Delft University of Technology

Traffic Congestion Policies analysis of Chinese Cities Based on System Dynamics

Yiyi Ren (4626656)
Engineering and Policy Analysis
Faculty of Technology, Policy and Management
Delft University of Technology
Date 2021-09-22

Title page

Title	Traffic Congestion Policies analysis of Chinese Cities Based on System Dynamics
Author	Yiyi Ren
Date	2021-09-22
Email	ryyrenee@126.com
University	Delft University of Technology Faculty of Technology, Policy and Management
Program	Engineering and Policy Analysis
Graduation Committee	Chairman: Prof. Tao Ma First Supervisor: Prof. Xiaofeng Hui Second Supervisor: Dr. Ylin Huang

Acknowledgement

The more I look up to him, the higher he towers; the more I study him, the more profound he becomes. It has been five years since I received the admission notice, and thesis writing is also a long process. It is thankful for teachers and classmates' help during the learning journey. First of all, I sincerely thank my tutor, Prof. Hui. Thank to Prof. Hui for taking time out of his busy schedule to help me with my thesis, and put forward valuable opinions on the conception and writing of the thesis. Although due to the work reasons, I failed to give feedback to the teacher in time, as long as I encountered problems, teachers would always patiently guide me, give me solutions and help me to treat problems from a new perspective, so as to complete the paper filled with motivation. Secondly, I would also like to thank the teachers of the defense committee. Thank you for reading my graduation thesis and give their opinions. I have benefited a lot from the whole process. In addition, I would like to thank all the teachers of EPA project. Thank for their wonderful teaching to make me gradually understand the unfamiliar field of management and have more knowledge of life and academic. Thank to the teacher who encouraged me to participate in this project, Prof. Hou, who is my master tutor of Harbin Institute of Technology. He encouraged me and supported me to participate in the EPA project to go abroad and feel the outside world.

Thank to my family and friends. In the journey of study, you gave me courage and motivation to overcome difficulties, forge ahead bravely, feel the beauty of the world, and let me conquer difficulties to complete this degree. Thank you for my partners who accompany with my all the way in the Netherlands. In a strange country, with your company, life is always full of laughter.

Finally, I would like to thank the school of management of Harbin Institute of Technology. Thanks to the school of management of Delft Institute of Technology for providing us with such an opportunity. The chance to participate in the EPA project is the most correct choice I have ever made. I hope the two Alma Maters will get better and better!

Thank you!

Abstract

Since the reform and opening up, Chinese economy has developed rapidly, and people's living standards have been greatly improved. Chinese GDP in 2019 is 270 times of that in 1978 and per capita GDP in 2019 is 180 times of that in 1978. The income has increased a lot during the past 40 years, especially in metropolis like Beijing, Shanghai, Guangzhou and Shenzhen. These cities have attracted a lot of investment, providing a large amount of job opportunities, so the population of these cities expands rapidly as well as the scale of the cities. The number of civil automobile in 2019 is almost 5 times of that in 2000 and the travel distance is almost 3 times of that in 2000. Therefore, traffic congestion has become more and more serious in recent years. It takes more than twice as much time to travel during rush hours. The research object is to find out measures to control traffic congestion in Chinese cities.

In this paper, system dynamic is applied to study the transportation system which is also known as the policy laboratory. According to system dynamics, it is important to understand that the system is dynamic and the change of one variable can influence the performance of the whole system. In this research, system dynamics is used to establish a simplified model to reflect the real transportation system. By adjusting the values of the variables, the effect of different policies can be simulated, and the efficiency of the policy can be evaluated.

Firstly, this paper analyzes the traffic development process at home and abroad, summarizes the development characteristics of each stage, and summarizes different measures of congestion control. Secondly, the paper analyzes the traffic operation characteristics of Chinese cities and the causes of road network congestion. Traffic congestion in China mainly includes external factors and internal factors. The external factors refer to the growth of traffic demand caused by economic development, population growth and urban expansion. The internal factors refer to the poor management of the transportation system. Thirdly, based on the causality relationship between different factors, the system dynamic model with virous policies is established. Due to the fact that most of the developed cities located in the southeast China and Shanghai is the largest city in the south, it is selected to be the example of this research. In the end, specific measures are put forward based on the simulation result of the model.

