





Research on Low Carbon Development Planning of Public Transportation Energy Based on System Dynamics

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Abstract. Due to current energy shortage and climate change in China, it is necessary to predict the energy demand and carbon emission of urban passenger transport in the future. Firstly, the urban passenger transport is divided into three parts: bus, taxi and car, and the demand of future urban passenger transport is forecasted by using the national energy technology model. Modeling the urban passenger transport network from a System dynamics perspective. In the transport part, the number of vehicles, the proportion of fuel types and the energy consumption per 100 km are considered, and the energy consumption of transport travel is calculated by using the transport energy consumption equation. Using 2021 as the base year, four scenarios were set to assess the energy saving and emission reduction potential under different policy needs, including keeping the baseline scenario of urban development inertia, considering the speed limit of urban vehicles and further optimizing the speed control scenario of public transport system, and considering the promotion of shared mode of travel shared scenarios, and according to the national renewable energy automobile industry development planning overall goal of electric vehicle scenario. This paper analyzes travel demand, energy consumption demand and carbon emission intensity under different scenarios, and puts forward policy suggestions on public transportation energy saving and emission reduction planning.

Keywords: public transportation development planning · low carbon energy · energy saving and emission reduction · system dynamics

1 Introduction

Transportation is an important department carrying out human social and economic activities. With the advancement of urbanization and the increasing demand for transportation in China, the energy consumption and carbon emissions of Transportation show a growing trend. In terms of global greenhouse gas emissions, the transportation industry has surpassed industry and construction, becoming the second largest emission

sector in the world [1]. As an important part of transportation, urban passenger transport should contribute to energy conservation and emission reduction. So there are two problems:

First, how to evaluate the energy consumption and carbon emission level of urban passenger transport, and provide methods and basis for the government to formulate energy conservation and emission reduction targets for urban passenger transport? Second, how to reduce the energy consumption and carbon emission level of urban passenger transport through policy means while trying to meet the travel needs of residents?

Chinese urban passenger transport energy consumption and carbon dioxide emissions may show a sustained and rapid growth trend in the coming period, mainly considering:

(1) The fuel structure of urban traffic vehicles is single, and most of them use petroleum products such as gasoline and diesel. The excessive use of fossil fuels will lead to the continuous increase of greenhouse gases and pollutants; (2) The further improvement of urbanization rate and the rise of residents' income not only bring about the increase of travel demand, but also cause the rapid growth of car ownership [2]; (3) The travel sharing rate of public transport has not reached the international advanced level. Only a few cities have a public transport travel sharing rate of 50% [3], most of which are below 40%, and some big cities are even less than 10%, which still has great room for improvement.

Therefore, it is of great significance to scientifically predict the energy consumption and emissions of urban passenger transport in the future and take active measures to intervene its rapid growth.

However, due to the diversification of urban passenger transport residents' travel modes and types of motor vehicles, how to change urban residents' travel modes, how to choose travel modes, and how to develop vehicle technology in the future under the situation of social and economic transformation, these uncertain factors lead to the prediction of urban passenger transport energy demand and carbon emissions is very complex and full with great uncertainty.

Existing relevant studies have analyzed and predicted energy consumption and carbon emissions in many fields in terms of model tools and prediction means. As a key industry of energy consumption, transportation industry has always been the research object of scholars. Internationally, the prediction methods of transportation energy consumption and carbon emissions mainly use bottom-up micro prediction models, supplemented by some top-down macro prediction models. As the main tool for predicting transportation energy consumption and carbon emissions, micro prediction models include long-term energy alternative planning system (LEAP) model, terminal energy consumption model, Primes-Tremove and so on.

Domestic researchers often use some more direct prediction methods. Including exponential decomposition method [4, 5], the elastic coefficient method [6], regression model [7, 8], time series prediction model [9], and combined prediction model [10], etc. These methods are mainly used to predict various passenger and freight traffic volume or passenger and freight turnover, combined with energy intensity, and then predict energy consumption and carbon emissions.

However, both macro and micro energy consumption prediction models have shortcomings: macro models are usually difficult to describe the role of technological progress, which affects the prediction results; However, micro models are weak in analyzing the impact of economy, and often overestimate the impact of economy on the model [11]. The system dynamics method can partially solve this contradiction by examining the research object from the perspective of system.

