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Environmental impacts of transformative land use and transport developments in the Greater Beijing Region: Insights from a new dynamic spatial equilibrium model

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ABSTRACT

This paper reports the insights into environmental impacts of the ongoing transformative land use and transport developments in Greater Beijing, from a new suite of dynamic land use, spatial equilibrium and strategic transport models that is calibrated for medium to long term land use and transport predictions. The model tests are focused on urban passenger travel demand and associated emissions within the municipality of Beijing, accounting for Beijing's land use and transport interactions with Tianjin, Hebei and beyond. The findings suggests that background trends of urbanization, economic growth and income rises will continue to be very powerful drivers for urban passenger travel demand across all main modes of transport beyond 2030. In order to achieve the dual policy aims for a moderately affluent and equitable nation and reducing the absolute levels of urban transport emissions by 2030, road charging and careful micro-level coordination between land use, built form and public transport provision may need to be considered together for policy implementation in the near future.

1. Introduction

Beijing's passenger transport annual CO_2 emissions rose from 9.38 million tonnes in 2003 to 15 million tonnes in 2012 (Wang et al., 2015). That is a rise by 60% over a decade. Such rises are typical in fast growing cities of emerging economies. Urban passenger transport is in fact one of the most challenging sectors for carbon and pollutant emission reduction across the world's cities. In faster growing regions the crux of the environmental impact problem is to cut emissions and emission exposure without stunting the initiatives for improving shared prosperity, social equity and economic growth.

Some radical travel demand management measures are already in place to stem the rapid rises in car use and car ownership. For instance, Beijing has implemented a weekday car use restrictions rota by the last digit of the car number plate in the main built area since 2008 and car purchase permit lottery since 2011; on high pollution days around half of the car fleet is kept off road; there have also been massive investments and operating subsidies in public transport.

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Nevertheless, greater growth in passenger travel demand may yet to come in such city regions owing to the increase in income and leisure time, transition to a knowledge-based economy and continued suburbanisation. Better vehicle and system control technologies might actually add to this growth, since they help reduce generalised journey costs.

The difficulties are to understand the magnitudes of such growths several decades into the future. Recent work by Schäfer (2015) is a rare example of modelling the long term travel demand trends in the US from 1900 to 2100 through aggregate modelling. The need for such a long planning horizon comes from slow timelines for getting major urban development projects approved and delivered, and from the very long lifespan of associated infrastructure assets. However, there is an apparent gap in medium to long term travel demand forecasting, which arises from the complexity of influences upon and interactions with urban traffic as well as uncertainties in vehicle, fuel and transport system control technologies. Although there are well known computable general equilibrium models and integrated land use and transport models that are capable of travel demand forecasting under relatively steady growth in developed countries (e.g. Anas and Liu, 2007; Anas et al., 2009; Bröcker and Korzhenevych, 2011; Echenique et al., 2013; Batty et al., 2013; Simmonds et al., 2013), there are few models available in fast growing developing countries that are capable of modelling the medium to long term trends under rapid transformations in land use and transport.

This paper aims to fill some of this gap in medium to long term travel demand forecasting for fast growing city regions through establishing a new type of operational urban land use and transport modelling. We then demonstrate its use through a systematic range of land use and transport scenarios in the Greater Beijing city region.

This model has three basic components: the first is a spatial equilibrium model regarding location and travel choices for millions of businesses and households in the city region and the urban agglomeration effects that arise from concentration of jobs and people (see Fig. 1(a)); the second is a dynamic model for allocating lumpy and non-divisible land and building floorspace investments, accounting for natural growth arising from extensions of existing premises, probabilistic distribution of discretionary investments and ad hoc policy interventions (see Fig. 1(b)); the third is a strategic transport model which share similar features of a conventional land use/transport model or a four-step transport model (see Fig. 2). Travel demand is forecast at the same time of predicting where people choose to travel in the city region, so that the forecasting procedure can engage with both land use and transport planners. Both traditional and new, online data sources are used to calibrate and validate the models.

In applying this model to Beijing, the time horizon is divided into decade-long periods in line with the observed government administration cycles and timelines for Five Year Plans (see Zhang, 2010). For each period, the models are first calibrated on observed data for two preceding decades (1990–2000 and 2000–2010), and subsequently run in forecasting mode for model verification and validation through comparing the modelled quantities and building rents with observed

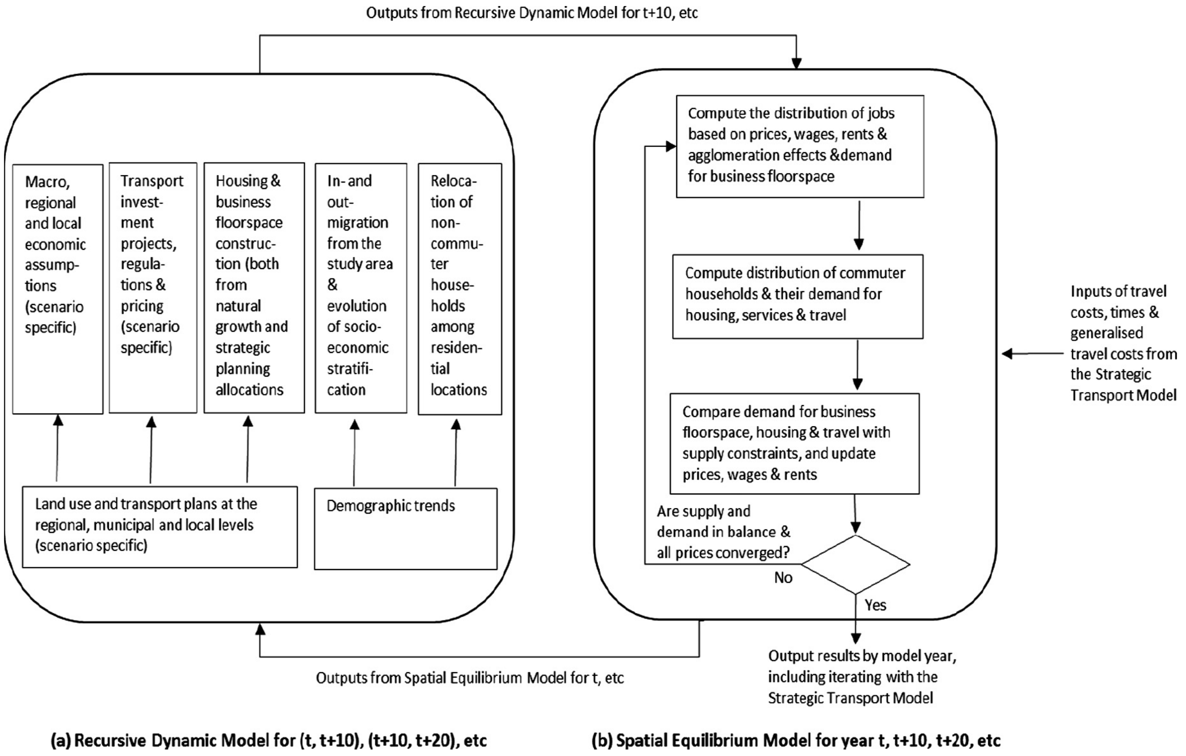

Fig. 1. Model components (1): Spatial Economic and Land Use Models.