Keywords: traffic congestion, system dynamic, congestion control policy

Table of Contents

1 Introduction

Science and technology update rapidly since the industrial revolution and all the development has greatly affected people's life style, promoted the urbanization process and increased urban population. These changes have brought greater pressure on the urban transportation system in both western countries and China and put forward higher requirements for the development and management of the city. Taking China for example, due to the reform and opening up policy in 1978, China's economy has increased dramatically. As shown in Fig.1, China's GDP in 2019 was 99,086 billion yuan almost 270 times of that in 1978[1]. The fast growth of economy leads to the increase of residential income and living standard. On one hand, instead of walking and using public transport, people nowadays prefer to choose safer, more comfortable and more convenient modes of transportation, which result in a surge in the number of private cars. On the other hand, with 676 million rural people moving to urban areas during the past 40 years, there are 16 cities whose population is over 10 million. In order to contain the growing number of the urban population, all the Chinese cities have expanded to different level. Since the scale of the city is getting larger and the travel distance is getting longer, the traffic demand is increasing significantly. However, in the early stage of urban planning, most Chinese planners failed to predict the traffic volume, which will lead to a lack of traffic supply. On the other hand, China's car culture has been formed for a short time, and it still needs to be improved in terms of civilized driving and compliance with traffic rules. The growth of total population, GDP, per capita GDP, vehicles and highways are shown in figures below:

