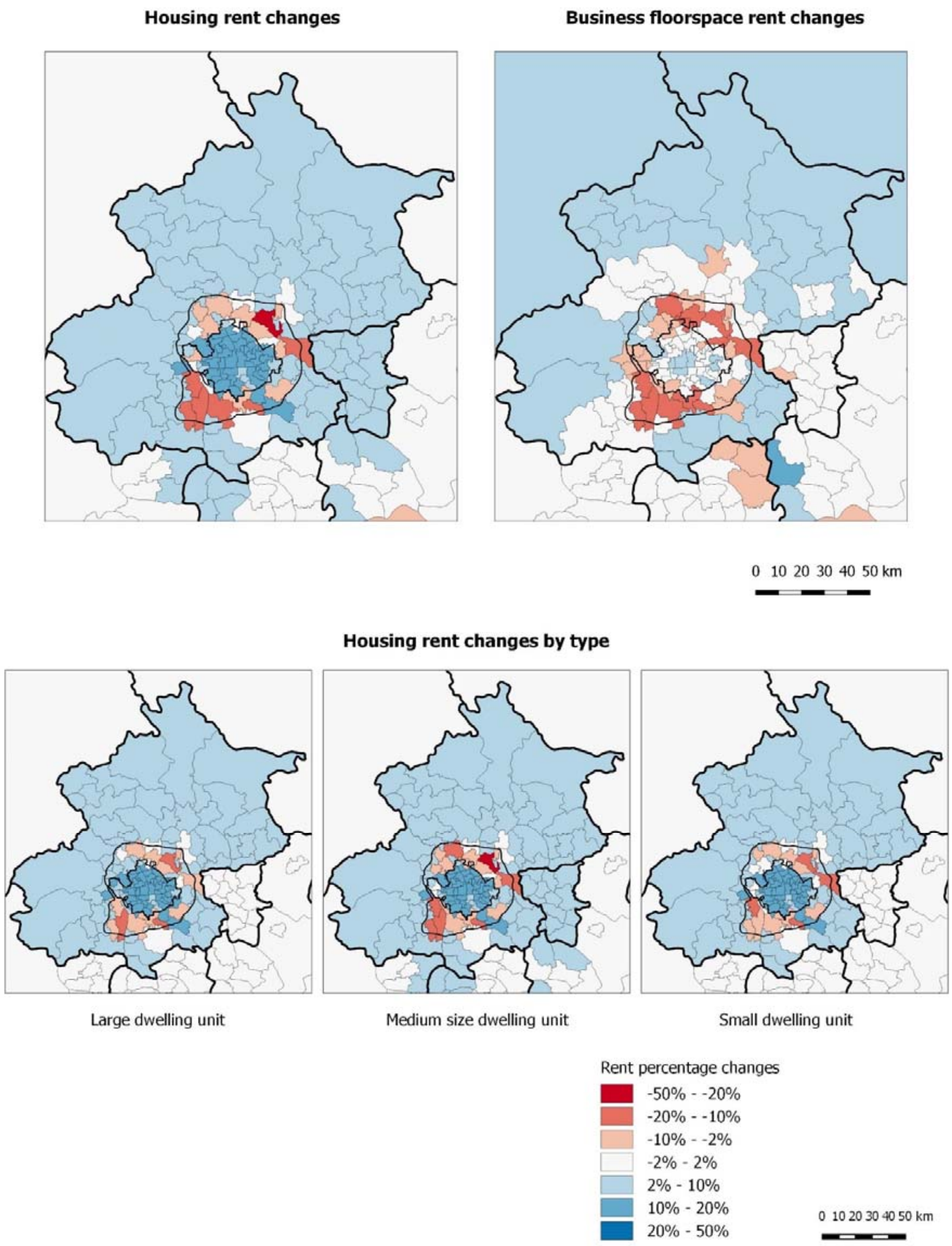


Figure 6-50 Rent change by type, GB compared to Ref 2030

6.5.2.3 Utility, wage and price analysis

In general, the GB scenario fails to improve the consumption utility for the most zones, except for the greenfield zones (Figure 6-51). With the outward movement of population and the drop in rent, the greenbelt turns into an affordable areas at the cost of making the rest of Beijing more expensive. Figure 6-52 shows that high socio-economic group can benefit from living in the greenbelt or several zones in the far suburb. Middle and low socio-economic groups suffer an overall decrease of consumption utility, with the exception of increases in a few greenbelt zones. Non-employed households experience a sheer drop of consumption utility, because they have no wage income and they are more sensitive to price change.

In Ref, average wage level forms a gradient that falls from the central city to the suburb. The greenbelt policy stresses this gradient, and makes the drop of wages even sharper from the centre. Average wage becomes higher in the central city, inner city and the greenbelt, but lower in the rest of Beijing. For poorer people, apart from working in the greenbelt zones, their wages will drop despite where they work. This is because of the increase of labour supplies.

Price changes resemble wage changes. Prices in the main employment centres (northwest high-tech company clusters and the east Central Business District) become even higher.

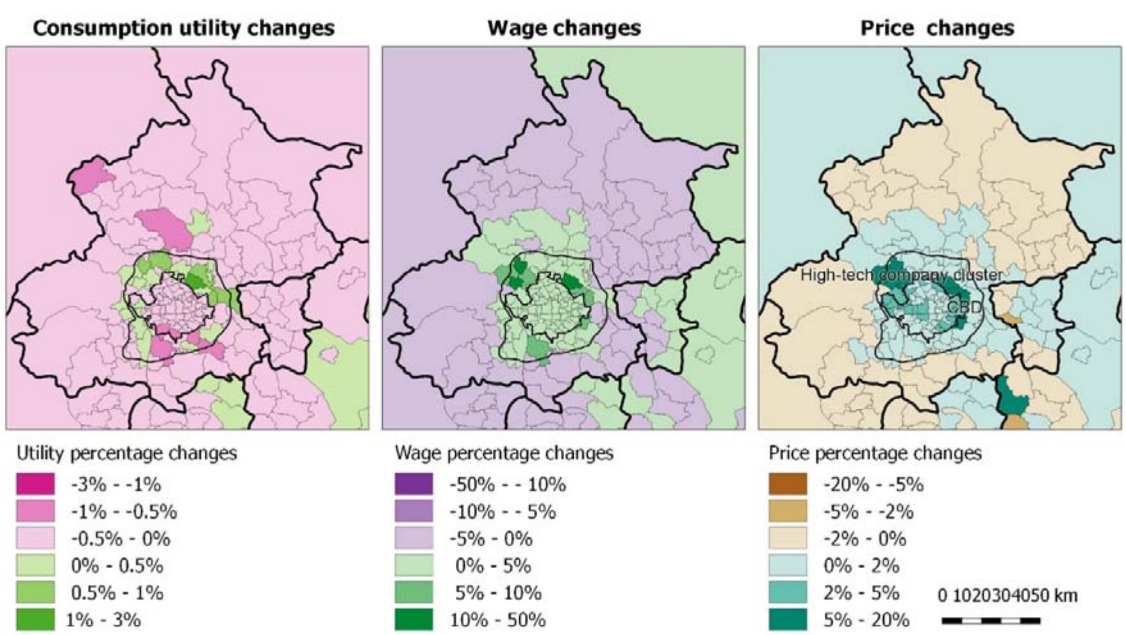


Figure 6-51 Utility, wage, and price change, GB compared to Ref 2030

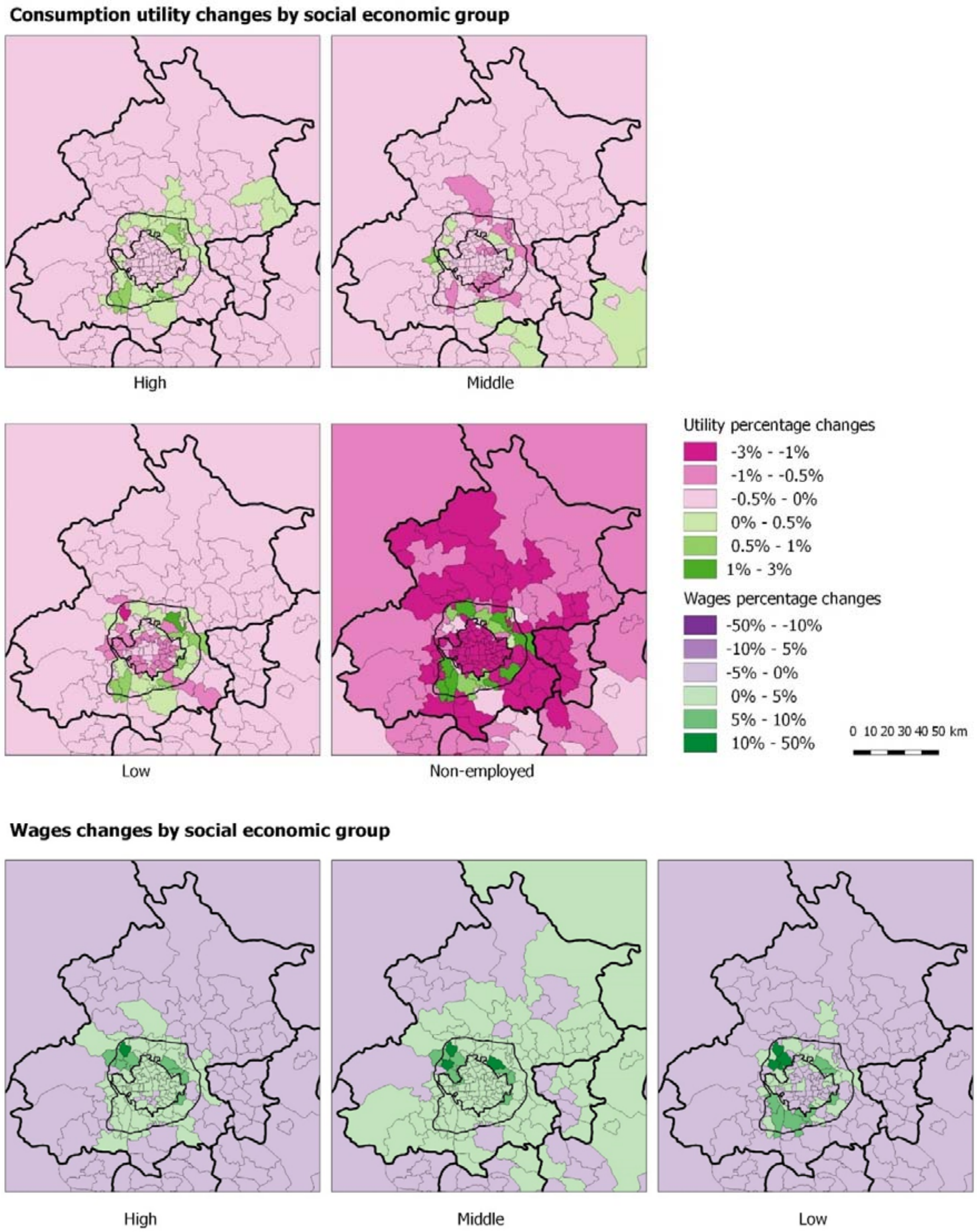


Figure 6-52 Utility and wage change by socio-economic group, GB compared to Ref 2030

6.5.2.4 Transport analysis

Table 6-22 has summarised the relative changes of travel profiles to Ref. The results are limited to Beijing Municipality. The general decrease of trip volume results from the loss of population from Beijing to the rest of the region. Average commuting trip lengths decrease for high and middle socio-economic groups. The reason behind this is that they relocate to the zones near employment centres.

Educational trips are mainly intra-zonal. The increase of educational trip distance results from the preference of doing longer distance intra-zonal trips. There are two factors contributing to this distance increase. Firstly, more people live in the large suburban zones, and these zones have longer intra-zonal bands. Secondly, the band choice constants for greenbelt zones are set to prefer long distance travel, in order to present the dispersed built-form in the greenbelt. The increases of distance for other trips (Flow 10-12) are also caused by this reason.

	Flow	Average distance	Average cost	Average time	Average speed	Trip volume	Passenger-km/year
1	Commuting High	-3.2%	-5.0%	-1.3%	-1.9%	0.0%	-3.2%
2	Commuting Middle	-1.6%	-3.9%	-0.9%	-0.7%	-8.8%	-10.3%
3	Commuting Low	0.7%	-1.3%	-0.1%	0.9%	0.0%	0.7%
4	Educational High	0.5%	-0.2%	0.8%	-0.2%	-3.2%	-2.7%
5	Educational Middle	6.2%	7.1%	2.8%	3.4%	-3.5%	2.5%
6	Educational Low	2.8%	3.2%	1.4%	1.4%	-0.1%	2.7%
7	Business High	-1.2%	-2.3%	-0.8%	-0.5%	0.0%	-1.2%
8	Business Middle	-1.6%	-2.6%	-0.5%	-1.1%	-6.8%	-8.3%
9	Business Low	-3.5%	-5.3%	-1.0%	-2.5%	0.0%	-3.5%
10	Other High	-1.6%	-2.5%	-0.3%	-1.2%	-3.7%	-5.2%
11	Other Middle	2.7%	2.6%	1.8%	0.9%	-4.4%	-1.8%
12	Other Low	0.3%	-0.2%	-0.1%	0.3%	-0.4%	-0.2%
	Total	0.1%	-1.8%	0.2%	-0.1%	-4.7%	-4.6%

Table 6-22 Change of travel profiles, GB compared to 2030 Ref (Table 6-21)

Figure 6-53 is not too different from the Ref case in Figure 6-44, apart from the slight decrease of trips within the 1-2 and 2-5 km distance ranges. Trips within in these ranges are mainly intra-zonal. Thus, the decrease is also caused by choosing longer distance bands.

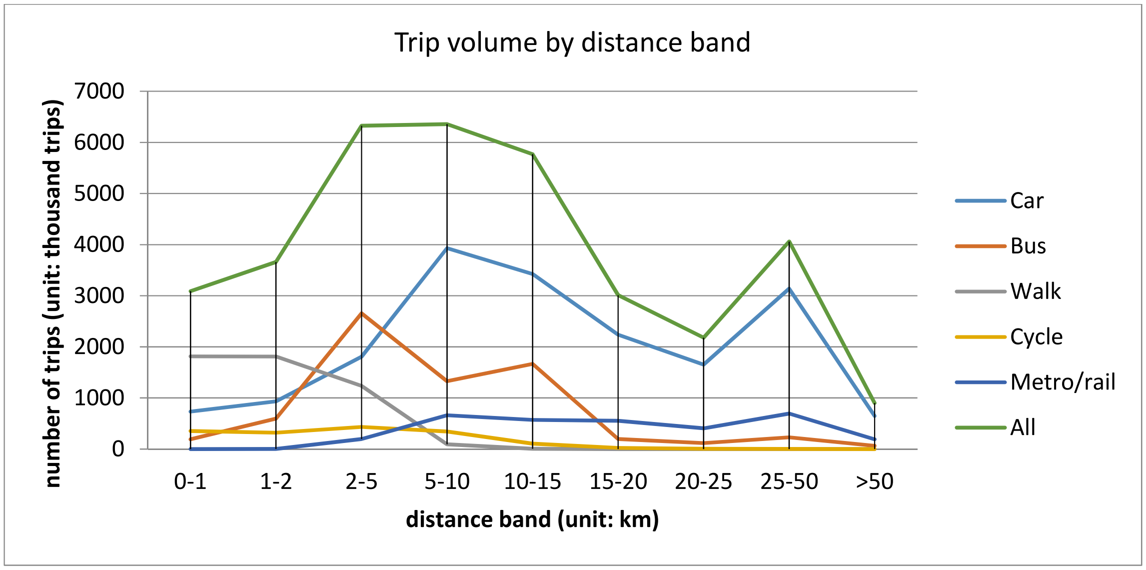


Figure 6-53 Trip volume by distance band by mode, 2030 GB scenario

Road traffic decreases sharply in the greenbelt, while increases in the far suburb and the Ecological Protection Area. The low traffic volume in the greenbelt is understandable, because less population generates less demand. The increase in the far suburb is caused by the increasing travel demand. Metro travel is promoted in the city centre while suppressed in the greenbelt. The population in the centre stays relatively stable, and the increase of metro traffic volume indicates a mode share shift to metro/rail from other modes.

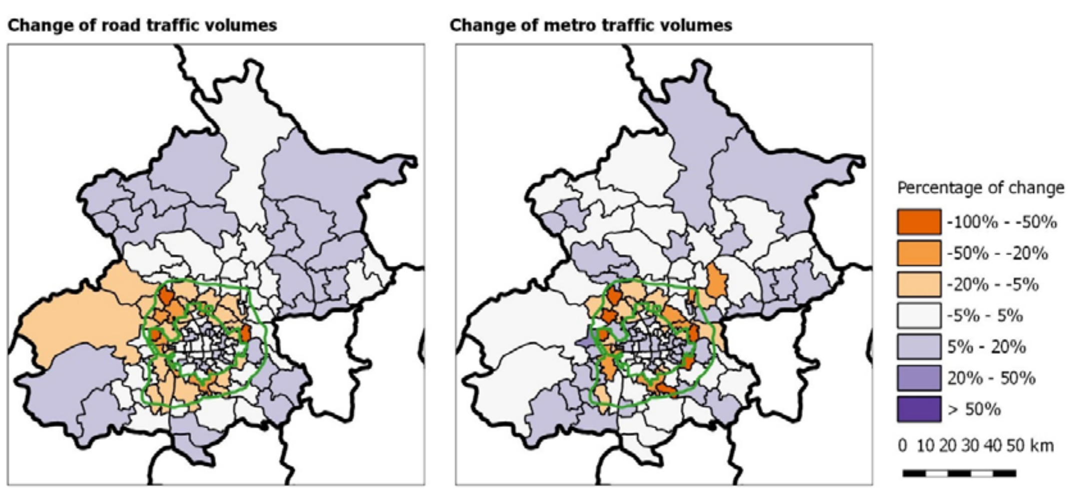


Figure 6-54 Change of traffic volume by zone, GB 2030 to Ref 2030

The popularity of car trips in the greenbelt zones are clearly depicted in Figure 6-55. While in 2010, about a quarter of trips are done by car, in 2030, about half of the trips are car trips. On the other hand, due to the urban containment policy, the travel demand shrinks over time in the greenbelt zones, apart from several existing built-up zones (marked red in Figure 6-15 on Page 164 and Figure 6-55 in red background).

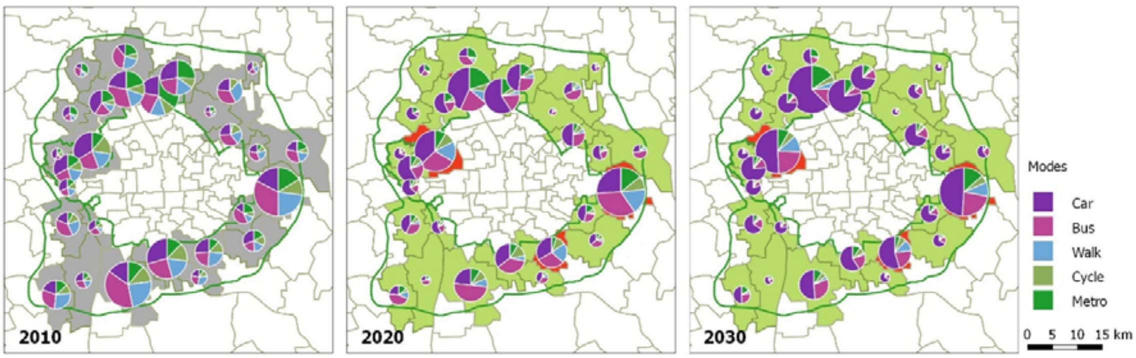


Figure 6-55 Mode share from the greenbelt zones 2010-2030, GB scenario

To sum up, the GB scenario successfully controls the development in the greenbelt zones at a low level. It therefore fulfils the aim of protecting the greenfield and open spaces. This scenario promotes the development in the greenbelt-nearby zones and also channels development to the wider southeast of the Greater Beijing region, along the major transport corridors. The poly-centric spatial structure of Beijing is not formed as expected in the policies (Beijing Municipal Government 2003a; Beijing Municipal Commission of Urban Planning 2012). New towns are not particularly attractive to the diverted development. This policy results in a higher wage and price in the main employment centres and a lower wage and price in the suburb. The sparse built-form in the greenbelt leads to the boom of car journeys. The greenbelt does not cause long distance commuting. Instead, commuting and business trips tend to be shorter due to the relocation of residents and jobs. Educational and other personal trips tend to be longer because of the longer intra-zonal travel.

6.5.3 Greenbelt-New Town Scenario (GB-NT)

As shown in the result overview section 6.4, at the municipal/provincial level, the Greenbelt-New Town scenario activates cross-boundary population and job movement from Beijing to the rest of the region. On the zone-categorical scale, new towns absorb some development diverted from the greenbelt, but not able to accommodate all of them. In this section, we will investigate into zonal level to see where the changes of population, employment and floorspace development take place.

6.5.3.1 Socio-demographic analysis

Similarly to the GB scenario results, the greenbelt zones lose more than half of their employed residents and workers (Figure 6-56). Employed residents dissolve into almost all the other zones in Beijing, including the city centre and the inner city, while jobs mainly move outwards into the suburban areas. With the support of new town-oriented policy, not only the new towns near the greenbelt, but also those in the far suburb see a more than 50% increase in population size.

Unlike the GB scenario where jobs are channelled to the wider southeast Greater Beijing region, GB-NT delivers jobs into new towns. Of course the surrounding Tianjin and Hebei counties also gain some jobs, but not as many as that in the GB scenario.

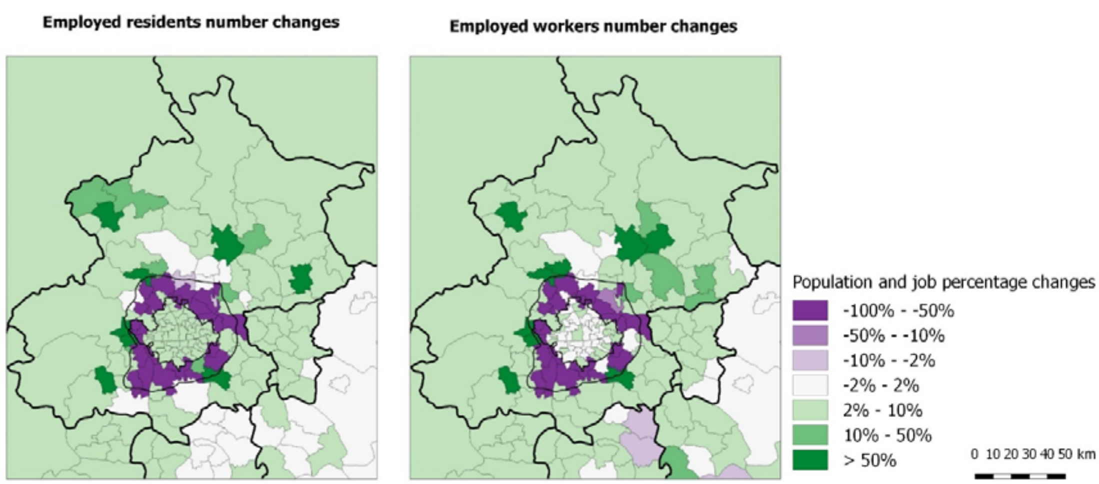


Figure 6-56 Employed residents and workers change, GB-NT compared to Ref 2030

Figure 6-57 shows that the suburban areas are generally more attractive to richer people. Amongst the suburban zones, new towns are particularly appealing. Moreover, richer people can also relocate in the centre and inner city, despite the high rent. The middle and lower classes mainly move outwards to the new towns, but some of them will choose to enter the city centre. Although the centre is expensive, there are small sized dwellings for lower income people to stay. New town development provides an option for the non-employed households diverted from the greenbelt. Instead of moving to Hebei and Tianjin, they can remain in the new towns in Beijing.

The numbers of high and middle level jobs barely increase in the central city. Alternatively, they choose to settle in the new towns because of the sufficient floorspace supply and high production demand. It is expected that the number of low profile jobs sees an increase in the new towns. Interestingly, it also increases in the city centre. This is caused by the high attractiveness residual terms for low income group in the city centre.

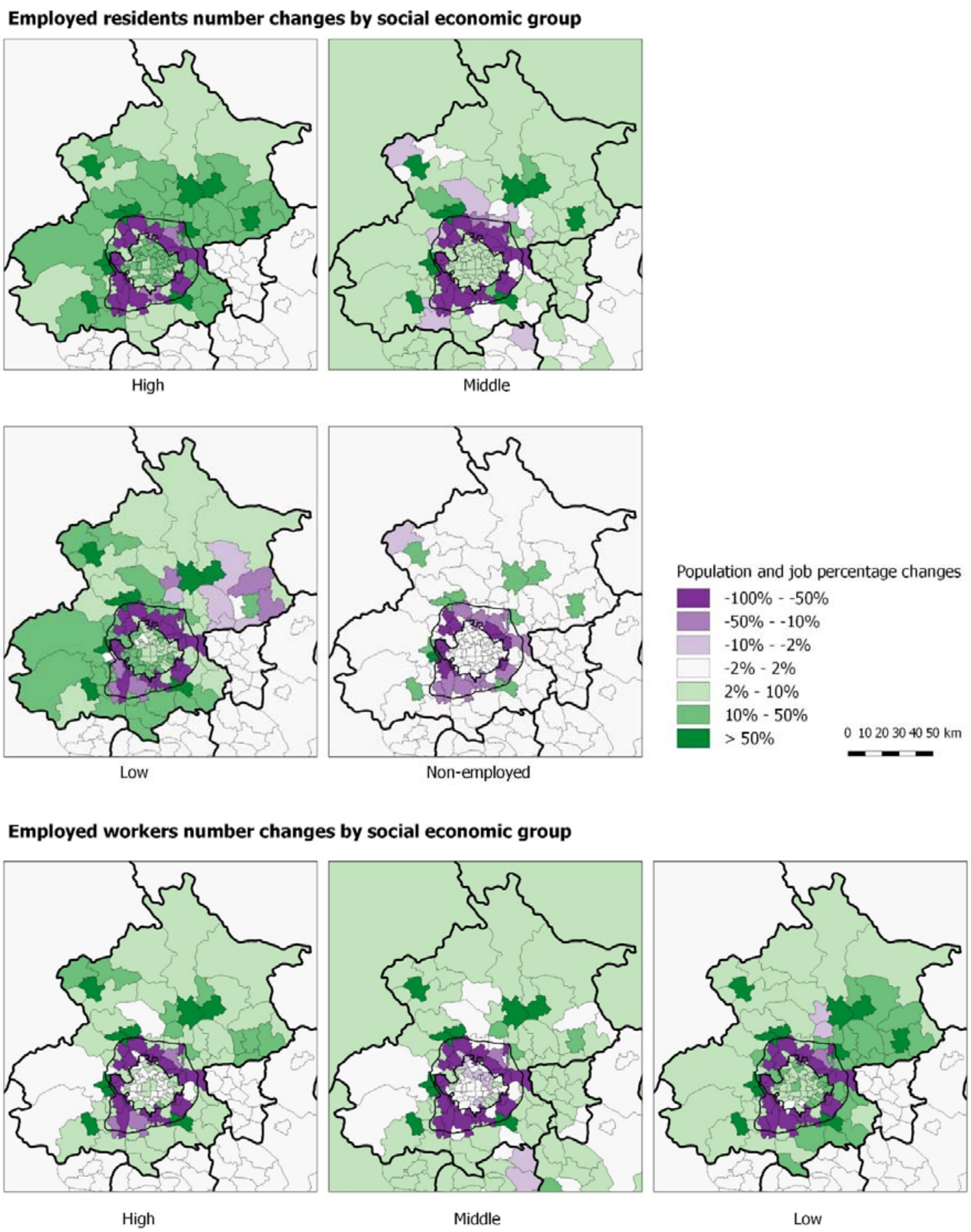


Figure 6-57 Employed residents and workers change by socio-economic group, GB-NT compared to Ref 2030

6.5.3.2 Building floorspace and rent analysis

Compared to the 2030 Ref, housing floorspace distribution is essentially a trade-off between the greenbelt zone and the new towns, while other zones remain unaffected. The GB-NT policy channels the majority of the development from the greenbelt to the new towns. The patterns for the 3 housing types are not too different from each other.

Compared to 2030 Ref, business floorspace does not increase in the city centre and the Ecological Protection Area, but in the inner city, the far suburb and the new towns. If there is no new town supplementary policy, the greenbelt will push the business floorspace development to the zones next to the greenbelt spontaneously. This has been shown in the GB scenario in Figure 6-49. With a new town supplementary policy, instead of the spontaneous growth inwards and outwards from the greenbelt ring, the diverted development displays a more ordered pattern.

Housing rent declines in the greenbelt zones (with the exception of the 4 already built-up zones marked in Figure 6-15) while increases in the rest of Beijing. Two new towns, which are closest to the greenbelt and the main city see a considerable rise in rent (25% increase in Mentougou to the west of the greenbelt, 23% increase in Yizhuang to the southeast of the greenbelt). Other new towns do not stand out as high housing rent zones.

The change of business floorspace rent is moderate. With the rent decrease in the greenbelt zones, other zones have marginal increases. The exceptions are the inner city zones and some far suburb zones, whose rents are not affected by the GB-NT policy. Rents in the new towns are not particularly high, although there is a considerable increase of total production (40% more than that in Ref). This is because there is a high level of additional supply of business floorspace in the new towns under this scenario.