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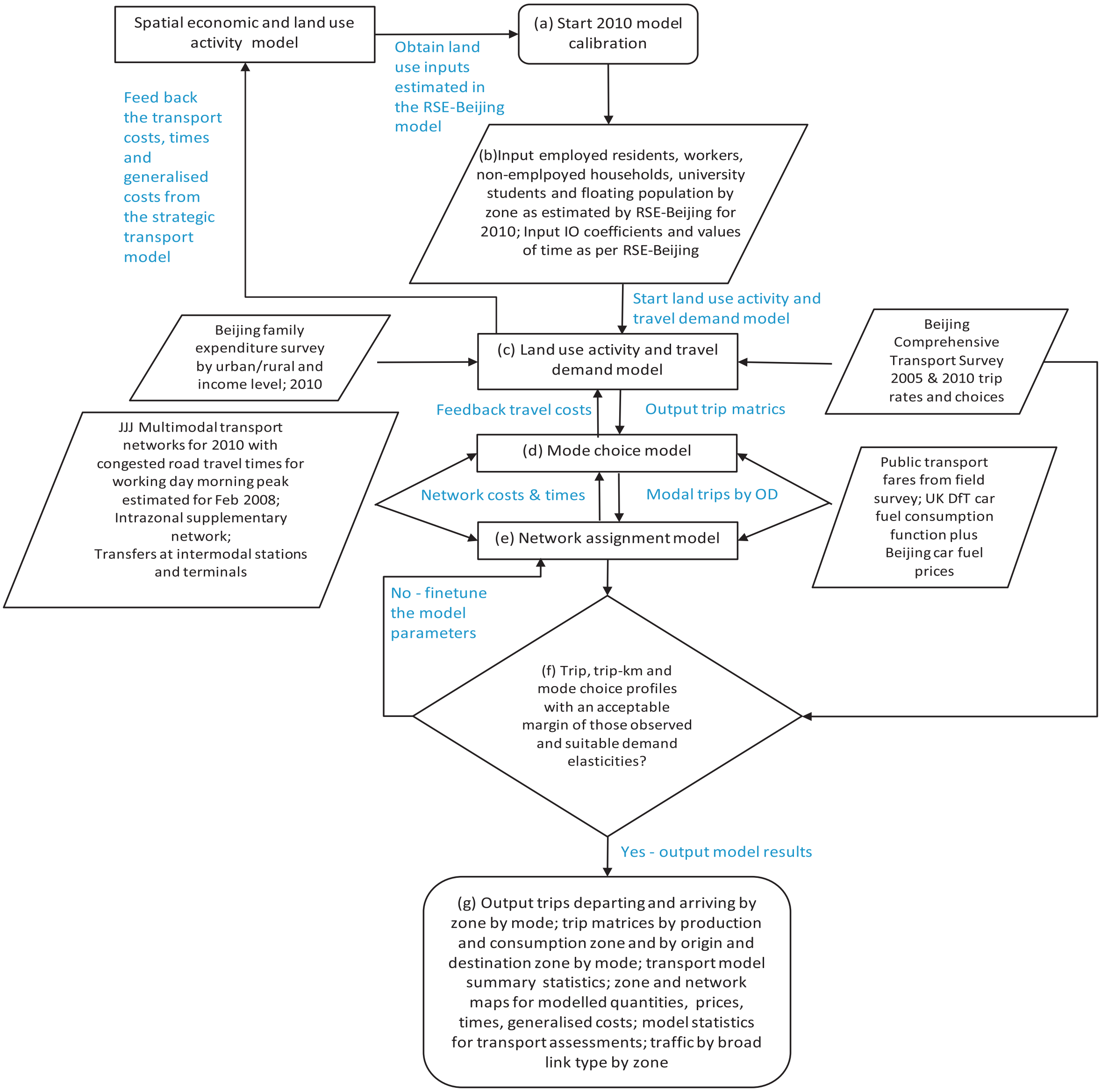

Fig. 2. Model components (2): Strategic Transport Model.

data from property sales and rental websites. The model is then used to predict land use and transport evolution in the coming decades (for this paper, for four decades from 2010 to 2050). Geographically, the model divides a city region into contiguous model zones – for instance in this application there are 130 zones for Beijing Municipality and further 185 zones in Tianjin, Hebei and rest of China.

Because of the inherent uncertainties, the forecasts are carried out through a range of scenarios using alternative inputs as specific boundary conditions of the forecasts – the range of scenarios may be extended to cover a wide spectrum of tests. However, because of considerable inertia of developed land, buildings, transport infrastructure and vehicle fleets, the recursive dynamic scenario tests over decade-long periods exhibit remarkable stability which makes model sensitivity tests more straightforward to discuss than many short term urban dynamics such as market sentiments in the estate property markets modelled in microscopic agent based models.

In this paper we use the model to explore five main strategic land use development scenarios. They are (1) a **trend** scenario;; (2) a **decentralisation** scenario where both business floorspace and housing to the far suburbs (except in ecologically sensitive areas); (3) a **densification** scenario focusing new growths in existing built-up areas; (4) a **spatial mismatch** scenario where housing follow decentralisation but business floorspace follow densification; (5) a targeted **major new town** scenario for development in and around Tongzhou to the east of the central built-up area, in line with our interpretation

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of recent official announcements by the municipal government. The purpose of the five land use scenarios is to cover the full range of land use and master planning options being discussed in the urban development policy arena. This forms a systematic backdrop to investigating strategic transport interventions and land use/transport coordination at the micro-scale.

A major difficulty in long term land use and transport forecasting is to make medium to long term assumptions on what transport infrastructure investment projects will be coming forward. In practice, the projects are continuously progressed with many uncertainties at any given time in terms of specification and design. Governments and transport operators are usually reluctant to speculate about medium to long term projects beyond the current plans approved in the formal planning process.