The urban passenger transport is divided into three parts: bus, taxi and car. The urban passenger transport level is counted from the perspective of the sharing rate of urban passenger transport modes and the average travel intensity, and the national energy technology model is used to predict the passenger transport demand of urban transport in the future. The urban passenger transport network is modeled from the perspective of system dynamics, which organically links transportation with social, economic and environmental modules. In the transportation part, the number of vehicles, the proportion of fuel types and energy consumption per 100 km are considered, and the energy consumption of transportation travel is calculated by using the transportation energy consumption equation. Based on the predicted passenger transport demand, the regional urban transport energy consumption and carbon emissions can be divided and calculated from a systematic perspective.

Taking a city as a case study, this paper provides a method for evaluating and predicting urban passenger transport energy consumption and carbon emissions through the verification, calculation and analysis of the model. Taking 2021 as the base year, four scenarios are set to evaluate the potential of energy conservation and emission reduction under different policy needs, including the benchmark scenario of maintaining the inertia of urban development, the speed control scenario of considering the city's speed limit for cars and further optimizing the public transport system, the shared travel scenario considering the promotion of shared travel mode, and the electric vehicle scenario according to the overall goal of the national renewable energy vehicle industry development plan. By comparing and analyzing the travel demand, energy consumption demand and carbon emission intensity under different scenarios, the results show that the speed control, shared travel and electric vehicle policies have changed the travel mode and energy technology structure to a certain extent, especially the fossil fuel consumption in the electric vehicle scenario will be largely replaced by power consumption.

At the same time, it can evaluate the energy conservation and emission reduction potential of the city in urban passenger transport, and put forward relevant suggestions and development plans for the government in the field of energy conservation and emission reduction in urban passenger transport.

2 Prediction Model of Urban Passenger Transport Demand

2.1 National Energy Technology Model

The optimization principle of the national energy technology (Net Transport) model is to minimize the total cost of vehicle technology that meets the service demand in the planning year. The total cost is decomposed into the annual initial acquisition cost of new technology, the operation and maintenance cost and fuel cost of all equipment in

the planning year. In addition, energy tax and emission tax can be increased according to the setting of scenarios.

$$\min TC_t = \sum_j \left(\sum_l (AIC_{t,j,l} + OM_{t,j,l} + FC_{t,j,l}) \right) + \sum_e K_e Q_{t,e} + \sum_m K_m Q_{t,m} \quad (1)$$

where, t represents the planning year; l represents the means of transportation, including bus and trolley bus, rail transit, taxi, car and electric bicycle; l represents the vehicle technology category, distinguishing fuel types and energy efficiency levels; e indicates the type of energy, including gasoline, diesel, natural gas, liquefied petroleum gas, bio-gasoline, electricity, etc. m indicates the type of gas produced by the fuel consumed by the vehicle, such as CO₂; TC_t represents the total cost of the planning year; $AIC_{t,j,l}$ represents the annual initial acquisition cost of vehicle technology l of mode j ; $OM_{t,j,l}$ represents the annual operation and maintenance cost of transportation mode j vehicle technology l ; $FC_{t,j,l}$ represents the annual fuel cost of transportation mode j vehicle technology l ; K_e represents the energy tax levied on behalf of energy consumption units; $Q_{t,e}$ represents energy consumption of e ; K_m represents emission tax levied on behalf of emission unit gas m ; $Q_{t,m}$ represents gas emissions of m .

The initial investment cost of the new transportation mode j vehicle technology l in the t year is converted by the total initial investment cost $IC_{t,j,l}$ at the depreciation rate $\alpha_{j,l}$, as shown in formula (2):

$$AIC_{t,j,l} = IC_{t,j,l} \frac{\alpha_{j,l}(1 + \alpha_{j,l})^{T_{j,l}}}{(1 + \alpha_{j,l})^{T_{j,l}} - 1} \quad (2)$$

where, $IC_{t,j,l}$ represents the total cost of initial acquisition of vehicle technology l of transportation mode j ; $\alpha_{j,l}$ represents the depreciation rate of vehicle technology l of transportation mode j ; $T_{j,l}$ represents the service life of vehicle technology l of transportation mode j . Formula (2) apportions the initial total purchase cost of vehicles to each year within the service life, so as to obtain the annualized investment cost.

