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Integrated Simulation and Optimization Approach for Studying Urban Transportation-Environment Systems in Beijing

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ABSTRACT. Based on a systematic analysis of Beijing's Urban Transportation-Environment Systems (UTES), an integrated model is built, seeking an optimized and feasible trip mode structure on the premise of resident trip demands, environmental and resource capacity, and feasibility of policy adjustment in Beijing. First, a system dynamics model and a linear optimization model are founded for the Business-as-Usual simulation and best results of transportation development. Next, eight ameliorated scenarios combining four policies on Clean Transportation, Bus Priority, Subway Priority, and Car Trip Restriction are re-simulated. Finally, the results from nine scenarios are compared with the optimized results through grey correlation assessment. Findings show that adjustment policies have positive effects on the improvement of UTES, although these are varied and occur at different time scales. Integrated adjustment measures for sustainable transportation should be employed in Beijing because a combination of policies yields better effects than individual regulations. The derived optimized trip mode structures of Beijing in 2020 for subways, taxis, cars, buses and bicycling or walking are 19.41, 2.58, 24.99, 32.57 and 20.46% respectively, while daily resident trips reach 59.5 million. In this scenario, the environmental and land use demand are within supply capacity, whereas energy supply remains limited.

Keywords: Beijing, linear optimization, system dynamics, trip mode structure, urban transportation-environment systems

1. Introduction

With rapid social and economic development in the past 20 years, the urban area and population size of the municipality of Beijing have expanded dramatically. Studies show that over 75% of the population is exposed to air that does not satisfy the National Ambient Air Quality Standards for cities (Shao et al., 2006), and the dominant source of air pollution is vehicular emissions (Mayer, 1999). The large number of resident trips associated with socio-economic development and increasing level of motorization are the most significant characteristics of Beijing's urban transportation system. Such changes bring convenience, swiftness, and flexibility to daily commuting, but at the same time also cause heavy resource-environment pressures and traffic jams. Promoting sustainable transport in big cities has become a popular issue since it was formally raised in 1996 (Rodríguez and Joo, 2004).

To consider all the aspects related to city transportation as a whole, environmental issues such as air pollution and land availability for transportation were introduced into the urban transportation system, forming an integrated system called Urban Transportation-Environment Systems (UTES). It is an open, massive, and complex system focusing on the interaction among society, economics, environment, and transportation in a city. It can be divided into four subsystems: social, economic, transportation, and resource-environment. Every subsystem is closely related, with information transferring among each, resulting in a series of changes in the entire system every time an individual subsystem is modified. Thus, to study such massive systems, the components and interactions in each subsystem are determined, as well as the influence of each subsystem on one another. The characteristics of the actual system can be reflected, creating a solid foundation for the following model design.

Current studies on such a complex system focus on two aspects. One is simulation using the framework of the Long-range Energy Alternatives Planning (LEAP) System, developed at the Stockholm Environment Institute (Dhakal, 2003; Kumar et al., 2003; Huang et al., 2005; Song et al., 2007). Other simulation models include life cycle analysis (Schmid et al., 1999; Tan et al., 2004), spreadsheet model (Zhang et al., 2003), long-term least cost vehicular mix model (Shrestha et al., 2005), and three-stage problem structuring model (Ulengin et al., 2010). Most of the simulation models have been applied in case studies of Beijing (Zhu and Jiang, 2002; Zhang et al., 2003; Shrestha et al., 2005; Li and Zhang, 2006). Scenario

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analysis (SA) is always used with simulation models (Bose, 2007; Liu et al., 2007). The common perspective generated through simulation analysis is that for sustainable development of urban transportation in Beijing, the best mode is public transportation, followed by bicycles, and finally, private cars (Shi et al., 2004; Liu and Guan, 2005).

The second aspect focused on is the optimization model, which aims to seek the best trip mode structure of a city. The linear optimization model is widely used (Ge et al., 2004; Shen and Lu, 2005; Tian, 2006; Lv et al., 2007). Other models such as the system dynamics model (Shen et al., 1997) and decomposition models for reliability optimization (Lin, 2001) have been used in studies of Beijing. These models are generally formed with the object of maximum sustainable indexes or transportation efficiency, and with environmental capacity and resident trip demands as constraints.

Current studies focus on a single model, aiming at calculating environmental and resource pressures of certain trip mode structures, or deriving best trip mode structures under constraints of resident trip demands and resource-environment capacity. The former does not consider the environmental and resource constraints of transportation development, whereas the latter ignores the feasibility of results. The lack of integration of simulation models and optimization, and its limited application to the management of the urban transportation system in Beijing is another issue that needs to be addressed. In this study, simulation and optimization are combined to determine an optimized and feasible trip mode structure for Beijing, taking into account the entire UTES. Models including system dynamics, linear optimization, scenario analysis, and grey correlation assessment are integrated to fill the deficiency of single models. The results derived in Beijing serve as valid instructions for sustainable transportation development in the city.

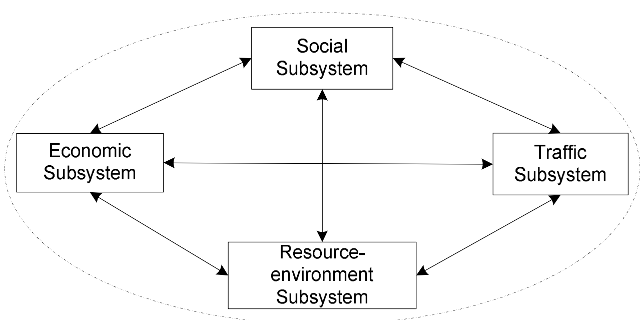

Figure 1. Interactions among four subsystems in the UTES.

2. Methodology

2.1. Urban Transportation-Environment Systems

The interactions among the four subsystems in the UTES are shown in Figure 1. Social and economic development is the fundamental reason for increasing demand for transportation. Larger populations and increased business connections generate more travel. At the same time, a well-developed urban transporttation system plays an important role in promoting socio-economic development. Moreover, an interplay exists between population growth and economic development. Labor is one of the fundamental elements of economy, and good economy leads to larger populations. The resource-environment subsystem is an effective support for the development of the other three subsystems, supplying necessary resources such as energy and land, as well as containing emitted pollutants, especially air pollutants. Once development exceeds the resource and environment capacity of a region, progress slows down.