For this paper we therefore adopt a new kind of assumptions based on the observations that successful and innovative cities in the world tend to have stable travel times between locations for many decades. For instance this is shown in the travel time statistics in San Francisco (www.vitalsigns.mtc.ca.gov/) and London (www.gov.uk/government/collections/transport-statistics-great-britain). For our modelling we start from an all-mode-average morning peak travel time matrix that is found broadly acceptable by the residents in the recent past and assume that in the future such travel times will be maintained through adjustments in infrastructure and operations investment, modal shifts, relocation of jobs and households, pricing and regulation. In the case of Beijing we have chosen such a travel time matrix for early 2008 which was perceived to be serving the travel needs adequately. We then use the assumed average travel times between locations to work out associated monetary costs and then input the times and costs into spatial equilibrium model to predict the demand for travel between the locations.

In other words we first assume that the residents in the city would demand a certain level of service from the future urban transport system, and work out what the jobs and residents location patterns will be, given the changes in city size, income levels, expected lifestyle changes, etc. The strategic transport model then takes the predicted locations of people and businesses to work out what the patterns of travel demand will emerge and how much pressure different parts of the transport system will be under, for any given investment, regulation and pricing scenario.

The approach we are adopting is the opposite to what has been commonly used in conventional transport assessments, where the proposed infrastructure investment and regulatory projects are first input into the model, and the model is used to predict the levels of congestion and associated travel times. The conventional approach is useful for investigating incremental and marginal changes under steady growths, but it can only play a marginal role when the bulk of transport projects and regulations are yet to be determined, or where the policy makers and transport operators wish to investigate the likely magnitudes of medium to long term demand growth in order to reserve adequate rights of way or throughput capacities of transport infrastructure.

Our new approach investigates travel demand trends and the requirements for infrastructure investment, regulation and pricing in the opposite way to conventional assessment practice, thus shedding a new light onto non-marginal transformations of the economy, demography, lifestyles and travel demand. It should be noted that our approach is not an act of predict-and-provide, because the assumptions are only concerned with all-mode-average travel times and we assume that the packages of transport improvement measures do include demand management through regulation and pricing as well as investment. This approach can also be generalised to include improving or worsening average travel times (e.g. in the case of a targeted improvement programme around a New Town, or where the citizens accept a certain degree of worsening congestion in some high density areas) and the assumptions can be made in fine grain on any origin and destination zone pair or part of the transport network.

Each spatial equilibrium model run generates a specific set of travel patterns for journeys to work, education, business and other purposes. The forecast travel patterns (in the form of demand matrices between model zones) are then input into a strategic transport model in order to investigate specific transport interventions, such as road charging, adjustments of public transport fares, car parking charges or entry restrictions, and the coordination of BRT and metro/rail investments with surrounding land use and urban design. Where the transport interventions have altered the average travel times significantly between zones, the travel time and cost matrices are fed back into the spatial equilibrium model. It may take a number of iterative runs between the strategic transport model, the spatial equilibrium model and the dynamic land use and building floorspace model to achieve mutually consistent predictions.

For this paper, our investigations are focused on urban travel demand and its implications on carbon emissions, particularly the city-level emission profiles to 2030 and 2050 and strategic policy options. The model results can also be used to predict the emission profiles of other pollutants in an analogous way or examine locally specific impacts. The modelling suite covers the whole of Jing Jin Ji area (i.e. Beijing municipality, Tianjin Municipality and Hebei province) for land use and transport interactions, but the travel demand and emission predictions are focused on Beijing municipality only. This is not only because Beijing is the most challenging part of the city region for its complexities in land use and transport; it is also because currently Beijing has the best empirical data for model calibration and validation.

The estimation of the transport emission effects is made possible by a number of empirical studies that have emerged recently on unit emission factors, many of which have directly estimated unit emission rates for the Beijing area using either aggregate (Li and Jones, 2015; Ke et al., 2015; Fan et al., 2015; Mittal et al., 2015; Wang et al., 2015 or vehicle level microdata (Yu et al., 2009; Wu et al., 2014). In particular, the unit emission factor approach that relates transport emissions per passenger km travelled can be connected to forecasts of travel demand forecasts at an aggregate level, and when our modelling suite is interfaced with a detailed road traffic model, the vehicle level estimation is also feasible. For this paper we adopt the

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aggregate approach for easy verifiability and the CO_2 emission factors estimated by Wang et al. are used because they represent the latest and empirically verified figures for Beijing.

Section 2 below summarises the main components of the model, their theoretical justifications and the verification and validation using a wide range of data sources. Section 3 presents the design and specification of future scenarios. Section 4 presents the main results. We then consider the wider implications of the results, study conclusions and further work in Section 5.

2. Model design, verification and validation

As outlined in Introduction, our modelling suite consists of three modular components: (1) a spatial equilibrium model for location and travel choices; (2) a recursive dynamic model for land and building floorspace developments; (3) a strategic transport model.

For a systematic exposition of the theoretical structure of the model suite and its pedigrees, see Jin et al. (2013). For a comprehensive review of urban models see Batty (2009) and more specifically land use and transport models, see Wegener (2011). Here we illustrate its application in a non-specialist language (Note for the editor: the main model equations can be provided in an appendix to this paper if there is space for it). Further technical details regarding the spatial equilibrium model and the recursive dynamic model including model calibration and validation is found in Rong (2016) and Wan (2016) and the equivalent material for the strategic transport model in Deng (2015).

In this paper we articulate the modular components based on an assumption that the morning peak travel times in the medium to long term will remain at an acceptable level in a city with effective travel demand management and governance – the acceptable travel times contain effects of traffic congestion, but such congestion is contained within an acceptable level through adjustments both in transport demand and supply. We then use the model to explore the implications of this type of scenarios for land use planning and infrastructure investment. Although the constancy of travel time in city regions has attracted scholarly attention, notably by Anas (2015) in the context of general equilibrium models for city regions, this phenomenon has not often been used in exploring medium to long term urban development scenarios.

The data flows for the model year 2010 can be used to illustrate model design, calibration, verification and validation:

(a) As it will be clear below the data flows in the model are circular and iterative. However, it is appropriate to start from the spatial equilibrium model. The core of this model consists of constant-elasticity-of-substitution (CES) functions for producer choices for inputs and household choices for consumption. Initially this model receives two main inputs: one for the estimated quantities of housing and business floorspace (for estimation methods and data, see Rong et al. (2015) and Rong (2016)), and the other the estimated average morning peak (6.30am-9.30am) travel times between all origin and destination zone pairs from the calibrated strategic transport model (see below). This enables the calibration of the location of businesses and residents, and the spatial distribution of journeys to work and trade in goods and services, based on statistics published the municipal statistics bureau on production output, the Population Census, the Economic Census, and average journey lengths to work and services from the OD survey as reported for 2010 by BTRC (2012). Workers are classified into three socio-economic groups based on the Erikson-Goldthorpe-Portocarero (EGP) system (see Section 3 below); in addition, those households that are either retired or unemployed are represented separately. This enables their distinct demand elasticities for goods and services, housing and travel can be accounted for. The calibrated spatial equilibrium model outputs its predictions for each zone of the levels of business production, residents, workers, demand for business floorspace and housing, prices, and rents. The predictions verify well when compared with the input data for calibration (i.e. the 2010 model can reproduce the zonal activities, associated prices and consumer wellbeing).