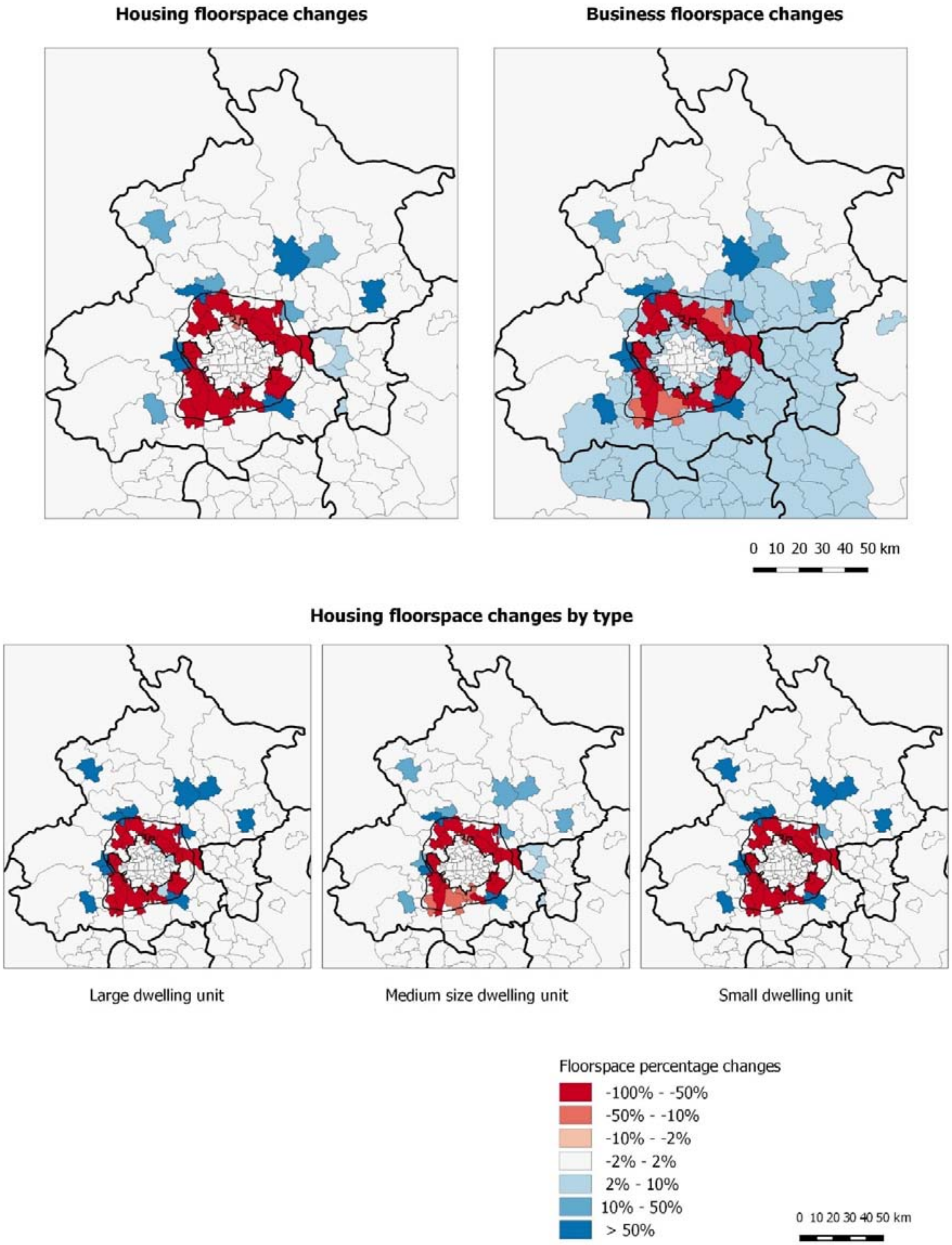


Figure 6-58 Floorspace change by type, GB-NT compared to Ref 2030

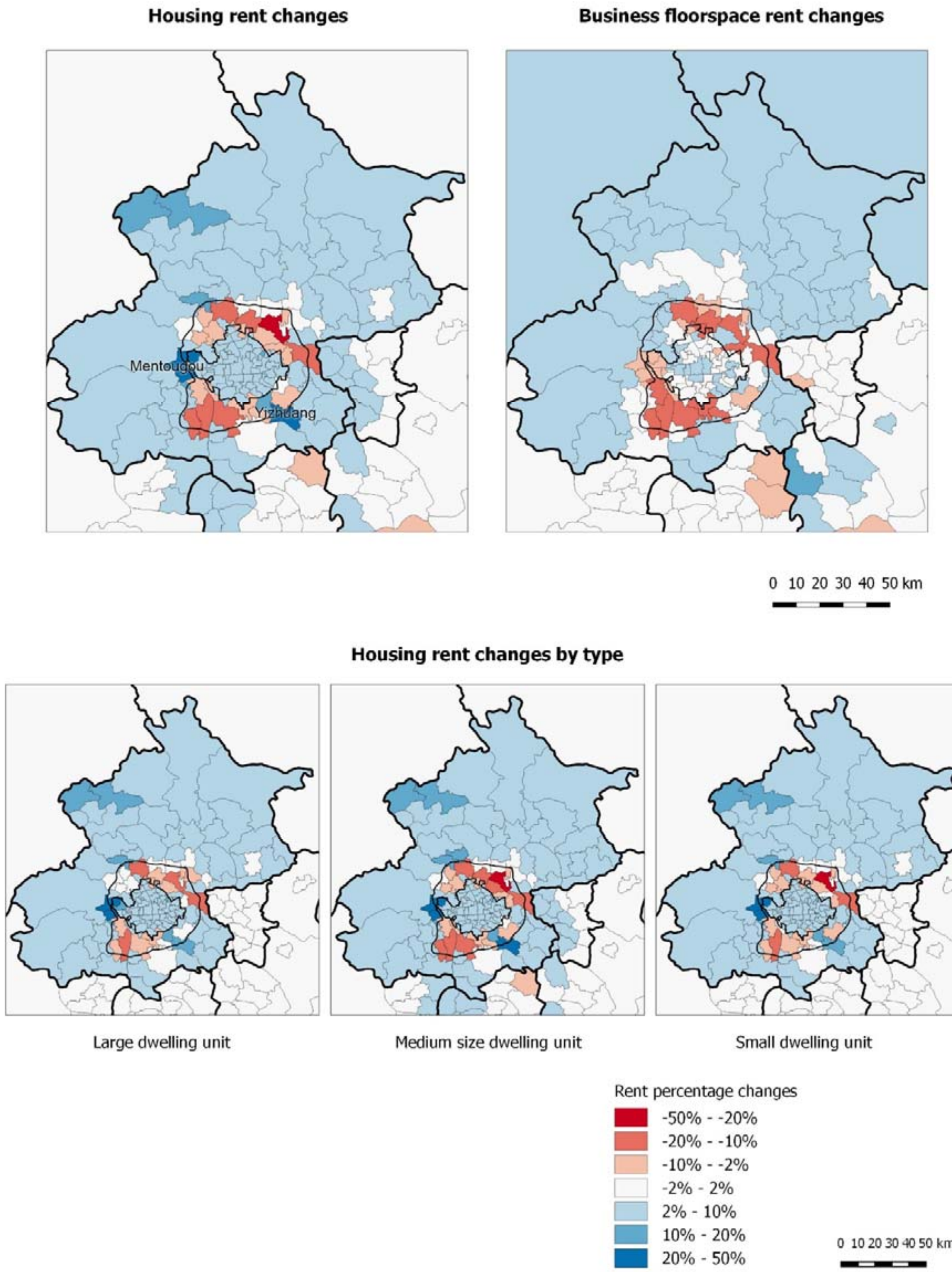


Figure 6-59 Rent change by type, GB-NT compared to Ref 2030

6.5.3.3 Utility, wage and price analysis

Consumption utility in the greenbelt increases as population moves out. New towns do not show a consistent form of changes. Some new towns suffer a decrease of utility level because of the rising rent. Other new towns improve their utility levels because of the additional housing development. In general, the city centre, inner city and suburbs do not benefit from the GB-NT intervention.

Figure 6-61 shows that the GB-NT affects different socio-economic groups in different ways. This policy benefits richer people on a wider geographical extent. Middle class will not benefit from the policy, unless they settle in the west and northwest of the greenbelt. Similarly, only those poorer people who live in the greenbelt can benefit. Non-employed households experience an even severer drop of consumption utility, compared to the drop in the GB scenario. This additional drop is from the fact that more non-employed households will remain in Beijing instead of moving to Tianjin and Hebei.

All of the zones within the outer greenbelt boundary and some zones in the far suburb and the Ecological Protection Area see a wage increase. Wage for high socio-economic group mainly increase in the main city, the greenbelt and the southern suburb. Wage level for middle class is widely improved. Poorer people do not widely benefit from this GB-NT policy in term of wage improvement. Price sees an overall marginal increase in Beijing with several zones in the EPA as exceptions. Prices of the main employment centres increase the most.

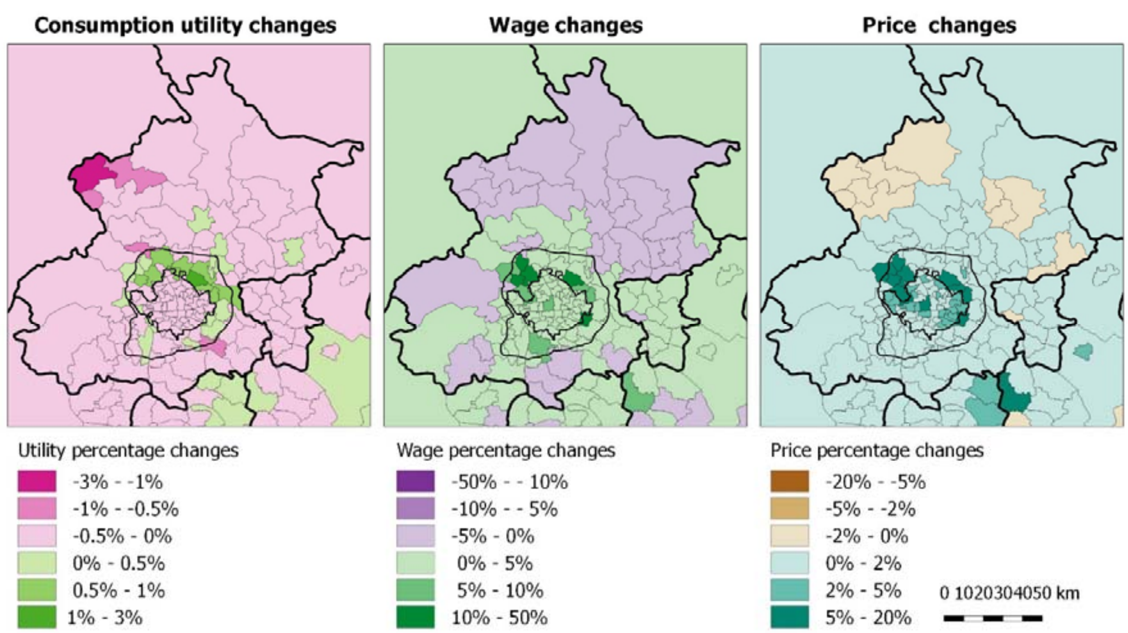


Figure 6-60 Utility, wage, and price change, GB-NT compared to Ref 2030

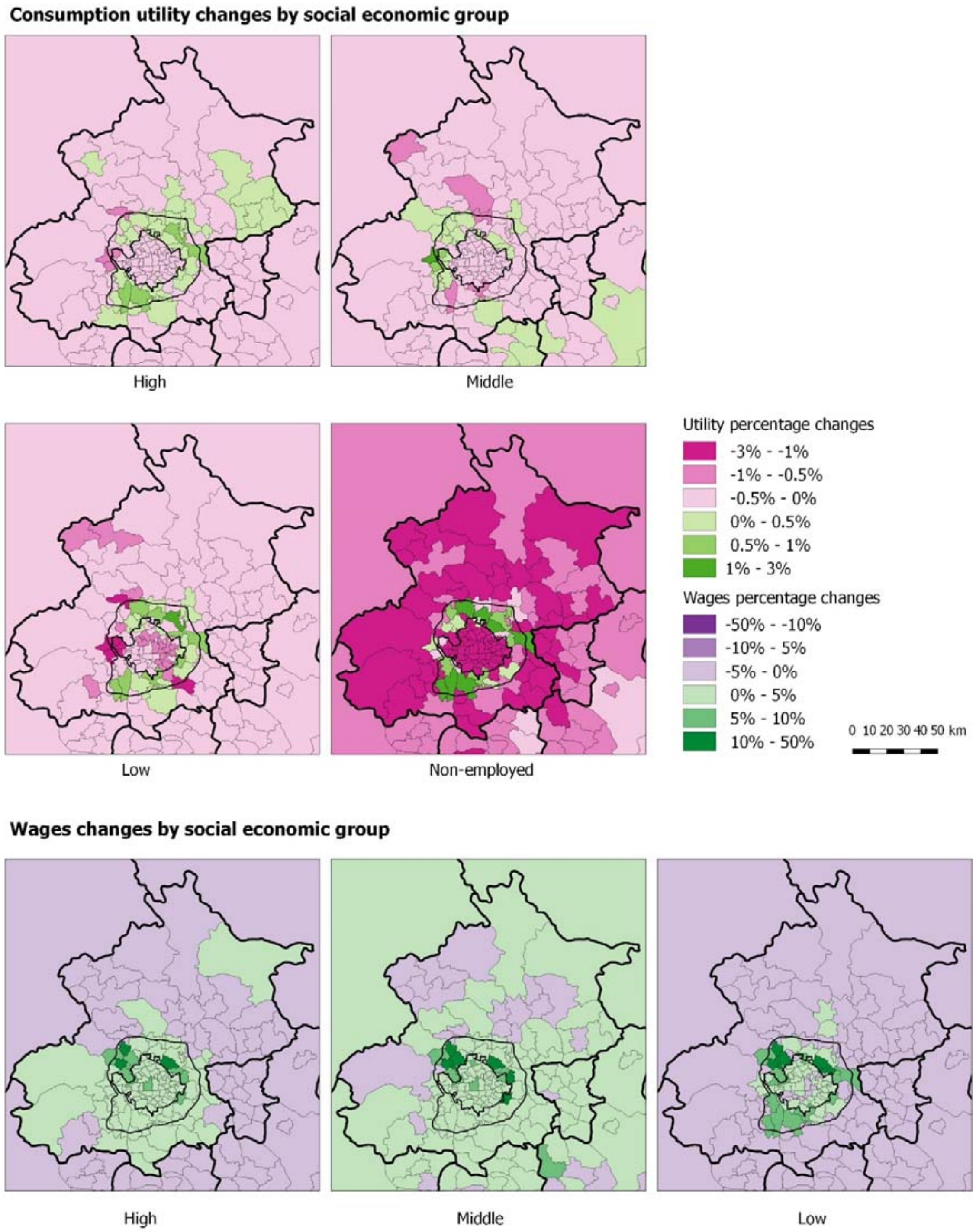


Figure 6-61 Utility and wage change by socio-economic group, GB-NT compared to Ref 2030

6.5.3.4 Transport analysis

Table 6-23 summarises the relative changes of travel profiles to Ref. The results are limited to Beijing Municipality. The general decrease of trip volume results from the loss of population from Beijing to the rest of the region. The loss is not as severe as that in the GB scenario.

The average commuting trip length decreases for high and middle socio-economic groups, while increases for low socio-economic group. The closeness between employment and residential locations in new towns contributes to the decrease in commuting distance. Meanwhile, the distance increase for low socio-economic population is caused by the decentralisation of jobs and residential locations. That is to say that for poorer people, the overall decentralisation effect outweighs the concentration effect in the new towns. Similar to the GB scenario, increase of educational trip distance is associated with the tendency of doing longer distance intra-zonal trips.

	Flow	Average distance	Average cost	Average time	Average speed	Trip volume	Passenger-km/year
1	Commuting High	-2.0%	-4.0%	-1.2%	-0.8%	0.0%	-2.0%
2	Commuting Middle	-1.7%	-4.5%	-1.3%	-0.4%	-5.3%	-6.9%
3	Commuting Low	3.2%	-1.3%	0.4%	2.8%	0.0%	3.2%
4	Educational High	0.5%	-0.6%	0.6%	-0.1%	-1.9%	-1.5%
5	Educational Middle	6.7%	7.1%	2.8%	3.7%	-2.1%	4.4%
6	Educational Low	3.6%	2.4%	1.7%	1.9%	-0.1%	3.5%
7	Business High	-0.1%	-0.8%	-0.4%	0.3%	0.0%	-0.1%
8	Business Middle	-1.3%	-2.4%	-0.5%	-0.8%	-4.1%	-5.4%
9	Business Low	-4.2%	-6.3%	-1.3%	-2.9%	0.0%	-4.2%
10	Other High	-1.0%	-2.3%	-0.1%	-0.9%	-2.1%	-3.1%
11	Other Middle	3.1%	2.7%	2.0%	1.2%	-2.6%	0.4%
12	Other Low	0.9%	-0.7%	0.7%	0.2%	-0.2%	0.6%
	Total	0.6%	-1.8%	0.3%	0.3%	-2.8%	-2.2%

Table 6-23 Change of travel profiles, GB-NT compared to 2030 Ref (Table 6-21)

The trip range distribution in Figure 6-62 is very similar to the Ref scenario, in which car dominates the long distance journeys while walking dominates short distance journeys. Although more people live in the new towns and the travel demand is high, 70% of them do not travel back to the city and do not generate long distance journeys. Most of the trips in the new towns are local.

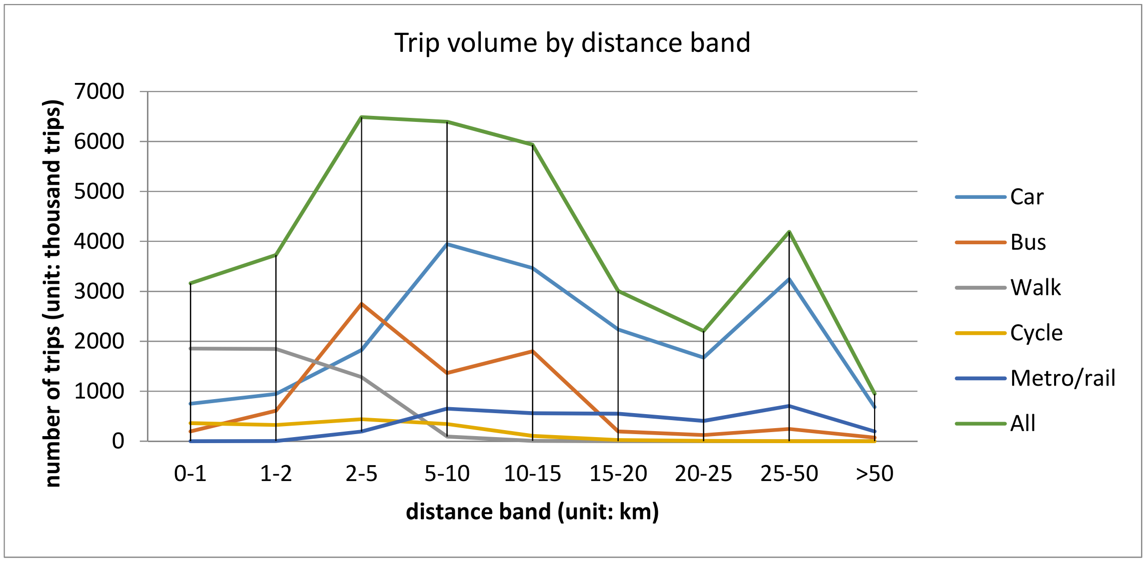


Figure 6-62 Trip volume by distance band by mode, 2030 GB-NT scenario

Figure 6-63 presents a distinct traffic volume pattern to the Ref scenario. Both road traffic and metro traffic in the new towns rise by more than 20%. This results from the increase of population size in new towns, which generates more travel demands. The road capacity in our model is considered as constant congestion speed. The metro capacity is not measured in our model yet. That is to say, the roads and metros/rails will accommodate all of the travel demands from new towns. Since all of the new towns are connected with metros/rails in 2030, metro/rail traffic will rise greatly as population grows.

In fact, the metros that link new towns to the city centre were already extremely crowded in 2016. This indicates that if the travel demand keeps increasing in the new towns from now on to 2030, the existing lines are incapable of accommodating the booming passengers. We expect that if the capacity restrain is applied in this model, the metro traffic in new towns under GB-NT policy will not increase that much anymore. The overall travel cost will increase in the new towns, which in turn makes new towns less attractive. In other words, the GB-NT modelling results in our current model is an optimistic new town scenario. We suggest that the results after capacity restraint would not be as good, unless transport improvements are added to the lines connecting new towns to the city centre.

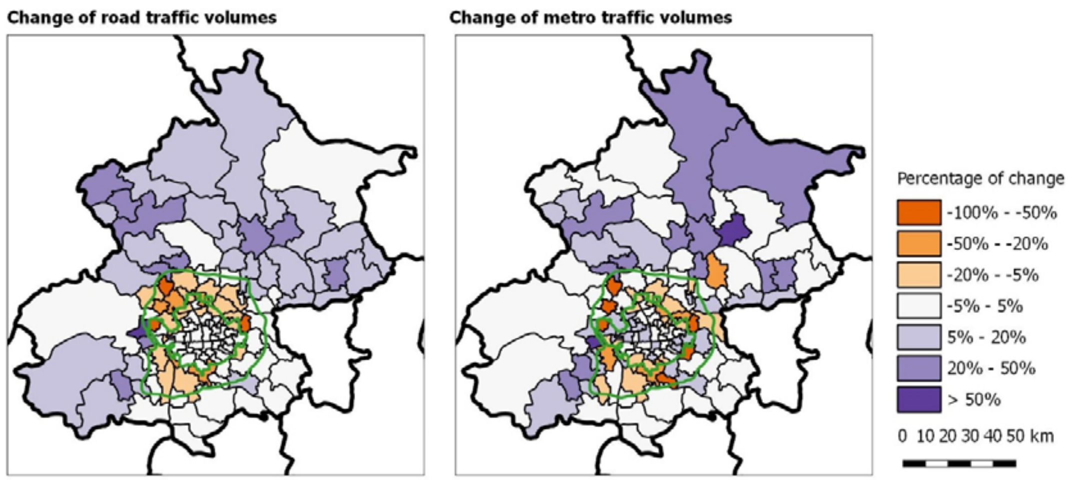


Figure 6-63 Change of traffic volume by zone, GB-NT 2030 to Ref 2030

Figure 6-64 shows the zonal mode share of the greenbelt zones. It is therefore not different from the result of the GB simulation (Figure 6-55). The prevailing car usage and the shrinking travel demand in the greenbelt are captured.

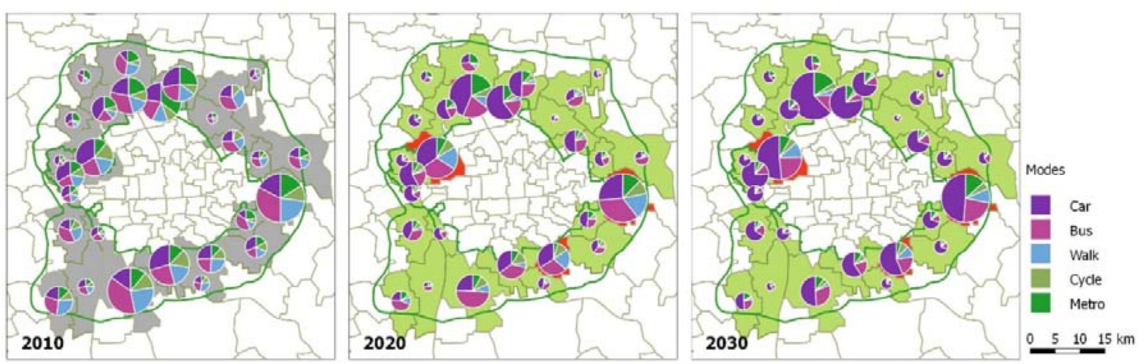


Figure 6-64 Mode share from the greenbelt zones 2010-2030, GB-NT scenario

To sum up, the GB-NT scenario shows a relatively moderate impact from the implementation of stringent greenbelt, because the new towns mitigate the radical changes of losing population, jobs and floorspace from Beijing to the rest of the region. Compared to the GB scenario, GB-NT localises the policy impact within Beijing Municipality to some extent, as about 40% of the diverted floorspace development from the greenbelt goes to the new towns. However, without transport improvements, the new towns are not competitive enough in attracting all of the diverted development, residents and jobs. The employment centre is still the central and inner Beijing, as they are just as dense as they are in Ref in terms of employment density and business floorspace density.

From the environmental perspective, the policy prevents development to happen in the greenfield at the urban fringe. Metro/rail travel is promoted for journeys between new towns and the city. In term of the spatial structure, GB-NT can be regarded as a decentralisation scheme. However, we need to bear in mind that if the capacity restraint is applied on networks that link the new towns and the city centre, the decentralisation may not be as effective.

6.5.4 Green-Wedges Scenario (GW)

Result overview in section 6.4 already indicates that on the municipal/provincial level, the Green-wedges policy performs differently from GB and GB-NT. The cross-boundary movements of population and employment are less obvious. Beijing will not lose development to Hebei and Tianjin. The zone-categorical results have shown that the population, jobs and floorspace stock in the greenbelt zones will be almost as high as that in Ref. In this section, we will investigate, within the designated greenbelt boundary, in which zones the development happens, where population and jobs move to, how price changes and how travel behaviour changes at zonal level.

6.5.4.1 Socio-demographic analysis

The impacts of the GW policy is relatively local within the greenbelt ring. With the sheer drop of the number of residents in some greenbelt zones regarded as built-form type 1 greenfield, other zones which are designated as TOD nodes become popular. Of course, there are some changes of the number of population and jobs beyond the greenbelt or in the inner city, but compared to the other scenarios, the zones affected are geographically close to the greenbelt. Population change is mainly a trade-off between the greenfield zones (built-form type 1) and TOD nodes (built-form type 3) in the greenbelt. Meanwhile, the impacts on job distribution are wider. The TOD nodes not only attract jobs from the greenfield zones, but also from the inner city and a fair number of far suburb zones.

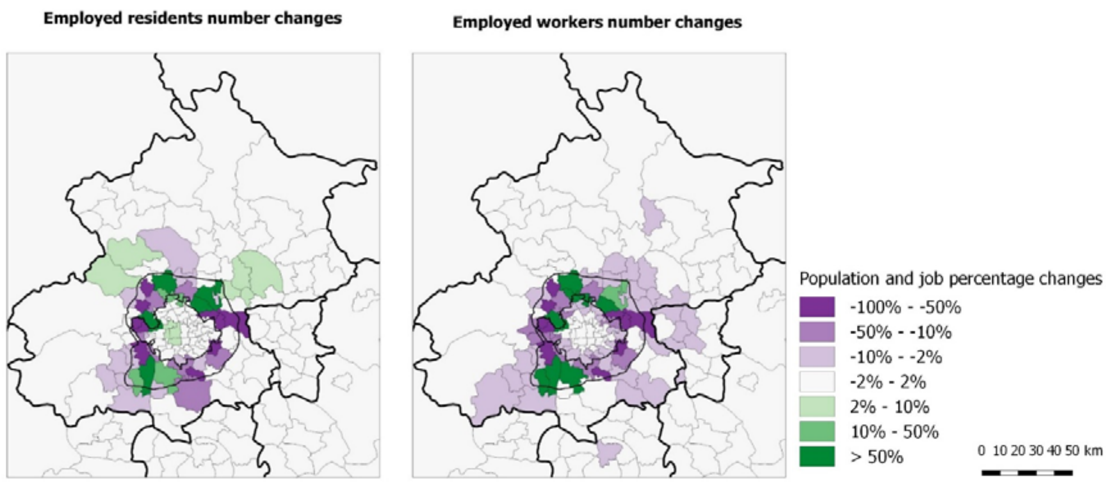


Figure 6-65 Employed residents and workers change, GW compared to Ref 2030

Residents in high socio-economic group move out of the designated greenfield and redistribute ubiquitously across Beijing. Meanwhile, the TOD nodes gain relatively more residents. High profile jobs increase in the north far suburb and city centre marginally, while increase in the TOD nodes substantially.

Middle class is driven out of the designated greenfield into the TOD nodes as well. Unlike richer people, middle group is mainly attracted by the advantages of the TOD nodes and move from the suburb to the TOD nodes. The advantages include the abundant housing development and the convenient locations to public transport.

Residents in low socio-economic group concentrate in the TOD nodes. Meanwhile, low profile jobs also move from the inner city and the far suburb to the TOD nodes, so that the residence and job locations are close to each other. As the value of time and car ownership of poorer people are low, living close to metro/rail stations benefit them by reducing travel costs.

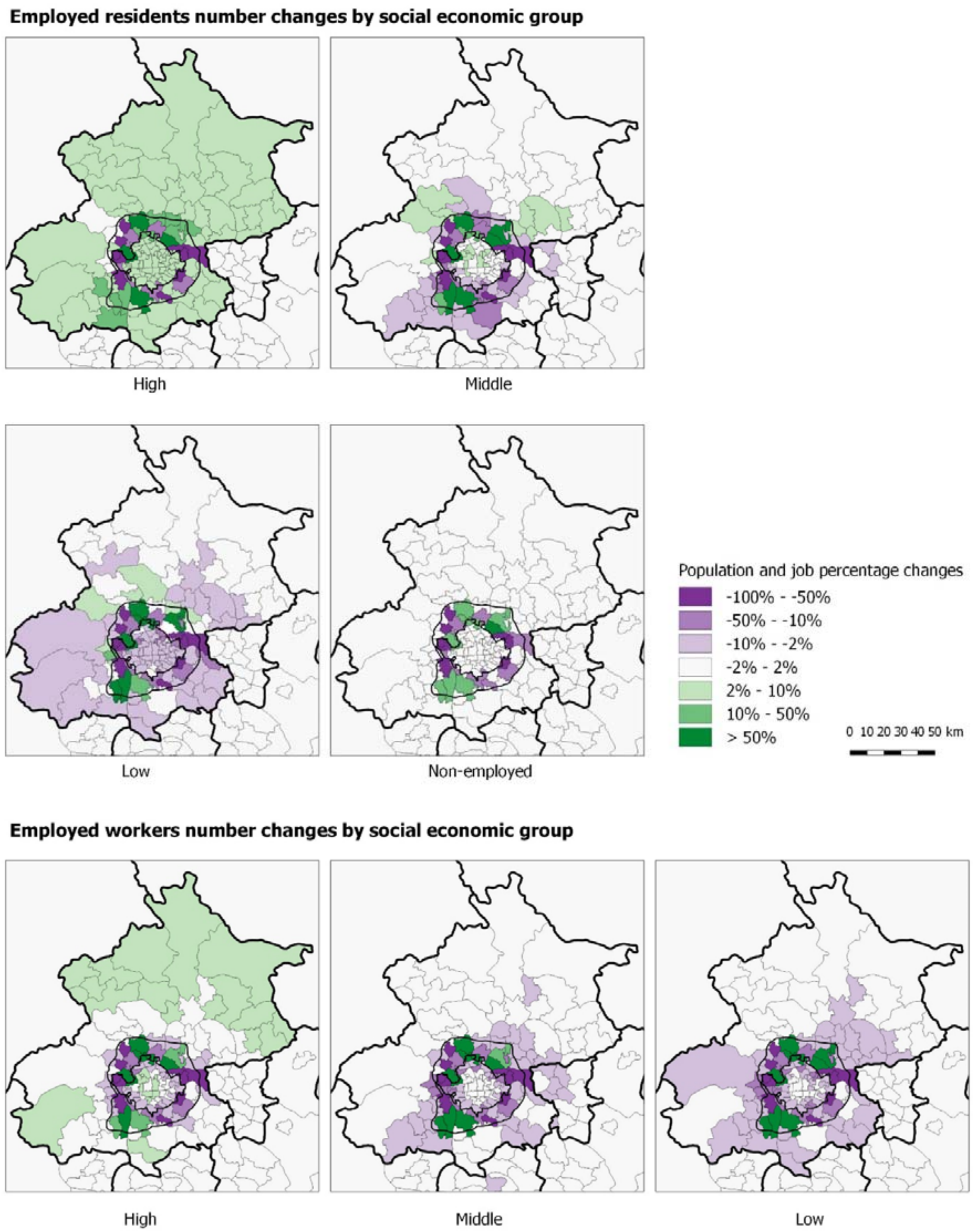


Figure 6-66 Employed residents and workers change by socio-economic group, GW compared to Ref 2030

6.5.4.2 Building floorspace and rent analysis

The TOD nodes become popular primarily because of the sufficient floorspace supply. Most of the nodes earn more than 50% of the floorspace increase. The change of housing floorspace within the greenbelt is local. The impacts on business floorspace provision are wider. The TOD nodes win the floorspace development which is supposed to be in the inner city and the nearby suburban zones under trend development in Ref.