The fuel cost $FC_{t,j,l}$ of transportation mode j vehicle technology l year is calculated by formula (3), which is related to the total annual energy consumption and energy price of vehicles:

$$FC_{t,j,l} = \sum_e Q_{t,j,l,e} O_{t,j,l} Price_{t,e} \quad (3)$$

where, $Q_{t,j,l,e}$ represents the consumption of t transportation mode j vehicle technology l energy e in the planning year; $O_{t,j,l}$ represents the operation quantity of transportation mode j vehicle technology l in the planning year t ; The product of the operating quantity and the annual transportation capacity of the unit vehicle technology of mode j represents the service volume provided by mode j vehicle technology l in the planning year, which is optimized by the model based on the principle of cost minimization. In addition, the number of operations should not exceed the number of vehicles owned by transportation mode j and vehicle technology l in the planning year. $Price_{t,e}$ represents the unit price of energy e in the planning year t .

The energy consumption $Q_{t,j,l,e}$ of mode j vehicle technology l in the planning year is calculated from the driving mileage of mode j vehicle technology l and the unit energy

consumption of the vehicle. The gas emission $Q_{t,j,l,m}$ is related to energy consumption and gas emission factor, as shown in formula (4) and formula (5):

$$Q_{t,j,l,e} = X_{t,j,l}E_{t,j,l,e} \tag{4}$$

$$Q_{t,j,l,m} = Q_{t,j,l,e}f_{t,e} \tag{5}$$

where, $X_{t,j,l}$ represents the annual driving mileage of vehicle technology l of mode j ; $E_{t,j,l,e}$ represents the energy consumption per unit mileage of transportation mode j vehicle technology l ; $f_{t,e}$ represents the emission factor of energy e with respect to gas m .

The energy consumption $Q_{t,e}$ (Gas m emission) of the transportation department in the planning year is multiplied by the annual single vehicle energy consumption (Annual single vehicle emission) of the transportation mode j vehicle technology l by the operation quantity $Q_{t,j,l}$ in the planning year, as shown in formulas (6) and (7):

$$Q_{t,e} = \sum_j \sum_l Q_{t,j,l,e}O_{t,j,l} \tag{6}$$

$$Q_{t,m} = \sum_j \sum_l Q_{t,j,l,m}O_{t,j,l} \tag{7}$$

2.2 Prediction Model of Urban Passenger Transport Demand

This paper establishes a prediction model of urban passenger transport demand based on the classification of cities from the size of population development. The model considers the number of future urban residents in cities with different population sizes, residents' travel intensity, the sharing rate of each travel mode and the travel distance of each travel mode. Using this model, we can get the passenger turnover of various travel modes in cities with different population sizes in the future.

The passenger transport turnover D_j^f of mode j in the future is calculated by the urban passenger transport demand generation model, as shown in formula (8):

$$D_j^f = \sum_i P_i I_i S_{j,i} DIS_{j,i} 365 \tag{8}$$

where, i represents the city level classified by population size; P_i represents the total population of grade i cities; I_i represents the number of trips per capita of grade i urban residents (times/person/day); $S_{j,i}$ represents the travel sharing rate of public transportation modes j of grade i ; $DIS_{j,i}$ represents the average travel distance (km/time/person) of grade i public transportation mode j (Fig. 1).

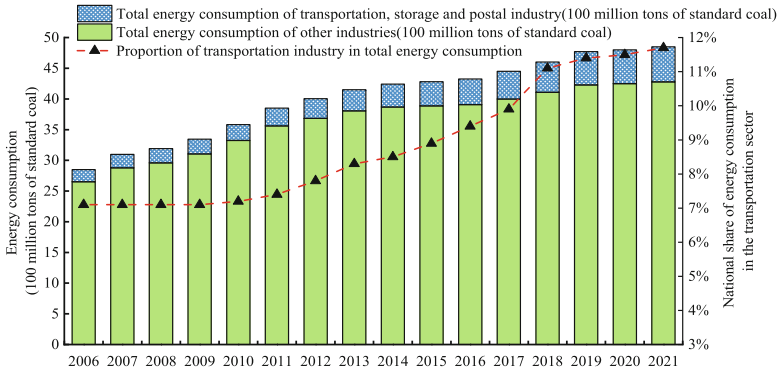


Fig. 1. Energy consumption and national ratio in transportation, storage and postal industries.