2.2. Integrated Optimization Model for UTES

An urban transportation system is the basic carrier of resident trips, with its trip mode structure being the key issue in trip studies and transportation policy making. The development of a transportation system in a city not only depends on the socio-economic setting, but is also restricted by resource and environmental conditions. Thus, taking account of complicated feedback relationship among socio-economic circumstances, resource, environmental conditions, and urban trip mode structure, is very important in the system optimization of UTES. The optimization model used in this article was developed with resident trip mode structure as core, integrating system dynamics, linear optimization, scenario analysis, and grey correlation assessment (Liu et al., 2010). The methodology of the integrated optimization model for UTES is shown in Figure 2.

System Dynamics (SD) was first introduced in 1956 by Forrester, and it focuses on identifying and solving problems through systematic models created with the help of computer simulation technology. This was based on the relationship among systematic behavior, structure, and function (Wang, 1995). In our integrated model, SD was used to simulate the development characteristics of the urban transportation system, as well as its environmental and resource effects, based on the systematic analysis of causal relationship among society, economy, environment, and resources related to urban resident trips. Defining the boundary of a system is the foundation of systematic analysis (Jia and Ding, 2002), and it is assumed that the changes beyond the boundary will not crucially influence the system. Therefore, the inner elements of the system should explain all behaviors. In our case, these inner elements are defined as socio-economic, environmental, and resource elements closely related to resident trips.

In addition, a linear optimization model was created to seek the optimized trip assignment structure, with the objective of maximizing transportation efficiency under resource and environmental constraints. The classification of the trip modes is identical to those in the SD model; however, the subsystems here were simplified, focusing on resource and environmental pressures. The total resident trips in this model, which is determined by socio-economic development, were directly derived from the SD model.

The result of the optimization model was derived under strict constraints of environmental and resource conditions, without considering its feasibility, and the Business-as-Usual (BAU) scenario simulated through the SD model restricted sys-

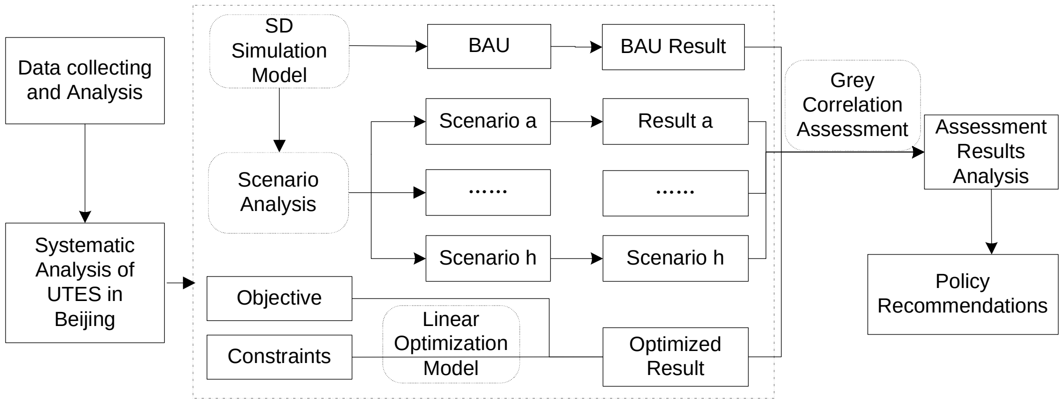

Figure 2. Construction flow of the optimized model of UTES.

tem development under the present trend, and new policy implementation was not taken into account. SA was introduced into the integrated model to study the feedback on UTES development of environmental and resource constraints. SA, which was generally paid attention to because of the publication ***Limits to Growth*** (Shiftan et al., 2003), comprises expert knowledge, prediction of the future, and human choice behaviors. It is a powerful tool for policy making (Swart et al., 2004). In our model, based on the results of the two former models, possible bottleneck factors were identified and several scenarios of different policies were designed. Amending effects were resimulated through the SD model, reflecting the possible development of UTES under feasible policy mix.

Finally, grey correlation assessment (GCA) was utilized on the premise of socio-economic support, feasible policy, and minimized pressures on resource and environment to select the optimized assignment structure. GCA is based on grey system theory, firstly put forward by Deng Julong (Deng, 1987). The fundamental principle is that the smaller the relative distance between two statistical series, the more similar the two series are. In our model, the result of linear optimization model was considered as an ideal series, and the results of other scenarios were compared with it, obtaining the relative pressures on resource and environment of each scenario, and the lowest result as the optimized trip mode structure. The transportation policy can also be evaluated based on this.

The connection of these two models was the loosely coupled simulation and optimization of the UTES. System analysis was the basis of the optimization model, which in turn conducted the scenario design and re-simulation. Such a combination can realize optimized and feasible trip mode structure in the future, as well as support urban transportation system planning and management.

3. Study Area and Data Sources

The study area in our model is the city of Beijing, which comprises 16 districts and 2 counties, with a total area of 16,410 km^2. Considering data availability and systematicity, the base year used is 2005.

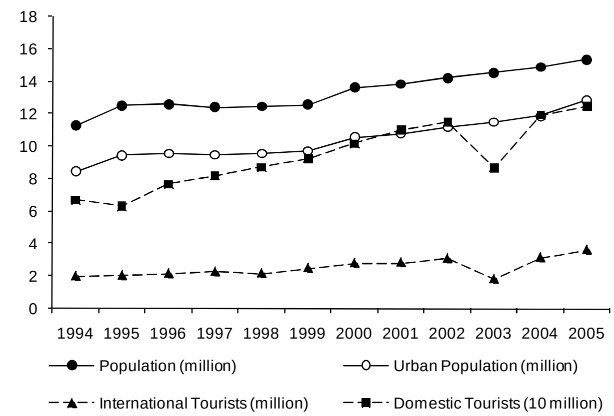

Figure 3. Population and tourists of Beijing (1994-2005).

Beijing, the capital of P.R.C., is located in North China and is the largest economic center. It is also an unparalleled cultural center, attracting many tourists and new residents every year. The population and number of tourists in Beijing in 2005 are shown in Figure 3. The permanent population of Beijing increased at an average of 2.88% every year from 1994 to 2005, and at the end of 2005, its population was 15.38 million. The urban population had almost the same increasing trend with permanent population, but at a higher rate of 3.88%. International and domestic tourists visiting Beijing showed a constant increase as well, except in 2003, when SARS broke out. The sizeable population as well as tourists brought greater pressure to the transportation system in Beijing. The heavy traffic jams, especially during rush hour, is an efficient illustration. Aside from this, the increasing daily trip intensity from 1.61 times per capita in 1986 to 2.42 in 2004 is another factor contributing to pressure in the transportation system.