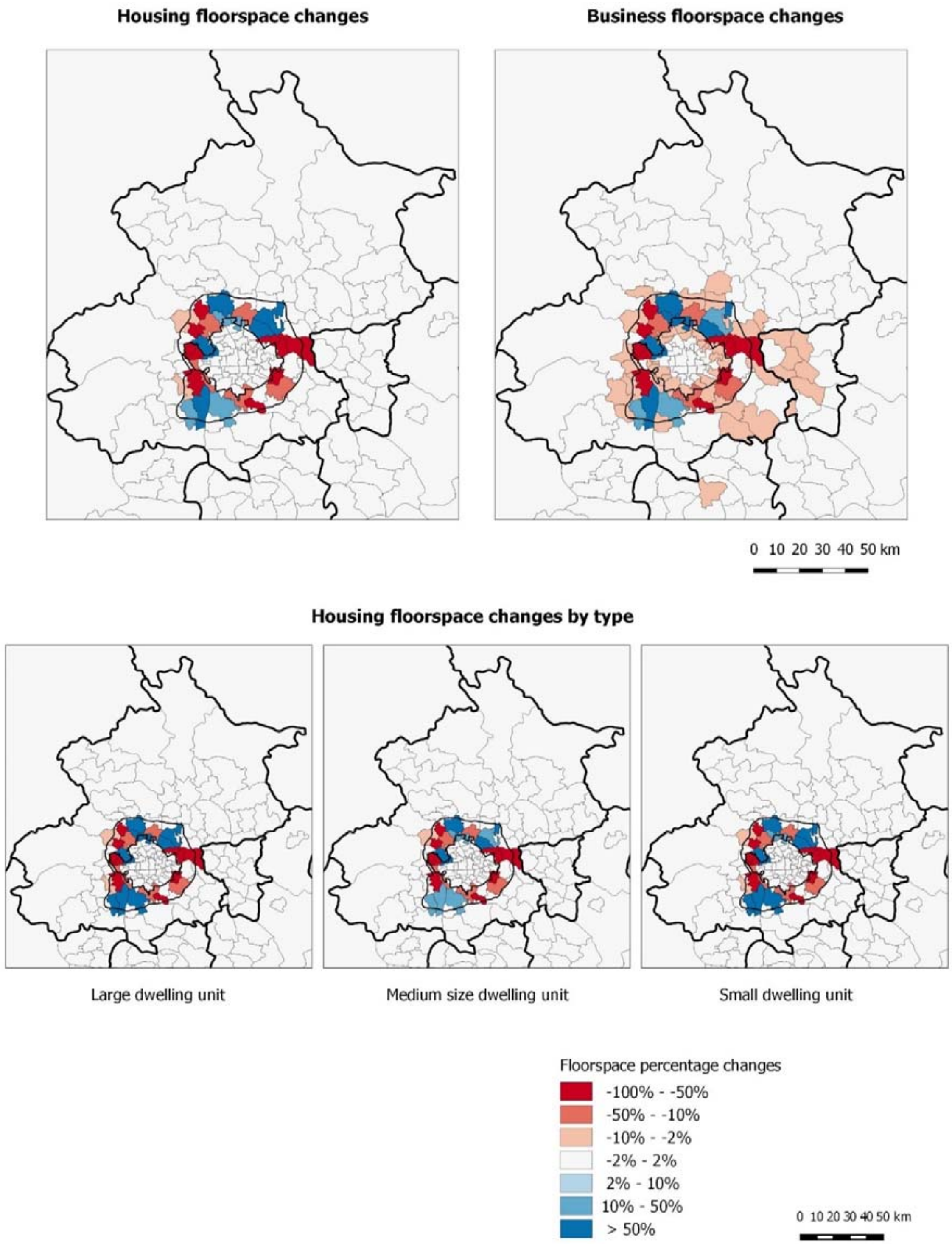


Figure 6-67 Floorspace change by type, GW compared to Ref 2030

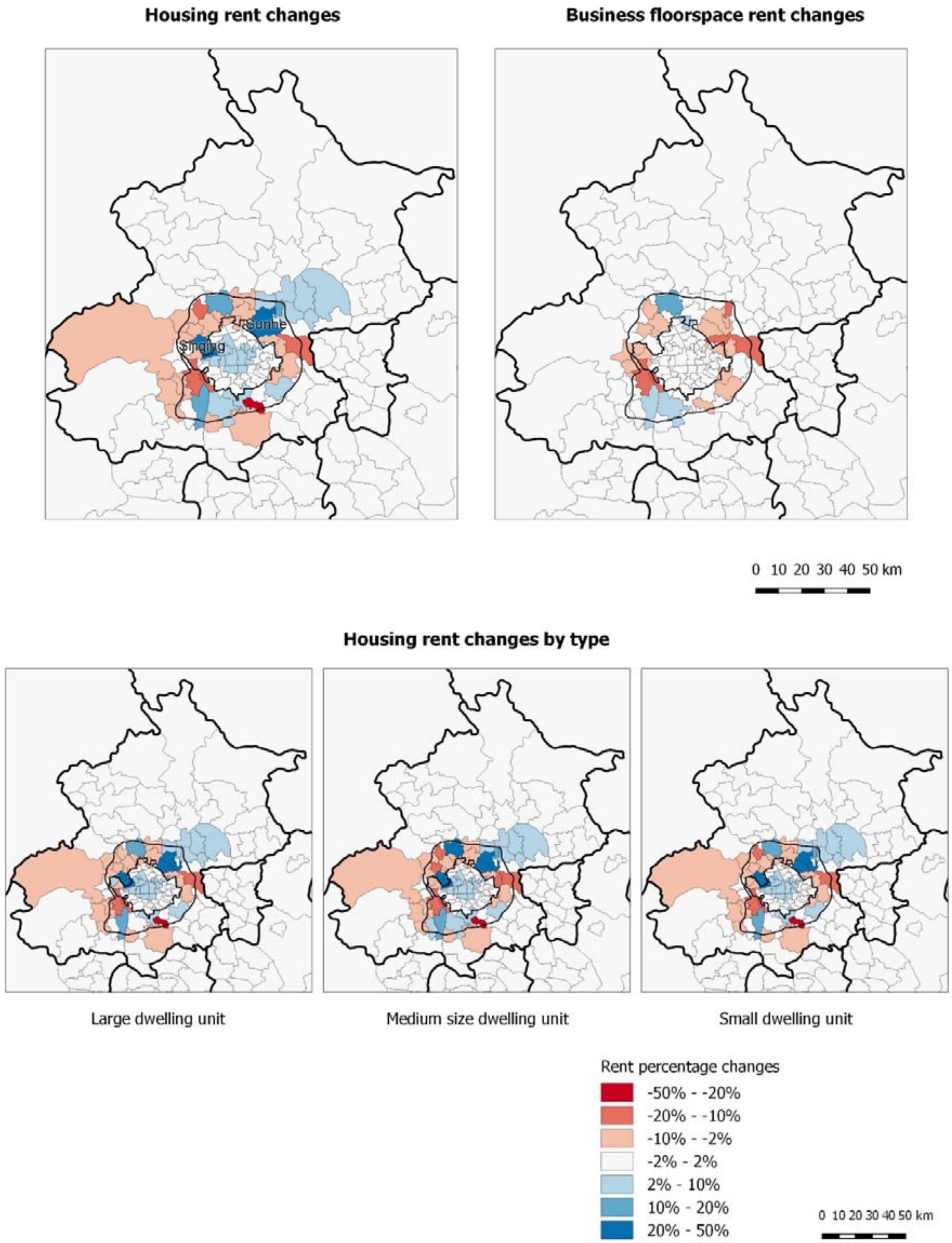


Figure 6-68 Rent change by type, GW compared to Ref 2030

Housing rent increases accordingly in the TOD nodes (see Figure 6-68). Two TOD nodes are particularly popular due to their locations. Sijiqing is close to the science park; Sunhe is on the transport link between the city centre and the airport. Rent in the city centre also has a subtle increase as the result of the increase of residents. Business floorspace rent has a moderate change. Due to the sufficient supply of floorspace, only a limited number of TOD nodes see rent increases.

6.5.4.3 Utility, wage and price analysis

The consumption utility witnesses an overall increase in Beijing, with a limited number of TOD nodes and suburban zones as exceptions. Richer people will benefit from living in the greenbelt and in the south and northeast of the suburb. For middle class, the impacts are modest with some positive changes in the greenbelt and the far suburb. Poorer people will benefit from living in the south of the far suburb. Living in the greenbelt may well be a good option. However, as a large number of people concentrate in the TOD nodes, these nodes become less affordable for poorer people. The overall increase of utility in the greenbelt is likely to be from the decrease of transport cost (see Table 6-24 on page 240).

Wage change and price change follow the same spatial pattern. In general, the overwhelming majority of the zones have a marginal wage and price increase. The exceptions are Xicheng district in the centre and several of TOD nodes. The wage change by socio-economic group in Figure 6-70 has an inverse correlation to the labour supply. For example, as high skill workers move to the suburb, their wage level declines. However, wage in the TOD nodes does not drop much, despite the abundant labour supply. This is because the total production is high as well, so that the TOD nodes demand more workers.

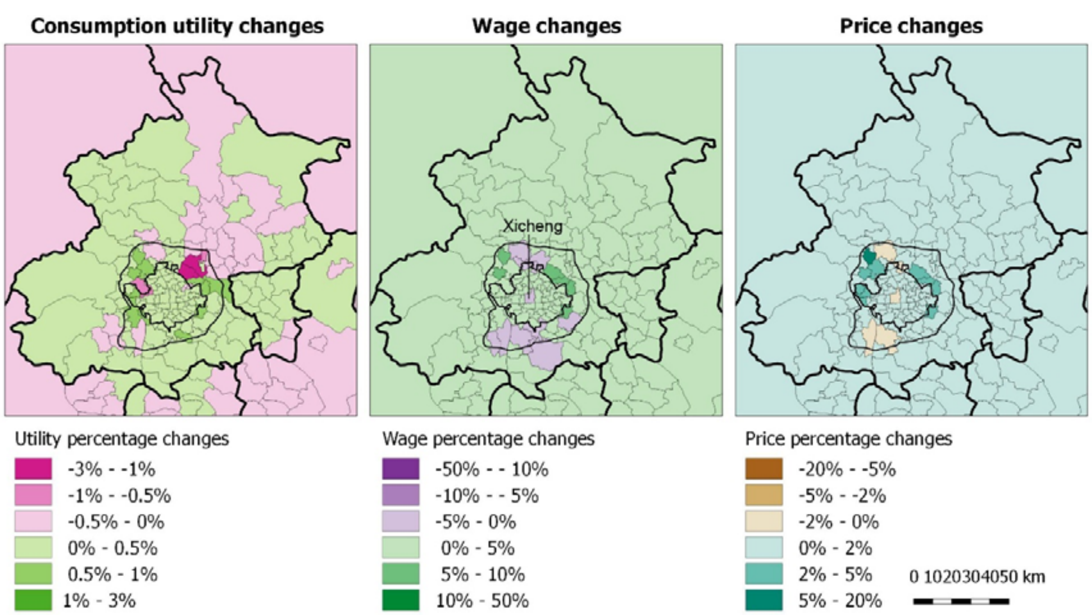


Figure 6-69 Utility, wage, and price change, GW compared to Ref 2030

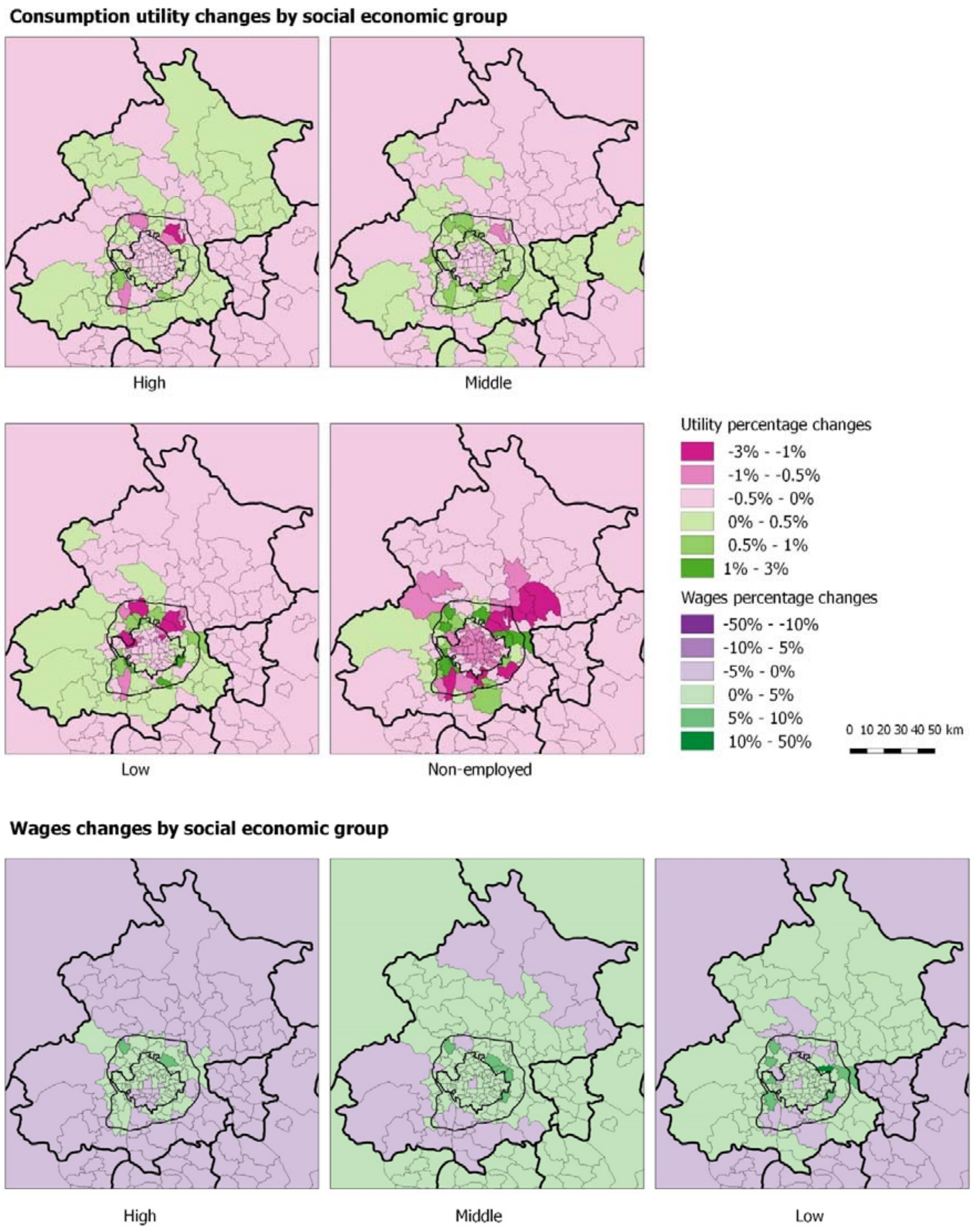


Figure 6-70 Utility and wage change by socio-economic group, GW compared to Ref 2030

6.5.4.4 Transport analysis

Table 6-24 summarises the relative changes of travel profiles to Ref scenario. The results are limited to Beijing Municipality. There is a decrease of the total trip volume because of population moving to Hebei and Tianjin, but the decrease is not as large as that in the GB or the GB-NT scenarios.

Average travel distances for all trip purposes decrease. Accordingly, average travel times all decrease, except for Flow 1. Flow 1 is the commuting trips for high socio-economic group, within which car is commonly used. Because the GW policy discourages car usage, richer people need to shift to other slower modes and their commuting time therefore increases. Speeds for all flows decrease too. The speed decrease implies the travel modes shift from faster travel modes to slower travel modes, namely from car to metro, cycle, walking and bus. Such mode shifts also result in cheaper journeys. As shown in the table below, monetary costs decrease as a result of mode choice shifting from car to public transport or non-motor vehicles. Decreases in travel times and costs diminish the spatial costs for travelling, which in return enable residents to spend more time and money on rent, goods and services. This is the main reason of the overall increase in consumption utility.

	Flow	Average distance	Average cost	Average time	Average speed	Trip volume	Passenger-km/year
1	Commuting High	-3.2%	-5.4%	0.4%	-3.6%	0.0%	-3.2%
2	Commuting Middle	-4.1%	-7.9%	-0.5%	-3.6%	-2.9%	-6.9%
3	Commuting Low	-1.7%	-6.4%	-0.6%	-1.1%	0.0%	-1.7%
4	Educational High	-6.0%	-7.7%	-2.0%	-4.1%	-1.0%	-7.0%
5	Educational Middle	-4.1%	-5.4%	-1.9%	-2.3%	-1.1%	-5.2%
6	Educational Low	-9.7%	-9.0%	-4.4%	-5.5%	0.0%	-9.7%
7	Business High	-2.1%	-2.6%	-0.3%	-1.7%	0.0%	-2.1%
8	Business Middle	-5.4%	-5.8%	-0.9%	-4.6%	-2.2%	-7.5%
9	Business Low	-10.1%	-10.9%	-2.3%	-8.0%	0.0%	-10.1%
10	Other High	-7.1%	-8.4%	-2.2%	-5.0%	-0.8%	-7.9%
11	Other Middle	-5.3%	-6.1%	-2.1%	-3.3%	-1.2%	-6.5%
12	Other Low	-12.0%	-12.1%	-5.9%	-6.5%	0.2%	-11.9%
	Total	-5.0%	-7.1%	-1.5%	-3.6%	-1.4%	-6.3%

Table 6-24 Change of travel profiles, GW compared to 2030 Ref (Table 6-21)

The trip distance range distribution in Figure 6-71 differs from the other 3 scenarios. The number of shorter trips (<5 km) is far more than that in the other scenarios, while longer trips (>5 km) are less than that in other scenarios. This distance range transformation is caused by two reasons. Firstly, the TOD nodes provide a chance for people to work near where they live, which diminishes commuting distance. Secondly, the TOD nodes prompt people to stay close to the network and to travel through shorter intra-zonal bands more frequently.

For shorter trips, walking and bus are promoted. These trips are predominantly intra-zonal trips, and the tendency of choosing such modes for the shorter intra-zonal travel bands can be observed in the value modal specific constants in Appendix E. For longer trips, car is still the dominant travel mode. However, the car usage in each band is categorically less than that in the Ref scenario. Metro/rail is the remedy for long distance trips, but the increase of metro/rail usage is limited.

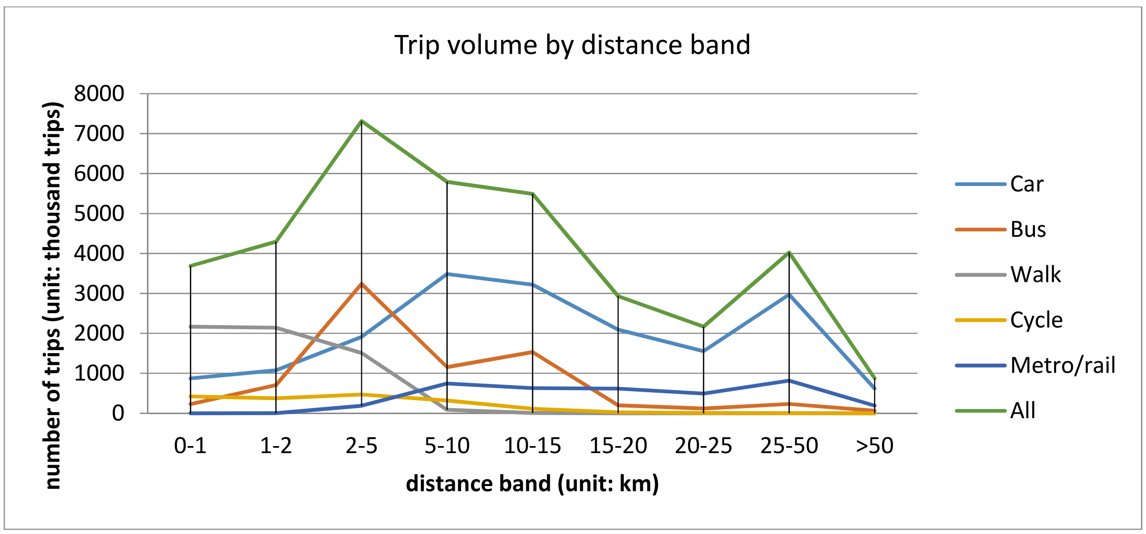


Figure 6-71 Trip volume by distance band by mode, 2030 GW scenario

Road traffic volume not only decreases in the greenfield where travel demands shrink, but also in the inner city and TOD nodes where the number of population remains unchanged or even goes up. Such a global decrease of road traffic indicates an overall mode share change. Car is not as popular in the GW scenario as it is in other scenarios.

Metro traffic volume increases in the main city and the majority of the greenbelt zones. It only decreases in the designated greenfield zones. We recall that both the GB and GB-NT policies cause the metro/rail traffic volume changes beyond the greenbelt (in the new towns, the far suburb and even the Ecological Protection Area), but in the GW scenario, the impact is mainly within the outer greenbelt boundary.

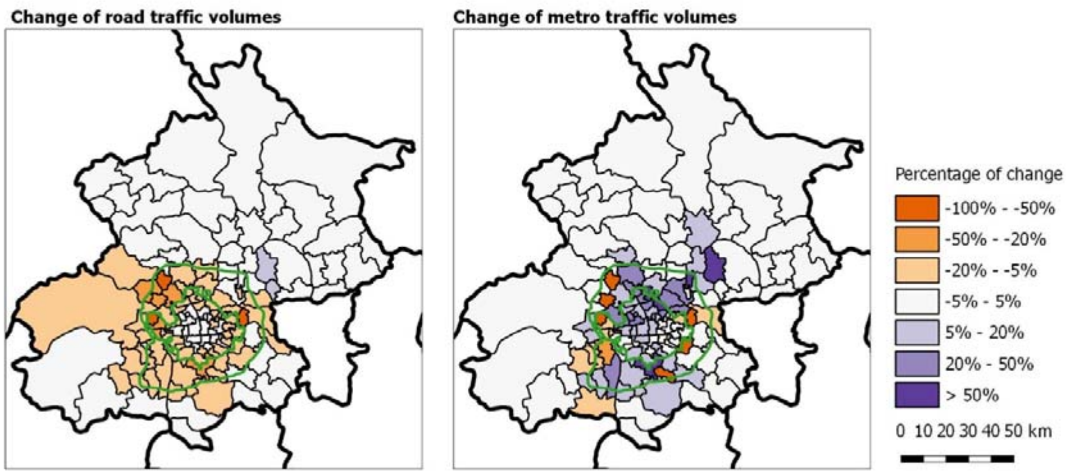


Figure 6-72 Change of traffic volume by zone, GW 2030 to Ref 2030

Figure 6-73 reveals the zonal mode share of the greenbelt zones. The sizes of pie charts in the greenfield zones (with green background) and those in the TOD nodes (with orange background) contradict each other. The total trip volumes, presented as sizes of pie charts, are minimal in the greenfield, where car mode share is normally more than 50%. The total trip volumes in the TOD nodes are increasing decade by decade, but car usage is curbed to less than 50%[16].

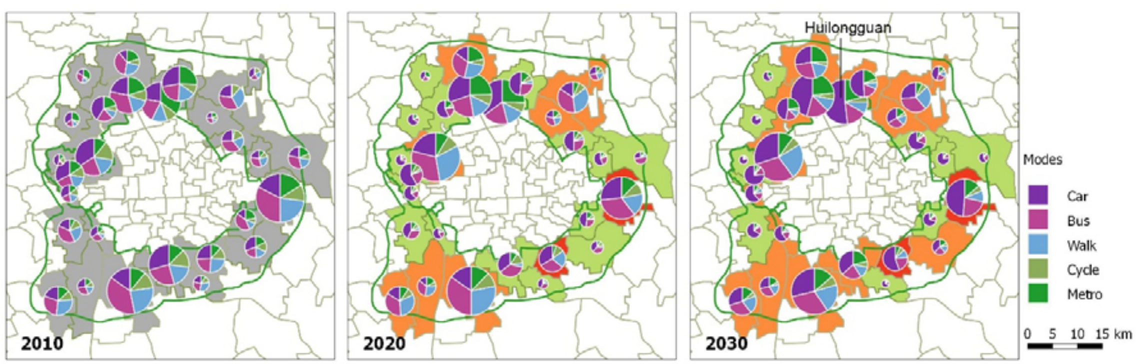


Figure 6-73 Mode share from the greenbelt zones 2010-2030, GW scenario

To sum up, the GW scenario balances the development pressure in Beijing's urban fringe and the assertion of preserving the greenbelt. The built-up areas in the urban fringe are separated by green spaces, and only 25% of the land in TOD nodes is built-up. Population and jobs within the greenbelt boundary is as high as that in the Ref scenario, but distributed unevenly. TOD

[16] Huilongguan zone in the north is an exception where car mode share is slightly more than 50%.

nodes possess 80% of the residents in the greenbelt. The two built-up towns have 11% of the residents. The rest of the greenbelt has 9% of the total greenbelt residents. The TOD nodes are competing with nearby zones, namely the inner city zones and the far suburb zones, and residents and jobs move to the TOD zones for the transport advantages. The Green-wedges scenario presents a small scale decentralisation pattern. This planned decentralisation does not channel development from the centre beyond the greenbelt, but from the centre to the designated TOD nodes within the greenbelt. The policy impacts are comparatively local, as Beijing does not lose floorspace development to the rest of the study area. The overall transport costs decrease as results of both the balanced of employment-residence locations and the proximity to the transport network. Although car is still popular, public transport and non-motor travel modes are promoted. In that sense, the GW scenario is relatively environmentally friendly.

6.6 What will happen if allowing Beijing's centre to grow?

After we have tested the four principal scenarios from section 6.3 to 6.5, we carry out a parallel study of the four aforementioned scenarios and briefly report the key findings in this section. The purpose of this section is to test how the city centre densification works in addition to the different green space configuration. The only variable in this section 6.6 is to allow the centre to grow.

The reason that such a parallel study is necessary is that allowing the city centre to grow follows the conventional concept of establishing a compact urban form through the greenbelt intervention. Testing the compact growth against the previous concentric growth can reveal the different performances of the two spatial typologies.

6.6.1 Parallel scenarios

In this parallel test, the four principal scenarios will evolve into four parallel scenarios, which are still the reference case, greenbelt, the greenbelt with new towns, and the green-wedges. The new scenarios are designed under the same background trend. The only policy variable of the scenarios is that both natural growth and discretionary growth are allowed in the city centre. We denote the 4 parallel scenarios as Ref-C, GB-C, GB-NT-C, and GW-C in Table 6-25. We then re-run the simulations.

Scenarios			Land Use Supply Specifications									Transport Supply Specifications
			Beijing							Tianjin	Hebei	
			Centre	Near Suburb	Greenbelt	TOD Nodes	New Towns	Far Suburb	EPA			
Reference	**Ref-C**	Concentric growth + allow development in the centre	√	√	√	NA	√	√	×	√	√	Network same as Ref
Greenbelt	**GB-C**	No growth in Greenbelt + allow development in the centre	√	√	O	NA	√	√	×	√	√	Network same as GB
	GB-NT-C	GB-C + additional new town development	√	√	O	NA	√+	√	×	√	√	Network same as GB-NT
Green-Wedges	**GW-C**	Additional growth in the TOD nodes in the built-up wedges + allow development in the centre	√	√	O	√+	√	√	×	√	√	Network same as GW
Note	√ denotes both natural growth and discretionary growth allowed. √+ denotes development is promoted with special policy support. × denotes natural growth allowed, but no discretionary growth. O denotes no growth at all											

Table 6-25 Parallel scenario variables overview

6.6.2 Modelling results

The main purpose of the parallel study is to understand the key differences between the compact development typology and the concentric development typology. Therefore, we present the findings of the four parallel scenarios in the following order. Firstly, we focus on the differences between the Ref-C scenario and the Ref scenario. This is to reveal the differences between the two typologies. Secondly, we compare each alternative scenario against Ref-C.

The comparisons between parallel scenarios and Ref-C resemble the comparisons between principal scenarios and Ref. Therefore, we believe that there is no radical change in the broad thrust of the performances regarding the greenbelt, new town or green-wedges interventions, because the relative differences among the four parallel scenarios are kept the same as they were in the principal scenarios. Therefore, we only briefly report the GB-C, GB-NT-C, GW-C modelling results. Relevant maps can be found in Appendix F.

6.6.2.1 Demographic change

Table 6-26 and Table 6-27 list the modelled employed residents and workers among the parallel scenarios and the principal Ref scenario. The comparison between Ref-C and Ref points out that if central Beijing is allowed for development, Beijing will acquire more population and employment. Beijing's leading position in the Greater Beijing region will be stronger, which contrasts the government's idea of regional integration and decentralisation. Then we compare the alternative scenarios (GB-C, GB-NT-C, and GW-C) against Ref-C. The relative difference is very similar to the differences in the previous respective scenarios (GB, GB-NT, and GW against Ref) in section 6.4.

		2030 parallel scenarios			
	2030 Ref	**Ref-C**	**GB-C**	**GB-NT-C**	**GW-C**
	Thousand people		Percentage of change compared to Ref-C		
Beijing	18887	20165	-4%	-2%	-2%
Tianjin	8444	8120	-5%	-5%	1%
Hebei	54829	53874	2%	2%	1%
Regional	82159	82159	0%	0%	0%

Table 6-26 Employed resident distribution at municipal/provincial level for parallel scenarios

	2030 Ref	2030 parallel scenarios			
		Ref-C	GB-C	GB-NT-C	GW-C
	Thousand people		Percentage of change compared to Ref-C		
Beijing	18,980	20,307	-3%	-2%	-2%
Tianjin	8,486	8,162	-5%	-5%	1%
Hebei	54,694	54,759	2%	2%	1%
Regional	82,159	82,159	1%	0%	0%

Table 6-27 Employed worker distribution at municipal/provincial level for parallel scenarios

We are confident that the zonal relative differences of population and jobs among the four parallel scenarios (comparing GB-C, GB-NT-C, and GW-C to Ref-C) resemble the patterns in the previous principal scenario comparisons (see the maps in Appendix F). Therefore, we mainly highlight the zonal differences between the Ref-C and Ref scenarios.

Essentially, the city centre shows a strong agglomeration effect. It absorbs employed residents and jobs from the most other zones to the city centre. Other zones, especially the zones in the south of the study area, witness losses of population and employment. The agglomeration effect of business is even stronger. Beijing's city centre is the predominant business centre in the region.

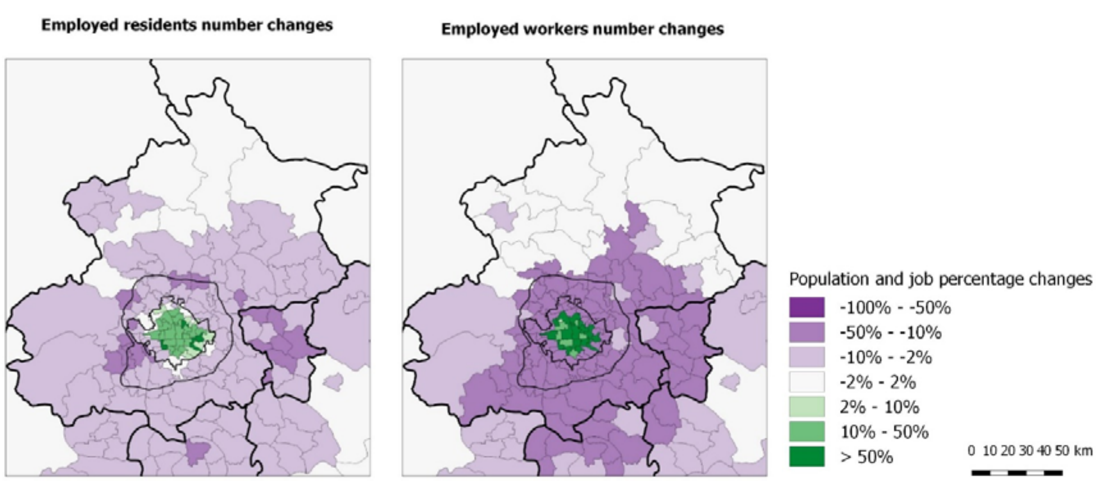


Figure 6-74 Employed residents and workers change, Ref-C compared to Ref

6.6.2.2 Floorspace change

Table 6-28 and Table 6-29 list the modelled housing floorspace and business floorspace among the parallel scenarios and the Ref scenario. If central Beijing is allowed for development, Beijing will win more floorspace from Tianjin and Hebei. The relative differences among the four parallel scenarios are still similar to the previous principal scenario comparisons, and we believe that the mechanism behind the relative changes is similar.