3 Construction of Urban Passenger Transport Network Module Based on System Dynamics

On the basis of system dynamics, the urban passenger transport is modeled, which is divided into three modules: bus, taxi and car. At the same time, the data statistics are carried out from the number of vehicles, the proportion of fuel types and the energy consumption of 100 km, and the energy consumption of transportation travel is calculated by using the transportation energy consumption equation (Fig. 2).

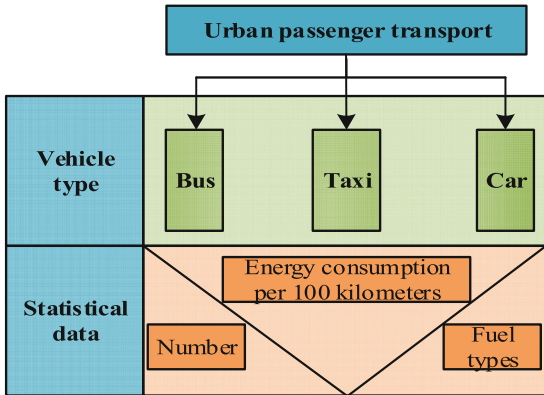


Fig. 2. Urban passenger transport network module diagram.

3.1 Data Related to the Number of Vehicles and the Proportion of Fuel Types

Take a city as a reference, and make statistics on the proportion of transportation vehicles and fuel types in the city from 2010 to 2021 (see in Tables 1, 2, 3 and 4).

Table 1. Number of Transportation Vehicles in the City from 2010 to 2021.

Date	Bus	Taxi	Car
2010	832	2241	130691
2011	891	2333	171145
2012	1018	2344	211600
2013	1124	2344	259681
2014	1119	2401	307267
2015	1294	2595	500197
2016	1837	3052	751307
2017	2488	3607	1102630
2018	3241	4783	1403319
2019	4609	5791	1702806
2020	5573	6700	2100074
2021	6730	7880	2551054

Table 2. Proportion of Bus Fuel Types in the City from 2010 to 2021.

Time	LNG	Gasoline	Electric	Petrol/electric hybrids
2010	0	100%	0	0
2011	0	100%	0	0
2012	3.9%	96.1%	0	0
2013	21.2%	78.8%	0	0
2014	21.4%	78.6%	0	0
2015	23.7%	76.3%	0	0
2016	26.9%	56.5%	3.8%	12.8%
2017	30.1%	46.1%	7.9%	15.9%
2018	32%	39.2%	12.4%	16.4%
2019	29.8%	28.5%	19.2%	22.5%
2020	20.8%	23.4%	25.1%	30.7%
2021	13.3%	20.9%	30.7%	35.1%

3.2 Energy Consumption Per 100 km of Urban Vehicles

The parameter setting of the base period of 100 km energy consumption of urban vehicles in the city follows the following principles: assign values according to the order of the city's survey data > literature data > locomotive test data provided by the network.

Table 3. Proportion of Taxi Fuel Types in the City from 2010 to 2021.

Time	LNG	Gasoline	Electric	Petrol/electric hybrids
2010	0	100%	0	0
2011	0	100%	0	0
2012	56.1%	43.9%	0	0
2013	56.1%	43.9%	0	0
2014	61.7%	38.3%	0	0
2015	61.7%	38.3%	0	0
2016	61.7%	38.3%	0	0
2017	59.9%	40.1%	0	0
2018	56.3%	43.7%	0	0
2019	50.5%	37.5%	0	12%
2020	37.8%	36.8%	5%	20.4%
2021	28.7%	30.9%	15.1%	25.3%

Table 4. Proportion of Car Fuel Types in the City from 2010 to 2021.