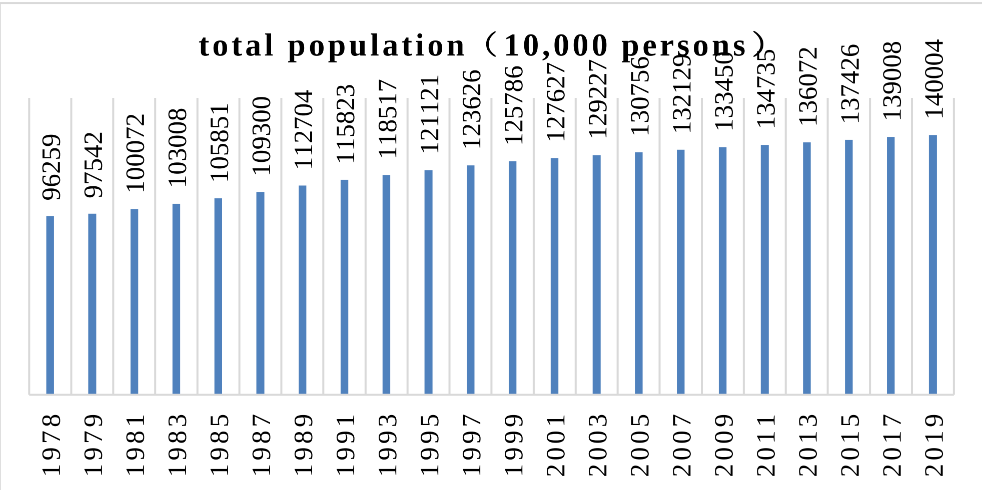

Fig. 1.1 Total population growth chart in China

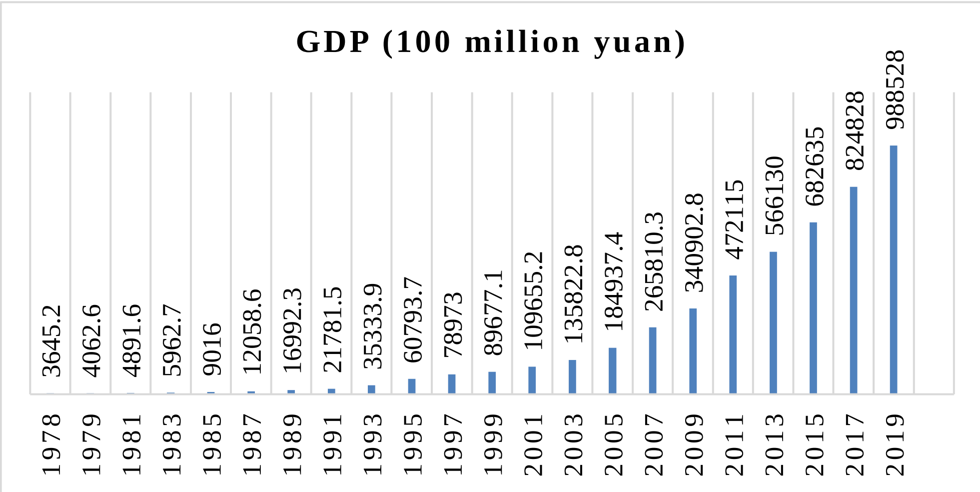

Fig. 1.2 GDP growth chart in China

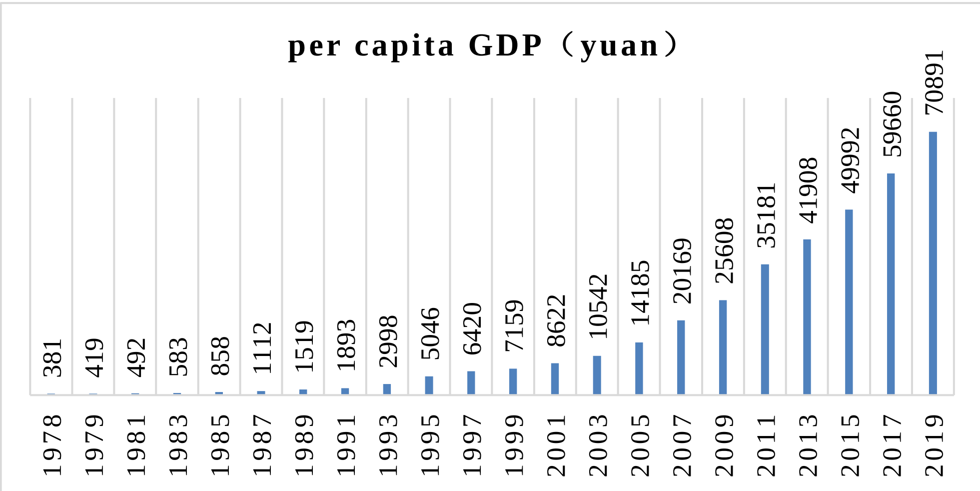

Fig. 1.3 Per capita GDP growth chart in China

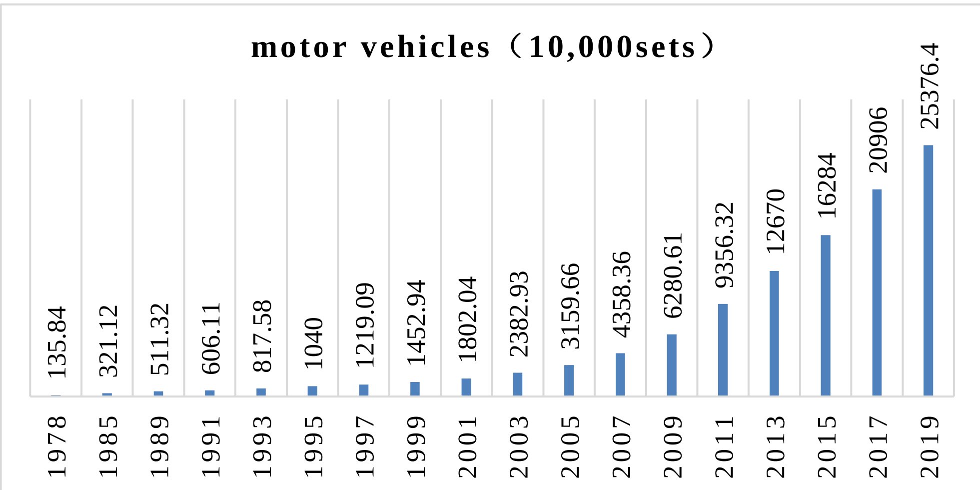

Fig. 1.4 Motor vehicles growth chart in China

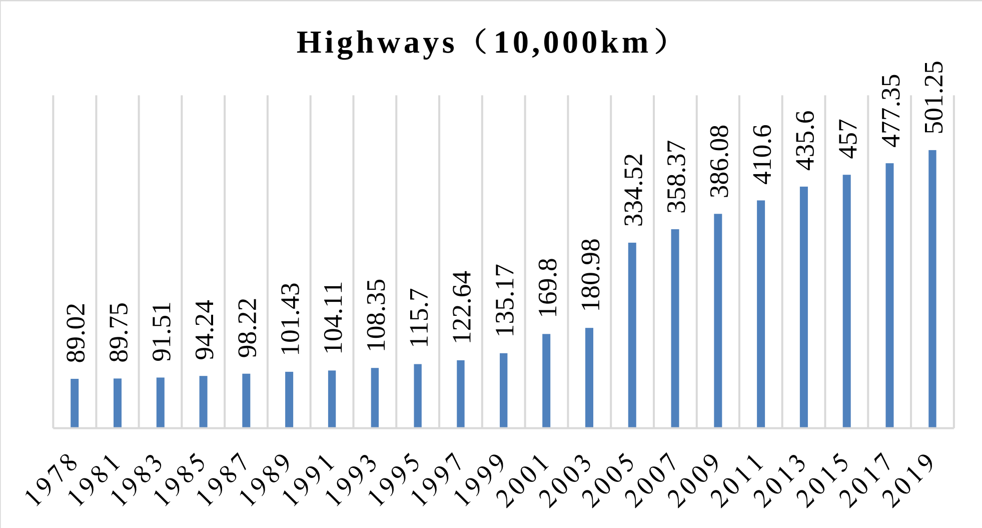

Fig. 1.5 Highways growth chart in China

These reasons lead to the increasingly serious congestion phenomenon. Traffic congestion has direct impact on economy, identity, efficiency, living standard and so on. Well-developed cities such as Beijing, Shanghai, Guangzhou and Shenzhen attract more talents than the other cites, so traffic congestion is more serious than that of other cities[2].. In recent years, with the increasingly serious congestion phenomenon in China, many researches in recent years have focused on the cause and measurement of congestion. Western scholars have studied in this field for more than 70 years and their results are worth to be learned from.

This paper aims to figure out solutions to traffic congestion in Shanghai and evaluate their effects. This chapter is organized as follows: traffic development in both western countries and China will be introduced firstly, various theories and methods of traffic congestion management will be introduced secondly, apart from that, the research question of this paper will be put forward, and the framework of this paper will be introduced at the end.

1.1 Research significance

Traffic congestion can cause various negative effects, such as: extra time cost, noise pollution, air pollution, additional traffic accidents, etc. These negative effects reduce efficiency of the transportation system and slow down the development process of the city. Traffic congestion is an increasingly serious social problem in Chinese metropolis.[3]

Economic loss caused by traffic congestion