	2030 Ref	2030 scenarios			
		Ref-C	**GB-C**	**GB-NT-C**	**GW-C**
	Floorspace (million m^2)		Percentage of change compared to Ref-C		
Beijing	1,169	1,217	-10%	-5%	0%
Tianjin	1,189	1,182	2%	1%	0%
Hebei	5,605	5,564	2%	1%	0%
Regional	7,964	7,964	0%	0%	0%

Table 6-28 Housing floorspace supply at municipal/provincial level for parallel scenarios

	2030 Ref	2030 scenarios			
		Ref-C	**GB-C**	**GB-NT-C**	**GW-C**
	Floorspace (million m^2)		Percentage of change compared to Ref-C		
Beijing	460,783	490,398	-2%	-2%	0%
Tianjin	197,889	189,665	1%	1%	0%
Hebei	984,517	970,934	1%	1%	0%
Regional	1,643,190	1,643,190	0%	0%	0%

Table 6-29 Business floorspace supply at municipal/provincial level for parallel scenarios

A strong agglomeration effect can be observed in the business floorspace change. The increase of business floorspace in the city centre is 64% more than that in Ref. The algorithm of business floor space allocation (see [Equation 4-30]) shows that the floorspace development is strongly correlated to the existing floorspace stock and rent. Therefore, without growth control, the city centre development will reinforce its preeminent position as the regional business and employment centre. Additionally, if a stringent greenbelt intervention is applied (GB-C), the city centre will be even more packed for business (see Figure 6-77).

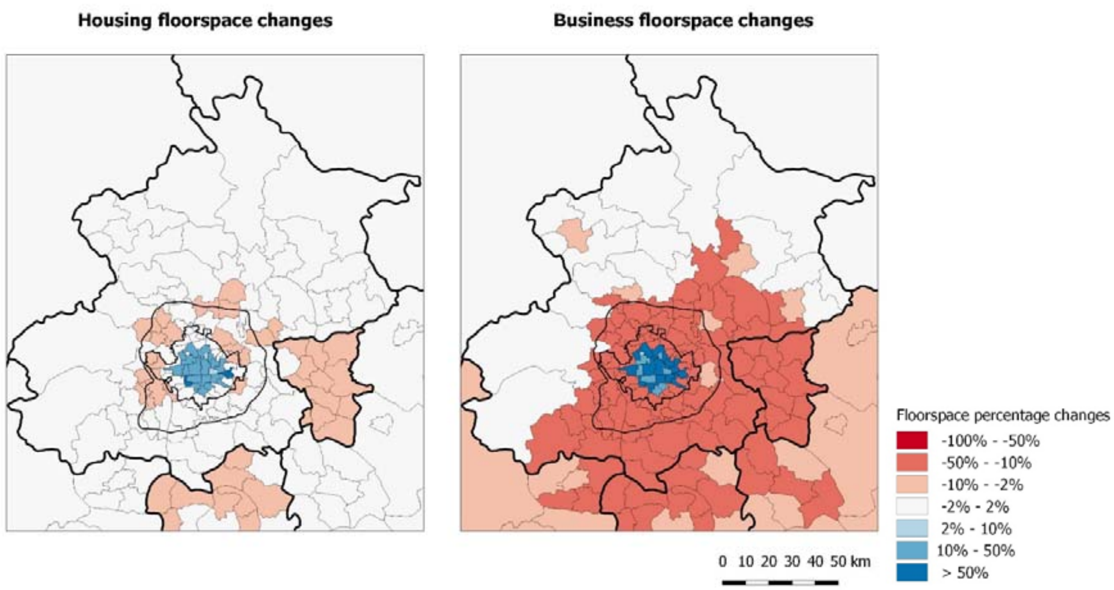


Figure 6-75 Floorspace change, Ref-C compared to Ref

Compare to the change of business floorspace, housing floorspace change is less radical. This is because the city centre's predominance in housing market is not as pronounced as that in the business market, and the agglomeration effect is not as strong. Implementing a stringent greenbelt in addition to housing densification and will add about 21% new housing in the centre, but this potential growth amount is not as radical as business floorspace increase.

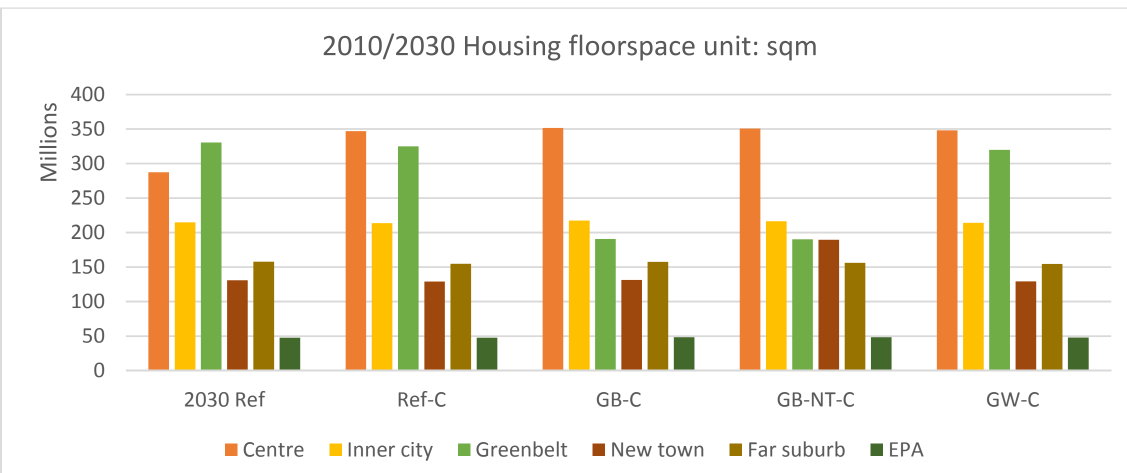


Figure 6-76 Housing floorspace supply in Beijing at zone-categorical level, parallel scenarios

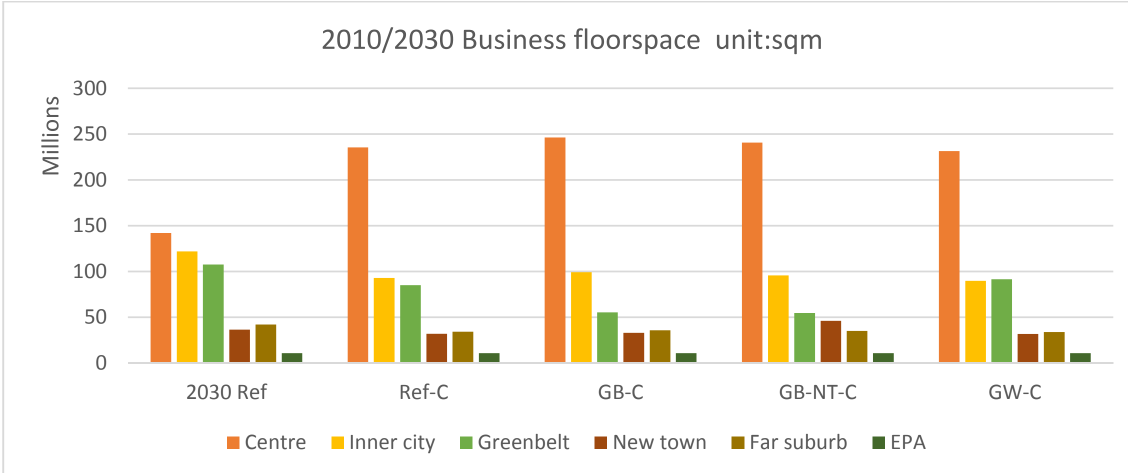


Figure 6-77 Business floorspace supply in Beijing at zone-categorical level, parallel scenarios

6.6.2.3 Rent change

In term of the housing rent, the additional floorspace supply in the city centre does not make housing more affordable in Beijing. Instead, as more residents move to the centre, rents go even higher in the parallel scenarios. The mono-centric spatial structure is exacerbated in Beijing by densification.

		2030 scenarios			
	2030 Ref	**Ref-C**	**GB-C**	**GB-NT-C**	**GW-C**
	Yuan/m^2/year		Percentage of change compared to Ref-C		
Beijing	1,291	1,300	8%	4%	-1%
Tianjin	545	528	-4%	-4%	1%
Hebei	479	470	0%	1%	1%
Regional	608	605	0%	0%	0%

Table 6-30 Housing floorspace rent at municipal/provincial level for parallel scenarios

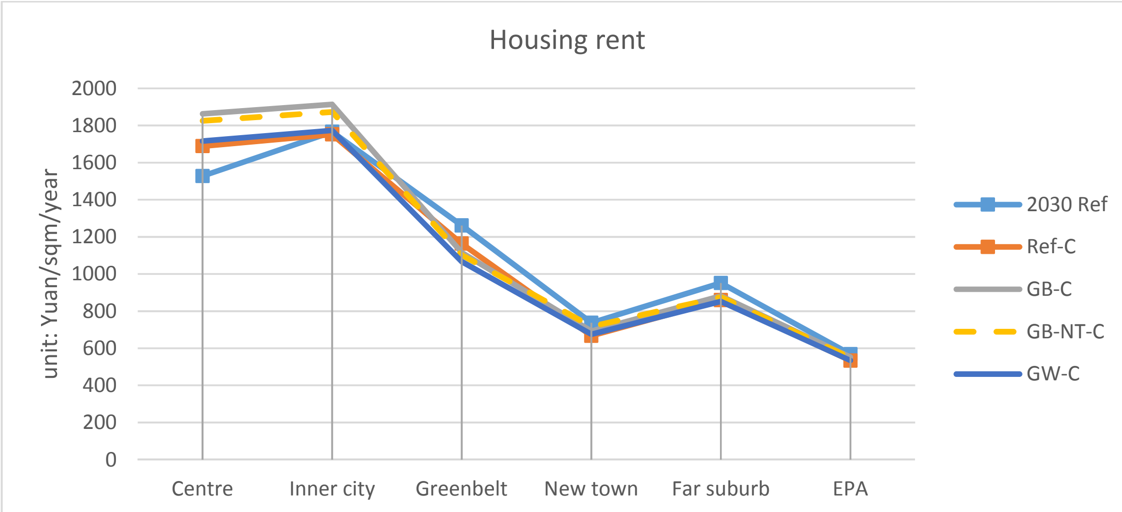


Figure 6-78 Housing rent in Beijing 2030, comparing parallel scenarios to Ref

Unlike housing rents, business floorspace rents in parallel scenarios drop to a lower level. This is because the city centre is always the regional business centre and the agglomeration effect of development is particularly strong. Business floorspace will increase drastically in the city, which brings down the rent. As the majority of the business opportunities are grabbed by the city centre, elsewhere suffers a loss of productivity. Therefore, the rent in other places will also drop slightly.

		2030 scenarios			
	2030 Ref	**Ref-C**	**GB-C**	**GB-NT-C**	**GW-C**
	Yuan/m²/year		Percentage of change compared to Ref-C		
Beijing	539	534	1%	1%	-1%
Tianjin	242	237	-6%	-5%	1%
Hebei	180	175	1%	1%	1%
Regional	288	290	0%	0%	0%

Table 6-31 Business floorspace rent at municipal/provincial level for parallel scenarios

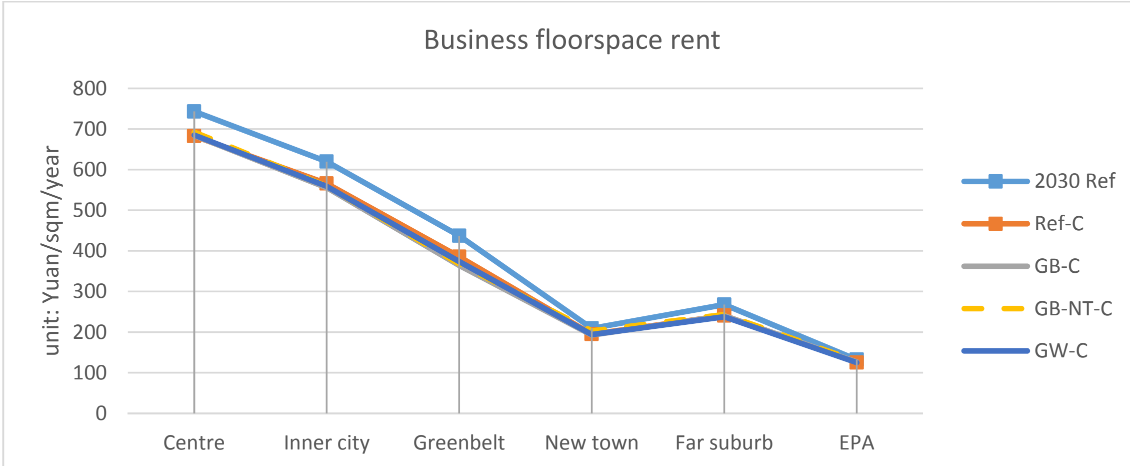


Figure 6-79 Business floorspace rent in Beijing 2030, comparing parallel scenarios to Ref

6.6.2.4 Production, wage, price change

Allowing Beijing's centre to develop benefits its productivity. The total production is much higher (6202 million in Ref-C, 5687 million in Ref) in Beijing, because of the sufficient labour supply and business floorspace supply. However, the central city densification scheme for Beijing is not beneficial for the whole region, as it decreases the overall productivity from 54,438 million to 53,646 million.

		2030 scenarios			
	2030 Ref	Ref-C	GB-C	GB-NT-C	GW-C
	Quantity (millions)		Percentage of change compared to Ref-C		
Beijing	5,687	6,202	-2%	-2%	-2%
Tianjin	8,166	7,867	-4%	-5%	1%
Hebei	40,585	39,577	2%	2%	1%
Regional	54,438	53,646	0%	0%	0%

Table 6-32 Total production volume in quantity of composite goods at municipal/provincial level

Both wage and price decrease globally. As we already explained, wage and price levels are not trade-offs among zones. Therefore, a global decrease is possible. Wage decreases in the city centre because of the higher labour supply. For elsewhere, the total production output decreases largely, which leads to a subtle decrease of wage level. The reduction of price results from the business floorspace rent decrease and wage decrease. Consumption utility increases marginally across the study area, apart from the main city and a number of suburban zones. This is because of the lower rent and price levels. In general, the highly concentrated business development in the city centre has brought down the overall price level.

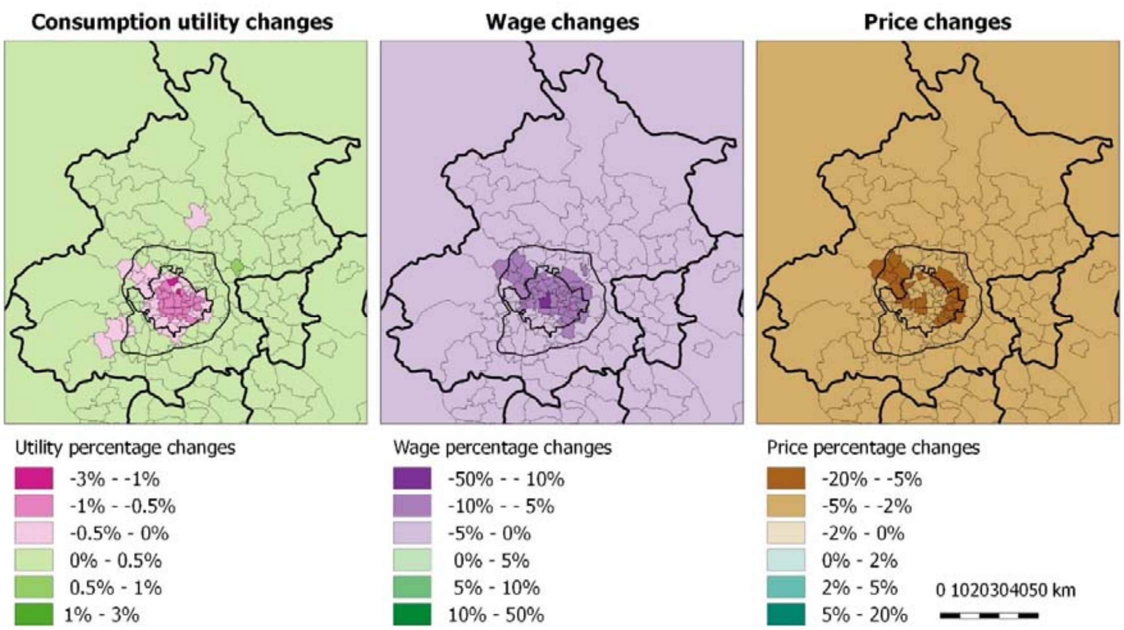


Figure 6-80 Consumption utility, wage and price change, Ref-C compared to Ref

6.6.2.5 Transport change

Average travel times generally increase in the parallel scenarios. Even if the travel time in the GW-C scenario is comparatively short (40.0 min), it is still slightly longer than that in the GW scenario (39.9 min). On the other hand, average travel distances decrease in the parallel scenarios. That is to say, the overall travel speeds become slow. Meanwhile, the overall mode shares of the parallel scenarios are not dissimilar to Ref (see Figure 6-82). Therefore, the speed decreases are not from mode shift. Given that our current model uses the constant congestion speed to the network, the slowed-down speed is not from a worsening congestion either. It is mainly from the relocation of trip origins and destinations. As residents and jobs concentrate in the city centre, trip volume will increase substantially in the centre, where the network speed is slow. So the overall speed decrease is reasonable. If our model considers the congestion effect in the city centre, this decrease of speed will be even more obvious.

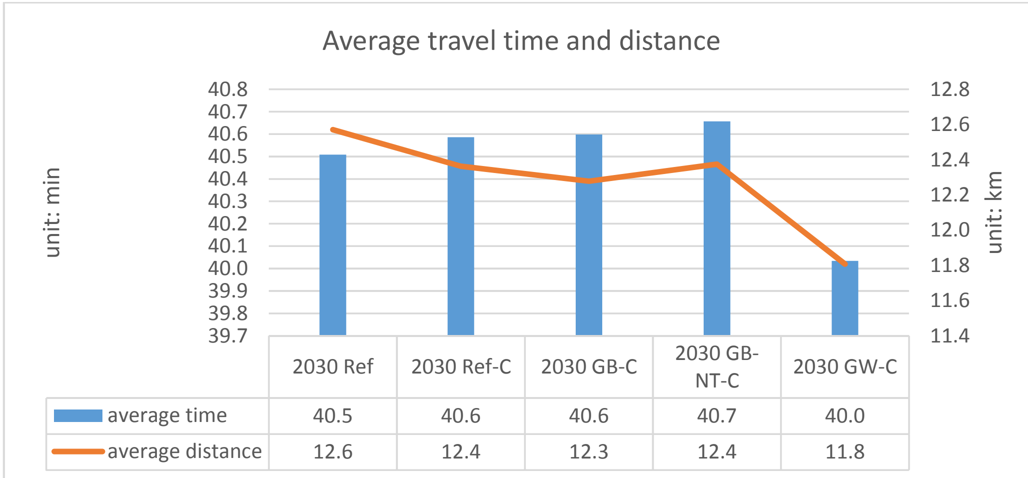


Figure 6-81 Average travel time and distance in Beijing 2030, comparing parallel scenarios to Ref

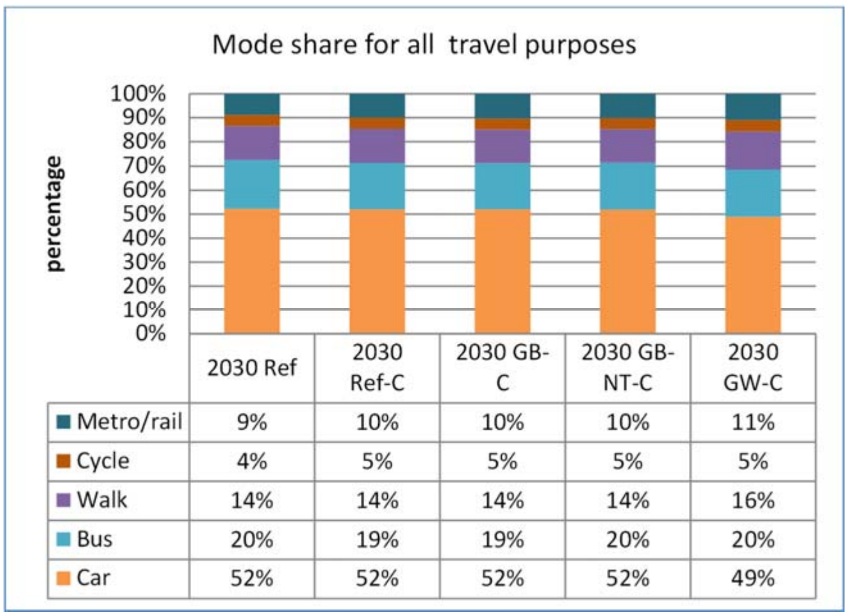


Figure 6-82 Mode share for all travel purposes in Beijing, parallel scenarios to Ref

To sum up, the parallel study adds the densification scheme to the aforementioned four scenarios. The results show that allowing the city centre to grow strengthens the predominant position of the central Beijing as the regional business and employment centre. It boosts the mono-centric spatial pattern and forms a compact spatial structure. Even with urban containment implemented to Beijing, the total productivity of Beijing is still higher than the scenarios without densification in the centre.

The overall spatial costs have been brought down by densification scheme, which results in a higher utility level. This is because the densification policy augments the city centre agglomeration effect and shortens the travel distances. Such a decrease of spatial costs occurs because our model has not measured the negative externalities brought by overcrowding, such as congestion. If congestion in the city centre is dynamically measured, the compact spatial structure may not necessarily be beneficial any more.

Comparisons between Ref-C and Ref have revealed drastic changes in population density, floorspace density and price level. Nevertheless, comparisons among the four parallel scenarios indicates that there is no drastic change in the broad thrust regarding the performances of greenbelt, new town or green-wedges interventions.

To summarise, this chapter firstly offers a retrospective test to review the scales and locations of Beijing's greenbelts from 1990 to 2010. Then a prospective test is carried out by predicting the performance of four possible future configurations for Beijing's moving urban fringe from 2010 to 2030. Finally, a parallel study is reported briefly to reveal the impact of city centre densification on the greenbelt variations. More general insights and implications for greenbelt policies will be outlined in the next chapter.

CHAPTER 7 CONCLUSIONS

To recap, this dissertation aims to answer three questions: 1) What are the short-term and long-term impacts of a greenbelt on a fast growing city? 2) Which alternative green space configuration performs better in terms of economic well-being and travel costs? 3) Where and how much should the greenbelt land be progressively reshaped or released as the city grows? In order to answer these questions, we have developed a new variant of the LUTI model and tested it using Greater Beijing as a case study. In this chapter, we first summarise the intellectual contributions of this new LUTI model in section 7.1. Then, we discuss the more general insights into the effects of greenbelt policies in fast growing cities in section 7.2. Finally, we point out the strengths and weaknesses of this research, and outline possible future work in section 7.3.

7.1 Improvements for modelling the greenbelt

The Greater Beijing LUTI Model builds upon four strands of generic model theories and is assembled to represent a more complete picture of urban activities. The four sub-models in the new LUTI model are: 1) The Spatial Equilibrium Model (SE) that is recast from general equilibrium theory (Anas & Liu 2007; Anas et al. 1998; Fujita 1989; Alonso 1960). 2) The Non-commuting Travel Demand Model (NCTD) modified according to the generic input-output framework (Echenique 2004; Echenique et al. 2013). 3) The Strategic Transport Model (ST) developed based on the generic four-step transport model (Ortuzar & Willumsen 2011; Boyce & Williams 2015; Williams 1994). 4) The Recursive Dynamic Model (RD) for floorspace development and non-employed households derived from the quasi-dynamic urban development model (Wegener et al. 1986; Simmonds et al. 2013; Jin et al. 2013).

Empirically, the Greater Beijing LUTI Model combines and extends two operational models of Greater Beijing, which are the Beijing-Tianjin-Hebei City Region Model (Wan 2016) and The Greater Beijing Strategic Transport Model (Deng 2015). Our new model has extended the existing models' capabilities as follows:

1) The new LUTI model is more complete than the existing models when measuring the effects of the greenbelt. It combines the four sub-models within the hybrid equilibrium-dynamic modelling framework and enables the tests of the greenbelt's long-term impacts on the real estate market, the labour market, the product market, and the transport market. It is the first time that the feedback loops are formed within the four markets with direct interfaces and modelled within one LUTI framework for a fast growing city, as envisaged in Jin et al. (2013). Whereas most of the conventional research focuses on examining the greenbelt's impacts on commuting related urban activities, such as employment-residence location choices, we extend the model to cover non-commuting urban activities and test for the greenbelt's impact on specific travel mode and path choices.

2) This LUTI model is capable of testing endogenous transport variations, while the existing spatial equilibrium models for Greater Beijing use user-defined transport variations. Different from user-defined exogenous inputs regarding transport improvements/dis-improvements, the new model establishes and calibrates an endogenous link between the land use and transport models. For example, in the existing models, the effect of a new metro line on the land use pattern is considered as a user-defined reduction in travel time. In the new model, the changes of travel time, cost, distance and travel mode due to the construction of new metro line are all modelled internally by the transport sub-model. Such a link provides a more transparent representation of transport changes. Besides this, a built-form component is developed so that the effects of spatial proximity between the built-up areas and the transport networks can be modelled endogenously. This is particularly suited for testing greenbelt and green-wedges scenarios where real estate development and transport access are interdependent.

3) We develop a method for synthesising modal travel demand matrices, working with aggregate travel demand data. For most cities in developing countries, observed travel demand data are very limited and this has always been one of the issues that hinders the development of urban models. Our calibration method provides a possible approach for working with trip generation and distribution in the Spatial Equilibrium Model and the Non-Commuting Travel Demand Model. It also deals with aggregate modal shares from relatively crude transport surveys and consensus expectations on travel demand elasticities. This may prove to be a feasible approach for LUTI modelling in the emerging economies before more sophisticated travel surveys become available.

4) For the Greater Beijing case study, we have extended the temporal range for the spatial equilibrium modelling to 1990, where only sketchy model inputs exist. This modelling year is valuable, because it represents a pre-greenbelt situation. In order to verify the model inputs for 1990, we develop a method that is to forecast backwards from the current year to a historic year and to compare the forecasting results with the aggregate data for 1990. This method provides a new approach to the verification of historic data where historic data series become progressively cruder. Additionally, the historic-what-if simulations not only test the greenbelt policy variations in historic time horizons, but also provide an improved test for model validation. We believe that such a retrospective test is beneficial because the historic-what-if models can take advantage of observed data in the past census years, and it is therefore a logical step towards a thorough understanding of the model's predictive capabilities.

In summary, the core purpose of building this LUTI model is to reveal the impacts of the greenbelt on various urban markets in a theoretically rigorous way. To the best of our knowledge, such a LUTI model has not been built previously.

7.2 Implications for greenbelt policies

We have presented the scenario analyses on a series of alternative configurations of the greenbelt in Chapter 6. Such analyses do not aim to identify the very optimum configuration of the green spaces, but aim to provide a coherent digital test bed for comparing alternative plans in fast expanding cities. Here we summarise the policy implications which may help policy makers and planners to predict and evaluate the possible consequences of specific land use or transport interventions.

1) The greenbelt policies of any stringency and any configuration are likely to impact upon a wide geographic area. The impacts will transcend the greenbelt boundary, and even the municipal boundary, onto the entire city region. In our case study, both the greenbelt (with or without the support of new towns) and the green-wedges lead to relocations of jobs and residents, not only among different areas inside Beijing Municipality, but also in Tianjin and Hebei. The implementation of either the greenbelt or the green-wedges will trigger a loss in jobs and residents in Beijing and this may lead to a corresponding increase of jobs and residents outside the municipality. When designating the

geographical scale of Beijing's greenbelt or green-wedges, planners can no longer focus on the impacts on Beijing alone, but should examine their impacts on the wider city region. The intricate relationship between Beijing and the rest of the region should be carefully assessed.

2) If there is no policy intervention, Beijing's concentric expansion will continue. The designated greenbelt area is the next for the city to expand into under the trend scenario. Building over the greenbelt will lead to the expansion of the existing, pancake-shaped built-up area with poor access to large green spaces for the majority of residents. The concentric expansion of Beijing is self-sustaining, and Beijing's predominance in the regional economy will be reinforced under such an expansion (the production volume in Beijing is at least 2% higher under concentric expansion than any other alternative scenarios).

3) A strict implementation of a ring-shaped greenbelt is unlikely to be the highest performing intervention. In our case study, the negative effects of the ring-shaped greenbelt, such as higher housing rent (overall 7% higher than Ref), lower productivity (3% lower than Ref), a decrease in consumption utility (0.5% lower than Ref), and a great dependency on private cars (52% car mode share, same as Ref, 3% higher than GW), would weaken the competitiveness of Beijing. Notably, the phenomenon of longer-distance commuting does not appear to occur in our modelling results for the greenbelt scenario. This is because the size of the planned greenbelt is relatively wide (about 10 km) and hard to commute across without improved transport. The implementation of the greenbelt as per the current plan would either confine residents and jobs in the main city or relocate both of them beyond the greenbelt. In either case, jobs are constrained to the close proximity of homes, and vice versa.

   Our greenbelt simulations cover a time span of 40 years, during which the enduring effects of the greenbelt as a long-term urban containment policy have a chance to be played out. The retrospective modelling results for 1990 – 2010 suggest that even a narrow greenbelt launched in the early age of urban expansion (without transport improvement across the greenbelt) could depress consumer well-being significantly, and such effects can linger for decades (consumer surplus is 0.4% lower in 2000, 2% lower in 2010 in Beijing, than the respective reference cases). During the rapid development phase, urban expansion can easily leap frog the narrow greenbelt, which leads to spatial mismatch between residents and jobs. A wide greenbelt which acts as a buffer to leapfrogging could encourage most people to work locally both in and outside the greenbelt, if transport across the greenbelt is not improved.

4) The green-wedges configuration would appear to be an option that better balances economic efficiency and environmental benefits. In effect, this option helps to seed a poly-centric urban structure along the spines of fast public transport services. Breaking the ring-shaped greenbelt into wedges could keep about 75% of the green spaces in the designated greenbelt, and the wedges-based spatial structure mitigates much of the economic losses that are caused by urban containment. Under this scenario, Beijing will not lose floorspace development to the rest of the region. The implementation of the green-wedges would still lead to a loss of 2% population and 2% jobs to Tianjin and Hebei, but the losses are the lowest among the alternative green space scenarios. Building around metro/rail stations at a relatively high density benefits local households, as housing rent is brought down by 1% and wage brought up by 1%. The coordination between land use and transport policies is crucial for reducing spatial costs, as the average travel time decreases by 1.5% and travel distance reduces by 5.6%. Journeys on sustainable travel modes (public transport, cycling or walking) increase by 3%. The case study shows that there may be potential benefits to reconsider existing land use planning constraints on where people want to live and where it is accessible by sustainable modes of transport.

5) The new town development as a complementary policy to the greenbelt would help to alleviate some of the negative effects from a ring-shaped greenbelt, but the improvements are very limited. Most residents and jobs will still concentrate in the main city. In Beijing's case, the population density in the main city under the new town scenario is just as high as without such an intervention.

6) City centre densification would also help to mitigate the economic loss of Beijing caused by urban containment. Densification would reinforce Beijing's leading position in the regional economy (9% higher in production volume than Ref, 7% more jobs than Ref). However, densification is likely to increase congestion and exposure to vehicle emissions. Although the impacts of congestion and pollution exposure have not been modelled here, there have been many studies that show how such externalities could lead to a poor policy outcome. We therefore do not consider densification to be a promising supplement to the greenbelt generally, although specific designs of densification that minimise air pollution exposure and congestion should be tested carefully to ascertain their potentials.