Time	Gasoline	Electric	Petrol/electric hybrids
2010	100%	0	0
2011	100%	0	0
2012	100%	0	0
2013	100%	0	0
2014	100%	0	0
2015	100%	0	0
2016	90%	0	10%
2017	85.5%	0	14.5%
2018	75.6%	5.3%	19.1%
2019	62%	13.6%	24.4%
2020	50.9%	20.9%	28.2%
2021	41.4%	25.7%	32.9%

For the situation that there are many values in the literature, this paper will refer to the authority of published journals and try to use “intermediate data” for quotation.

Since most documents do not indicate the specific year corresponding to the value in the assignment of 100 km energy consumption, this paper adopts a fuzzy treatment for this part of the data, in principle, the same data is used in 2021 and 2015, and slightly

adjusted according to other data sources. As shown in the Table 5 for the parameter settings.

Table 5. Energy Consumption Per 100 km of Various Transportation Vehicles in the City in 2021.

Vehicle	Gas (m3)	Diesel (Gasoline) oil (L)	Electric (kWh)	Petrol/electric hybrids	
				gasoline	electric
Bus	29.62	38.88	87.6	29.03	3.78
Taxi	9.45	10.15	16.71	2.53	8.4
Car	9.28	8.16	18.01	2.32	7.78

3.3 Public Transportation Passenger Transport Level

The data of public transport share rate and average daily mileage of buses are estimated according to the mileage in the Yearbook, passenger volume and number of residents' trips; The average passenger capacity of taxis is set according to the literature value. Transfer times, annual mileage of cars and annual mileage of taxis are considered through the survey data (Table 6).

Table 6. The Level of Public transportation and Passenger Transport in the City in 2021.

Taxi sharing rate	Bus sharing rate	Number of trips per capita	Annual mileage of taxi (km)	Transfer times	Annual mileage of car (km)	Average passenger capacity of taxi (person)	Average daily mileage of buses (km)
4.92%	7.74%	2.75	12198	1.24	8313	1.38	132

3.4 Prediction and Calculation Method of Energy Consumption and Carbon Emission

Combined with the prediction of passenger transport demand in Sect. 2, this section divides the transportation energy consumption into three modules from the perspective of system dynamics and calculates the consumption and carbon emissions of each module based on the prediction of passenger transport demand, so as to obtain the predicted energy consumption and carbon emissions.

This paper uses the transportation energy consumption equation to calculate the energy consumption of transportation travel. The energy consumption of different travel

modes and types of transportation energy technology can be expressed as a nonlinear equation of travel time, and the travel time of each means of transportation is calculated according to the driving speed of the relevant means of transportation. The energy consumption per unit distance of traveler’s choice of travel mode m and technology t is as follows (9):

$$E_{i,m,t} = \frac{e_{i,m,t}(e_1 + e_2(\frac{1}{t_{i,m,t}}) + e_3t_{i,m,t})}{f_{i,m}} \tag{9}$$

where, $e_{i,m,t}$ represents the exogenous parameters that calibrate the energy consumption of different vehicles and technology types; e_1, e_2, e_3 represent the given parameters used to evaluate traffic energy consumption; $t_{i,m,t}$ represents travel time; $f_{i,m}$ represents the load factor of the vehicle.

Taking 2021 as an example, using the above calculation method, we can get the passenger transport energy consumption and composition and total carbon emission composition of the city in 2021 (Fig. 3).

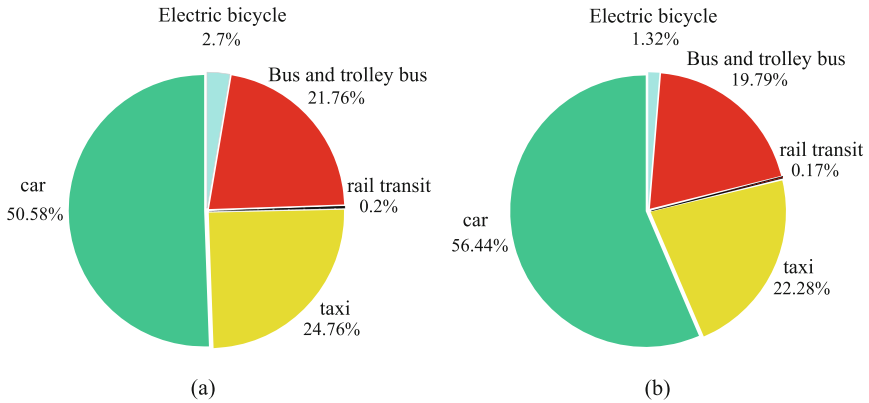


Fig. 3. Urban passenger traffic energy consumption composition (a) and carbon emission composition (b).