(b) By definition, the recursive dynamic model for land and floorspace development needs to be calibrated across two time periods. In order to do this, a spatial equilibrium model is calibrated in a similar way to that for 2010, and zonal level prediction models for incremental land and floorspace development over the 2000–2010 period are established through regressing the observed development against the outputs of the calibrated spatial equilibrium model for 2000. Once the recursive dynamic model is found to reproduce well the observed changes in floorspace supply for 2000–2010, its outputs replace the estimated quantities of housing and business floorspace which was used in the initial stages of the spatial equilibrium model.

(c) The strategic transport model starts from a multimodal transport network which is supported by road links as coded in the Open Street Map, metro and rail services represented by average peak and non-peak time service timetable speeds, and estimated morning peak congestion speeds using an openly available taxi GPS trace data for early 2008 (see Deng et al., 2015). Ideally the 2010 model should make use of 2010 speed data, but this is not yet openly available and has to await future opportunities. The discrepancy between the 2008 and 2010 network speeds is unlikely to be so high as to invalidate the model. The strategic transport model uses the network data to estimate modal travel costs and times for all zone pairs, which feeds into the mode choice calibration based on the observed 2010 modal travel demand as observed by BTRC (2012). It then receives the zonal employment and resident households output from the spatial equilibrium model and use it to predict the modal choices on each zone pair for each type of residents in the households (children of different ages, employed and non-employed adults, the elderly) for each type of travel

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Table 1
Comparisons of Modal Share by Trip Purpose, 2010, within the Sixth Ring Road. *Source:* Deng (2015).

	Commuting		Education		Business		Other		All purposes	
	Survey	Modelled	Survey	Modelled	Survey	Modelled	Survey	Modelled	Survey	Modelled
Car	26.2%	26.6%	16.3%	23.9%	72.0%	55.8%	26.0%	28.3%	27%	28%
Bus	25.7%	26.7%	32.0%	33.8%	11.0%	14.5%	23.0%	25.9%	24%	27%
Walk	19.4%	19.4%	32.6%	25.8%	3.0%	12.0%	29.0%	28.8%	25%	24%
Cycle	14.8%	9.3%	13.7%	11.9%	3.0%	3.5%	13.0%	8.5%	13%	9%
Metro	13.9%	18.0%	5.4%	4.6%	11.0%	14.1%	9.0%	8.6%	11%	12%

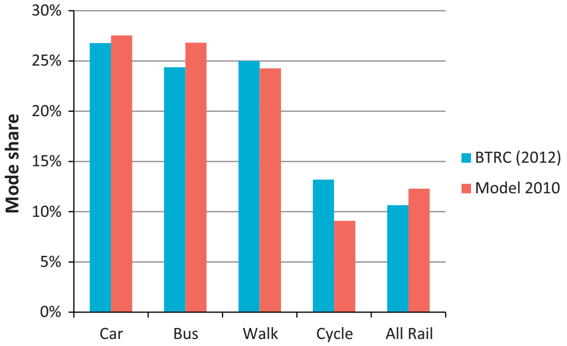

Fig. 3. Comparison of modelled and observed% mode share in trips, 2010, within the Sixth Ring Road. *Source:* Deng (2015).

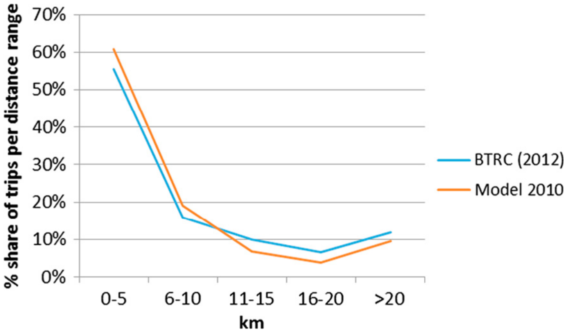

Fig. 4. modelled vs observed distribution of all trips across distance ranges, 2010, within the Sixth Ring ROAD. *Source:* Deng (2015).

(work, education, business and other, as defined by BTRC, 2012). Additionally, it also models the travel of persons not usually resident in households, such university and college students and non-residents who stay in the municipality for under 3 months. Finally the strategic transport model assigns the trips on each mode to the multimodal transport network, where each door-to-door mode may use feeder modes (e.g. metro as a door-to-door mode can use car, bus, walk and cycle as feeder modes).

The spatial equilibrium, recursive dynamic and strategic transport models perform well for verification and validation and the results are reported in detail in Deng et al. (2015), Deng (2015) and Rong (2016) in terms of predicted quantities, rents and demand elasticities. Here it is appropriate to present the comparisons between modelled transport results and the observed patterns reported by the comprehensive transport survey in Beijing for 2010 (BTRC, 2012). Both the observed and modelled data is for travel within the Sixth Ring Road in Beijing (which covers the bulk of the built-up area) where the data is available. Since the model outputs are produced with predicted modal matrices (which in turn are derived from outputs from the recursive dynamic and spatial equilibrium models), the comparisons should be considered as model validation rather than mere verification.

Table 1 presents the mode shares by trip purpose. The generally good match of the mode choice patterns show that the model is capable of reproducing the observed mode shares with a slight over-estimate of car, bus and rail and an under-estimate of walk and cycle. Note that in 2010, the shares for car, bus and walk trips are almost equal, which is a feature that

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resulted from a rapid rise in car share and falls in bus and cycling (BTRC, 2012); the share for walk has persisted for the existence of a large number of short non-commuting trips in the survey sample (BTRC, 2012). Overall, the overall modelled morning peak mode shares, which are the most difficult to reproduce, compare with the observed from the 2010 survey as reported by BTRC (2012), see Fig. 3.

Fig. 4 further compares the modelled with the observed by distance band, which shows that the model is capable of capturing the distance band profile, although there are indeed many discrepancies that can be further improved upon. Arguably those improvements would be more effectively done when more detailed observed data is available, such that the model could be calibrated using a formal numerical optimisation method such as maximum likelihood. We have further compared the average trip lengths (7.8 km for the modelled vs 7.6 km as reported by BTRC, 2012), and average travel times for commuting (46.4 min modelled vs 45.0 observed) and for school education (34.8 min modelled vs 34.0 observed).