From the aspect of trip purpose, the basic trip routine including going to and from work and school accounted for the largest proportion of transportation use, whereas the ratio of other trips such as shopping, visiting, entertaining, and so on, increased in recent years because of the improvement in quality of

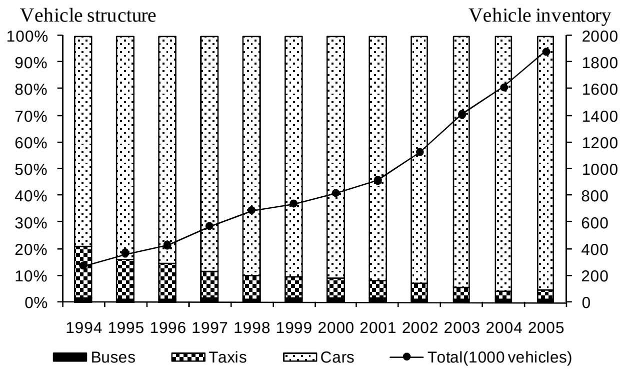

Figure 4. Growth of automobile inventory and evolution of its structure (1994–2005).

Table 1. The Changes of Trip Mode Structure (walking not included)

Trip mode	1986 (%)	2000 (%)	2004 (%)
Bicycling	62.66	38.49	39.87
Public transportation*	28.22	26.51	21.89
Taxi	0.35	8.76	1.52
Social cars**	5.04	23.24	25.32

Data Source: Annual Report of Transportation Development in Beijing (2005), Comprehensive Survey Report of Urban Transportation in Beijing (2nd).

*Including buses and subway.

**Data in 1986 include cars for official business only.

life. The trip mode structure changed dramatically in the last few decades (Table 1). The ratios of bicycling and public transportation decreased, whereas the ratios of taxis and cars, which were more convenient forms of transportation, increased. In 2004, bicycling or walking were the two main trip modes, accounting for more than 50% of resident trips. Cars, including self-owned and official-owned automobiles, and public transportation followed. These results also show that the possibility of choosing cars for trips out was much higher in families who owned cars than those who did not own cars. Changes in automobile inventory growth and structure evolution from 1994 to 2005 in Beijing are shown in Figure 4. Car inventory significantly increased, and its ratio in 2005 was 74.3%.

The motorization of trips brought convenience to residents. However, air pollutants and energy demand rose as well. Studies show that 40 to 80% of air pollutants in cities were emitted from automobiles (Ghose et al., 2004). The percentages of automobile emission of NOx and CO were 68.4 and 78.5%, respectively (Hao et al., 2006), which considerably de- graded the air quality in Beijing. Areas along the Ring Roads had especially high concentrations of air pollutants. Energy supplied for automobiles and land for roads also increased with motorization. Beijing was an area short on energy; thus, the energy supply would be a limiting factor in the future. Fortunately, the Beijing municipal government and the public have been working tirelessly since 1995 to control vehicular emissions. Strategies and measures have been introduced to regulate land use and transportation planning, emission control of in-use vehicles and new vehicles, fuel quality improvement, introduction of clean fuel vehicle technology, and fiscal incentives (Hao et al., 2006).

The data used in our model were mainly from the Beijing Statistical Yearbook, Comprehensive Survey Report of Urban Transportation in Beijing (2nd), and Annual Report of Transportation Development in Beijing.

4. System Dynamics Model Development and Simulation

The UTES can be divided into four subsystems, according to previous analysis. Thus, the SD simulation model utilized in this study was designed to include the same four subsystems. The model was created using Vensim-PLE and the time range is from 2005 to 2020.

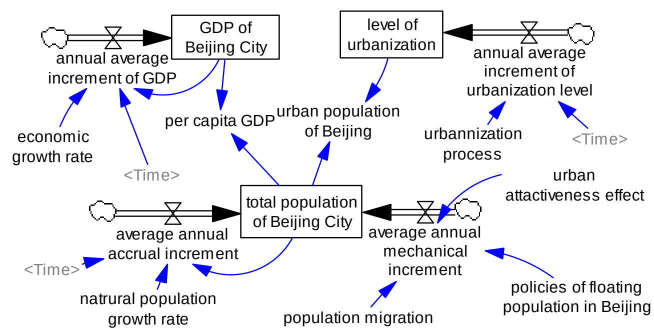

Figure 5. Social and economic subsystems.

4.1. Social and Economic Subsystems

Social and economic subsystems are closely related; thus, they were simplified and shown together in our model. Two level variables, the Gross Domestic Product (GDP) and the total population, are the base variables. According to historical data, the growth of GDP in Beijing is exponential. Two sources lead to the growth of total population: accrual increment and mechanical increment, which is always the main growth in cities such as Beijing. Mechanical growth is influenced by migration, attractiveness of the city, and policy on floating population. Additionally, the urban population and the per capita GDP were used to reflect the development state of the city. Figure 5 depicts the social and economic subsystem model.

4.2. Transportation Subsystem

Every trip mode significantly differs from each other in energy consumption, carrying capacity, speed, and pollution emission. In our study, according to the characteristics of resident trips in Beijing, we classified the trip modes into five types: buses, subway, taxis, cars, and bicycling or walking. Bicycling and walking have the same characteristics of low energy consumption, no pollution effects, and short trip distance; thus, we combined them as a single kind of trip mode.