4 Case Study

4.1 Scene Settings

This paper sets 2021 as the base year. Four different scenarios are set to evaluate the energy conservation and emission reduction potential of public transportation energy in a city under different policy needs.

- Scenario 1: the benchmark scenario of maintaining the inertia of urban development.
- Scenario 2: consider the speed control scenario in which the city adopts a speed limit for cars and further optimizes the public transport system.

Scenario 3: shared travel scenario considering the promotion of shared travel mode.

Scenario 4: electric vehicle scenario according to the overall goal of the national renewable energy vehicle industry development plan.

4.2 Analysis of Simulation Results

The travel demand of the city from 2010 to 2060 is shown in Fig. 4. In the benchmark scenario, due to economic development, urbanization and population changes, the total demand for travel increased from 3.1 billion person kilometers in 2010 to 5.8 billion person kilometers in 2060. In the benchmark scenario without any exogenous policies, car travel accounted for the largest proportion. Travel demand is driven by population growth, economic development, land use, travel mode, technological progress and other factors. Since the travel mode and transportation technology in the benchmark scenario do not change significantly without exogenous policy impact, the change of traffic demand is mainly affected by the future population and economic growth path.

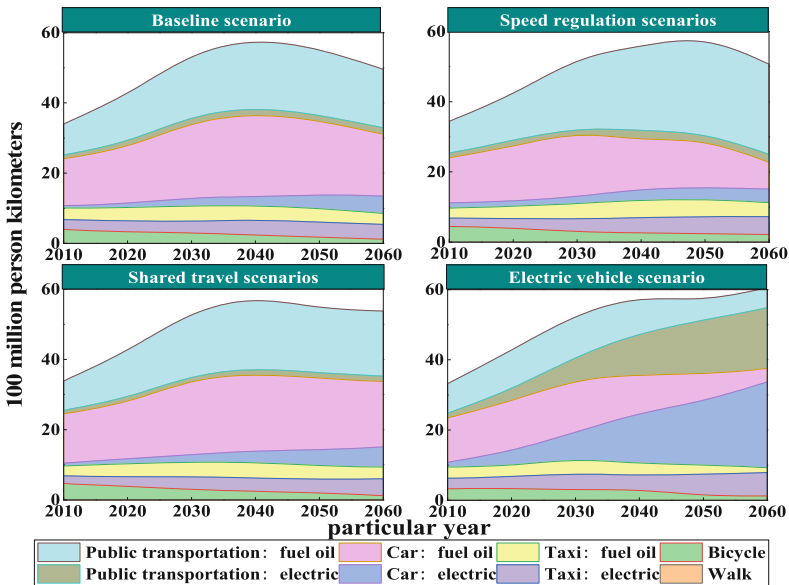


Fig. 4. Travel demand across scenarios.

According to the predicted value in SSPS, the future population change of the city will show a trend of first rising and then falling. Therefore, the traffic demand also shows a similar change path. In terms of energy technology types, due to the decline in battery costs and vehicle costs brought about by technological development and the comparative advantage of energy prices, the proportion of electric vehicles in car travel demand rose to 18% by 2060. The speed control scenario significantly changed the structure of travel mode. The travel demand of public transport increased from 2.1 billion person kilometers in the benchmark scenario to 2.9 billion person kilometers in 2060, while the

travel demand of cars decreased from 2.5 billion person kilometers in the benchmark scenario to 1.6 billion person kilometers. The number of car trips in the shared travel scenario increased slightly, because the promotion of shared travel mode has reduced the transportation cost of car travel to a certain extent. There are significant changes in the structure of transportation energy technology in the electric vehicle scenario, and the electric vehicle technology has increased significantly in the three motorized travel modes.

Traffic energy consumption and structure also show significant differences in different scenarios (Fig. 5).