3. Strategic and micro-level scenarios

The scenarios to be tested are first of all based on several assumptions on population size, rate of economic growth and socioeconomic profiles which are subject to national level policy coordination. The strategic land use and transport specifications are then made accordingly. For land use, we consider all generic alternatives as outlined in the introduction, within which finer grained variants such as different levels and timelines of floorspace delivery are considered. The transport scenarios are developed to reflect alternative approaches that are compatible with the land use strategies.

For economic growth, there is no official projection that goes as far as 2050. We refer to medium to long term projections from various research institutions (OECD, 2012; Goldman Sachs, 2007; PwC, 2013; HSBC, 2012), and we adopt OECD's projection of GDP growth for China for the whole city region. This is equivalent to an annual growth rate of 5.1% over the modelling period, tapering from 10% per year in the decade 2010–2020 to 2.5% in 2040–2050. This is in line with the current government policy targets, and may somewhat underestimate the growth of the national capital which expects higher growth than nationally. Note the projections have already taken the recent slowing down of growth into consideration, for example the growth rates beyond 2030 are similar to the US's in the last two decades.

We make a further assumption that the residents' per person average income levels will grow at the same rate as GDP, for two reasons: first, this is in line with the current government's policy objectives to rebalance the economy and promote domestic consumption; secondly, since China's total population in 2050 will be around 6% larger than 2010 (i.e. from 1.34 billion to 1.42bn, according to UN Population Fund), assuming Beijing's per person average income to grow at the overall GDP rate implies that the income of this region will grow by 6% more than the national average – this would seem appro-

Table 2
Headline economic and demographic assumptions 2020–2050 for Beijing Municipality.

Area		2010	2020	2030	2040	2050
All study area	Average annual GDP growth rate per decade	11.2%	10.0%	4.9%	3.2%	2.5%
Beijing	Average income per capita in Beijing (yuan in 2010 prices; 1 yuan = US$0.155)	22,200	57,800	93,400	129,000	164,500
Beijing	Employed residents	11.80	13.85	15.89	17.94	20.00
	Annual growth rate per decade		*1.6%*	*1.4%*	*1.2%*	*1.1%*
	College students	0.56	0.65	0.73	0.81	0.88
	Annual growth rate per decade		1.4%	1.2%	1.0%	0.9%
	Other residents	6.00	7.60	9.21	10.80	12.38
	Annual growth rate per decade		2.4%	1.9%	1.6%	1.4%
	All residents	18.36	22.10	25.84	29.55	33.25
	Annual growth rate per decade		1.9%	1.6%	1.4%	1.2%
	Short stay population	1.80	2.11	2.42	2.73	3.04
	Annual growth rate per decade		1.6%	1.4%	1.2%	1.1%
	All population	20.16	24.21	28.26	32.28	36.30
	Annual growth rate per decade		1.8%	1.6%	1.3%	1.2%
Tianjin and Hebei	Employed residents	47.62	54.76	61.90	70.23	78.57
	College students	1.22	1.45	1.67	1.90	2.13
	Other residents	22.19	25.70	29.20	33.15	37.09
	All residents	71.02	81.90	92.78	105.28	117.79
	Short stay population	4.64	5.51	6.38	7.25	8.13
	All population	75.67	87.42	99.17	112.54	125.91
	Annual growth rate per decade		1.45%	1.27%	1.27%	1.13%
All	Employed residents	59.42	68.61	77.80	88.18	98.56
	College students	1.78	2.09	2.40	2.71	3.02
	Other residents	28.18	33.30	38.42	43.94	49.47
	All residents	89.38	104.00	118.62	134.83	151.04
	Short stay population	6.44	7.62	8.80	9.99	11.17
	All population	95.83	111.62	127.42	144.82	162.21
	Annual growth rate per decade		1.54%	1.33%	1.29%	1.14%

Note: All population figures are in million.

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Table 3
Beijing's socio-economic composition in 2000 and 2010 and alternative projections for 2050.

	2000	2010	2050 as per western Europe trends 1970–2000	2050 as per US trends 1970–2000	2050 as per Brazilian trends 1973–1996
High income	16%	16%	25%	30%	20%
Middle income	46%	56%	65%	45%	55%
Low income	38%	28%	10%	25%	25%
All	100%	100%	100%	100%	100%

Table 4
Summary of the permitted locations for discretionary housing floor space and building floorspace growth by land use scenario.

		Central urban districts	Near suburbs	New Towns	Far suburbs	Ecological protection area at the western and northern periphery
Trend	Housing	×	✓	✓	✓	×
	Business floorspace	×	✓	✓	✓	×
Decentralisation	Housing	×	×	✓	✓	×
	Business floorspace	✓	✓	×	×	×
Densification	Housing	×	×	✓	✓	×
	Business floorspace	×	×	✓	✓	×
Spatial mismatch	Housing	✓	✓	×	×	×
	Business floorspace	✓	✓	×	×	×

Note: The four zoning categories follow standard administrative classification in Beijing.

priate (if not a little too conservative). Because the model uses constant 2010 prices throughout, the income levels (along with the price levels) reflect directly the GDP assumptions (Table 2).

For population size, the total population for Beijing municipality is the most debated variable, since the long term population may be subject to policy control. Here we follow the lower end of the projection by Wu et al. (2009) in line with the general sentiment for the need of population growth restraints in the region, and project the total population to around 36 million in 2050, which implies a rise by 80% from 2010. Tianjin and Hebei province are projected to grow at a lower rate, by 66% from 2010 through 2050. We further assume that the labour participation rate is 60% for the region's attraction to young and skilled adults, a little higher than the expected China average (at just under 50% by 2050, see Wang and Lin, 2006; Qi, 2010; UN 2010; 2015). In addition, short stay population (or 'floating population' in official statistics terminology referring to tourists and short stay workers) is projected to grow at the same rate as residents in each municipality/province (Table 2).

Because the model differentiates socioeconomic profiles of households and employed residents in three categories (which are broadly in line with income and car ownership), a further projection of the overall socioeconomic profile of the population is required for each municipality/province. Based on this overall composition assumption, the model can predict the probabilities of where each socioeconomic group choose to live amongst the model zones.