The total trips contain two components generated by the

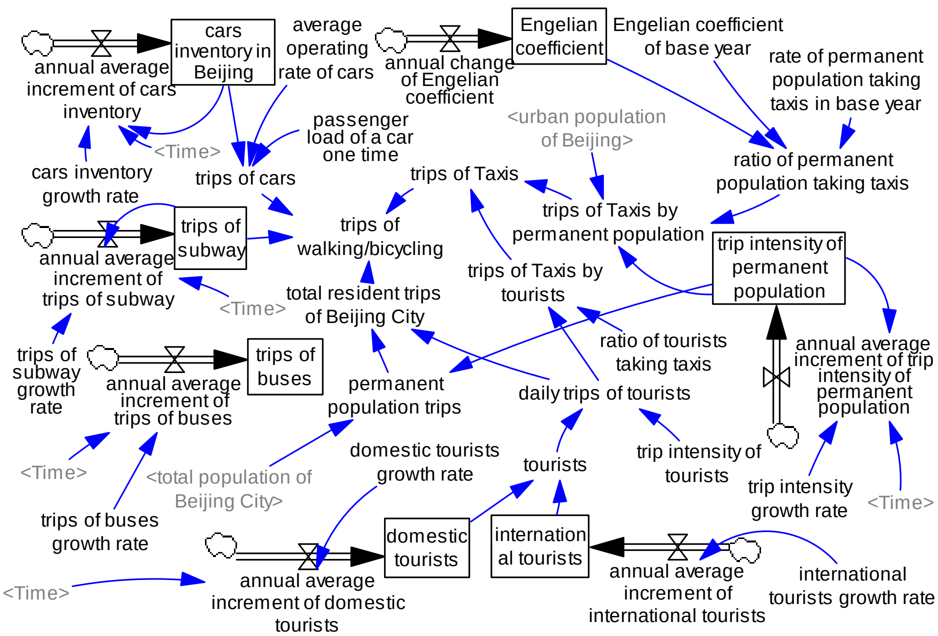

Figure 6. Transportation subsystem.

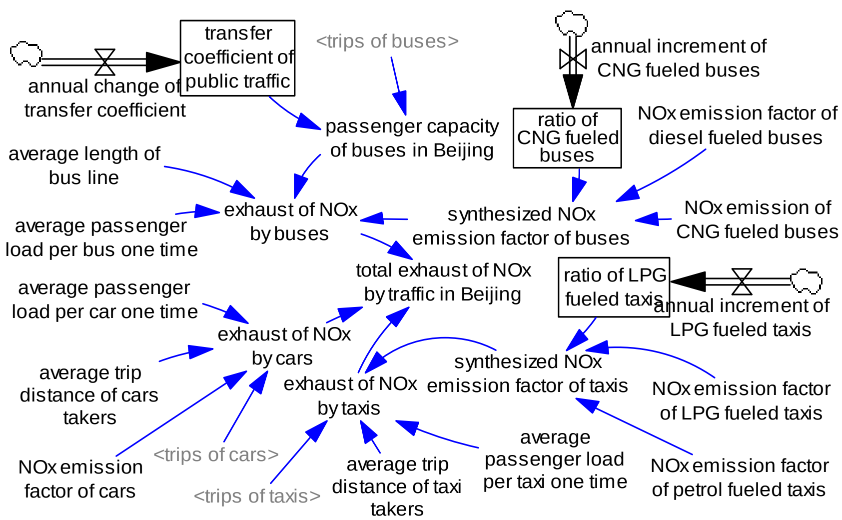

Figure 7. Exhaust sub-model for NOx.

permanent population and the floating population because these have different trip intensities and assignment structures. Similarly, the taxi trip mode is related to these two components. Trips via buses and subways, which are chosen mostly by the permanent population, are supposed to satisfy exponential growth according to historical data. Trips via cars are linked with inventory, the growth of which meets the logistic curve (Chen and Liu, 2007). The transportation subsystem model is depicted in Figure 6.

4.3. Resource-environment Subsystem

The resource-environment subsystem model focuses on

Table 2. Emission Factors of Different Automobiles in Beijing

	NOx (g/km)	CO (g/km)
Diesel-fueled buses	21.33	7.2
CNG-fueled buses	8.79	79.96
Petrol-fueled taxis	1.66	21.87
LPG-fueled taxis	1.51	15.5

Source: Hu et al., 2006

the environmental and resource effects of transportation subsystems, which include air pollution, noise, energy consumption, road building, water consumption for car washing, and so on. In our model, air pollutants NOx and CO, energy consumption,

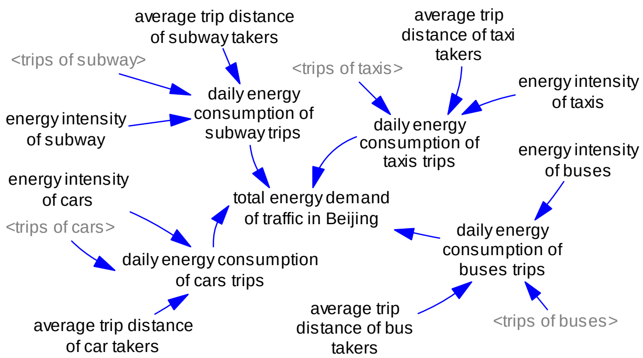

Figure 8. Transportation energy consumption sub-model.

and land for roads were chosen to represent the pressures on environment and resource.

4.3.1. Pollutant Emission

Emission factors are different not only for varying automobiles but also for different fuels (Table 2), because compressed natural gas (CNG) and liquefied petroleum gas (LPG) were introduced in 1999 and are used in buses and taxis for pollution control (Hao et al., 2006). The emission factors correspond to automobiles mileage, so that the resident trips are converted through passenger loads and trip distance per automobile derived from the Annual Report of Transportation Development in Beijing. The sub-models designed to simulate NOx and CO emission were essentially identical. Only the sub-model for NOx is shown here (Figure 7).

4.3.2. Energy Consumption

The energy consumption of the trip modes under different load carry duties is shown in Table 3 (Frost et al., 1997). Taxis are supposed to have the same energy consumption as cars, and bicycling or walking consumes no energy. The total energy consumption was then calculated (Figure 8).

4.3.3. Land for Roads

In this sub-model, land demand for roads are from cars, taxis, buses, and bicycling or walking, because the subway is mostly underground or overhead. Moreover, an effective transportation system should meet resident trips at any time; thus, the trips we considered were those that proceeded during traffic peaks--these accounted for the largest demand for roads (Zhai, 1991). Space needed for different vehicles are shown in Table 4 (Wang et al., 2004). The sub-model for transportation land use is shown in Figure 9.