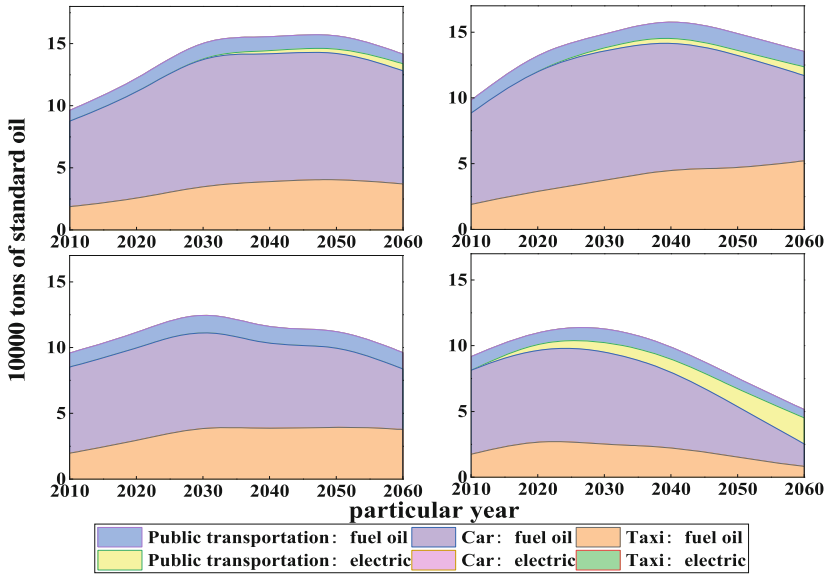


Fig. 5. Transportation energy consumption demand under different scenarios.

In the benchmark scenario, the total energy consumption of transportation increased from 90000 tons of standard oil in 2010 to 160000 tons of standard oil in 2060, and fuel vehicles accounted for the overwhelming proportion. In the speed control scenario, the energy consumption of public transportation increased slightly while that of cars decreased slightly, because speed control made more people use public transportation to replace cars. Shared travel reduces energy consumption by reducing the energy intensity of per capita travel. In 2050, the energy consumption of cars will drop from 110000 tons of standard oil in the benchmark scenario to 60000 tons of standard oil. Due to the technological progress brought about by the electric vehicle scenario, the energy consumption structure has changed greatly, and the power demand in the electric vehicle scenario has gradually increased instead of the use of fossil fuels.

The transportation energy demand in the four scenarios shows the characteristics of rising at first and then falling, which is consistent with the changing trend of transportation travel demand, and it is mainly affected by the future population growth path of

the city. The implementation of speed control, shared travel and electric vehicle policies will accelerate the transportation energy demand to enter the declining stage faster.

The medium and long-term traffic emission path of the city is shown in the Fig. 6.

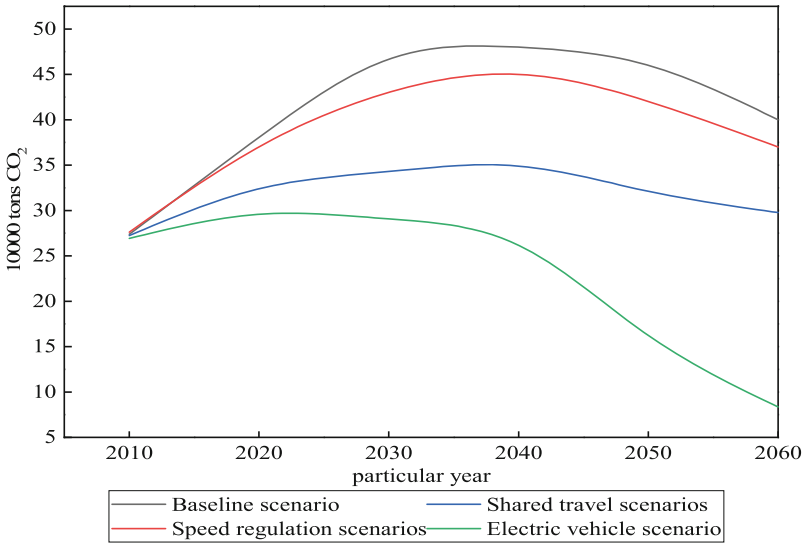


Fig. 6. Carbon emission pathways of different scenarios.