After an extensive review of methods, we base this assumption on social mobility studies of the forerunners of industrialisation that are based on the Erikson-Goldthorpe-Portocarero (EGP) schema of socioeconomic classification (Rong, 2016). We particularly focus on the studies on the western European countries 1970–2000 (Breen, 2004), the US 1970–2000 s (Mitnik et al., 2013) and Brazil 1973–1996 (Costa-Ribeiro, 2008), because the existing studies on Asian countries like Japan and Korea examine social mobilities for male workers (Kanomata, 2007; Park and Cha, 2008; Park, 2003), which are less informative for Chinese city regions where women's labour participation rates are high. The European pattern is characterised by large increases of the middle group, a continuous reduction of the low group and a modest growth of the high group. The USA pattern reflects the evolution trajectories in high inequality countries, with large growth of the high group and little reduction of the low group. The Brazil model represents a relatively stagnate socio-economic profile, which remains stable throughout in terms of socio-economic segmentation.

Based on the observed changes of the socio-economic composition from 2000 to 2010 in Beijing, three projections can be made for 2050 following respectively the three social mobility patterns (Table 3). It would seem that the 2050 pattern as per western European trends best align with the government's policy objectives for poverty reduction and shared prosperity, and it is adopted here for modelling. The same method is used for the segmentation of households.

The assumptions about the long term land use are first concerned with household size and space standards for housing and business floorspace. According to the projections in real estate studies (Chen & Chen, 2013; Sun, 2011), the average household size for China is projected to reduce from 3.1 people in 2010 to 2.5 by 2050. Considering that Beijing's average household size tends to be smaller (2.7 in 2010), we assume that it will decrease to 2.0 in 2050. On the other hand, we assume housing conditions will continue to improve, with average per household housing floorspace rising from 78.2 m^2 in 2010 to 83.6 in 2020, 89.1 in 2030, 94.5 in 2040 and 100 in 2050. We further assume that among the total growth of hous-

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Table 5

Rates of CO_2 emission reduction per passenger km: 2030 and 2050 assumptions.

	Car & taxi	All buses	Metro/rail
2010	1.00	1.00	1.00
2030	0.57	0.72	0.80
2050	0.49	0.69	0.63

Table 6

CO_2 emission rates per passenger-km by trip distance range: assumptions for 2010, 2030 and 2050 (gram per passenger-km).

	2010			2030			2050		
Journey distance range (km)	Car & taxi	All buses	Metro/rail	Car & taxi	All buses	Metro/rail	Car & taxi	All buses	Metro/rail
0–1	480.0	50.0	70.0	275.2	35.8	56.3	235.4	34.5	44.0
1–2	400.0	40.0	60.0	229.3	28.6	48.2	196.1	27.6	37.7
2–5	300.0	38.0	58.0	172.0	27.2	46.6	147.1	26.2	36.5
5–10	170.0	37.0	56.0	97.5	26.5	45.0	83.4	25.5	35.2
10–15	150.0	35.0	54.0	86.0	25.1	43.4	73.6	24.2	34.0
15–20	140.0	23.0	52.0	80.3	16.5	41.8	68.7	15.9	32.7
20–25	130.0	21.0	49.0	74.5	15.0	39.4	63.7	14.5	30.8
25–50	124.0	20.0	45.0	71.1	14.3	36.2	60.8	13.8	28.3
>50	120.0	20.0	45.0	68.8	14.3	36.2	58.8	13.8	28.3
Average	160.5	28.7	48.8	85.6	23.1	38.1	68.8	22.9	30.2
Wang et al. (2015)	160.4	28.6	48.9						

ing floorspace, 10% comes from the small sized dwellings, 60% comes from the medium sized and 30% comes from the large sized. For business floor space, we assume that average per worker floorspace remains at $20m^2$ throughout.

We then develop alternative strategic land use scenarios based on the assumptions above, which specifies the broad land use development strategies regarding where housing and business floorspace will be growing. The design of the land use scenarios aims to take into account the planning targets from the Municipal Masterplan of Beijing 2004–2020 (BMG, 2005), the observed pattern from the online land provision data and the plan to move government and administrative functions to Tongzhou. We classify three kinds of growths as follows.

The first is natural growth which is spontaneous expansions of housing estates and business premises as they mature through infilling and densification in and around existing built-up areas – it is difficult to foresee how much natural growth there will be and how they will be distributed, but it is reasonable to assume that it occurs in proportion to existing building stocks in a zone (Jin et al., 2013). We further assume that natural growth will be 50% of the total growth which is determined by the total population, total employed persons and floorspace standards assumed above.

The second is relatively small scale discretionary strategic investment that can be distributed probabilistically across the city region based on alternative land use development and zoning regulations. Here four distinct strategic land use scenarios can be defined: (1) a trend scenario which is a continuation of the growth patterns since the early 1990 s; (2) decentralisation where the main discretionary investment of both business floorspace and housing will be located in far suburbs (except in ecologically sensitive areas there); (3) densification, which is the opposite to (2); (4) a spatial mismatch scenario where discretionary housing development occur in the far suburbs (similar to (2)) whilst business floorspace in the centre (similar to (3)). The probabilistic allocation of the discretionary growth to model zones in these categories is calculated by the recursive dynamic model, following distinct assumptions about where such developments are permitted (see Table 4).

The third is a targeted New Town scenario which for this paper is additional development and densification in and around Tongzhou to the east of the central built-up area, in line with recent announcements by the city government. The second and third types of growths account for the other half of the total assumed growth 2010–2050.

The purpose of the five land use scenarios is to cover the full range of land use and master planning options being discussed in the urban development policy arena. This forms a systematic backdrop to investigating strategic transport interventions and land use/transport coordination at the micro-scale.

Building on the strategic land use scenarios, we test some finer grained land use and transport assumptions. This is particularly pertinent with the densification scenario, where the high costs in the centre and near suburbs of Beijing may constrain the total amount of delivery of floorspace construction. Meanwhile the denser urban environment may slow down the average speed of passenger travel through increased traffic congestion. The scenario test results we report below for the densification scenario is a variant that assumes that in the centre and near suburbs of Beijing there will be no net increase of building floorspace (i.e. neither natural nor discretionary growth), and that owing to increased number of residents and employment there traffic congestion will increase travel times to and from those areas by 3% each decade.

Table 7
Annual passenger kms (million), passenger trips and average travel distance (km) by mode: 2010.