4.4. SD Model Validation and BAU Simulation

4.4.1. Model Validation

After establishing the model, its validity, including operation calibration, historic calibration, and sensitivity analysis, was tested to ensure that it was comparable with the behavior of the actual system. Results of the previous two analyses show that the model is stable and can reflect the trend of the actual system (Figure 10 and 11). For sensitivity analysis, eight key para- meters and four decision variables were selected. A standard deviation of plus or minus 5% was used and the results of each parameter in response to each variable is shown in Table 5. Two parameters reflecting the growth of the socio-economic subsystem exhibit relatively greater effects on the entire system; thus, population and economic action that generate trips have considerable influence. The effects of other parameters on the entire system are insignificant. In general, these results indicate that the SD model can be utilized to simulate the actual system.

Table 3. Energy Consumption of Trip Modes under Different Load Carry Duties

Trip mode	Capacity	Energy consumption per km (MJ)	Energy consumption under different load carry duties (%) [MJ/(person•km)]			
			25	50	75	100
Cars	4	3.64	3.64	1.82	1.21	0.91
Subway	580	122	0.84	0.42	0.28	0.21
Buses	75	14.05	0.74	0.37	0.25	0.19

Table 4. Static and Dynamic Space Needs of Different Vehicles

Vehicle	Skeleton dimensions of automobiles (m; m^2)			Space headway (m)	Lane width (m)	Dynamic space need (m^2)
	Length	Width	Area			
Bicycle	1.9	0.6	1.14	7.4	1.0	7.4
Car	5.0	2.0	10.0	23.3	3.0	69.9
Bus	12.0	2.5	30.0	27.0	3.5	94.5

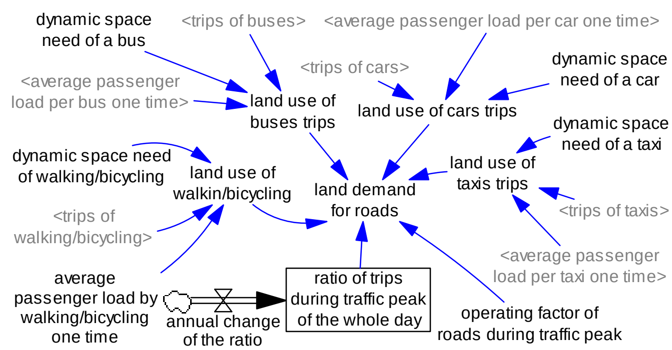

Figure 9. Land-for-roads sub-model.

4.4.2. BAU Simulation

The BAU scenario reflects the development trend of the system when all variables maintain the same changes as before. In 2020, daily resident trips will increase to 57.9 million. Ratio changes of different trip modes are shown in Figure 12. Motorization will increase considerably, especially car driving, which will reach a ratio of 55% in 2020. At the same time, the number of people who go out bicycling or walking will decrease signi-

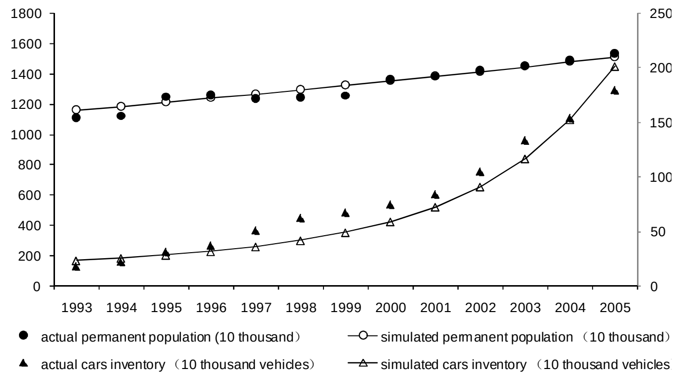

Figure 10. Results of historic calibration.

Table 5. Results of Sensitivity Analysis

	Total NOx	Total CO	Total energy demand	Land demand for roads	Average
Economic growth rate	0.2223	0.2456	0.2445	0.2068	0.2298
Natural population growth rate	0.0992	0.1076	0.1068	0.1089	0.1056
Urbanization process	0.0006	0.0006	0.0003	0.0008	0.0006
Trip intensity growth rate	0.0005	0.0005	0.0003	0.0073	0.0021
Trips of subway growth rate	0.0000	0.0000	0.0023	0.0039	0.0016
Domestic tourists growth rate	0.0052	0.0052	0.0031	0.0114	0.0062
International tourists growth rate	0.0005	0.0005	0.0003	0.0011	0.0006
Trips of buses growth rate	0.0145	0.0010	0.0028	0.0029	0.0212

Table 6. Results of BAU Simulation

Year	Resident trips (person-times per day)	Total NOx (10^2 t/d)	Total CO (10^2 t/d)	Energy demand (TJ/d)	Land demand for roads (km^2)
2006	41.06	3.40	38.45	645.42	308.37
2010	45.76	5.74	68.68	1149.27	504.65
2015	51.72	7.77	94.66	1582.46	676.39
2020	57.87	8.55	103.97	1738.31	744.34

ficantly. Taxis and public transportation will grow slowly, but in a stable manner. Associated with such changes, NOx and CO emitted as well as energy and roads demanded will expand sharply (Table 6), with an annual average growth rate of 6.81, 7.36, 7.33, and 6.50%, respectively.

5. UTES Optimization Model

5.1. Model Development

Since pollution emission, energy consumption and roads building are the main environmental and resources pressures of transportation, the linear optimization model was used to introduce the environmental capacity of UTES (TEC), supply capacity of transportation energy (ENG), and construction capacity for roads (RLD) as constraints to control the adverse effects on the environment of UTES development.

Different trip modes have comparative advantages and disadvantages. Cars have excellent transferability and traveling comfort, but their impacts on the environment and resources are largest. Public transportation, on the other hand, exhibits the opposite effects. As an integrated system, the development of UTES should simultaneously satisfy these requirements. Therefore, combined efficiencies of different trip modes (Table 7) were utilized in the objective function. The efficiencies were integrated evaluation values derived through a combined model on analytic hierarchy process and primary component analysis, based on the criteria of transportation function, passenger satisfaction, sustainability, investment, and policy support (Lv et al., 2003).