In the benchmark scenario, the total carbon emissions increased from 250000 tons in 2010 to 420000 tons in 2050. The speed control scenario can reduce carbon emissions to a certain extent, from 420000 tons in the benchmark scenario to 390000 tons in 2050. In the shared travel scenario, the change path of carbon emissions is more moderate. Due to the promotion of shared travel mode, carbon emissions increased slowly from 2010 to 2030, and decreased from 2030 to 2060. The electric vehicle scenario shows the most significant carbon emission reduction potential, which will be reduced to 160000 tons in 2050, even lower than the emission value in the benchmark year of 2010. It can be seen that the electric vehicle policy can decouple carbon emissions from the growth of travel demand. At the same time, to reflect the spatial differences in the development of transportation energy, four regions with different development conditions in the city are taken as examples.

It can be seen from the Fig. 7 reflects that the carbon emission intensity of four regions under different scenarios in 2060, which is used to measure the carbon emission per unit of travel demand. The carbon emission intensity of different scenarios shows the same change law as the carbon emission path in the four zones.

However, under the same scenario, carbon emission intensity shows certain spatial differences in different regions. In the benchmark scenario, speed control scenario and electric vehicle scenario, the carbon emission intensity in the central urban area is lower than that in other areas. However, the shared travel scenario shows the opposite spatial

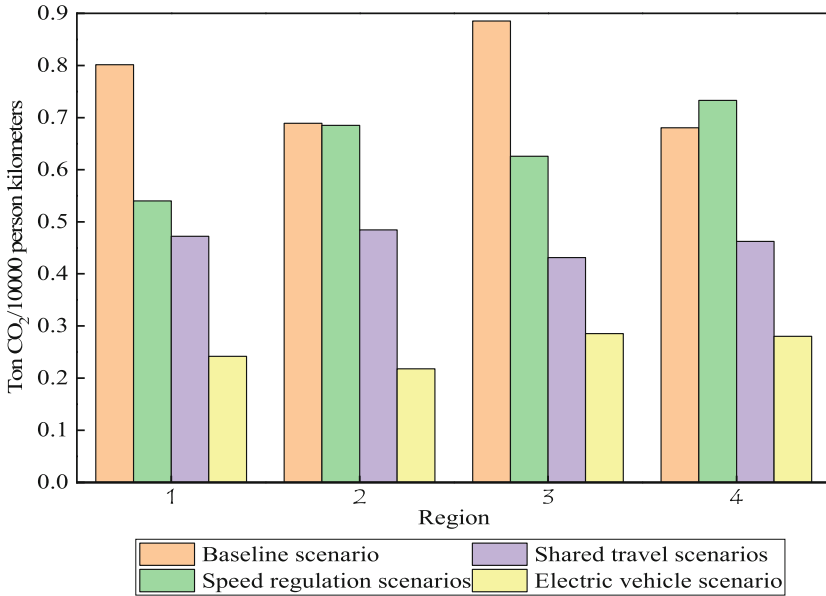


Fig. 7. Carbon emission intensity of different scenarios.

differences, reflecting that the shared travel mode is conducive to the decline of carbon emission intensity in the suburbs.

5 Conclusion

From the perspective of system dynamics, this paper constructs a system dynamics model for predicting energy consumption and carbon emissions of urban passenger transport based on the pre-measurement of urban passenger transport demand. Taking a city as an example, the energy consumption and carbon emission of public transportation in this city are predicted and analyzed. The simulation results show that there is a strong correlation between energy consumption and carbon emissions of urban passenger transport, indicating that the efficiency of urban passenger transport in energy conservation and carbon emission reduction is consistent.

The low carbon transport planning policy has a significant effect on energy conservation and emission reduction of urban passenger transport. Under the low-carbon scenario, the passenger transport in the city will generate 123300 tons of standard coal energy savings and 205700 tons of CO₂ emission reductions. Cars are the primary contributors to the energy consumption and carbon emission reduction of urban passenger transport, followed by taxi, and third is bus. As a priority travel mode recommended by the state, they will maintain a high share of public transport in the next few years.

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