Britain's annual loss caused by traffic congestion is about 15 billion pounds, which is the most serious loss country in Europe [4]; Spain's annual economic loss from congestion is as high as 15 billion euros, which is the second largest loss country in Europe; In 2003, Americans waste 3.7 billion hours of time and 8.7 billion liters of gasoline on traffic congestion resulting in a loss of as much as $63 billion. Xie Xuxuan has studied the social cost of traffic congestion in Beijing. The result shows that the total cost caused by traffic congestion in 2008 was 5-25 billion yuan, which is about 0.5% - 2% of Beijing's GDP [5].

Environment pollution caused by traffic congestion

There are two kinds of pollution caused by traffic congestion. The first type of pollution is caused by incomplete combustion, which is a waste of energy. The second type of pollution is vehicle exhaust emissions when the car is running at low speed. Since the amount of exhaust emissions will increase with the decrease of speed, there is no doubt that traffic congestion can make the environment even worse. According to the statistics, there are over 10 cities in China whose average annual PM2.5 are above 60. [6,7]

Psychological Damage caused by traffic congestion

In addition to the shortcomings mentioned above, traffic congestion can also lead to psychological damage. According to the US survey, people who lived in the city center are more likely to have heart attack due to the heavy traffic. People's blood pressure and chance of lung diseases will increase in traffic jams. In the process of traffic jam, people are more likely to have different kinds of negative emotions such as anxiety, irritability, impulsiveness, and even become very angry, which is called 'road rage'. In this condition, drivers are more likely to become irrational and violate traffic rules, so there are more traffic accidents in traffic jams.