Table 7. Combined Efficiency of Different Transport Modes

Trip mode	Combined efficiency
Subway	0.0893
Buses	0.0429
Cars	0.0237
Bicycling/Walking	0.0185
Taxis	0.0144

The constraint conditions contain five aspects. The air pollutants, energy consumption, and land demand for roads should be no higher than TEC, ENG, and RLD (Equations 2 to 4). Sum trips of different modes should meet the needs of the population (Equation 5). There are ratio limits of different modes (Equation 6). The model is shown below:

$$\max C = \sum_{i=1}^{5} \alpha_i X_i \tag{1}$$

s.t.

$$\sum_{i=1}^{5} X_i \times M \times \beta_i \times a_{ij} \le TEC_j \ (j \in P) \tag{2}$$

$$\sum_{i=1}^{5} X_i \times M \times b_i \le ENG \tag{3}$$

$$\sum_{i=1}^{5} X_i \times M \times \beta_i \times c_i \times \gamma \le RLD \tag{4}$$

$$\sum_{i=1}^{5} X_i = 1 \tag{5}$$

$$X_{\min i} \le X_i \le X_{\max i} \tag{6}$$

Table 8. Definitions and Expressions of Different Variables in Optimization Model

Variables	Definitions	Expressions	Units
M	Total trips	derived from the SD model	times per day
β_i	transfer coefficient	for public transportation, 1.5* is assigned to β_i; for taxis, cars and bicycling or walking, 1 is assigned.	null
a_{ij}	Coefficient of emission	emission factor (g per km) × trip distance per automobile one time (km per vehicle run) / average passenger load (person-time per vehicle run)**	g per person-time
b_i	Coefficient of energy-consumption	energy consumption (MJ per person per km) × average trip distance one time (km per person-time)**	MJ per person-time
c_i	Coefficient of land-occupying	dynamic space need (m^2 per vehicle) × average passenger load per automobile one time (person-time per vehicle run)**	m^2 per person-time

* 1.5 is the optimized transfer coefficient committed by Beijing Municipal Government.
** The values of these variables are the same as in the SD model except emission factors, since more stringent standards for vehicle emissions will be applied.

Table 9. Detailed Values of Different Variables in Optimization Model

Variable	Year	Subway	Taxis	Cars	Buses	Bicycling/Walking
NOx a_i (g per person-time)	2010	0	7.47	18.13	2.64	0
	2020	0	7.47	14.51	2.64	0
CO a_i (g per person-time)	2010	0	87.72	224.85	23.99	0
	2020	0	87.72	188.59	23.99	0
b_i (MJ per person-time)	2010	2.52	15.5	43.52	2.81	0
	2020	2.52	15.5	43.52	2.81	0
c_i (m^2 per person-time)	2010	0	46.6	46.6	0.756	4
	2020	0	46.6	46.6	0.756	4

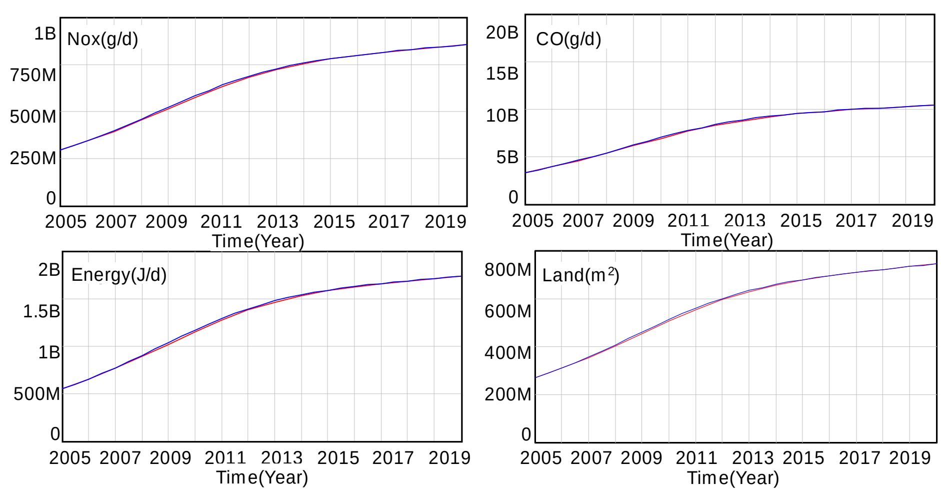

Figure 11. Results of operation calibration (The blue line shows the trend with step of one year, while the red shows that of half year).

where α_i is the combined efficiencies of different trip modes; X_i is the ratio of different trip modes; $i = 1 \sim 5$ refers to the five different trip modes respectively; P is the types of air pollutants; and j refers to NOx or CO. The definitions and expressions of M, β_i, a_{ij}, b_i and c_i are shown in Table 8, and the detailed values of a_{ij}, b_i, and c_i are shown in Table 9; γ represents characteristics of traffic peak.

TEC was calculated using the A value method recommended in the National Ambient Air Quality Standards of China. Contributions ratios of vehicle emission are derived from estimates of previous study of Beijing (Hao et al., 2006), and results are 353 t/d of NOx and 16,200 t/d of CO. ENG and RLD were derived from the Beijing City Comprehensive Planning (2004 ~ 2020).

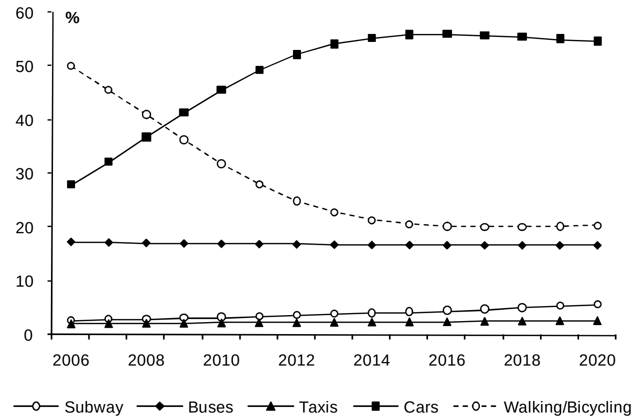

Figure 12. Trip mode structure of BAU simulation (2020).

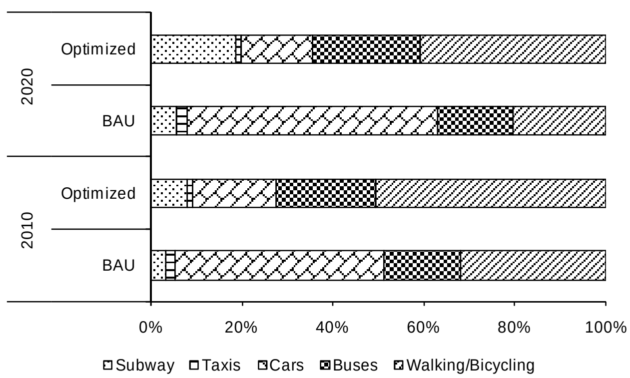

Figure 13. Comparison of trip mode structure between optimized and BAU results.