7.3 Strengths, weaknesses and future work

The Greater Beijing LUTI Model is an operational model that is suitable for policy tests. It has several strengths in such complex applications:

1) The design of the model has made it feasible to develop an operational model with data sources that are commonly available in most developing countries. The data sources include population censuses, statistical yearbooks, and periodic travel surveys. It is capable of revealing the complicated interdependencies between urban markets using a relatively small number of model parameters. The parameters are relatively easy to calibrate and interpret. The parsimonious design of the model makes it easier to trace through the causes and effects under a specific scenario.
2) The Greater Beijing LUTI Model can reveal a wide range of greenbelt impacts. It not only simulates the day-to-day adaptation of businesses, residents, travel and traffic, but also links several time cross-sections to reveal the long-term impacts of different green space configurations. The model outputs include: changes in employment-residence locations, changes in floorspace development locations, changes in travel demand for shopping, educational, business and personal trips as well as commuting, the impacts on rents, wages, prices and household utility, and changes in travel distances, times and travel modes between zone pairs.
3) The model has a general analytical framework that makes it suitable beyond testing the configurations of urban green spaces. This model can test a wide range of planning policies through careful scenario design. The testable policies include (but are not limited to) the constraints of regional or zonal land supply, interventions of housing supply for different types, urban density regulations, road traffic rationing, congestion pricing, and so on.
4) The simplified representation of the transport network makes it feasible to carry out a strategic transport scenario assessment, while limiting the data-hungriness of transport supply modelling. For example, the use of the constant congestion speed over time would help gauge the potential travel demand using current congestion levels as a benchmark. The aggregate intra-zonal multi-modal networks and the approach to modifying access link improve the accuracy of the representation of network supply while using coarse model zones.

However, the simplifications also lead to a number of weaknesses. They must be taken into consideration when interpreting the model results.

1) The land use model follows a broad-brush approach to modelling urban activities. The lack of data precludes a more detailed model representation and a more systematic parameter estimation. For example, the zoning is highly aggregate; there are no explicit developer and government sectors; the representation of producer's behaviour is at the level of industries rather than specific firms. The model design is tailored to current data limitations as well as the main thrust of policy needs. It is a starting point of representing the complex impacts of the green space configurations at the city-region scale. The model structure allows many new features to be added in the future versions of the model when more data are available.
2) The transport model sacrifices many spatial details because it is built upon relatively large zones. It has a limited capability to test small scale local network change with precision. The use of relatively large zones also creates a challenge in estimating the traffic volume, travel times and costs on local microcirculation networks. The granularity of spatial representation can be improved through either an increase in the number of model zones or an implementation of adaptive zoning (Hagen-Zanker & Jin 2012) in the future.
3) The model focuses on assessing the economic and social impacts of various greenbelt configurations. The model predictions of the future locations of jobs, residents, commuting and other travels are the essential inputs to environmental and ecological impact assessment. However, the model does not currently assess the environmental and ecological impacts. Neither the amenity value nor the aesthetic value of the green spaces is captured explicitly through the model. In the future, incremental improvements can be added to the model in order to expand the range of its assessment capabilities. Alternatively, the model can interface with other models that are specialised in environmental and ecological assessments.

Of course, the Greater Beijing LUTI Model and its application can be improved in many ways. Based on the discussions above, we suggest the following areas for future research in the next steps. We in particular focus on what we consider the most crucial and practically feasible improvements.

1) A land use model with detailed industrial segmentation is recommended. This would help to capture the impacts of urban containment policies on the behaviour of different industries. Greater Beijing is facing a rapid economic transformation and industrial upgrading in the coming decades. A model with detailed industrial segmentation will be able to delineate such phenomena. The detailed segmentation of industry sectors would also accommodate a wider range of policy variables to be tested

2) The current transport model can be improved through improving representation of the networks and services, when new data become available. The following improvements would seem feasible since the data needed are already in existence, although they are not available for scholars outside China: a) a more detailed road configuration and capacity data would enable congestion to be simulated in much greater detail; b) the representation of travel times of metro and rail could be improved through coding the detailed operation timetables into the transport model; c) the current car ownership estimation by income could be replaced by an explicit car ownership model, particularly when in the future parking becomes a critical constraint in central areas; 4) the emerging travel options in Greater Beijing, such as Didi Taxi (an Uber-like service), car-pooling, and electric bikes could be included as their market shares rise.

3) There could be a greater level of specific quantification of the greenbelt's impacts on the environmental well-being and ecological amenities in the LUTI model framework, such as carried out in Anas (2006), when more survey data emerge. The environmental assessments such as carried out in Echenique (2010; 2012) and the ecological assessments such as carried out by UK National Ecosystem Assessment (Davies et al. 2011) could be incorporated for a more comprehensive assessment of the impacts of alternative green space configurations and their sustainability.

In conclusion, this research answers the greenbelt related questions by assessing impacts of alternative green space configurations through a new variant LUTI model. The new LUTI model enables the simulation of the impacts of green spaces over different time scales: the Spatial Equilibrium Model, the Non-commuting Travel Demand Model, and the Strategic Transport Model depict the day-to-day adaptations of businesses, residents and traffic flows; the Recursive Dynamic Model reveals the long-term inertia-prone impacts upon estate property markets and non-commuter households. After analysing the modelling results over the decades to 2030, we consider the green-wedges configuration, instead of a strict ring-shaped greenbelt, as a better performing green space option in terms of economic well-being and travel costs in Beijing under a fast growing urban population in the city region. In the coming decades, the unprecedented scale of urbanisation will continue to bring uncertainties to the outcome of green space policies. Therefore, large scale urban green space policies should be reviewed constantly using tools such as the LUTI model developed in this dissertation. On the one hand, land use regulations such as the greenbelt or green-wedges need to be implemented as firm designations in order to safeguard the green spaces. On the other hand, under fast growing conditions, the population sizes and land use needs may radically change from assumptions previously made. It can be beneficial to modify development restraints in line with the new contexts of urban development. This is a difficult trade-off, and the LUTI model developed in this dissertation will help to shed light on the potential economic costs and benefits between the alternative propositions.

BIBLIOGRAPHY

Abercrombie, P., 1945. *Greater London Plan 1944*, London: HMSO, LONDON.

Abraham, J.E., 1998. *A review of the MEPLAN modelling framework from a perspective of urban economics*,

Abraham, J.E. & Hunt, J.D., 2013. Policy Analysis Using the Pecas Framework. In *TRB 92nd Annual Meeting*.

Adkin, K., 2009. *India's garden city? Bangalore's disappearing greenbelt: green to gone*.

Ai, W., Zhuang, D. & Liu, Y., 2008. 北京市城市用地百年变迁分析. *Geo-information Science*, 10(4).

Alonso, W., 1960. A theory of the urban land market. In *Papers and Proceedings of the Regional Science Association*. pp. 149–157.

Amati, M., 2005. *A study on the planning processes and future directions of the London Green Belt An investigation of local level planning*. University of Tsukuba.

Amati, M., 2008. Green Belts : A Twentieth-century Planning Experiment. In M. Amati, ed. *Urban green belts in the twenty-first century*. Ashgate Publishing Limited, pp. 1–17.

Amati, M. & Yokohari, M., 2006. Temporal changes and local variations in the functions of London's green belt. *Landscape and Urban Planning*, 75(1–2), pp.125–142.

Anas, A., 2015. Why are urban travel times so stable? *Journal of Regional Science*, 55(2), pp.230–261.

Anas, A., Arnott, R. & Small, K.A., 1998. Urban Spatial Structure. *Journal of economic literature*, 36(3), pp.1426–1464.

Anas, A. & Liu, Y., 2007. A Regional Economy, Land Use, and Transportation Model (Relu-Tran): Formulation, Algorithm Design, and Testing. *Journal of Regional Science*, 47(3), pp.415–455.

Anas, A. & Pines, D., 2008. Anti-sprawl policies in a system of congested cities. *Regional Science and Urban Economics*, 38(5), pp.408–423.

Anas, A. & Rhee, H.-J., 2006. Curbing excess sprawl with congestion tolls and urban boundaries. *Regional Science and Urban Economics*, 36(4), pp.510–541.

Anas, A. & Rhee, H.-J., 2007. When are urban growth boundaries not second-best policies to congestion tolls? *Journal of Urban Economics*, 61(2), pp.263–286.

Bae, C.-H.C., 1998. Korea's greenbelts: impacts and options for change. *Pacific Rim Law & Policy Association*, 7(3), pp.479–502.

Bae, C.-H.C. & Jun, M.-J., 2003. Counterfactual Planning: What if there had been No Greenbelt in Seoul? *Journal of Planning Education and Research*, 22(4), pp.374–383.

Ball, M. et al., 2014. Urban Growth Boundaries and their impact on land prices. *Environment and Planning A*, 46, pp.3010–3026.

Batty, M., 1971. Modelling Cities as Dynamic Systems. *Nature*, 231, pp.425–428.

Batty, M., 2013. *The New Science of Cities*, Cambridge, Massachusetts: The MIT Press.

Batty, M., 2009. Urban Modelling. In N. Thrift & R. Kitchin, eds. *International Encyclopedia of Human Geography*. Oxford: Elsevier, pp. 51–58.

Batty, M., 1976. *Urban Modelling-algorithms, calibrations, predictions*, Cambridge University Press.

Batty, M. & Torrens, P.M., 2005. Modelling and prediction in a complex world. *Futures*, 37(7 SPEC.ISS.), pp.745–766.

Beijing Bureau of Statistics, 2016. Beijing Bureau of Statistics. *population data*. Available at: http://www.bjstats.gov.cn/zt/rkjd/ [Accessed September 12, 2016].

Beijing Bureau of Statistics, 2015. 北京市情城市建设. Available at: http://www.bjstats.gov.cn/bjsq/csjs/.

Beijing Bureau of Statistics & NBS Survey office in Beijing, 2009. *Beijing 60 Years 1949-2009*, China Statistic Press.

Beijing Municipal Commission of Urban Planning, 2004. *Beijing Master Plan 2004-2020 (北京市总体规划2004-2020)*,

Beijing Municipal Commission of Urban Planning, 2012. 北京市主体功能区规划,

Beijing Municipal Government, 1994. *[1994]7号北京市人民政府批转首都 规划委办公室关于实施市区规划绿化 隔离地区绿化请示的通知*,

Beijing Municipal Government, 2003a. *[2003]15号北京市人民政府关于加快本市 第二道绿化隔离地区绿化建设的意见*,

Beijing Municipal Government, 2003b. *[2003]7号北京市人民政府关于北京市第二道绿化隔离地区规划的批复*, China.

Beijing Municipal Government, 2008. 【2008】17号北京市人民政府批转市发展改革委关于进一步推进本市第一道绿化隔离地区建设意见 的通知.

Beijing Transportation Research Centre, 2007. *2007 Beijing Transport Annual Report*,

Beijing Transportation Research Centre, 2011. 2011 Beijing Transport Annual Report.

Beijing Transportation Research Centre, 2013. *2013 Beijing Transport Annual Report*,

Beijing Transportation Research Centre, 2015. 2016 Beijing transport management analysis.

Beijing Transportation Research Centre, 2012. *The 4th Beijing transport survey report*,

Beijing Transportation Research Centre, 2016. *The 5th Beijing transport survey report*,

Beijing Urban Planning and Design Institute, 2007. 北京市绿地系统规划 规划文本 图 集, China.

Bengston, D.N. & Youn, Y.C., 2006. Urban containment policies and the protection of natural areas: The case of Seoul's greenbelt. *Ecology and Society*, 11(1).

Boyce, D. & Williams, H., 2015. *Forecasting Urban Travel*, Edward Elgar Publishing Lmited.

Brown, D. et al., 2004. Agent-based and analytical modeling to evaluate the effectiveness of greenbelts. *Environmental Modelling & Software*, 19(12), pp.1097–1109.

Brueckner, J.K., 2007. Urban growth boundaries: An effective second-best remedy for unpriced traffic congestion? *Journal of Housing Economics*, 16(3–4), pp.263–273.

Brueckner, J.K., 2001. Urban Sprawl: Lessons from Urban Economics. *Brookings-Wharton Papers on Urban Affairs*, 2001(1), pp.65–97.

Buxton, M. & Goodman, R., 2003. Protecting Melbourne's Green Belt. *Urban Policy and Research*, 21(2), pp.205–209.

Cambridge Futures, 2000. Cambridge Futures 1. Available at: http://www.cambridgefutures.org/futures1/intro.htm [Accessed July 12, 2016].

Cambridge Futures, 2004. Cambridge Futures 2 Executive Summary. Available at: http://www.cambridgefutures.org.

Campaign to Protect Rural England, 2010. *Green Belts: a greener future part 2 green belts in England*,

Campaign to Protect Rural England, 2016. *More than a quarter of a million houses now planned for green belt*,

Carter-whitney, M. & Esakin, T.C., 2010. *Ontario ' s Greenbelt in an International Context*,

Caruso, G. et al., 2009. Space - time patterns of urban sprawl, a 1D cellular automata and microeconomic approach. *Environment and Planning B: Planning and Design*, 36(6), pp.968–988.

Caruso, G. et al., 2007. Spatial configurations in a periurban city. A cellular automata-based microeconomic model. *Regional Science and Urban Economics*, 37(5), pp.542–567.

Central Political Bureau of China, 2015. *Master Plan of Jing-Jin-Ji Integrated Development*,

Chen, G., 2010. 用公租房解决北漂族住房. *xinhua.net*.

Chen, Y. & Chen, X., 2013. The Influence of Population Aging on China's Urban Housing Demand. *Economic Theory and Business Management*, 5, p.6.

Cheshire, P., 2013. Greenbelt myth is the driving force behind housing crisis. *The Conversation*.

Cheshire, P., 2014. Turning houses into gold : the failure of British planning. *The guardian*, pp.14–18.

Correll, M.R., Lillydahl, J.H. & Singell, L.D., 1978. The effects of greenbelts on residential property values: some findings on the political economy of open space. *Land economics*, 54(2), pp.207–217.

Davies, L. et al., 2011. *UK National Ecosystem Assessment: Technical Report*,

Deng, B. et al., 2015. Estimating traffic delays and network speeds from low-frequency GPS taxis traces for urban transport modelling. *European Journal of Transport and Infrastructure Research*, 15(4), pp.639–661.

Deng, B., 2015. *Incorporation of micro-level analysis in strategic urban transport modelling: with a case study of the Greater Beijing*. Doctorate degree thesis, University of Cambridge.

Department for Communities and Local Government, 2016. *Local Planning Authority Green Belt: 2015/16*, Department for Communities and Local Government, 2010. *Local Planning Authority Green Belt Statistics: England 2009/10*,

Department for Communities and Local Government, 1995. *Planning Policy Guidance 2 : Green belts*,

Department for Transport, 2015. *National Travel Survey: England 2014*,

Department of Transport & ME&P, 2002. *LASERLASER Enhancement Project:Final Report*,

Dobson, A. & Simmonds, D., 2009. *Representing Planning Policy in Land-Use and Land-Use/Transport Modelling*,

Echenique, M., 2004. Econometric models of land use and transportation. In *Handbook of Transport Geography and Spatial Systems*. pp. 185–202.

Echenique, M. et al., 2012. Growing Cities Sustainably. *Journal of the American Planning Association*, 78(2), pp.121–137.

Echenique, M., 2011. Land use/transport models and economic assessment. *Research in Transportation Economics*, 31(1), pp.45–54.

Echenique, M. et al., 2010. *SOLUTIONS final report: sustainability of land use and transport in outer neighbourhoods*,

Echenique, M.H. et al., 2013. LUISA: A land-use interaction with social accounting model; presentation and enhanced calibration method. *Environment and Planning B: Planning and Design*, 40(6), pp.1003–1026.

Edgar, L., 2016. RTPI: Greenfield and green belts can help provide homes. *The Planner*.

Van Eeten, M. & Roe, E., 2000. When Fiction Conveys Truth and Authority-the Netherlands Green Heart Planning Controversy. *Journal of the American Planning Association*, 66(1), pp.58–67.

Elson, M., 1986. *Green Belts-Conflict mediation in the urban fringe*, Heinemann London.

Fox, J., Daly, A. & Patruni, B., 2009. Improving the treatment of cost in large scale models. *European Transport Conference, 2009*, pp.1–16.

Freestone, R., 2002. Greenbelts in city and regional planning. In K. c. Parsons & D. Schuyler, eds. *From garden city to green city: the legacy of Ebenezer Howard*. pp. 67–98.

Fujita, M., 1989. *Urban economic theory: land use and city size*, Cambridge university press.

Gan, L., 2012. 基于遥感影像的北京绿隔规划控制成效分析. *Beijing Planning Review*, (5), pp.37–40.

Garside, P., 1984. West end, east end:London 1890-1940. In A. Sutcliffe, ed. *Metropolis 1890-1940*. Alexandrine Press, Oxford, pp. 221–258.

Geoghegan, J., 2014. Green belt polices are "discriminatory" and aim to keep "the urban unwashed out of the Home Counties" as well as causing spiralling house prices, according to new research by the London School of Economics. , (April 2014), pp.1–6.

Greater London Authority, 2008. *The London Plan Spatial Development Strategy for Greater London-Consolidated with Alterations since 2004*,

Greater London Regional Planning Committee, 1933. *Second Report*, London.

Hagen-Zanker, A. & Jin, Y., 2012. A New Method of Adaptive Zoning for Spatial Interaction Models. *Geographical Analysis*, 44(4), pp.281–301.

Hall, P., 2002. *Cities of Tomorrow* 3rd ed., Blackwell.

Hall, P., 1973. England circa 1900. In H. C. Darby, ed. *A New Historical Geography of England*. Cambridge University Press.

Hall, P., 1963. *London 2000*, Faber and Faber Limited.

Hall, P., 1984. Postscript: Metropolis 1890-1940. In A. Sutcliffe, ed. *Metropolis 1890-1940*. Alexandrine Press, Oxford, pp. 431–446.

Hall, P., 1964. The development of communications. In J. . Coppock & H. Prince, eds. *Greater London*. Faber and Faber Limited, pp. 52–79.

Hall, P., 1974. the green belt: its past and future justification. In *Occasional papers in estate management No.5:The future of the green belt*. Reading: College of Estate Management, pp. 1–8.

Han, H. & Long, Y., 2010. 绿色还是绿地——北京市第一道绿化隔离带实施成效研究. *Beijing Planning Review*, 3, pp.59–63.

Hilber, C.A.L. & Vermeulen, W., 2012. *The Impact of Supply Constraints on House Prices in England*,

Hill, D., 2014. London housing crisis : who dares campaign for building on the greenbelt ? *The guardian*.

Holroyd, E.M., 1966. *Theoretical Average Journey Lengths in Circular Towns with Various*

Routeing Systems,

Horowitz, A., 2004. Lowry-type land use models. In *Handbook of transport geography and spatial ….* pp. 167–183.

Howard, E., 1902. *Garden Cities of To-Morrow*, SWAN SONNENSCHEIN & CO., Ltd.

Iacono, M., Levinson, D. & El-Geneidy, A., 2008. Models of Transportation and Land Use Change: A Guide to the Territory. *Journal of Planning Literature*, 22(4), pp.323–340.

Irwin, E.G., Bell, K.P. & Geoghegan, J., 2003. Modeling and Managing Urban Growth at the Rural-Urban Fringe : A Parcel-Level Model of Residential Land Use Change. *Agricultural and Resource Economics Review*, 32(April), pp.83–102.

Jackson, A., 1973. *Semi-Detached London: Suburban Development, Life and Transport, 1900–39*, Didcot: Wild Swan.

Jin, Y. & Echenique, M., 2012. Employment location modelling within an integrated land use and transport framework: taking cue from policy perspectives. In *Advances in Spatial Science*. Springer, Heidelberg, pp. 133–158.

Jin, Y., Echenique, M. & Hargreaves, A.J., 2013. A recursive spatial equilibrium model for planning large-scale urban change. *Environment and Planning B: Planning and Design*, 40(6), pp.1027–1050.

Jin, Y., Williams, I. & Shahkarami, M., 2002. A new land use and transport interaction model for London and its surrounding regions. In *European Transport Conferece 2002*.

Jun, M.-J., 2004. The effects of Portland's urban growth boundary on urban development patterns and commuting. *Urban Studies*, 41(7), pp.1333–1348.

Jun, M.-J., 2011. The effects of Seoul's greenbelt on the spatial distribution of population and employment, and on the real estate market. *The Annals of Regional Science*, 49(3), pp.619–642.

Jun, M.-J., 2012. The effects of Seoul's new-town development on suburbanization and mobility: A counterfactual approach. *Environment and Planning A*, 44(9), pp.2171–2190.

Jun, M.-J. & Bae, C., 2000. Estimating the commuting costs of seoul's greenbelt. *international regional science review*, 23(3), pp.300–315.

Jun, M.-J. & Hur, J.W., 2001. Commuting costs of "leap-frog" new town development in Seoul. *Cities*, 18(3), pp.151–158.

Kim, J. & Kim, T., 2008. Issues with Green Belt Reform in the Seoul Metropolitan Area. In M. Amati, ed. *Urban green belts in the twenty-first century*. Ashgate Publishing Limited, pp.

37–57.

Knaap, J., 1985. The Price Effects of Urban Growth in Metropolitan Portland , Oregon Gerrit. *Land economics*, 61(1), pp.26–35.

Knowles, R.D., 2012. Transit Oriented Development in Copenhagen, Denmark: From the Finger Plan to Orestad. *Journal of Transport Geography*, 22, pp.251–261.

Kühn, M., 2003. Greenbelt and Green Heart: Separating and integrating landscapes in European city regions. *Landscape and Urban Planning*, 64(1–2), pp.19–27.

Lee, C.-M., 1999. An Intertemporal Efficiency Test of a Greenbelt: Assessing the Economic Impacts of Seoul's Greenbelt. *Journal of Planning Education and Research*, 19(1), pp.41–52.

Lee, C.-M. & Fujita, M., 1997. Efficient configuration of a greenbelt. *Environment and Planning A*, 29(7), pp.1999–2017.

Lee, C.-M. & Linneman, P., 1998. Dynamics of the greenbelt amenity effect on the land market. *real estate economics*, 26(1), pp.107–129.

Long, Y. et al., 2010. Form Scenario Analysis Using Constrained Cellular Automata. *Acta Geographica Sinica*, 65(6).

Long, Y., Han, H. & Mao, Q., 2009. Establishing Urban Growth Boundaries Using Constrained CA. *Acta Geographica Sinica*, 64(8), pp.999–1008.

Long, Y. & Shen, Z., 2015. *Geospatial analysis to support urban planning in Beijing*, Springer, Heidelberg.

Long, Y., Shen, Z. & Mao, Q., 2011. An urban containment planning support system for Beijing. *Computers, Environment and Urban Systems*, 35(4), pp.297–307.

Lowry, I., 1964. *A model of metropolis*, Rand Corporation.

Lynch, R., 2015. Lets build on green belt to ease squeeze on commuters. *Evening Standard*, p.61.

Ma, M. & Jin, Y., 2015. Alternative Configurations of Beijing ' s Greenbelt : New Insights from a Recursive Spatial Equilibrium Model. *14th International Conference on Computers in Urban Planning and Urban Management*, pp.1–22.

McFadden, D., 1974. Conditional logit analysis of qualitative choice behavior. In *Frontiers in Econometrics*. Academic Press: New York, pp. 105–142.

Mieszkowski, P. & Mills, E., 1993. The Causes of Metropolitan Suburbanization. *Journal of*

Economic Perspectives, 7(3), pp.135–147.

Miller, E.J., Kriger, D.S. & Hunt, J.D., 1999. *Integrated Urban Models for Simulation of Transit and Land Use Policies Guidelines for Implementation and Use*,

Miller, H.J. & Shaw, S.-L., 2001. *Geographic Information Systems for Transportation*,

Miner, P. & Sinden, N., 2010. Green Belts : a greener future. *Town and country planning*, 79, pp.292–298.

Ministry of Housing and Local Government, 1955. *Green belts. Circular 42/55*,

Ministry of Housing and Urban-Rural Development, 2001. *China Urban Construction Statistical Yearbook 2000*,

Ministry of Housing and Urban-Rural Development, 2005. *China Urban Construction Statistical Yearbook 2005*,

Ministry of Housing and Urban-Rural Development, 2011a. *China Urban Construction Statistical Yearbook 2011*,

Ministry of Housing and Urban-Rural Development, 2011b. 城市用地分类与规划建设用地标准,

Moore, R., 2014. Is it Time to Rethink the Green Belt? *The guardian*.

Munton, R., 1983. *London's green belt: containment in practice*, George Allen & Unwin Ltd.

National Bureau of Statistics of China, 2016. National Data Webpage. Available at: http://data.stats.gov.cn/english/easyquery.htm?cn=E0103 [Accessed November 4, 2016].

Natural England & Campaign to Protect Rural England, 2010. *Green Belts : a greener future*,

Nelson, A.C., 1988. An empirical note on how regional urban containment policy influences an interaction between greenbelt and exurban land markets. *Journal of the American Planning Association*, (December 2012), pp.37–41.

Nelson, A.C., 1986. Using Land Markets to Evaluate Urban Containment Programs. *Journal of the American Planning Association*, 52(2), pp.156–171.

Okata, J. & Murayama, A., 2011. Tokyo ' s Urban Growth , Urban Form and Sustainability. In A. Sorensen & J. Okata, eds. *Megacities: Urban Form, Governance, and Sustainability*. Springer, Heidelberg, pp. 15–41.

Ortuzar, J. de D. & Willumsen, L., 2011. *Modelling transport* 4th ed., John Wiley & Sons, Ltd.

Perino, G. et al., 2014. The Value of Urban Green Space in Britain: A Methodological Framework for Spatially Referenced Benefit Transfer. *Environmental and Resource Economics*, 57(2), pp.251–272.

Porter, R., 1998. *London: A Social History*, Harvard University Press.

Priced Out, 2014. Breaking the Green Belt Taboo. Available at: http://www.pricedout.org.uk/breaking_the_green_belt_taboo [Accessed September 15, 2015].

Qi, M., 2010. Labour Supply and Labour Demand Forecasting in China 2010-2050. *Population Research*, 34(5), pp.76–87.

Rong, X., 2016. *Housing the Poor in the Outskirts of a City - The Case of Beijing*. University of Cambridge.

Rudlin, D. & Falk, N., 2014. *Uxcester Garden City: Second Stage Submission for the 2014 Wolfson Economics Prize*,

Rydin, Y. & Myerson, G., 1989. Explaining and interpreting ideological effects: a rhetorical approach to green belts. *Environment and Planning D: Society and Space*, 7(4), pp.463–479.

Shi, Y. et al., 2012. Characterizing growth types and analyzing growth density distribution in response to urban growth patterns in peri-urban areas of Lianyungang City. *Landscape and Urban Planning*, 105(4), pp.425–433.

Simmonds, D., 1999. The design of the DELTA land-use modelling package. *Environment and Planning B: Planning and Design*, 26, pp.665–684.

Simmonds, D., Waddell, P. & Wegener, M., 2013. Equilibrium versus dynamics in urban modelling. *Environment and Planning B: Planning and Design*, 40(6), pp.1051–1070.

Staley, S., Edgens, J. & Mildner, G., 1999. *A line in the land: Urban-growth boundaries, smart growth, and housing affordability*,

Stanilov, K. & Jin, Y., 2013. The co-evolution of adaptive transport infrastructure: Modelling rail and road network growth in Greater London. In Applied Urban Models conference, University of Cambridge.

Sun, W., 2011. Number of Households, Structural Changes and Real Estate Demand. *Mid-term Report of China's Macroeconomic Forum, Renmin University of China*.

Tanabe, H., 1978. Problems of the New Towns in Japan. *GeoJournal*, 2(1), pp.39–46.

Tang, B.S., Wong, S.W. & Lee, A.K.W., 2007. Green belt in a compact city: A zone for conservation or transition? *Landscape and Urban Planning*, 79(3–4), pp.358–373.

Tayyebi, A., Pijanowski, B.C. & Tayyebi, A.H., 2011. An urban growth boundary model using neural networks, GIS and radial parameterization: An application to Tehran, Iran. *Landscape and Urban Planning*, 100(1–2), pp.35–44.

The Economist, 2012. Belt too tight. *the Economist*, pp.1–2.

The State Council, 1994. 汽车工业产业政策,

Thomas, D., 1970. *London's Greenbelt*, Faber and Faber Limited.

Transport for London, 2016. London Travel Demand Survey.

U.S. Department of Transport, 2015. *Passenger Travel Facts and Figures 2015*,

Waddell, P., 2013. *Draft Technical Documentation : San Francisco Bay Area UrbanSim Application*,

Waddell, P., 1998. Simulating the Effects of Metropolitan Growth Management Strategies. In *Conference of the Association of Collegiate Schools of Planning*.

Waddell, P., 2002. UrbanSim: Modeling urban development for land use, transportation, and environmental planning. *Journal of the American Planning Association*, 3(March 2015), pp.297–314.

Wan, L., 2016. *A Recursive Spatial Equilibrium Model for the Beijing-Tianjin-Hebei City Region*. University of Cambridge.

Wang, K., 2015. 新常态下的京津冀协同发展. In *Conference proceedings of China Annual National Planning Conference 2015*.

Warren-Evans, J.R., 1974. The Growth of Urban areas. In *Occasional papers in estate management No.5:The future of the green belt*. Reading: College of Estate Management, pp. 19–24.

Watanabe, T., Amati, M. & Yokohari, M., 2008. The Abandonement of Tokyo ' s Green Belt and the Search for a New Discourse of Preservation in Tokyo ' s Suburbs. In M. Amati, ed. *Urban green belts in the twenty-first century*. Ashgate Publishing Limited, pp. 21–36.

Wegener, M., 2014. Land-Use Transport Interaction Models. In M. Fischer & P. Nijkamp, eds. *Handbook of Regional Science*. Springer, Heidelberg, pp. 741–758.

Wegener, M., 2004. Overview of land-use transport models. In D. A. Hensher & K. Button, eds. *Transport geography and spatial systems*. Kidlington: Pergamon/Elsevier Science, pp.

127–146.

Wegener, M., 2011. *The IRPUD Model*,

Wegener, M., Gnad, F. & Vannahme, M., 1986. The time scale of urban change. In B. Hutchinson & M. Batty, eds. *Advances in Urban Systems Modelling*. Northholland. Amsterdam, pp. 175–197.

Wheaton, W.C., 1974. A comparative static analysis of urban spatial structure. *Journal of Economic Theory*, 9, pp.223–237.

Wheaton, W.C., 1982. Urban residential growth under perfect foresight. *Journal of Urban Economics*, 12(1), pp.1–21.

Williams, I., 1994. A model of London and the South East. *Environment and Planning B: Planning and Design*, 21(5), pp.535–553.

Wilson, A., 1998. Land-use/transport interaction models: Past and future. *Journal of Transport Economics and Policy*, 32(1), pp.3–26.

Wu, L. & Wu, W., 2012. *Beijing 2049: study on spatial development strategies*, Beijing, China: Tsinghua University Press.

Wu, W., 2010. The progress of Beijing region study 2009-2010.

Yang, J. et al., 2011. Transport Impacts of Clustered Development in Beijing: Compact Development versus Overconcentration. *Urban Studies*, 49(6), pp.1315–1331.

Yokohari, M. et al., 2000. Beyond greenbelts and zoning: A new planning concept for the environment of asian mega-cities. *Landscape and Urban Planning*, 47, pp.159–171.

Zhang, L., 2014. 375家污染企业关停退出. *Morning Post*, p.A09.

Zhang, Y., Zheng, S. & Sun, C., 2014. What's the effect of urban villages on commercial housing price？An Analysis Based on Second-Hand Housing Transactions in Beijing. In *proceedings of the 17th international symposium on advancement of construction management and real estate*.

Zhou, X. & Wang, Y.C., 2011. Spatial-temporal dynamics of urban green space in response to rapid urbanization and greening policies. *Landscape and Urban Planning*, 100(3), pp.268–277.