In order to alleviate urban traffic congestion, developed countries have tried various measures. In the 1960s, the solution in the United States was to build new roads. However, it’s gradually realized that with the increase of new roads, people tend to travel by car. As a result, the vehicle population growed rapidly and traffic congestion was aggravating. This phenomenon is also called "Down’s law"[8]. While the solution in Singapore was to control the traffic demand. The amount of new vehicles is limited by the government and the public purchases vehicles through bidding. Japanese government focuses on how to built an efficient public transport system to reduce congestion. London reduces congestion by imposing a congestion tax in the center of the city. Chinese government tries to solve traffic congestion from two aspects. One way is to control the growth rate of vehicle population; another way is to restrict the travel of cars.

The significance of this study is to analyze the features of transport system, establish system dynamic model, simulate different traffic policies, so that measures and suggestion can be provided to the local government.

1.2 Research background

1.2.1 Research background in developed countries

Traffic congestion occurred in developed countries in the 1950s, so their researches on the causes of traffic congestion and related theories were carried out very early. The research on traffic congestion control policies by scholars in various countries can be divided into the following stages:

The first stage is to design policies from the perspective of traffic supply and build more roads to increase traffic supply, to solve the growing traffic demand. However, as the "Down's law" introduced in the previous article, when the traffic supply increases, the traffic demand will also increase, and the traffic congestion can only be temporarily alleviated, and then the congestion situation will be worse than before [9].

The second stage is traffic system management. In the 1970s, when increasing traffic supply was no longer effective, scholars from various countries improved the efficiency of the whole road network from the perspective of enhancing the management of the traffic system.

The third stage is to formulate governance policies from the perspective of traffic demand management. The government guides and regulates the choice of travel mode of citizens through different policies, and reduces the traffic volume the city. Taking London as an example, In 1980, British scholars proposed two policies, including that one is to increase both purchase tax and fuel tax so that the enthusiasm of the consumer can be reduced [10], and the other one is congestion charging to ease the traffic jams in the city.

The fourth stage is through the development of intelligent transportation to improve efficiency and service of the whole transportation network.[11]

1.2.2 Research background in China

China lags the western countries in industrialization and motorization so the study about transportation system is quite late compared to that of the developed countries. Developed countries' studies are very helpful when solving traffic congestion in China. On the other hand, Chinese cities can also be quite different from each other in terms of culture, development, climate, etc. [12]

In recent years, Chinese researches are focusing on the following aspects:

Management of traffic demand

In 1995, Huapu Lu proposed to introduce the traffic demand management model from developed countries; Yue Chen introduced the theory of traffic demand management (TMD) and its implementation effect at home and abroad [13]. Based on this theory and traffic condition, he put forward several policies of traffic management in Wenzhou. Based on TMD, Dunhou Li analyzed the relationship between dynamic traffic and static traffic by economic theory, then he redefined the relationship between traffic demand and traffic requirement[14]. In the end, he put forward the suitable measures for some Chinese cities.

Intelligent transportation system

With the development of intelligent technology, people are using information technology and other intelligent projects in all aspects of daily life and transportation is one of them. On the basis of the advanced experience at home and abroad， recent attempts focused on studying the traffic intelligence system. Through the internal traffic information, an advanced traffic information database is established[15]. By analyzing different kinds of information in the database, an intelligent transportation system that suits Chinese traffic condition can be set up. Up to now, intellectual Pre-alarm system, signal control system and traffic guidance system have been put into use [16].

Relationship between city and transportation system

In 2013, Minghao Zhu established a model which contains transportation system, environment system, socioeconomic system based on system dynamics [17]. The efficiency of different traffic policies in Beijing had been evaluated. In 2016, Ying Liu explored the relationship between Rail Transit and development of the city and explain the influence of Rail Transit on various industries [18]. In 2017, Xianpeng Wei suggested the relationship between emission of traffic pollutant and traffic congestion, The results show that when the traffic load is greater than 1.62, the emission of pollutants increases rapidly [19].

With the rapid development of transportation and society, people pay more attention to the quality of travel. To reduce traffic congestion, experts put forward new ideas based on new technology and theory. Through the above research, it's hoped that traffic congestion can be alleviated to a certain degree.