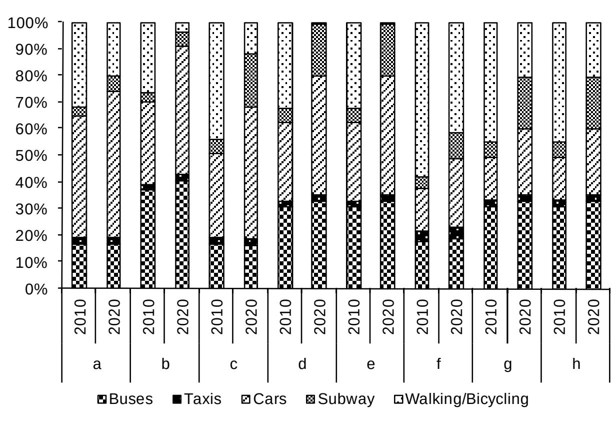

Figure 14. Trip mode structures of different scenarios (2010 and 2020).

5.2. Results

Results compared with those of the BAU scenario are shown in Figure 13 and Table 10. Because of the limit of environmental and resource constraints, the optimized results display the characteristics that unmotorized mode dominates, and the use of public transportation increases considerably, whereas that of cars is limited. As a result, pollutant emission as well as energy and land demand decreases significantly, almost 70% less than that observed in the BAU scenario. These also show that energy is a stringent constraint, whereas environmental capacity and land are relatively loose.

6. Policy Scenarios and Discussion

6.1. Policy Scenarios

6.1.1. Scenario Design

According to the results of the abovementioned models, the existing planning is related to transportation in Beijing and policies taken for sustainable transportation in other such cities. Thus, four policies on sustainable transportation in Beijing were selected. The first is Clean Transportation (CT), containing two aspects. One is promoting the replacement of public automobiles using clean fuels such as CNG and LPG. The other is the enactment of more stringent standards for vehicle emissions. Beijing has already applied National Standard III and IV in 2003 and 2005. Presently, the new standard V is under investigation. The second policy is Bus Priority (BP), which involves enhancing bus trips through a new bus network design, price discounts, and more buses in operation. The third is Subway Priority (SP). According to the Beijing Transport Development Outline (2004 ~ 2020), subway construction will expand quickly while a flat rate on all lines makes the subway a much cheaper transportation option. The subway has the unique characteristic of time reliability; thus, it is predicted that rapid subway development will attract passengers who normally ride on taxis, cars, and even buses. The last policy is Car Trip Restriction (CTR). Measures of car control by plate numbers, fuel oil tax, and parking fee increase are being implemented or are currently under discussion.

With human-computer interaction, eight scenarios were derived and results were re-simulated. Scenarios *a*, *b*, *c*, and *f* correspond to the abovementioned policies, respectively. In scenario *d*, if development of buses and subway are both carried out, public transportation trips will considerably increase and the attractiveness of car trips will be diminished to some extent. Scenario e is a combination of scenarios ***a*** and *d*. Scenario ***g*** is a combination of ***d*** and *f*. Scenario ***h*** integrates all the policies.

6.1.2. Simulation Results

The trip mode structures and environmental and resource pressures of different scenarios are shown in Figure 14 and Table 11. Trip mode structures differ under different policy scenarios. In scenarios *b* and *c*, the ratios of buses and subways significantly increase because BP and SP policies were applied. Level of motorization is low in scenario *f*, with approximately 60% in 2020 because only the measure of CTR was applied. By contrast, scenario d carries out measures of BP and CP, without simultaneous control of cars. As a result, level of motorization is as high as 95% in 2020, with public transportation and cars accounting for almost 50% of the trips. Scenario ***g*** takes the most powerful measures of structural adjustment, including

Table 10. Contrast of Environmental and Resource Pressure between Optimized and BAU Results

	2010		2020	
	BAU	Optimized	BAU	Optimized
Total NOx (10^2 t/d)	5.74	1.84	8.55	1.72
Total CO (10^2 t/d)	68.68	21.96	103.97	20.94
Energy demand (TJ/d)	1149.27	415.20	1738.31	556.30
Land demand for roads (km^2)	504.65	216.90	744.34	232.60

BP, SP, and CTR. The level of motorization still reaches 80% and the ratio of cars is controlled to about 20%.

The environmental and resource pressures vary, as well. Compared with the BAU scenario, pollution discharges decrease by about 40% in 2020. The pressures in scenario *b*, *c*, and *d* are still considerable because levels of motorization are all high. The introduction of CT in scenario *e* significantly influences pollution discharge. The integrated scenario *h* creates the least pressure on environment and resources.

Table 11. Environmental and Resource Pressures of Different Scenarios

		Total NOx (10^2 t/d)	Total CO (10^2 t/d)	Energy Demand (TJ/d)	Land demand for roads (km^2)
2010	BAU	5.74	68.68	1149	505
	a	4.35	49.13	1149	505
	b	4.7	48.57	833	365
	c	4.16	48.07	809	374
	d	4.38	45.6	780	349
	e	3.37	33.28	780	349
	f	2.65	27.65	457	254
	g	2.94	26.59	389	231
	h	2.28	19.8	389	231
2020	BAU	8.55	103.97	1738	744
	a	5.06	63.54	1738	744
	b	8.26	94.53	1615	664
	c	7.72	93.97	1593	667
	d	7.91	88.86	1527	622
	e	4.64	56.29	1527	622
	f	4.74	52.63	878	426
	g	5.06	51.21	755	388
	h	2.92	33.9	755	388

6.2. Policy Evaluation and Discussion

6.2.1. Grey Correlation Assessment

The score between two series at a certain point is called grey relational coefficient $\zeta_i(k)$, where k means pollutants discharge, energy demand, or land demand. Before calculating grey relational coefficients, grey data processing is often necessary. A series with various units needs to be transformed to have the same numeric order. Usually, each series is normalized by dividing data from the original series by their averages. Next, let the transformed reference sequence of optimized results be $X_0(k)$, and the results of nine scenarios be $X_i(k)$. The relational coefficient $\zeta_i(k)$ between the reference series $X_0(k)$ and the compared series $X_i(k)$ can be calculated by Equation (7), which represents relative distance. Resolution ratio is represented by ρ with a range of 0 to 1 and the general is 0.5. In Equation (8), γ_i is called equal-weight relational coefficient, from the order of which the closeness of optimized results and scenario results can be known.