Distance range (km)	Car & taxi	All buses	Walk	Cycling	Metro & Rail	All
Passenger km by distance range (million/year)						
0–1	259	11	1179	195	–	1644
1–2	857	290	1378	864	–	3388
2–5	9479	4729	3853	5782	523	24,365
5–10	12,061	12,369	75	2182	1674	28,360
10–15	7308	8809	–	247	4013	20,378
15–20	3624	7602	–	46	6022	17,294
20–25	2815	7168	–	–	7559	17,543
25–50	26,364	6450	–	–	8409	41,224
>50	13,055	6122	–	–	7157	26,334
All passenger-km	75,822	53,551	6486	9316	35,356	180,531
All passenger trips (million/year)	6022	6788	5515	2055	2545	22,926
Average distance of travel (km)	12.59	7.89	1.18	4.53	13.89	7.87
Observed weekday average distance of travel (km; from BTRC, 2012)	9.3–11.5	10.8–14.8	0.9	3.7	18.0	7.6

In addition we test a number of transport interventions to ascertain the medium to long term impacts of travel demand management measures. The interventions tested include road pricing for passenger cars at a rate of 0.2 yuan/km (in 2010 prices) across the city region, in line with the current, active interest in road charging in Beijing, adjustments of bus and metro fares (both fare reductions and increases), car access and parking restrictions in central Beijing, and micro-scale land use and building design that is coordinated with bus stops (including BRTs) and metro/rail stations.

In particular, the micro-scale land use and transport coordination is expected to reduce the average door to door journey times by public transport. We test different levels of coordination. In the results we report below are derived from a top level coordination where the door-to-door public transport journey times are cut by 5 min at each end for short, intra-zonal journeys (mainly from more efficient access and egress from stops/stations), 7.5 min for medium length journeys (through more efficient access, egress and interchange) and 10 min for journeys to remote far suburb and rural areas (through more efficient access, egress, interchange and coordination of service departure times).

Finally, to calculate transport CO_2 emission reduction over the decades to 2050, it is necessary to make assumptions of technical progress and lifestyle changes (e.g. adopting a more environmentally sustainable attitude towards the means and needs of travel). Here we adopt the assumption that citizens in the Greater Beijing region will have the same rate of progress as in a developed country like the UK, as projected by the UK 2050 energy pathways (DECC, 2013). The rates of CO_2 emission reductions per passenger km for 2030 and 2050 are assumed accordingly in Table 5. Further, we assume the CO_2 emission rates per passenger km vary by trip distance range (due to emissions from fixed installations, cold starts for cars, and engine fuel consumption profile), which are calibrated to match the observed average rates reported in the latest literature (Table 6).

4. Model results for 2030 and 2050

The suite of dynamic land development and building space model, the spatial equilibrium model and the strategic transport model are run from the validated 2010 base year in decade-long increments to 2020, 2030, 2040 and 2050. We focus on presenting the results for 2030 and 2050 because they are the key policy horizons. We also focus on the results for the Beijing Municipality because there is data to compare and validate the forecasts.

The headline finding of the range of scenarios is that, in spite of the recent slowdown in national economic growth, urban travel demand (especially that for car travel) in Beijing is likely to surge further along with income growth and a large number of residents moving into the high and medium income strata. The transition is likely to involve a non-marginal change in travel demand, which to begin with would be inappropriate to investigate using an approach for marginal transport improvements. The model results have a much greater level of spatial and temporal details than we have space for in this paper. We will first consider the realism of the passenger-km results by transport mode, which are central to estimating emissions of CO_2 and other pollutants. We will then estimate the CO_2 emissions by model scenario and variant. The modal passenger-km outputs can be used analogously to estimate other pollutants which we will not include here.

Table 7 summarises the profile of the annual passenger-km travelled by distance range of the trips for 2010. The spatial granularity of the model allows micro-level investigation of the trips for specific origins, destinations, routes and time period. However, we choose to analyse the passenger-km profiles at a less detailed, meso level for two reasons. First, at this level we can make use of the existing data on travel patterns (such as BTRC, 2007, 2012) to scrutinise the realism of the model. Second, we engage with the current literature which tends to estimate transport emissions through total passenger-kms by mode (although usually NOT by distance range). This meso level analysis has the advantage of analytical transparency as far as the existing contributors are concerned. Table 7 also compares the modelled average journey lengths by mode against the observed weekday journey lengths reported for 2010 by BTRC (2012). Although the comparison of grossed annual data for all

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travellers (residents and floating population) is not strictly comparable with the observed weekday figures, the comparison serves to indicate that there are good reasons to suggest that the modelled passenger-kms are reasonably realistic.

We further compare the percentage modal share of passenger kms as output by the model against the figures reported for 2010 by BTRC (2012) in Table 8. Here again the two patterns are similar, and give us some confidence in the capability of the model in representing existing travel.

On this basis we proceed to analyse the model outputs for the main land use planning scenarios in the middle part of Table 8. The forecasts show that by 2030, car passenger-km is to grow from 42% to 52% (under densification) through 54% (under decentralisation) of the total as land use development continues in the near suburbs and beyond. By 2050, the car passenger-km share is to increase further to 67% (under densification) through 71% (under decentralisation). Since by 2050 Beijing's household income profiles are similar to those of a mid level western European country today, such percentage of share in car travel is not surprising. Such trends however do imply that car use (particularly in the wider suburbs) will rise very strongly beyond 2030, which will need to be carefully considered in implementing the plans of reducing the absolute levels of CO_2 emissions after 2030.

The forecasts also highlight the strong demand growth for buses, metro and suburban rail services from 2010 to 2030. Typically demand for buses will rise by more than 20% and for metro/rail more than double, if the assumed 2008 mobility pattern is to be maintained. It is also of interest to note that further land use expansion during 2030–2050 would make it more difficult for public transport to attract new patronage as the rise of income and car ownership erodes its existing market share. This does serve as a warning for long term land use planning and built form design.

The effects of proactive travel demand management are reflected in the road charging and land use/public transport coordination tests which are reported at the bottom of Table 8. These two measures appear to be more effective than greater subsidies for public transport fares or physical restrictions on cars in dense urban areas (which were also tested). The encouraging news is that they are very effective in reducing car travel demand – particularly when implemented together – but the model also suggests that in order to maintain an equivalent level of personal mobility across the city, demand on both buses and metro/rail will increase dramatically. An improved level of service in public transport may also erode the modal share of walking and cycling. Even under a combination of both demand management measures, car travel will still grow to 191.4 billion passenger-km by 2050, which is two and half times that in 2010.

Of course, the expected technical progress and lifestyle changes will mitigate to some extent the increase in transport emissions. Table 9 summarises the headline CO_2 emission estimates for the city region as a whole, using emission factors that are variable across the journey distance ranges (cf Table 6). Table 9 first reports the estimated 2010 CO_2 emissions. The estimates are slightly higher than those reported by Wang et al. (2015) because here the model has a more comprehensive coverage of all travel in Greater Beijing and the model estimates of passenger-kms might have slightly biased upwards. However, the figures are of a very similar level.