NOMENCLATURES

Superscripts and subscripts

i	Residential zone i or trip origin zone i
j	Production zone j or trip destination zone j
f	Labour type f
r	Industrial type r
k	Floorspace type k
s	Goods and service type s
z	Production zone z for retail goods
h	Household type h
c	Individual category c in a household
t	Trade type t
m	Travel mode m
B	Intra-zonal travel band B
l	Built-form type l
T	Modelling time section T

The Spatial Equilibrium Model

Variables (producer)

X_{rj}	output X of a certain industrial type r in zone j
K_r	The capital input variable for industrial type r
L_{rfj}	The labour force input for labour type f in zone j
B_{rkj}	The business floorspace input for floorspace type k in zone j
Y_{rsj}	The intermediate goods input for goods type s used in industrial type r in zone j

p_{rj}	Product price for industrial type *r* in zone *j*
w_{fj}	Hourly wage for labour type *f* in zone *j*
R_{kj}	Average rent for business floorspace type *k* in zone *j*
r_{ki}	Average rent for housing floorspace type *k* in zone *i*

Variables (consumer)

U_{fij}	An individual's consumption utility for labour type *f* living in zone *i* working in zone *j*
V_{fij}	The non-stochastic consumption utility for labour type *f* living in zone *i* working in zone *j*
$Z_{rz\|fij}$	The quantity of retail goods and service *r* bought in zone *z*, given an individual in labour type *f* living in zone *i* working in zone *j*
b_{kfi}	The quantity of housing floorspace variable rent by an individual in labour type *f* living in zone *i* working in zone *j*
l_{fij}	Leisure time variable for an individual in labour type *f* living in zone *i* working in zone *j*

Variables (commuting disutility)

d_{fij}	Commuting travel disutility for an individual in labour type *f* living in zone *i* working in zone *j*
χ_{fij}	Generalised travel cost for an individual in labour type *f* living in zone *i* working in zone *j*
g_{fij}	Weighted average one way commuting cost over all travel modes
G_{fij}	Weighted average one way commuting time over all travel modes

Variables (locational choice)

$v_{fi\|j}$	Non-stochastic residential utility variable, given a fixed working zone *j*
$P_{fi\|j}$	Probability of choosing residential location given a fixed job location zone *j*
v_{fj}	Non-stochastic employment utility given a fixed working zone *j*
M_{fj}	Non-wage income, given a fixed working zone *j*
P_{fj}	Probability for an individual of choosing to work in zone j, regardless the residential location
$V_{f\|j}$	Log-sum utility for an individual given working in zone j while living in any zone i
P_{fij}	Probability of choosing a combined employment-residence location

Parameters (producer)

E_{rj}	The scale parameter
A_{rj}	The economic mass parameter

ν_r	The share of capital input for industrial type *r*
δ_r	The share of labour force input for industrial type *r*
μ_r	The share of business floorspace input for industrial type *r*
γ_{rs}	The share of intermediate goods type *s* input for industrial type *r*
θ_r	$\frac{1}{1-\theta_r}$ is the elasticity of substitution between any two types of labour forces
ζ_r	$\frac{1}{1-\zeta_r}$ is the elasticity of substitution between any two types of business floorspace
κ	Input-specific constant for choosing between types of labour forces
$\mathcal{H}$	Input-specific constant for choosing between types of business floorspace

Parameters (consumer)

α_f	The share of disposable income spent on retail goods and service for labour type *f*
β_f	The share of disposable income spent on housing for labour type *f*
γ_f	The share of disposable income spent on leisure time for labour type *f*
η_f	$\frac{1}{1-\eta_f}$ is the elasticity of substitution between any two types of goods and services
σ_f	$\frac{1}{1-\sigma_f}$ is the elasticity of substitution between any two types of housing
ι	Input-specific constant for choosing between types of housing

Parameters (commuting disutility)

a_f	Log-linear parameter for labour type *f*
D	Total working days per annum

Parameters (locational choice)

S_i	Size parameter for residential location *i*
S_j	Size parameter for employment location *j*
$\lambda_{f\|I}$	Concentration parameter for residential location choice
$\lambda_{f\|J}$	Concentration parameter for employment location choice
λ_F	Concentration parameter for non-employed household residential location choice
$E_{fi\|j}$	Residential location residual attractiveness for labour type *f* living in zone *i*
E_{fj}	Employment residual attractiveness for labour type *f* working in zone *j*

The Non-Commuting Travel Demand Model

Variables

N_i^f	Number of resident
H_i^h	Number of household
Y_i^c	Number of individual of *c* socio-economic category
T_i^t	Number of non-commuting trade type *t* generated at the origin zone *i*
T_{ij}^t	Number of non-commuting trade type *t* from zone *i* to zone *j*
d_{ij}^t	Travel disutility of type *t* activities from zone *i* to zone *j* for non-commuting trips
D_{ijm}^t	Travel disutility on a certain mode

Parameters

a^{hf}	Household composition matrix
a^{ch}	A matrix defining how many individuals in each category *c* in a certain household type *h*
a^{tc}	Trade generation matrix
λ^t	Non-commuting trip distribution concentration parameter
λ_m^t	Concentration parameter for the log-sum of different modes
S_j^t	Size parameter of type *t* activities ended in zone *j*

The Strategic Transport Model

Variables

F_{ij}	Commuting trips for a typical week day morning peak from zone *i* to zone *j*
F_{ijf}^{t}	Non-commuting trips type *t* for a typical week day morning peak from zone *i* to zone *j*
c_{ijm}^{t}	Out-of-pocket travel cost
t_{ijm}^{t}	Travel time on mode *m*
t_0	Free-flow travel time
t	Congested travel time
A_l	Access link length for built-form *l*
r	Radius of the zone

Parameters

α_{ijf}	Proportion of outwards trips
ω_{jif}	Proportion of return trips
Φ_f	Convert monthly commuting trips into an average number of trips for a typical week day for a employed resident in socio-economic group *f*.
δ_f^t	Converts monthly non-commuting trips into an average number of trips for a typical week day
ϕ^t	Marginal utility of money
p_{jm}^{t}	Destination disutility for mode *m* in destination zone *j*
Ω^{Bt}	Band constant
Ω_m^t	Modal specific constant
λ_m^t	Concentration parameter for inter-zonal mode choice
$\lambda_{m\|B}^t$	Concentration parameter for intra-mode choice within each band
λ^{Bt}	Concentration parameter for band choice
C	Link capacity
a_l	The ratio of access link length to radius for built-form *l*

The Recursive Dynamic Model

Variables

V_{ki}	Non-stochastic location-based utility for floorspace growth
$\mathcal{D}_{ki}^{T}$	Zonal floorspace density
M_{ki}^{T}	Zonal economic mass
$\beth_{\mathrm{ki}}$	Policy dummy variable
E_D	Provincial residual attractiveness
υ_{Fi}	Non-stochastic location utility for non-employed households

Parameters

n	Proportion of natural growth
λ_b	Concentration parameter for floorspace growth allocation
ρ	Proportion of non-employed households who choose to relocate
λ_H	Concentration parameter for non-employed household allocation

APPENDICES

A. Summary of parameters for the land use sub-model

Key parameters for the Spatial Equilibrium Model

Parameters	1990 value	2010 value	Sources
δ_r labour cost share	0.76	0.88	Beijing IO table (1990 & 2010)
μ_r business floorspace cost share	0.24	0.12	Beijing IO table (1990 & 2010)
ζ_r elasticity of substitution for business floorspace varieties	0.90	0.90*	Anas and Rhee (2006)
θ_r elasticity of substitution for labour varieties	0.75	0.75	Beijing-Tianjin-Hebei Model, Wan (2016)
σ_f elasticity of substitution for housing varieties	0.9	high: 0.90 mid: 0.90 low: 0.90	Anas and Rhee (2006)
κ_{fj} input-specific parameters for labour varieties	/	varies among labour types & across zones	Beijing-Tianjin-Hebei Model, Wan (2016)
ι_{kfi} input-specific parameters for housing varieties	/	varies among consumer types & across zones	Beijing-Tianjin-Hebei Model, Wan (2016)
E_j productivity multiplier	1.00	1.00	Anas and Rhee (2006)
c_f Cost for delivering a unit of local services as percentage of commuting trip cost	0.10	0.10	Anas and Rhee (2006)
α_f utility coefficient for goods & services	0.36	high: 0.23 mid: 0.27 low: 0.30 non-emp.: 0.50	Beijing statistical year book 1991, 2011
β_f utility coefficient for housing	0.14	high: 0.17 mid: 0.26 low: 0.35 non-emp.: 0.50	Beijing statistical year book 1991, 2011
γ_f utility coefficient for leisure time	0.50	high: 0.60 mid: 0.47 low: 0.35 non-emp.: 0.00	Beijing statistical year book 1991, 2011
a_f log-linear travel cost function parameter	0.003	high: 0.003 mid: 0.003 low: 0.003	Beijing-Tianjin-Hebei Model, Wan (2016)

Parameters	1990 value	2010 value	Sources
$\lambda_{f\|J}$ concentration parameter for employment location choices	1.00	high: 1.00 mid: 1.00 low: 1.00	Model specification
$\lambda_{f\|I}$ concentration parameter for residence location choices	2.00	high: 3.25 mid: 4.40 low: 4.40 non-emp.: 1.00	Own calibration using observed commuting statistics
E_{fj}, $E_{fi\|j}$ residual attractiveness for residence-employment location choices	varies across zones	varies among commuter types & across zones	Own calibration using observed zonal number of employed residents and workers
D total number of working days	250	250	Model specification

*There are a few parameters that we do not currently have data to calibrate. In such cases, we have taken values that prove to be fairly stable in the existing literature on models of this type. Such parameters are mainly concerning the elasticities of substitution among floorspace varieties and labour varieties. These parameters are selected through elasticity tests (Wan 2016) and based on previous studies (Anas and Rhee, 2006). With more data published in the future, the parameters can be estimated for any given area.

Key parameters for the Recursive Dynamic Model

Parameters	Values	Sources
Business floorspace update		
n portion of natural growth net from the aggregate growth	0.5	Model specification
λ_b concentration parameter	1.0	Model specification
β_1 coefficient for $\ln \sum_k B_{ki}^T$	0.513	Beijing-Tianjin-Hebei Model, Wan (2016)
β_2 coefficient for $\frac{\overline{\bar{R}_{ki}^T}}{\bar{R}_{D_I}^T}$	0.005	
β_3 coefficient for $\mathcal{D}_{ki}^T$	-0.014	
β_4 coefficient for M_{ki}^T	0.124	

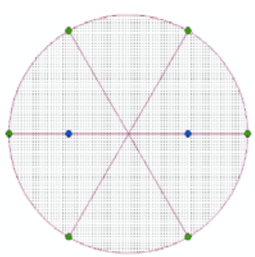
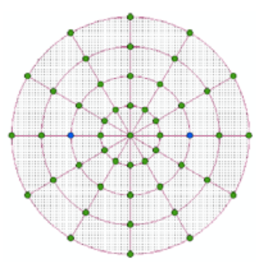
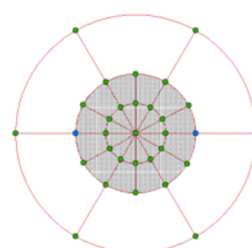
Parameters	Values	Sources
β_5 Coefficient for $ב_{ki}$	0.965	
E_D residual attractiveness term for BFS growth	Beijing: -0.613 Tianjin: 0.564 Hebei: 0.050	
Business floorspace update		
n portion of natural growth net from the aggregate growth	0.5	Model specification
λ_b concentration parameter	1.0	Model specification
β_1 coefficient for $\ln \sum_k B_{ki}^T$	0.872	Beijing-Tianjin-Hebei Model, Wan (2016)
β_2 coefficient for $\overline{\frac{\bar{R}_{ki}^T}{\bar{R}_{D_\iota}^T}}$	0.009	
β_3 coefficient for $\mathcal{D}_{ki}^T$	-0.015	
n portion of natural growth net from the aggregate growth	0.875	
λ_b concentration parameter	-1.230	
E_D residual attractiveness term for HS growth	Beijing: 0.296 Tianjin: 0.089 Hebei: -0.385	
Non-employed household location update		
ρ lag coefficient	0.5	Model specification
λ_H concentration parameter	1.0	Model specification

B. The access link length calculation and verification

This section first reports the method we used to calculate the theoretical average length from any built-up patch to a road access node or to a station in a circular city. Then we present the method for validating the theoretical average length, based on the data collected in Beijing.

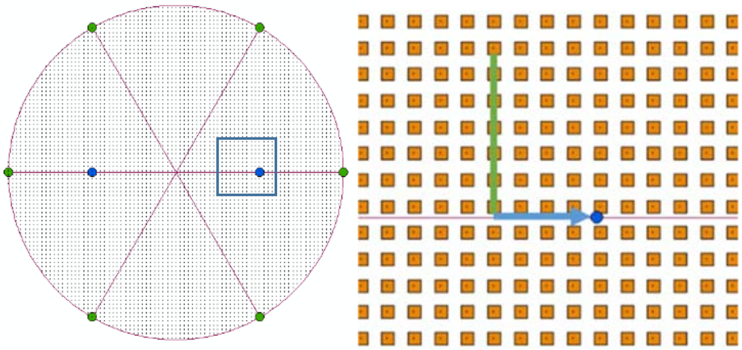
1. Theoretical length calculation

In order to find the distance from where urban activities generate to the road access nodes or stations, a circular city zone with a radius of 4 km is built. The size of the zone is determined based on the approximate average size of the greenbelt zones in Beijing. There are 5088 dots (on a 100m*100m grid) distributing homogenously in the circle, each of which represents an urban activity, namely the origin of a trip. Green dots are the road access nodes while the blue dots are the stations. There are 3 zone types according to the built-form: 1) greenfield, 2) built-up towns, 3) TOD nodes.

Type 1 greenfield	**Type 2 built-up towns**	**Type 3 TOD nodes**
		

Appendix Table 1 Circular cities by built-form

The length from built-up patches to the nearest node consists of two parts. The first part is the average distance from any built-up patch onto the nearest link, namely the green line. The second part is the distance on the link to the nearest node, either road access node or station, namely the blue line.



Appendix Figure 1 Diagram of length composition

We use a Monte Carlo method to simulate Part 1 and Dijkstra's algorithm to simulate Part 2. Then the two parts are added to find the total average distance from urban activities to access node.

Urban activities will be either sorted or unsorted according to their trip destinations. “Sorted urban activities” means that activities choose to locate around the node which is near the destination zone for inter-zonal travel. For example, if a man lives in a zone and works in another zone to the west of this zone, he will choose the western part of the residential zone to reside, because the very west node is the one he uses to travel to the job zone. “Unsorted urban activities” is the opposite. Even if someone commutes to the west to work, he might live in the east of his residential zone and still choose the access node in the west. When calculating the distance, we use the average of sorted and unsorted length.

	Part 1 door to road			**Part 2 on road to road access node**						**Total**		
Built-form type	1	2	3	1		2		3		1	2	3
Distance to road access nodes as a percentage of radius	11.3%	4.5%	3.1%	88.8%		88.3%		93.1%		100.1%	92.8%	96.2%
				sorted	unsorted	sorted	unsorted	sorted	unsorted			
				41.9%	135.7%	54.8%	121.8%	73.4%	112.8%			

Appendix Table 2 Theoretical average distance from any built-up patch to road access node in a circular city

As Appendix Table 2 shows, the average distance that people travel to their nearest road access nodes (at the border) to another zone is about the radius of the zone. If ubiquitous road system is built, the distance should be slightly shorter because there are more roads to choose and short cut may exist.

	Part 1 door to road			**Part 2 on road to station**						**total**		
Built-form type	1	2	3	1		2		3		1	2	3
Distance to stations as a percentage of radius	11.3%	4.5%	3.1%	102.7%		81.9%		55.2%		114.0%	86.4%	58.3%
				sorted	unsorted	sorted	unsorted	sorted	unsorted			
				93.4%	112.0%	65. 8%	98.0%	46.3%	64.0%			

Appendix Table 3 Theoretical average distance from any built-up patch to station in a circular city

The difference of distance change in Appendix Table 3 is caused by the provision of roads to the stations and also by the density of population around the stations. TOD is a type of built-form that high density urban activities concentrate around stations. As a result, travel distance to stations are shortened.

2. Validating the theoretical access link length

We measure several zonal access distances in the greenbelt area of Beijing and use the empirical data to validate the ratios we obtained in the theoretical circular model. Radius of greenbelt zones are defined as the arithmetic average distance from the centroid to all the perimeter vertices.

Land use data

We selected zone 23, 86, and 89 as our case study area. The case study area contains Yizhuang[17] town centre and its surrounding hinterland. The selected zones are between the 5th and 6th ring-road and in the greenbelt boundary. Zone 86 is a *built-form type 2* built-up town with ubiquitous roads. Zone 23 and 89 are *built-form type 1* greenfield with sparse roads. We map the land cover

[17] Yizhuang is a town in the southeast suburb of Beijing, between the 5th and the 6th ring-road. Most of the Yizhuang town is designated as the Beijing Economic and Technical Development Area. There are a lot of high-tech companies, factories and joint ventures.

data, based on Google Earth historic maps in 2005, 2010 and 2015. Land cover is classified into 7 types according to the planning code (Ministry of Housing and Urban-Rural Development 2011b).

Land use types	Land use code in planning regulation	Estimated FAR	FAR Source
Village	H12,H13,H14,	0.8	estimated from map
Low density housing	R1	1.5	
Medium-high density housing	R2	2.5	Estimated from
Industry+warehouse	M,W	1.5	Yizhuang
Commercial+service	A,B,U	3.5	regulatory plan
Road	S1,S2	\	\
Open space	The rest land use types	\	\

Appendix Table 4 Land use type classification in case study zones

Appendix Figure 2 Land overage, 2005 (top left) 2010 (top right) 2015 (bottom)

Based on the census and mini census, the zonal employed residents and employed workers are calculated as follows:

	Zone 86		Zone89		Zone23	
	Employed resident	Employed worker	Employed resident	Employed worker	Employed resident	Employed worker
2005	52,465	153,660	41,500	44,877	37,383	22,519
2010	84,074	221,250	60,526	57,139	57,282	29,657
2015	101,931	275,223	78,728	67,922	67,970	34,909

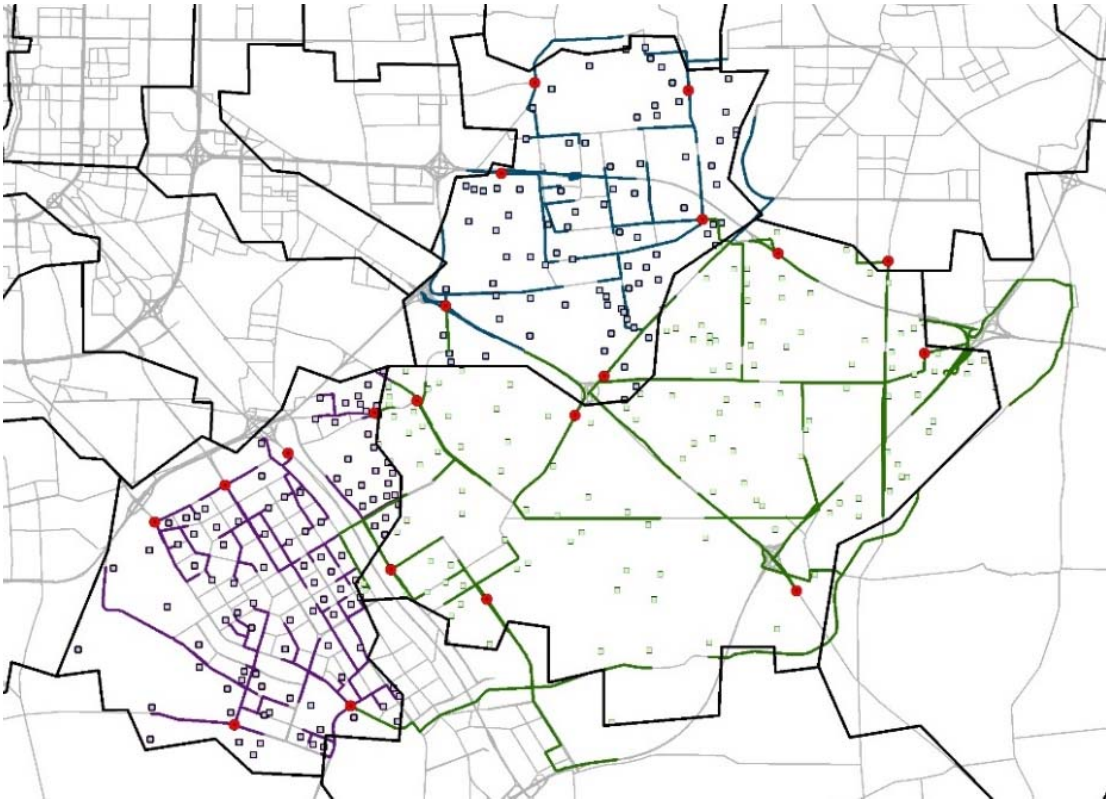
Appendix Table 5 Number of employed residents and workers

Population will be distributed according to the plot area, land use type and FAR of each patches. We use the FAR defined in Appendix Table 4 and then allocate employed residents to land use type H12,H13,H14, R1 and R2; allocate employed workers to land use type M,W,A,B and U. In that case, travel demands are generated from each patch.

The following steps are used in access link length calculation

1. Find patch centroids to represent patches in 2005, 2010, 2015, as origins of trips. Each origin has got an assigned number of road users from the allocation of employed workers and residents.
2. Select road access nodes at the border; normally one road access node leads to one zone. Select stations as access nodes; normally one station leads to one direction.
3. Generate the access link length from all patches to nearest road access node under perfect sorted assumption; from all patches to a certain road access node under unsorted assumption, using ArcGIS software.
4. Find the weighted average trip length from each patch.

$$L = \frac{\sum(access\ link\ length * number\ of\ road\ users)}{\sum number\ of\ road\ users}$$



Appendix Figure 3 Finding shortest path using ArcGIS

The tables below list the measured distance to road access nodes and stations for the zones in Yizhuang.

	Zone 23 type1 greenfield			Zone 86 type2 built-up towns			Zone 89 type1 greenfield		
Radius	3519			3724			5152		
	unsorted	sorted	ave	unsorted	sorted	ave	unsorted	sorted	ave
2005	6124	1784	3954	5337	2104	3720	7401	2474	6175
2010	5784	1829	3807	5676	1793	3734	7202	2935	6536
2015	5459	1918	3689	5875	1782	3828	7173	2726	6313
Distance to road access nodes as a percentage of radius	104% - 112%			99% - 102%			96% - 98%		
Ratio from theoretical model	100%			93%			100%		

Appendix Table 6 Comparison of empirical number against theoretical number for road access link length

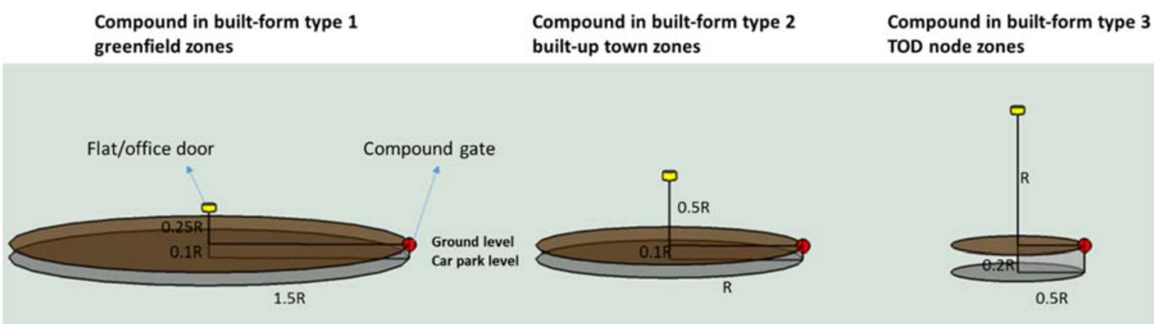
	Zone 86 type2 built-up towns			Zone 89 type1 greenfield		
Radius	3724			5152		
	unsorted	sorted	ave	unsorted	sorted	ave
2010	4326	2525	3426	7554	4279	5917
2015	4357	2515	3436	8165	3795	5980
Distance to stations as a percentage of radius	91%-92%			115%-116%		
Ratio from theoretical model	86%			114%		

Appendix Table 7 comparison of empirical number against theoretical number for station access link length

The empirical results suggest that the ratios from the theoretical model are close enough to reality. We did not measure and validate type 3 zone for its access link length. Type 3 TOD node is a future ideal built-form that promoted by the government, and there is no historic example for such a type. Therefore, we directly use the theoretical ratios for type 3 zones.

C. Off-network time calculation for the built-form variations

The off-network travel times are calculated based on the generic shapes that represent the geometries of gated compounds in Beijing's suburb. Firstly, we build 3 compounds in cylindrical shapes according to the built-form type. The largest one is to represent the sparse built-up compound in the greenfield. The medium one is to represent the most commonly seen gated compound in a ubiquitously built-up area in medium density. The small one is to represent the gated compound with tall buildings inside.



Appendix Figure 4 Cylinders to represent the geometries of compounds in different built-form zones

Secondly, we assign an average length for the radius of the compound and calculate the average distance from the flat door to the residential compound gate, or from the industrial compound gate to the office door.

	Average radius (measured from Beijing's satellite map)
Residential compound in greenbelt	250
Industrial compound in greenbelt	210

Appendix Table 8 Radius set for the generic compound

Thirdly, the average distance is converted into time. For metro travel, we also add the average waiting time on the platform and the boarding time into the total off-network travel time. Such times can be found in travel surveys. Appendix Table 9 - Appendix Table 12 list the off-network origin time by car, off-network origin time by metro, off-network destination time by car, off-network destination time by metro respectively.

Built-form	Distance (metre)		Time (min)		
	Walking from flat door to car park	Starting engine in car park- driving to compound gate	Walking from flat door to car park	Starting engine in car park- driving to compound gate	Total time
1	87.5	400	1.75	4.8	6.55
2	150	275	3	3.3	6.3
3	300	175	6	3.5	9.5

Appendix Table 9 Trip origin off-network time by built-form if travelling by car

Built-form	Distance (metre)	Time (min)				
	Walking from flat door to compound gate	Walking from flat door to compound gate	Security and queueing outside station	Waiting on the platform	Boarding	Total time
1	437.5	8.75	10	3	1	22.75
2	375	7.5	10	3	1	21.5
3	375	7.5	5	2	0.5	15

Appendix Table 10 Trip origin off-network time by built-form if travelling by metro

Built-form	Distance (metre)		Time (min)		
	Driving from compound gate to car park	Walking from car park to office door	Driving from compound gate to car park	Walking from car park to office door	Total time
1	336	73.5	4.032	1.47	5.502
2	231	126	2.772	2.52	5.292
3	147	252	2.94	5.04	7.98

Appendix Table 11 Trip destination off-network time by built-form if travelling by car

Built-form	Distance (metre)	Time (min)			
	Walking from compound gate to office door	Boarding	Walking from platform to station gate	Walking compound gate to office door	Total time
1	367.5	1	3	7.35	11.35
2	315	1	3	6.3	10.3
3	315	0.5	3	6.3	9.8

Appendix Table 12 Trip destination off-network time by built-form if travelling by metro

D. Off-network time for base year 2010

	Inter-zonal user mode							Intra-zonal user mode				
	car	bus	walk	cycle	rail	metro	HSR	car	bus	walk	cycle	metro
Beijing central 4 districts	10	15	0	5	10	10	30	8	8	0	3	8
Beijing suburban 4 districts	10	15	0	5	10	10	30	8	8	0	3	8
other Beijing zones within 6th	10	20	0	5	10	10	30	8	8	0	3	8
the rest of Beijing	10	20	0	5	10	10	30	8	8	0	3	8
Tianjin central	8	15	0	5	10	10	30	8	8	0	3	8
Tianjin suburban zones	5	20	0	5	10	10	30	5	8	0	2	8
the rest of Tianjin	5	15	0	5	10	10	30	5	8	0	2	8
Hebei zones nearby Beijing	5	15	0	5	10	10	30	5	5	0	2	5
Hebei zones around Beijing	5	15	0	5	10	10	30	5	5	0	2	5
the rest of Hebei	5	15	0	5	10	10	30	5	5	0	2	5
the rest of China	5	15	0	5	10	10	30	5	5	0	2	8

Appendix Table 13 Off-network time setting, origin time for base year 2010

	Inter-zonal user mode							Intra-zonal user mode				
	car	bus	walk	cycle	rail	metro	HSR	car	bus	walk	cycle	metro
Beijing central 4 districts	10	15	0	5	10	10	15	8	8	0	3	8
Beijing suburban 4 districts	10	15	0	5	10	10	15	8	8	0	3	8
other Beijing zones within 6th	10	20	0	5	10	10	15	8	8	0	3	8
the rest of Beijing	10	20	0	5	10	10	15	8	8	0	3	8
Tianjin central	8	15	0	5	10	10	15	8	8	0	3	8
Tianjin suburban zones	5	20	0	5	10	10	15	5	8	0	2	8
the rest of Tianjin	5	15	0	5	10	10	15	5	8	0	2	8
Hebei zones nearby Beijing	5	15	0	5	10	10	15	5	5	0	2	5
Hebei zones around Beijing	5	15	0	5	10	10	15	5	5	0	2	5
the rest of Hebei	5	15	0	5	10	10	15	5	5	0	2	5
the rest of China	5	15	0	5	10	10	15	5	5	0	2	8

Appendix Table 14 Off-network time setting, destination time for base year 2010

E. Distance band constants and modal specific constants

Flow1	**Inter-zonal modal specific constant**						
Commuting High Socio-economic Group	car	bus	walk	cycle	rail	metro	HSR
	-23	-18	-9	5	1	-9	1

Intra-zonal travel band	**Intra-zonal modal specific constant**					**Band constant**
	car	bus	walk	cycle	metro	
0-1km	1	2	3	16	0	-65
1-2km	3	-2	4	19	2	-75
2-5km	8	-8	3	29	-8	-105
5-10km	1	-2		34	-11	-110
10-15km	0	-4		38	-41	-120
15-20km	0	2			-45	-125
20-25km	0	10			-45	-145
25-50km	0	0			0	-155
>50km	0	0			0	-275

Flow2	**Inter-zonal modal specific constant**						
Commuting Middle Socio-economic Group	car	bus	walk	cycle	rail	metro	HSR
	-21	-18	-9	3	1	-9	1

Intra-zonal travel band	**Intra-zonal modal specific constant**					**Band constant**
	car	bus	walk	cycle	metro	
0-1km	1	2	3	14	0	-65
1-2km	3	-2	4	17	2	-75
2-5km	8	-8	3	27	-8	-105
5-10km	1	-2		32	-11	-110
10-15km	0	-4		36	-41	-120
15-20km	0	2			-45	-125
20-25km	0	10			-45	-145
25-50km	0	0			0	-155
>50km	0	0			0	-275

Flow3	**Inter-zonal modal specific constant**						
Commuting Low Socio-economic Group	car	bus	walk	cycle	rail	metro	HSR
	-19	-18	-9	3	1	-20	1

Intra-zonal travel band	**Intra-zonal modal specific constant**					**Band constant**
	car	bus	walk	cycle	metro	
0-1km	1	2	3	14	-3	-65
1-2km	3	-2	4	17	-1	-75
2-5km	8	-8	3	27	-11	-105
5-10km	1	-2		32	-11	-110
10-15km	0	-4		34	-41	-120
15-20km	0	2			-45	-125
20-25km	0	10			-45	-145
25-50km	0	0			0	-155
>50km	0	0			0	-275

Flow4	**Inter-zonal modal specific constant**						
Educational High Socio-economic Group	car	bus	walk	cycle	rail	metro	HSR
	-30	-29	-21	4	0	-8	1

Intra-zonal travel band	**Intra-zonal modal specific constant**					**Band constant**
	car	bus	walk	cycle	metro	
0-1km	-3	-1	5	10	-1	-60
1-2km	0	-3	6	12	1	-70
2-5km	3	-7	8	22	4	-100
5-10km	0	7		34	-19	-110
10-15km	0	-4		34	-36	-130
15-20km	0	0			0	-135
20-25km	0	0			0	-140
25-50km	0	0			0	-155
>50km	0	0			0	-275