1.3 Research issues

The goal of this research is to reduce traffic congestion in Chinese metropolis and give useful suggestions based on the feature of Chinese transportation system. There are three sub-research issues:

1. What the main causes of traffic congestion in Chinese metropolis?

Due to the vast territory of China, there are huge differences in climate, culture and economy. In order to fully understand the causes of congestion and prepare for the system dynamics model, it is necessary to collect various data of population, economy, transportation and traffic policies. Combined with local traffic condition, the main causes of traffic congestion in different metropolis can be figured out. In order to find out those efficient measures, this paper summarizes the governance measures adopted in different periods for different congestion situations in big cities in China.

2. How to make traffic policy to alleviate congestion?

The traffic system is a complex system, which is affected by many factors such as population, economic, climate, etc. Based on system dynamics, this paper constructs a system dynamics model that is suitable for Chinese metropolis. By defining the purpose and boundary of the model, the scope of the study is defined. By combing the relationship between various factors, causality diagram is established. Based on the causality diagram and data, the model is established.

3. What measure can be used to control traffic congestion in Shanghai?

As one of the economic centers of China, Shanghai attracts a large number of enterprises, and creates a large number of business opportunities and employment opportunities. The population in Shanghai increased rapidly during the past 20 years so the travel volume also increased a lot. This paper conducts an empirical study of Shanghai based on the traffic characteristics and the system dynamic model. By simulating Shanghai transportation system and evaluating the effects of different policies, the more effective strategy is put forward.