The CO_2 emissions for the future years are reported as percentage changes for ease of comparison. Indeed the rise in CO_2 emissions are ameliorated through transport technology advances and lifestyle changes (as included in the 2030 and 2050 assumptions, cf. Table 5). However, even under such fairly optimistic assumptions, the overall CO_2 emissions in 2050 are to rise steeply from the 2010 levels, unless both road pricing and land use/public transport coordination are implemented (see bottom of Table 9).

Table 8
Modelled annual passenger kms (billion) for 2010 and 2030/2050 scenarios.

		Car & taxi	All buses	Walk	Cycling	Metro & Rail	All
2010	Base Year total passenger-km	75.8	53.6	6.5	9.3	35.4	180.5
	%mode share of passenger-km	42%	30%	4%	5%	20%	100%
	Observed weekday % mode share of passenger-km	43%	28%	4%	6%	19%	100%
Scenarios							
2030	Trend	185.2	63.1	6.8	3.7	82.8	341.6
	Decentralisation	182.2	68.2	6.5	3.6	80.1	340.6
	Densification	170.7	59.7	7.0	3.8	84.4	325.7
	Mismatch	191.4	64.1	6.6	3.6	94.9	360.6
	Tongzhou New City	186.0	68.7	6.6	3.6	83.1	348.0
2050	Trend	378.7	66.1	6.9	3.6	76.6	531.8
	Decentralisation	388.3	75.4	6.5	3.4	71.7	545.3
	Densification	332.7	60.7	7.2	3.8	84.3	488.8
	Mismatch	415.7	67.0	6.5	3.4	90.4	583.0
	Tongzhou New City	367.6	76.0	6.7	3.4	67.3	521.0
Variants of the Trend scenario							
2030	+Road charging	99.4	79.1	7.9	4.4	120.3	311.0
	+PT & land use coordination	125.9	108.0	4.0	2.1	109.5	349.4
	+Both above	59.5	123.7	4.3	2.3	139.4	329.3
2050	+Road charging	274.5	78.8	7.7	4.1	110.4	475.5
	+PT & land use coordination	285.6	119.5	4.1	2.1	112.2	523.5
	+Both above	191.3	133.8	4.4	2.3	147.4	479.1

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Table 9
CO_2 emissions as derived from passenger-kms: car & taxi, all buses and metro/rail.

		Car & taxi	All buses	Metro/rail
2010	CO_2 emissions (million tonnes/year)	12.2	1.5	1.7
Land use development scenarios:% change vs 2010				
2030	Trend	130%	95%	183%
	Decentralisation	128%	101%	176%
	Densification	122%	90%	188%
	Mismatch	133%	95%	209%
	Tongzhou New City	130%	102%	183%
2050	Trend	214%	99%	134%
	Decentralisation	218%	110%	125%
	Densification	193%	91%	150%
	Mismatch	231%	99%	157%
	Tongzhou New City	208%	113%	117%
Variants of the Trend scenario:% change vs 2010				
2030	+Road charging	77%	117%	264%
	+PT & land use coordination	86%	163%	244%
	+Both above	45%	184%	309%
2050	+Road charging	161%	116%	191%
	+PT & land use coordination	157%	178%	198%
	+Both above	109%	198%	257%

5. Discussions, conclusions and further work

The approach we have adopted in this paper first assumes that the residents in the city would demand a certain level of service from the urban transport system in the medium to long term in terms of door to door travel time. The modelling suite then works out where people and jobs will choose to be, given the changes in city size, income levels, expected demographic and lifestyle changes, and alternative land use planning scenarios. The location predictions are then used to work out on what modes and routes the travel demand will be and how much pressure different parts of the transport will be under, for different transport investment, regulation and pricing scenarios. In particular, the modelling suit may be used for testing non-marginal changes in land use and transport.

The findings suggests that background trends of urbanization, economic growth and income growths will continue to be very powerful drivers for urban passenger travel demand across all main modes of transport beyond 2030. The model tests provide the first evidence of the likely magnitude of the rises in urban travel demand and CO_2 emissions in the city region.

The tests of a wide range of strategic land use scenarios show that policies to densify urban areas does help somewhat to restrain car use and may accordingly slow down the rise in CO_2 emissions if such policies are applied persistently over decades and without causing traffic congestion to worsen. Nevertheless even under such scenarios the overall impacts are limited. This is in line with the findings in developed countries (see e.g. Ewing and Cervero, 2010; Echenique et al., 2012). The reasons for the small differences lie in the spatial equilibrium processes through which businesses and households adapt to maximise respectively production efficiency and wellbeing.

In order to achieve the dual policy aims for a moderately affluent and equitable nation and reducing the overall levels of urban transport emissions from 2030, road charging and careful micro-level land use/transport coordination may both need to be considered for policy implementation in the near future. Both types of measures are still facing significant practical barriers in project design and implementation. However, it is of particular interest to note that the model results suggest that the combined effects of both measures are far greater than the each implemented alone. A combined implementation design also makes practical sense, since improvements in the level of service of public transport provide efficient mobility alternatives to car, and thus help to garner support for road charging proposals.

One of the most interesting findings is that 2050 may represent the close of a narrowing time window for travel demand management measures to take significant effect. As household incomes rise, price elasticities for travel drop and travel demand in Beijing increasingly reflects characteristics of developed countries where car ownership and car travel react weakly to public transport investments (see e.g. Cao and Cao, 2015; Jahanshahi et al., 2015).

The insights for Greater Beijing are likely to resonate in many fast growing city regions both in China and elsewhere in the world. The magnitudes of the challenges in those other cities are likely to be similar as they share similar circumstances and background trends.

We expect that this analysis will shed a new light on the impacts of transformations of the regional economy, demography, lifestyles and travel demand, and thus would help to fill some of the gap regarding the medium to long term visions for designing a sustainable transport system for fast growing cities such as Beijing.

Because the empirical data and validation is the strongest for the municipality of Beijing, the analyses presented are only for this area. Other areas in the region such as Tianjin and Hebei can be analysed analogously, although at present the empirical foundation for those areas is less strong and may require further work.

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We note also that the land use and transport intervention measures tested in this paper represent in themselves complex policy and project packages. For simplicity we started from what those packages could achieve in altering travel costs (e.g. by car) or travel times (e.g. by public transport). The specific regulations and investment projects are likely to be locally specific and they require adjustments from time to time over the decades. Furthermore, the locally specific patterns of emissions (such as revealed by Reyna et al., 2015 for the US) may be worth investigating. A modelling suite such as demonstrated in this paper can also help policy analysts to explore the interventions locally and within a specific decade. In doing so the model may benefit from being checked and validated in progressively more detail.

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