Flow5	Inter-zonal modal specific constant						
Educational Middle Socio-economic Group	car	bus	walk	cycle	rail	metro	HSR
	-28	-29	-21	4	0	-8	1
Intra-zonal travel band	**Intra-zonal modal specific constant**						
	car	bus	walk	cycle	metro	**Band constant**	
0-1km	-3	-1	3	10	-1	-60	
1-2km	0	-3	4	12	1	-70	
2-5km	3	-7	6	22	4	-100	
5-10km	0	7		34	-19	-110	
10-15km	0	-4		34	-36	-130	
15-20km	0	0			0	-135	
20-25km	0	0			0	-140	
25-50km	0	0			0	-155	
>50km	0	0			0	-275	

Flow6	Inter-zonal modal specific constant						
Educational Low Socio-economic Group	car	bus	walk	cycle	rail	metro	HSR
	-26	-29	-21	4	0	-8	1
Intra-zonal travel band	**Intra-zonal modal specific constant**						
	car	bus	walk	cycle	metro	**Band constant**	
0-1km	-3	-3	3	10	-1	-60	
1-2km	0	-5	4	12	1	-70	
2-5km	3	-9	6	22	4	-100	
5-10km	0	5		34	-19	-110	
10-15km	0	-6		34	-36	-130	
15-20km	0	0			0	-135	
20-25km	0	0			0	-140	
25-50km	0	0			0	-155	
>50km	0	0			0	-275	

Flow7 Business High Socio-economic Group	**Inter-zonal modal specific constant**						
	car	bus	walk	cycle	rail	metro	HSR
	-58	-13	-18	6	1	-5	1

Intra-zonal travel band	**Intra-zonal modal specific constant**					**Band constant**
	car	bus	walk	cycle	metro	
0-1km	-29	6	15	10	0	-60
1-2km	-27	0	15	19	2	-70
2-5km	-20	-12	17	27	-8	-95
5-10km	-23	-1		32	-12	-100
10-15km	-26	-5		35	-41	-120
15-20km	0	0			0	-150
20-25km	0	0			0	-165
25-50km	0	0			0	-180
>50km	0	0			0	-275

Flow8 Business Middle Socio-economic Group	**Inter-zonal modal specific constant**						
	car	bus	walk	cycle	rail	metro	HSR
	-56	-13	-18	6	1	-6	1

Intra-zonal travel band	**Intra-zonal modal specific constant**					**Band constant**
	car	bus	walk	cycle	metro	
0-1km	-27	6	13	10	0	-60
1-2km	-25	0	13	19	2	-70
2-5km	-18	-12	15	27	-8	-95
5-10km	-21	-1		32	-12	-100
10-15km	-24	-5		35	-41	-120
15-20km	0	0			0	-150
20-25km	0	0			0	-165
25-50km	0	0			0	-180
>50km	0	0			0	-275

Flow9 Business Low Socio-economic Group	**Inter-zonal modal specific constant**						
	car	bus	walk	cycle	rail	metro	HSR
	-54	-13	-18	6	1	-6	1

Intra-zonal travel band	**Intra-zonal modal specific constant**					
	car	bus	walk	cycle	metro	**Band constant**
0-1km	-26	5	13	10	0	-60
1-2km	-24	-1	13	19	2	-70
2-5km	-17	-13	15	27	-8	-95
5-10km	-20	-2		32	-12	-100
10-15km	-23	-6		35	-41	-120
15-20km	0	0			0	-150
20-25km	0	0			0	-165
25-50km	0	0			0	-180
>50km	0	0			0	-275

Flow10 Other High Socio-economic Group	**Inter-zonal modal specific constant**						
	car	bus	walk	cycle	rail	metro	HSR
	-25	-20	-20	7	0	-11	1

Intra-zonal travel band	**Intra-zonal modal specific constant**					
	car	bus	walk	cycle	metro	**Band constant**
0-1km	-5	1	3	13	0	-75
1-2km	-3	-6	3	21	2	-85
2-5km	0	-11	8	28	-9	-90
5-10km	-3	2		32	-13	-95
10-15km	-4	-7		35	-41	-145
15-20km	-10	2			-50	-160
20-25km	-20	10			0	-180
25-50km	0	0			0	-200
>50km	0	0			0	-275

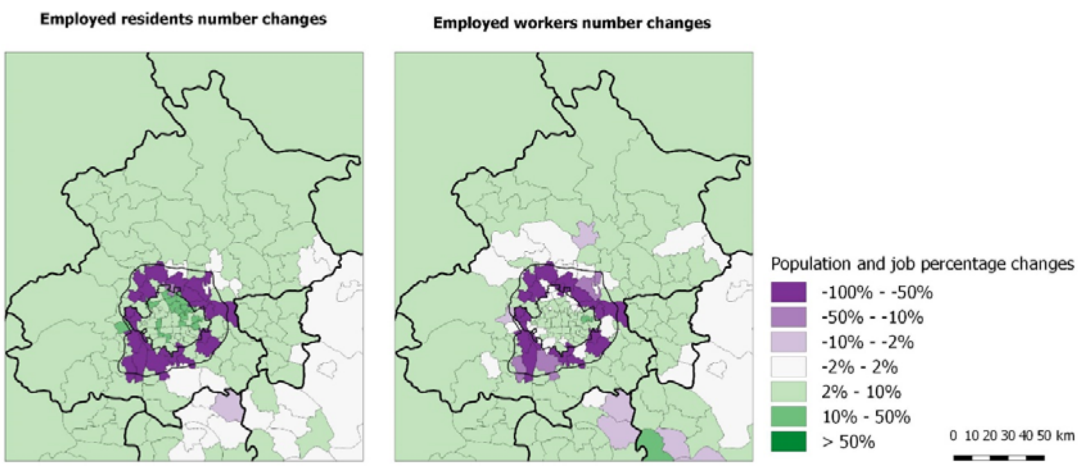
Flow11 Other Middle Socio-economic Group	**Inter-zonal modal specific constant**						
	car	bus	walk	cycle	rail	metro	HSR
	-23	-20	-20	7	0	-11	1
Intra-zonal travel band	**Intra-zonal modal specific constant**					**Band constant**	
	car	bus	walk	cycle	metro		
0-1km	-5	1	1	13	0	-75	
1-2km	-3	-5	1	21	2	-85	
2-5km	0	-11	6	28	-9	-90	
5-10km	-3	2		32	-13	-95	
10-15km	-4	-7		35	-41	-145	
15-20km	-10	2			-50	-160	
20-25km	-20	10			0	-180	
25-50km	0	0			0	-200	
>50km	0	0			0	-275	

Flow12 Other Low Socio-economic Group	**Inter-zonal modal specific constant**						
	car	bus	walk	cycle	rail	metro	HSR
	-21	-20	-20	7	0	-11	1
Intra-zonal travel band	**Intra-zonal modal specific constant**					**Band constant**	
	car	bus	walk	cycle	metro		
0-1km	-5	-1	1	13	0	-75	
1-2km	-3	-8	1	21	2	-85	
2-5km	0	-13	6	28	-9	-90	
5-10km	-3	0		32	-13	-95	
10-15km	-4	-9		35	-41	-145	
15-20km	-10	0			-50	-160	
20-25km	-20	8			0	-180	
25-50km	0	0			0	-200	
>50km	0	0			0	-275	

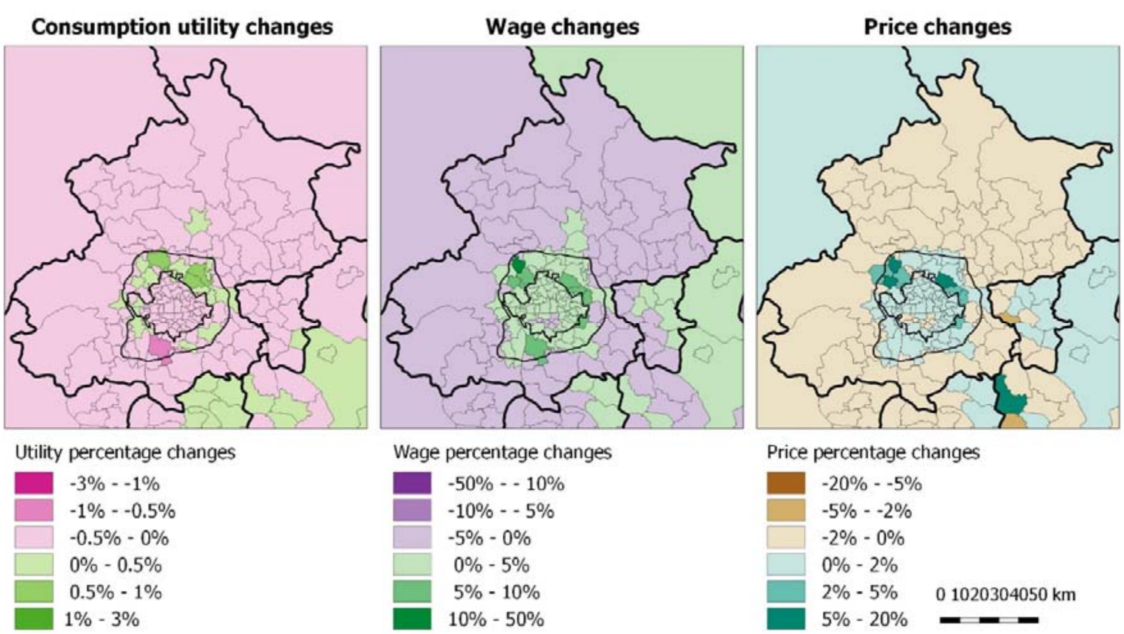
Appendix Table 15 Distance band constants and modal specific constants for base year 2010

F. Maps for parallel scenario comparisons

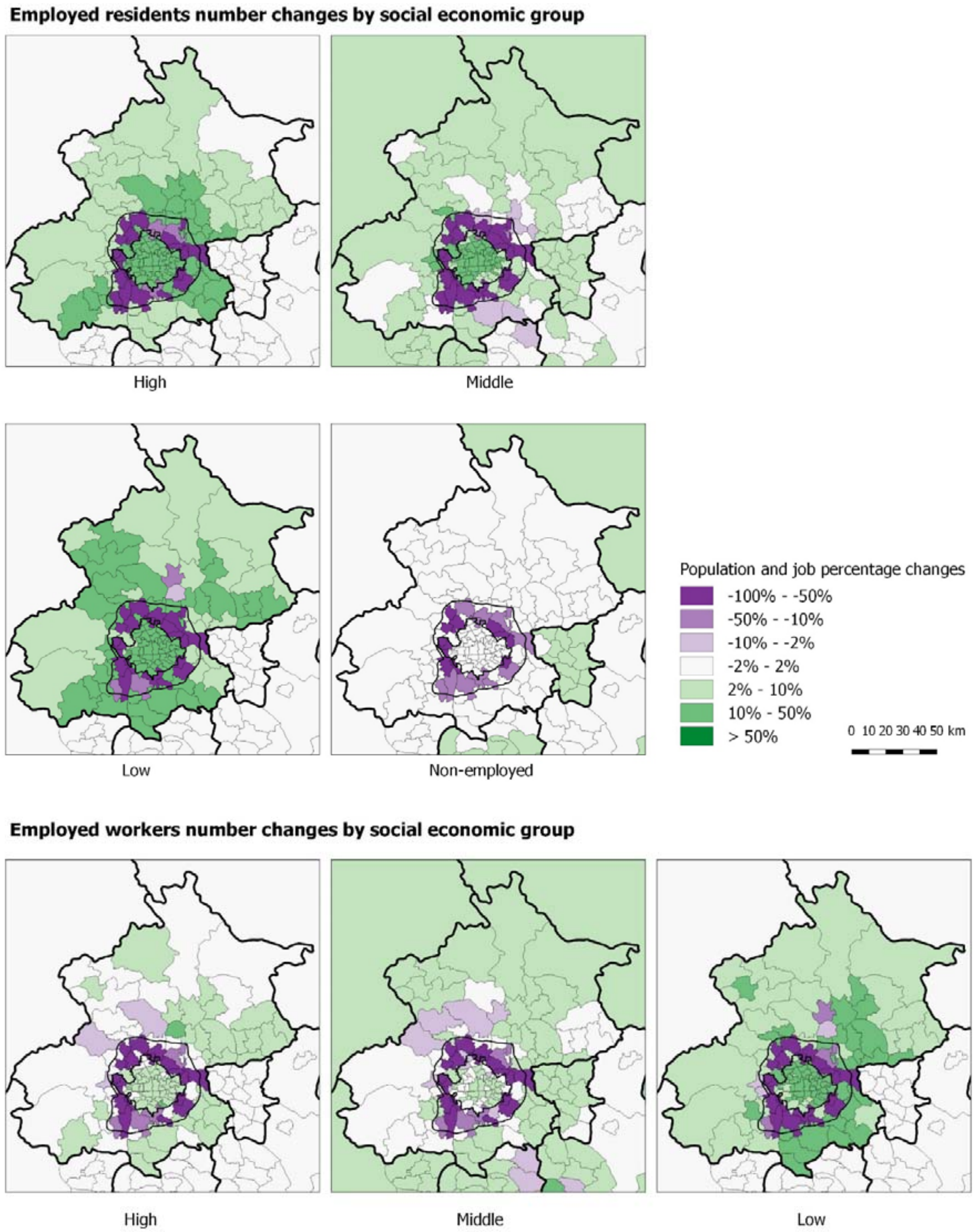
F-1 GB-C versus Ref-C



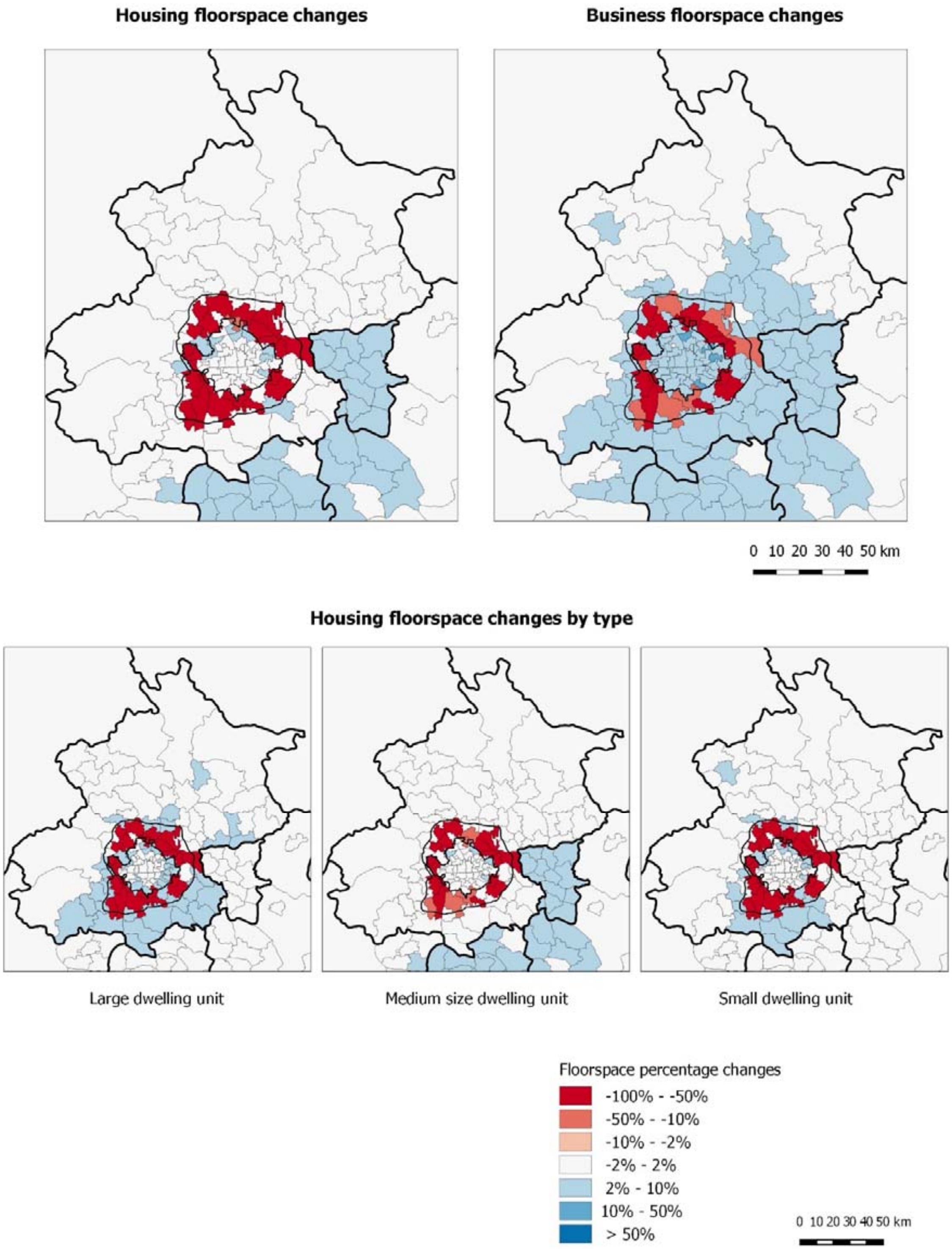
Appendix Figure 5 Employed residents and workers change, GB-C compared to Ref-C



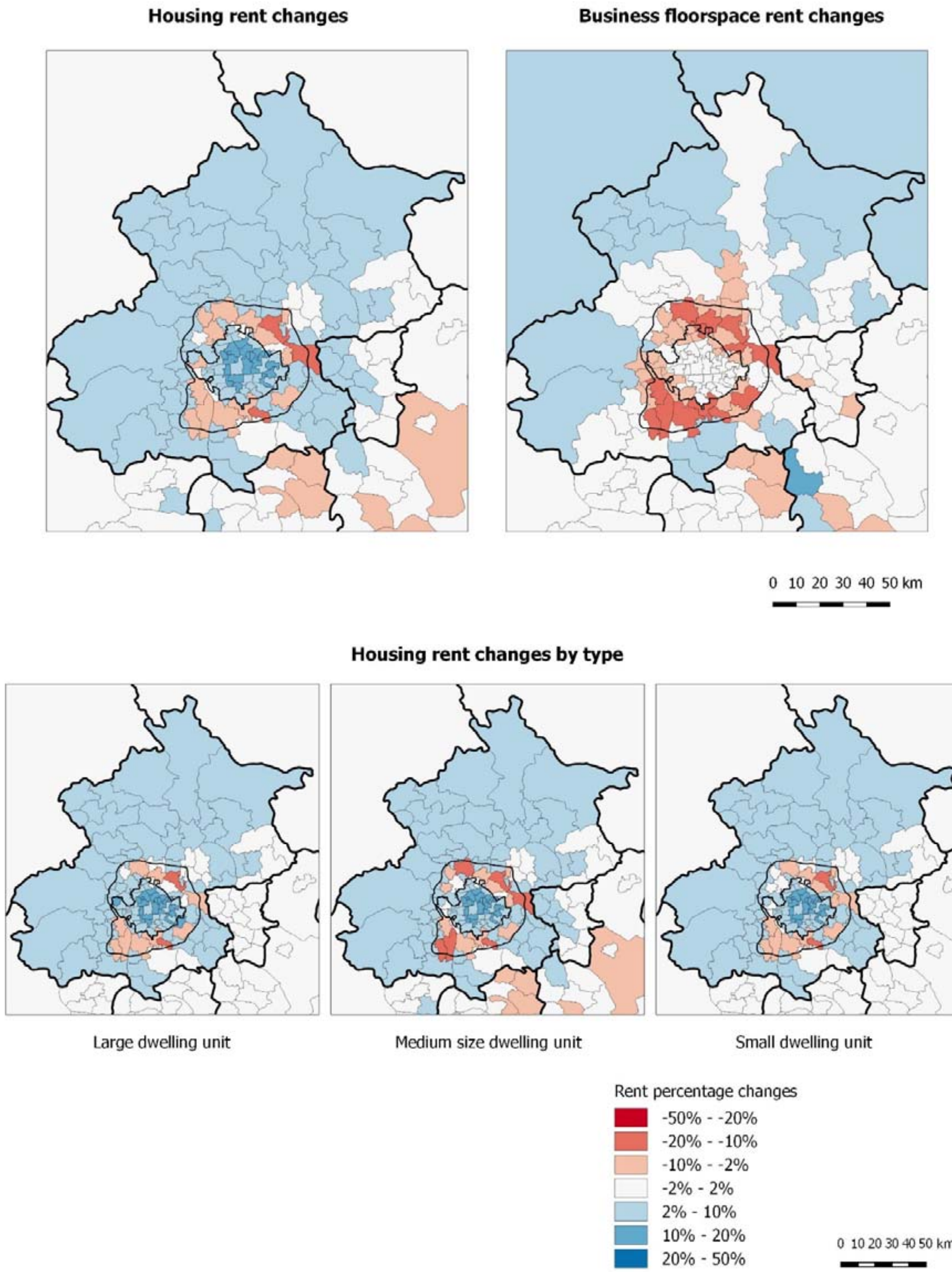
Appendix Figure 6 Utility, wage, and price change, GB-C compared to Ref-C



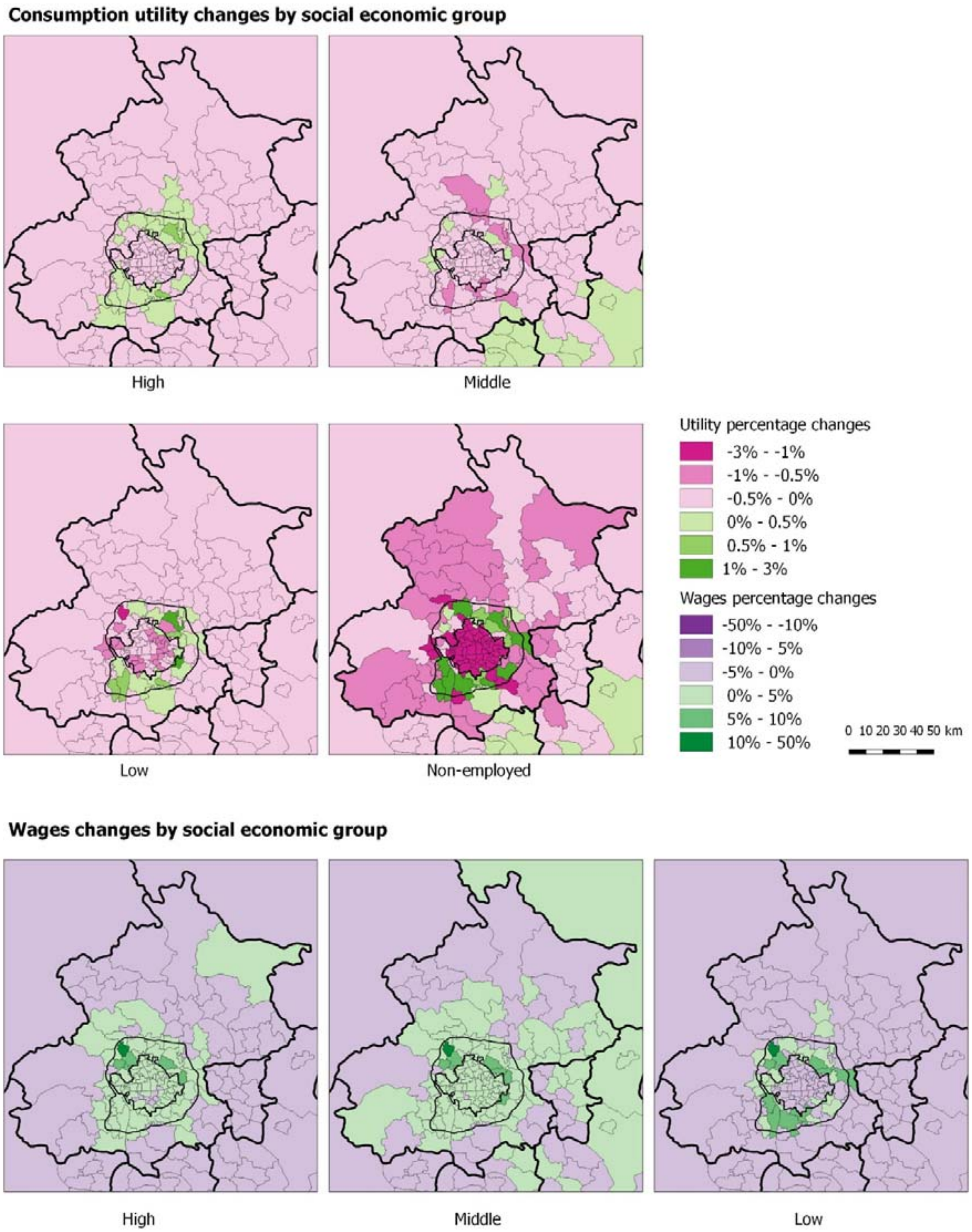
Appendix Figure 7 Employed residents and workers change by socio-economic group, GB-C compared to Ref-C



Appendix Figure 8 Floorspace change by type, GB-C compared to Ref-C

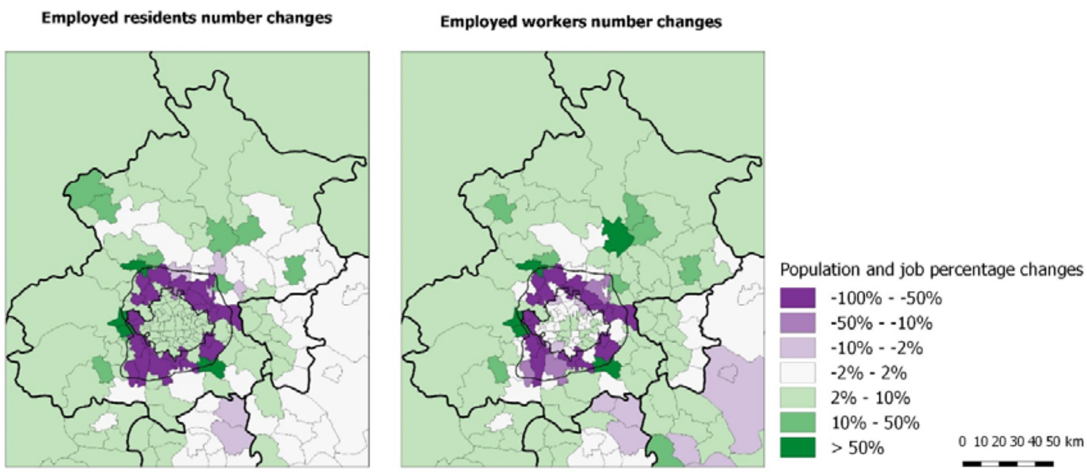


Appendix Figure 9 Rent change by type, GB-C compared to Ref-C

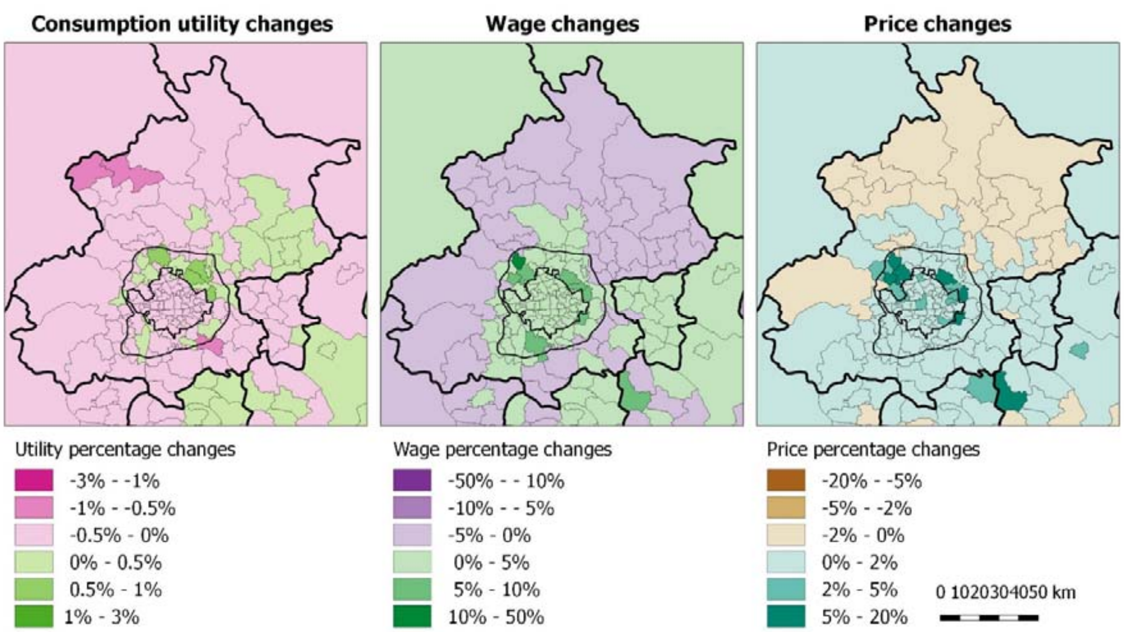


Appendix Figure 10 Utility and wage change by socio-economic group, GB-C compared to Ref-C