$$\zeta_i(k) = \frac{\min_i \min_k |X_i(k) - X_0(k)| + \rho \times \max_i \max_k |X_i(k) - X_0(k)|}{|X_i(k) - X_0(k)| + \rho \times \max_i \max_k |X_i(k) - X_0(k)|} \quad (7)$$

$$r_i = \frac{1}{n} \sum_{k=1}^{n} \zeta_i(k) \quad (8)$$

6.2.2. Results

Relational coefficients of each variable and equal-weight relational coefficients of nine scenarios compared with the optimized results are shown in Table 12. Every policy has a positive effect because the BAU scenario is farthest from the optimized results at every variable. The effects of CTR are most significant, whereas the policy of public transportation priority is not so effective. Its effects are weaker than those of CT in terms of pollution discharge control. Whether in the short or long term, a mixed policy scenario generates better influence than merely a single scenario, especially a policy mix of different aspects. Therefore, should public transportation priority be associated with CT or CTR, environmental and resource pressures of transportation in Beijing can be effectively alleviated. The effectiveness of the different policies dominates different time scales. Policy on public transportation priority has a significant effectiveness in the short term, whereas CT works well in the long term.

Scenario *h* can be considered the optimized trip assignment structure for the future, on the premise of meeting resident trip demand, environmental and resource constraints, and policy attainability. In 2010, the daily resident trips in Beijing will reach 46.3 million, with subways, taxis, cars, buses, and bicycling or walking accounting for 5.66, 2.17, 16.20, 30.86, and 45.11%, respectively. In 2020, the corresponding data are 59.5 million, 19.41, 2.58, 24.99, 32.57, and 20.46%, respectively. The level of motorization increases gradually, bringing pas-

Table 12. Results of GCA

		Total NOx	Total CO	Energy demand	Land demand for roads	γ_i	Rank
2010	BAU	0.3547	0.3531	0.3979	0.5840	0.4224	9
	a	0.4651	0.4897	0.3979	0.5840	0.4842	8
	b	0.4309	0.4952	0.5446	0.6449	0.5289	7
	c	0.4857	0.5002	0.5600	0.6296	0.5439	6
	d	0.4613	0.5265	0.5803	0.6730	0.5603	5
	e	0.5960	0.7135	0.5803	0.6730	0.6407	4
	f	0.7499	0.8519	0.9678	0.9121	0.8704	3
	g	0.6788	0.8841	1.0000	0.9973	0.8901	2
	h	0.8663	0.9696	1.0000	0.9973	0.9583	1
2020	BAU	0.4066	0.4094	0.5280	0.5815	0.4814	9
	a	0.6308	0.6193	0.5280	0.5815	0.5899	5
	b	0.4190	0.4446	0.5613	0.6379	0.5157	8
	c	0.4439	0.4469	0.5676	0.6356	0.5235	7
	d	0.4346	0.4688	0.5875	0.6720	0.5407	6
	e	0.6763	0.6819	0.5875	0.6720	0.6544	4
	f	0.6648	0.7186	0.8992	0.8937	0.7941	3
	g	0.6314	0.7340	1.0000	0.9554	0.8302	2
	h	0.9560	0.9920	1.0000	0.9554	0.9759	1

sengers convenience, swiftness of travel, and comfort. Pressures on the environment and resources are controlled effectively because public transportation develops well and pollution decreases because of new technologies.

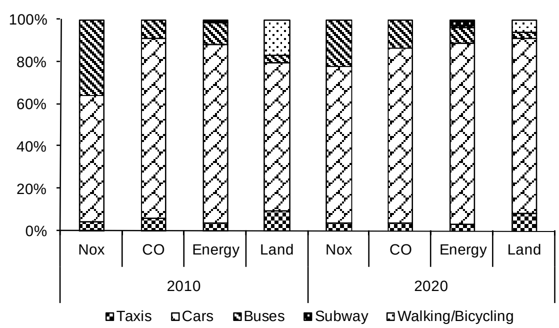

Figure 15. Structures of different trip modes of environmental and resource pressures in scenario h.

In scenario *h*, pollutant discharge and land demand are under environmental and land supply capacity; however, the supply of energy is not positive. Energy supplied for passenger transportation in 2010 can satisfy energy demand, but in 2020, energy shortage will occur. The percentages that different trip modes account for in terms of environmental and resource pressures are shown in Figure 15. Cars trips are the major contributors to pollution discharge and resource demands. Thus, decreasing energy demand, especially that of cars, and improving the city's energy supply capacity for transportation in the future are key issues for the Beijing UTES.

7. Conclusions

In this study, an integrated model was utilized to search for an optimized and feasible trip mode structure on the premise of resident trip demand, environmental and resource capacity, and feasibility of policy adjustment in Beijing. Results show that pollutants, energy consumption, and land demand for roads will exceed the capacity of Beijing in 2020, if UTES develops at its present pace. Policies such as CT, BP, SP, and CTR all have positive effects on the improvement of UTES, although the effects and time scale vary. Policies on public transportation priority are significantly effective in the short term, whereas CT policies work well in the long term. The combination of policies yields better effects; thus, integrated adjustment measures for sustainable transportation should be employed in Beijing. The derived optimized trip mode structures of Beijing in 2020 for subways, taxis, cars, buses, and bicycling or walking are 19.41, 2.58, 24.99, 32.57, and 20.46%, respectively, whereas daily resident trips reach 59.5 million. Under such a structure, the environmental capacity and land supply are sufficient for transportation; however, the energy constraint is still a limitation. Decreasing energy consumption of each trip mode and improving the city's energy supply capacity for transportation are future challenges to Beijing.

As the UTES is an open, massive, and complex system, the foundation of the model of Beijing used abstraction and simplification. There is a possibility that the development of transportation will undergo breakthroughs with the rapid development of society, economy, and technology. Therefore, the simulation of the system under present technology still suffers from uncertainties and inaccuracies. The improvement of the model created and adjustments in its operation may require deeper analysis.

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