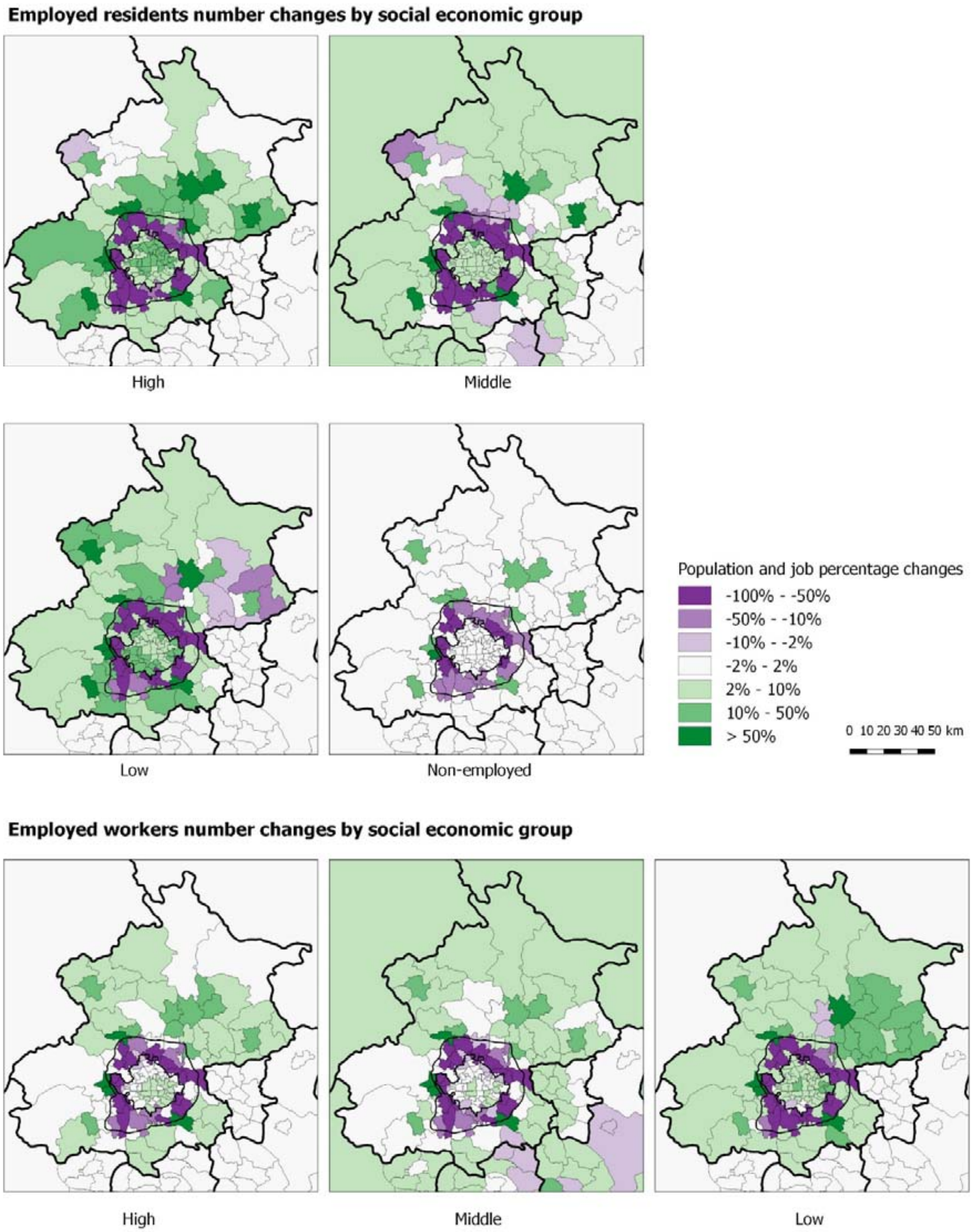
F-2 GB-NT-C versus. Ref-C



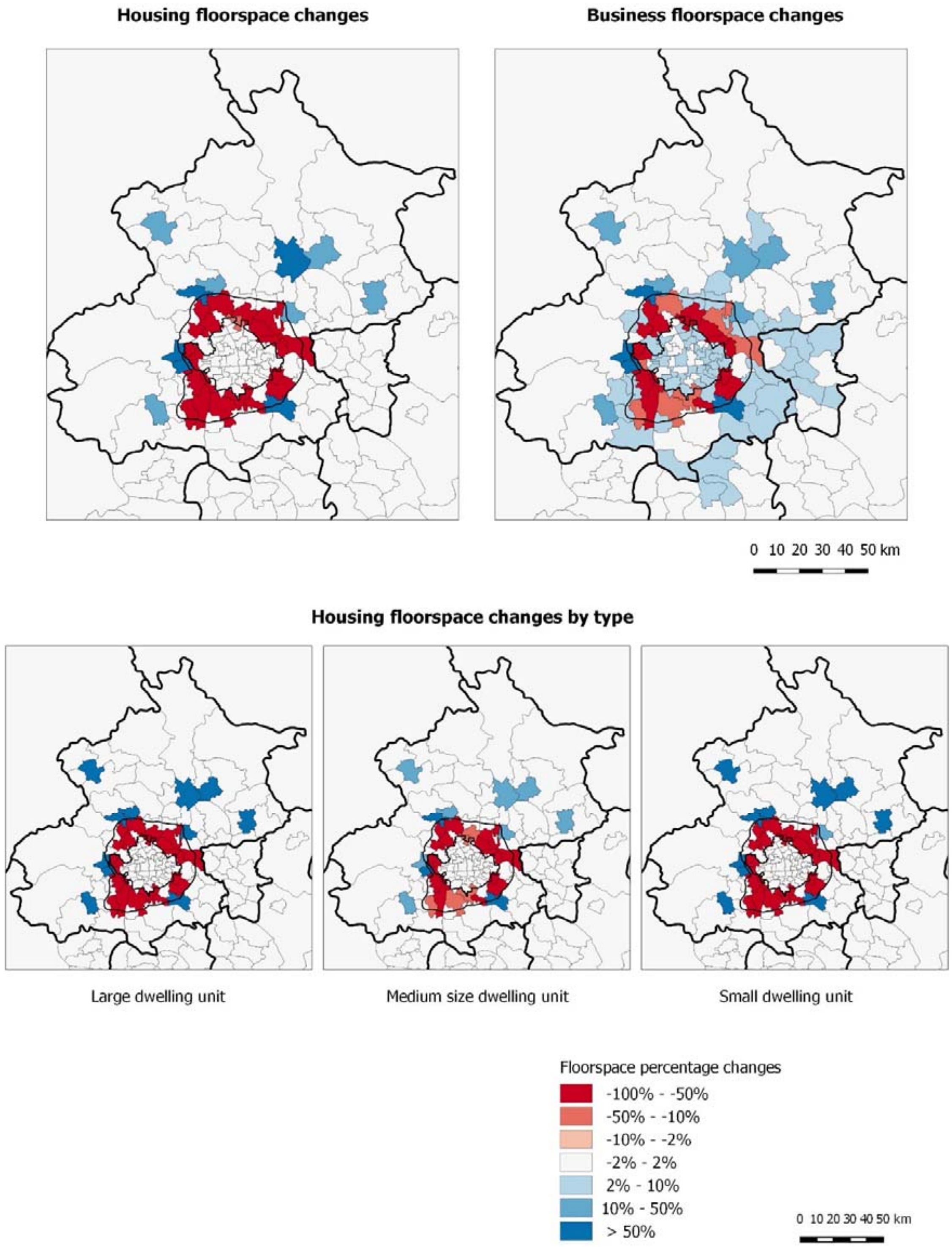
Appendix Figure 11 Employed residents and workers change, GB-NT-C compared to Ref-C



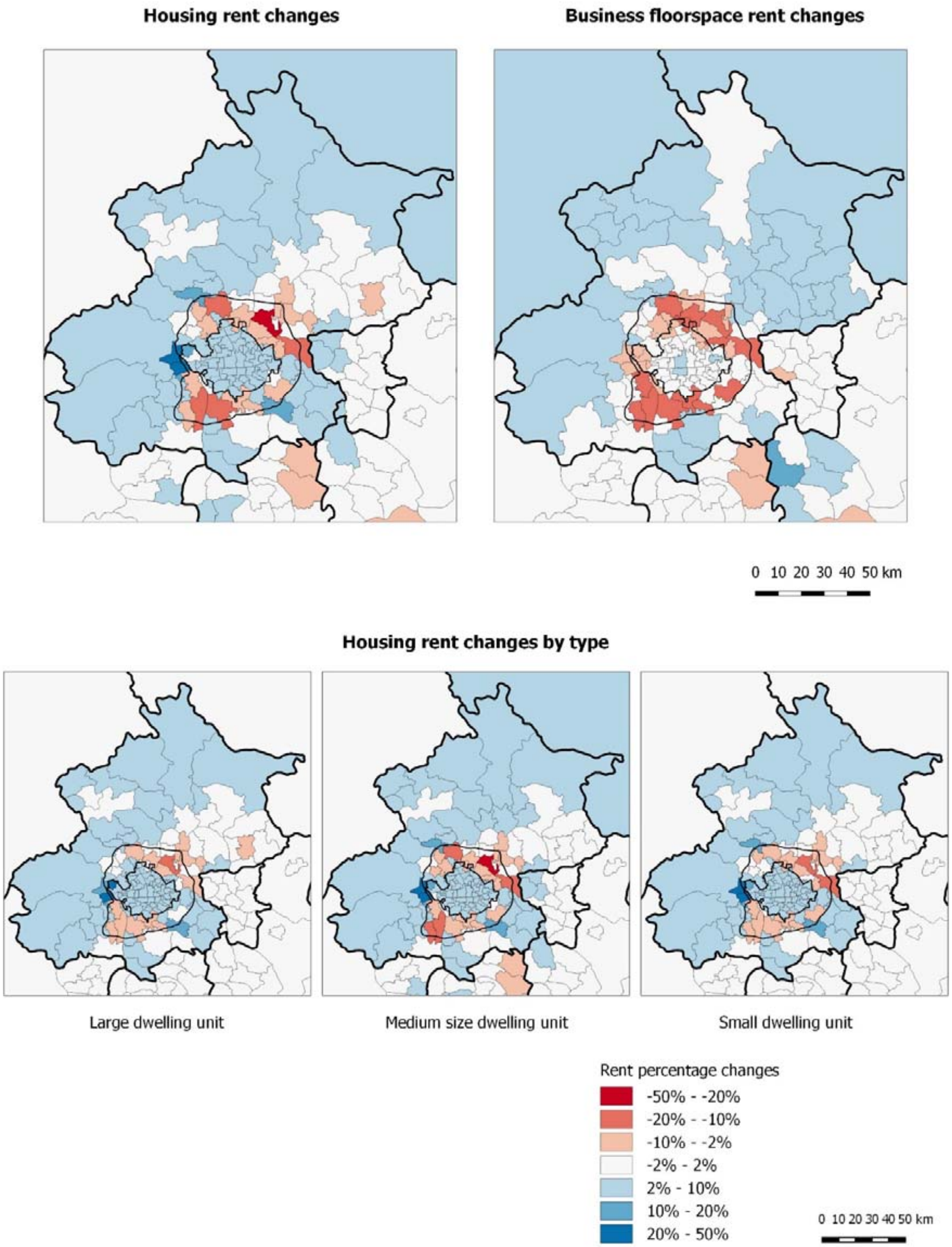
Appendix Figure 12 Utility, wage, and price change, GB-NT-C compared to Ref-C



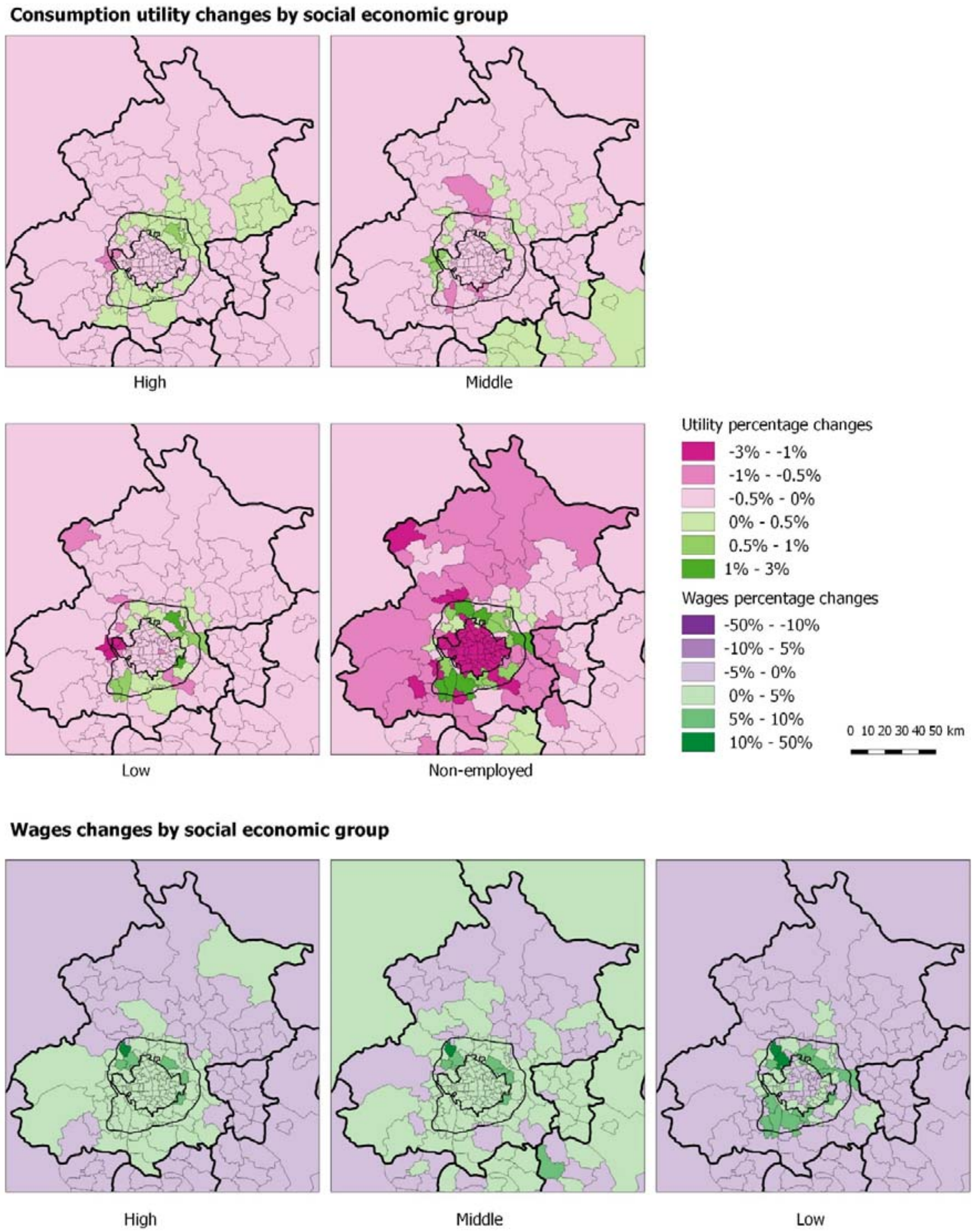
Appendix Figure 13 Employed residents and workers change by socio-economic group, GB-NT-C compared to Ref-C



Appendix Figure 14 Floorspace change by type, GB-NT-C compared to Ref-C

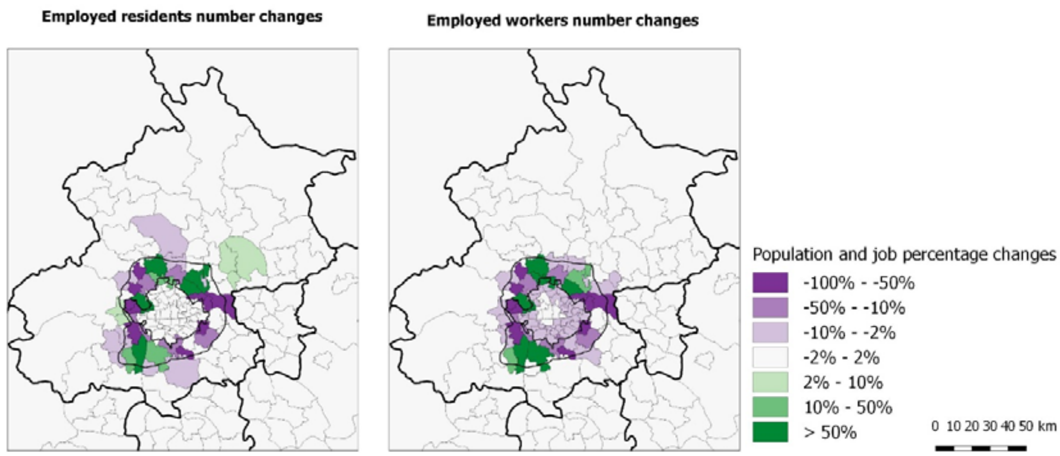


Appendix Figure 15 Rent change by type, GB-NT-C compared to Ref-C

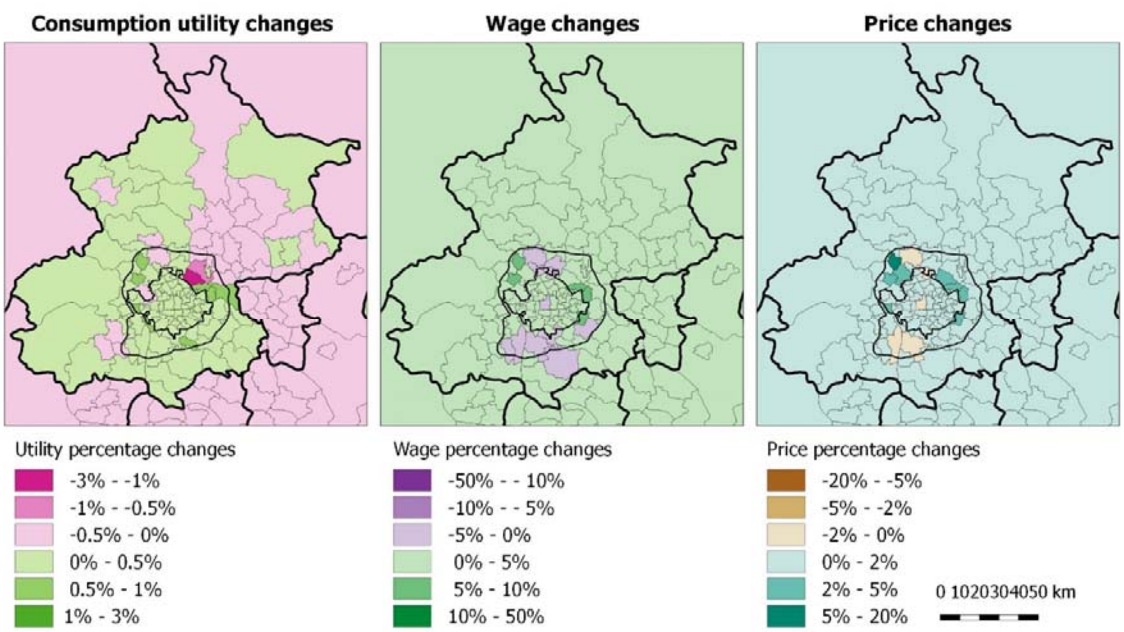


Appendix Figure 16 Utility and wage change by socio-economic group, GB-NT-C compared to Ref-C

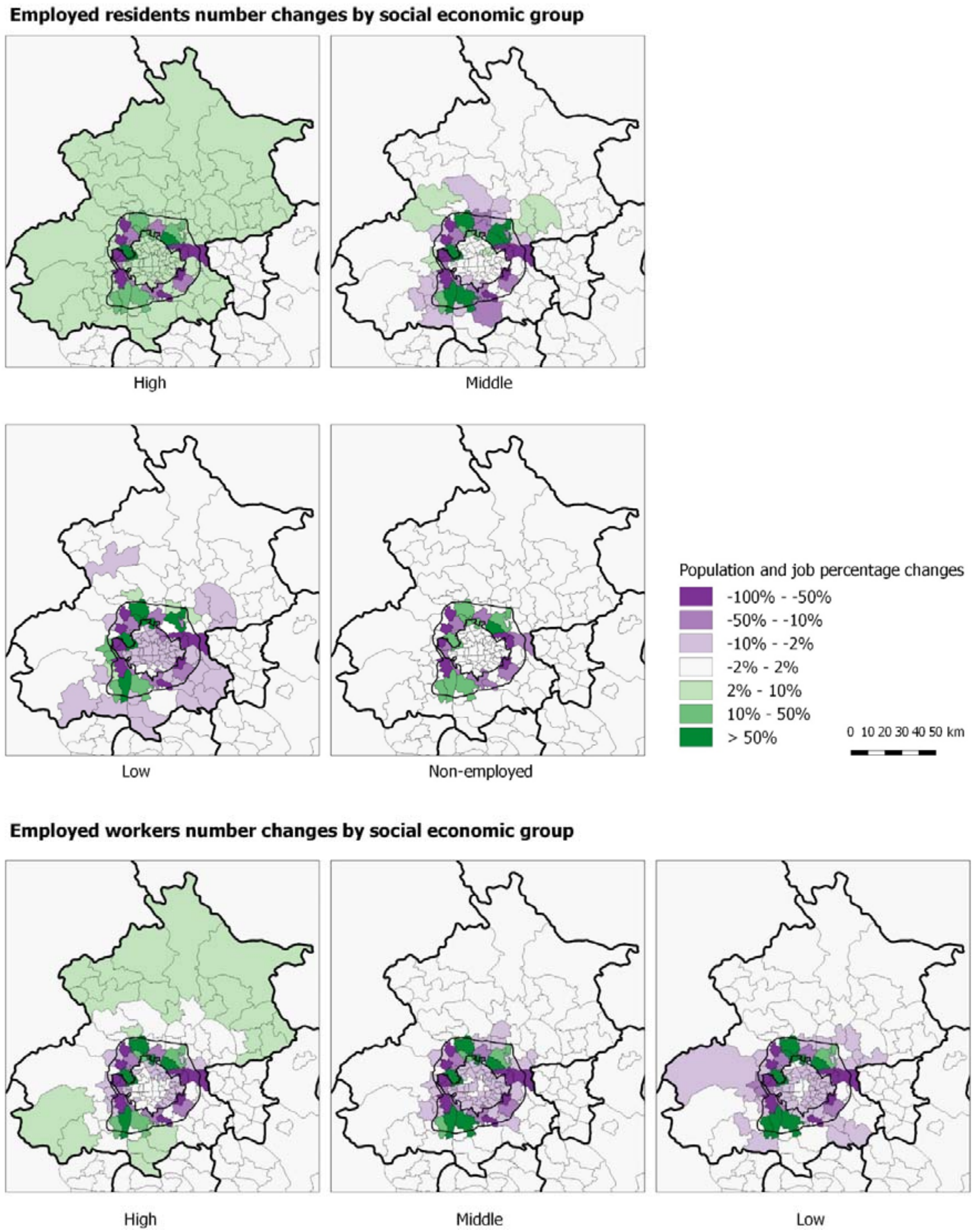
F-3 GW-C versus Ref-C



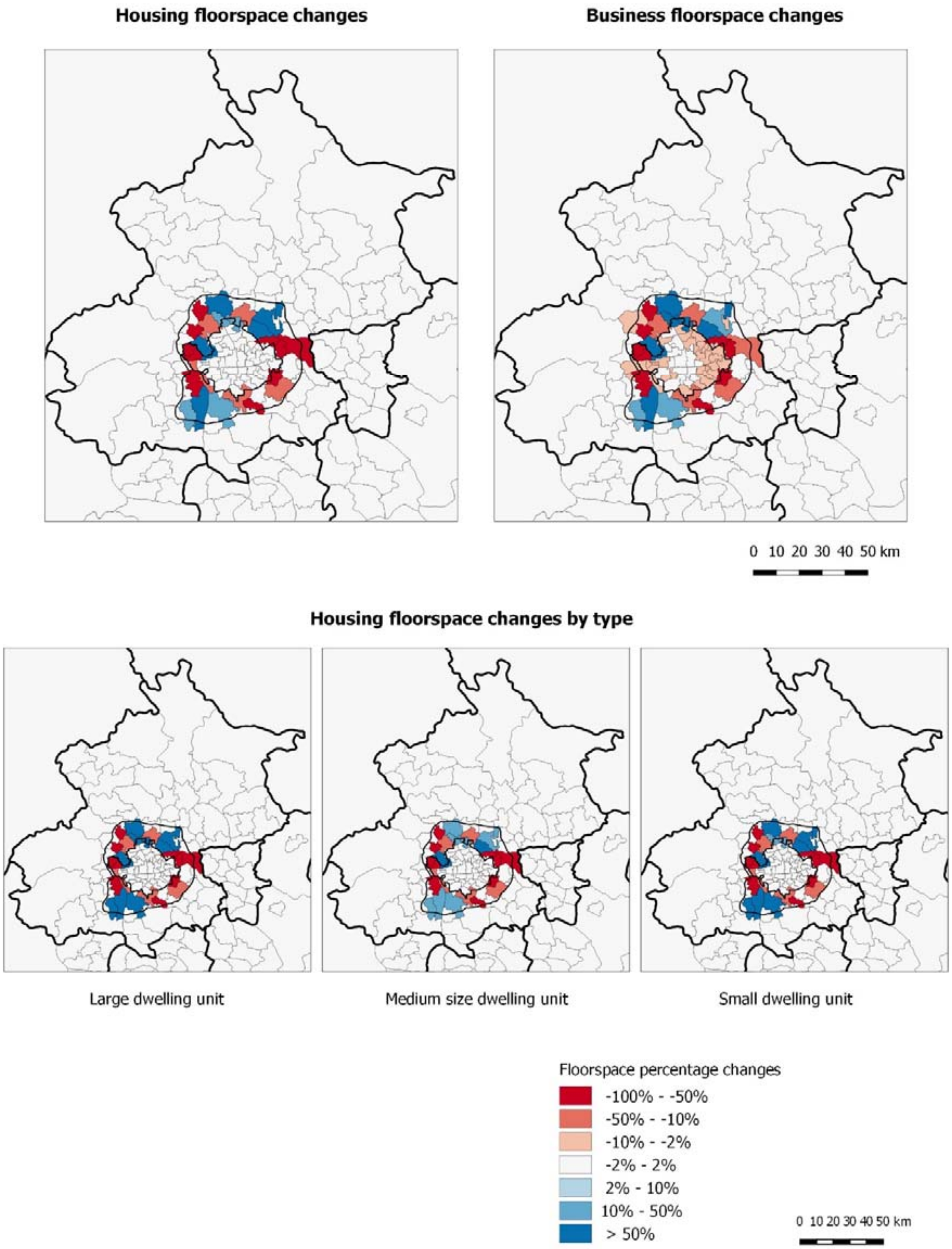
Appendix Figure 17 Employed residents and workers change by socio-economic group, GW-C compared to Ref-C



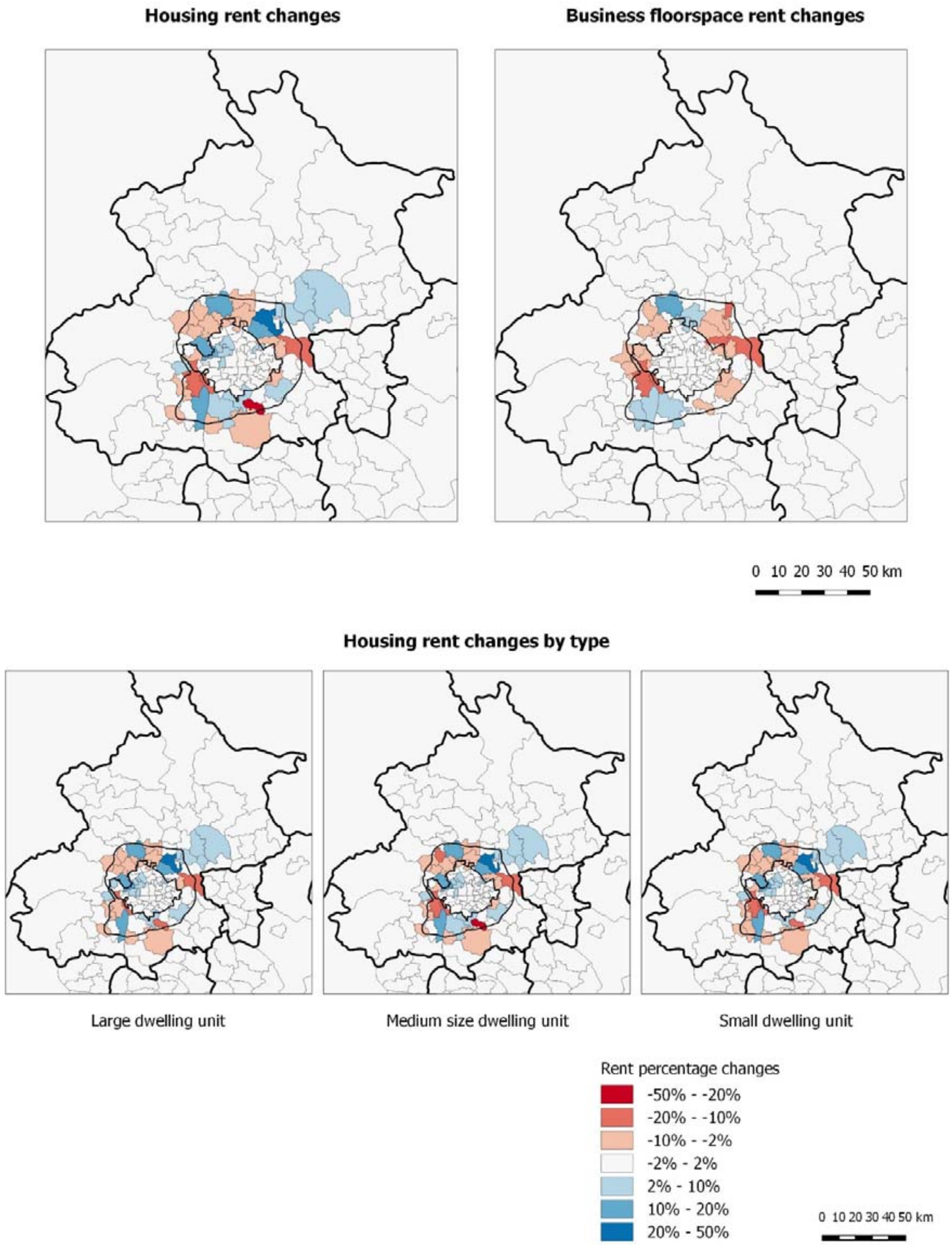
Appendix Figure 18 Utility, wage, and price change, GW-C compared to Ref-C



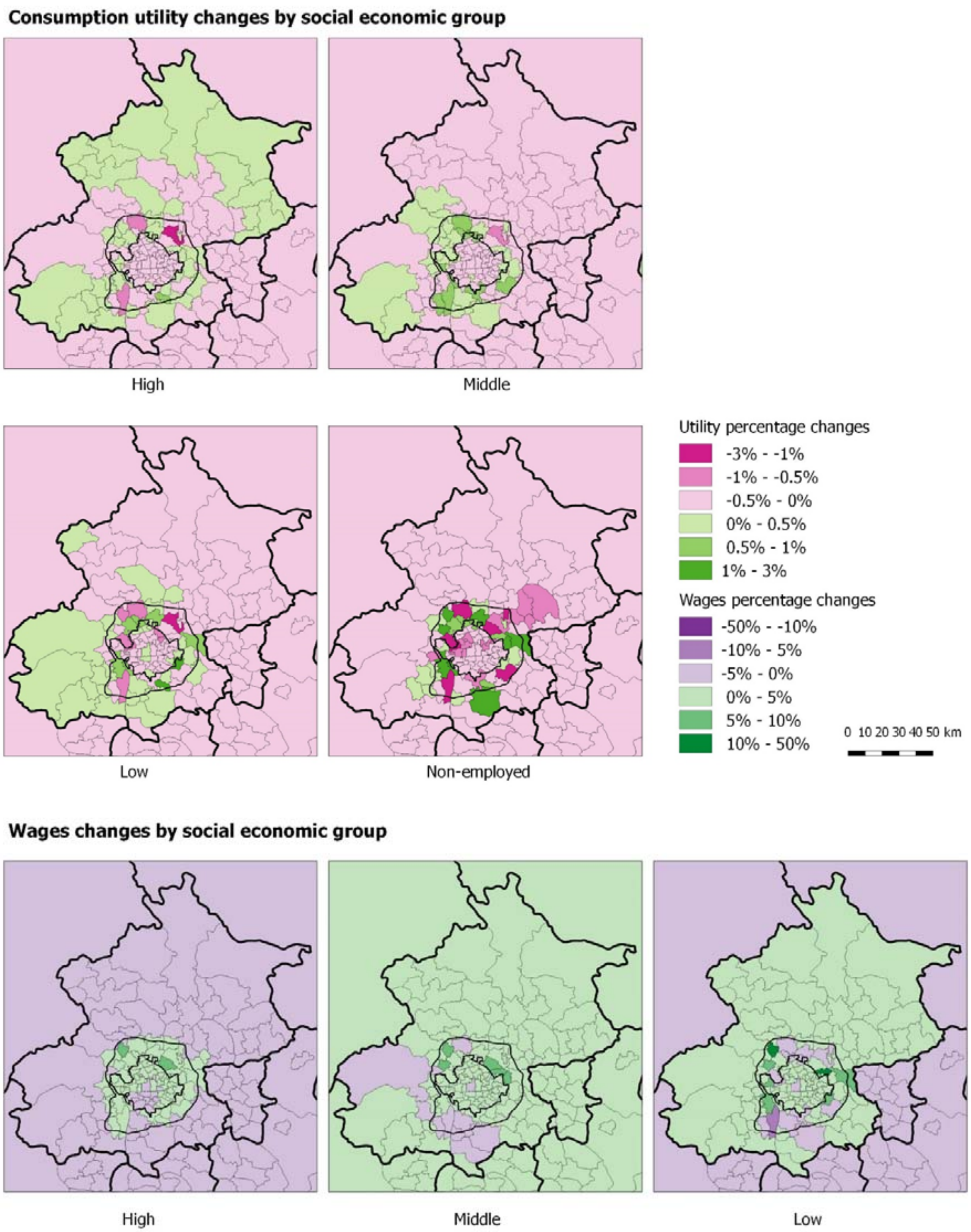
Appendix Figure 19 Employed residents and workers change, GW-C compared to Ref-C



Appendix Figure 20 Floorspace change by type, GW-C compared to Ref-C



Appendix Figure 21 Rent change by type, GW-C compared to Ref-C



Appendix Figure 22 Utility and wage change by socio-economic group, GW-C compared to Ref-C