1.4 Research framework

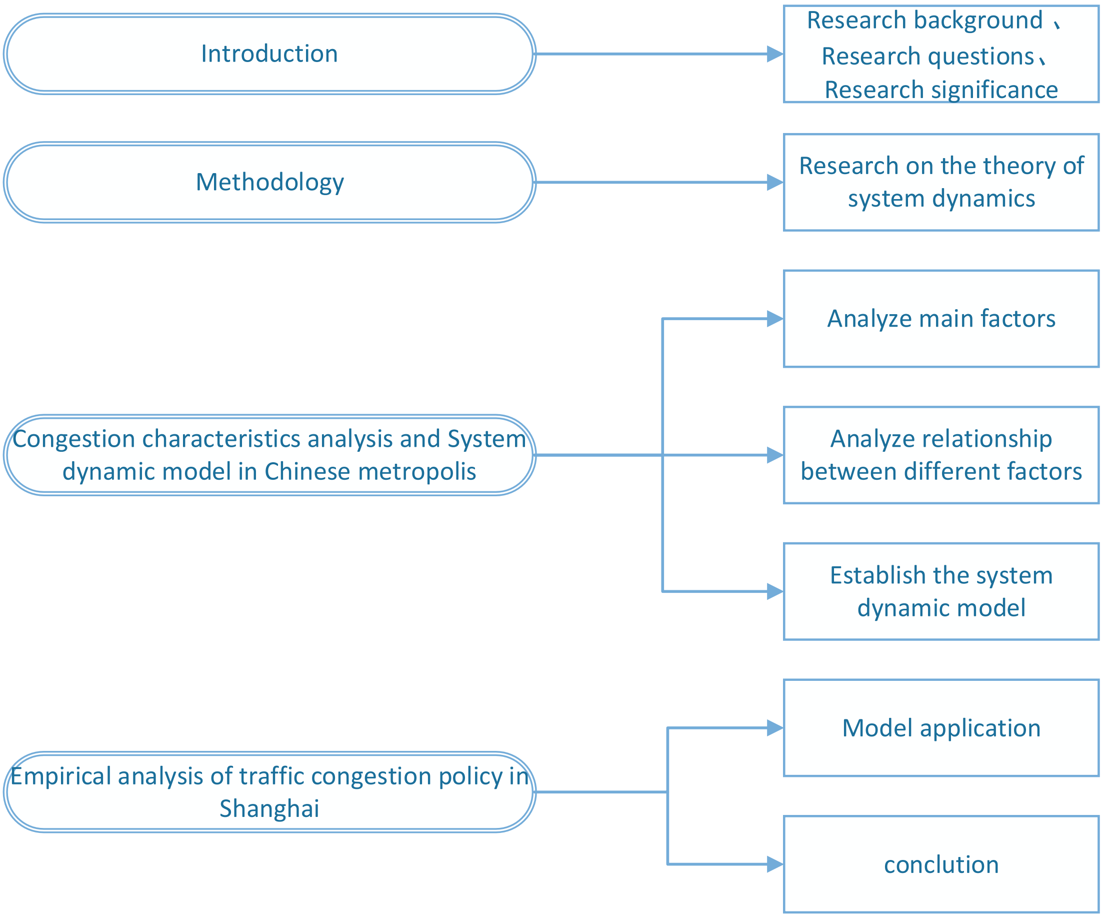

Fig. 1.6 Research framework

The research framework of this paper is shown in Fig. 1.6. This paper consists of four chapters. The first chapter is the introduction, which mainly describes the research background, research significance and research question; The second chapter is the methodology, which can be divided into two parts. The first part introduces the development of transportation system and congestion measures in different countries; the second part introduces the theory of system dynamics. The third chapter describes the process of establishing the system dynamics model. The last chapter is empirical analysis of traffic congestion policy in Shanghai.

2 Literature review and methodology

2.1 Literature review

2.1.1 Traffic development process of metropolis

Traffic development process in developed countries

With the development of modern industry, science and technology, people's travel mode, travel distance and travel demand are quite different from before. Industrialization started in the west and western cities began to design modern transportation system and formulate traffic rules very early. Western countries have experienced in solving traffic problems. Take traffic congestion for example.

Table. 2.1. Transportation development process in developed countries

Year	Event	Features and influence
Before 1840	Walking & Riding	The city has small scale, high population density and compact land use
1840-1860	Public carriage	The city expanded along the route of public carriage.
1863	The first London subway	Strengthen the connection between the center and the suburbs
1888	The first tram	Travel become more convenient
1900	The first bus	Preliminary establishment of public transport system
1913	Mass production of cars (Fords)	Free travel leads to the further spread of the city and the travel demand increases greatly
After 1977	Rail transit becomes a trend	Efficient and environmental-friendly; Part of modern metropolis

The development of transportation system also affects the traffic rules. The Athens Charter put forward by the International Architectural Association in 1933 pointed out that with the development of automobile and urban traffic, a new road system should be considered to be adapted to the transportation system, that is, the city should adapt to the development of automobile [20] . However, with the improvement of economic level, the number of cars is growing rapidly. The significant increase of residents' travel demand leads to more and more serious traffic congestion. In 1977, the Machu Picchu charter revised the idea of urban transport development, and proposed that the future urban transport policy should be based on the public transport system, The development of the city should take the public transport system into consideration. After that Rail transit becomes a trend. The evolution of transportation idea further reflects the development process of transportation policy, from "let the city adapt to cars" to "developing public transportation system"[21].

In developed countries, there are 3 stages to solve the traffic problems
When private car first appeared, the urban transportation infrastructure was improved to meet the travel needs of residents;
By optimizing the traffic management system and improving the efficiency of existing facilities, the traffic supply will be increased;
When the traffic supply reaches the limit and can't be increased, traffic policy should be formulated to manage the traffic demand and solve the increasingly serious traffic problems [22].

Traffic development process in China
The development of transportation in China is later than that in Western industrialized countries. Shanghai is an early city to introduce industrialization. In 1868, the bicycle was introduced in Shanghai. In 1874, the rickshaw increased rapidly. However, the development of the city and the motorized transportation system appeared after the reform and opening up in 1978.

Table 2.2 Transportation development process in China

Year	Transportation mode	Features and influence
Before 1977	Non-motorized travel	The city has small scale, high population density and compact land use
1978-1985	Public transportation	The travel volume increased significantly Passenger volume of bus increased rapidly Bicycle retention increases rapidly
1986-2019	Private cars travel	The scale of the city is expanding

		The number of motor vehicles increased rapidly Individual traffic demand is increasing Higher requirements for road network
After 2000	Rail transit becomes a trend	Guide people to give priority to public transport Strengthen the construction of rail transit

It's found that with the rapid development of social economy and traffic demand, transportation system developed rapidly. Metropolis in China have gone through 5 stages: lack of transportation infrastructure, rapid development of public transportation, rapid development of individual traffic, shrinkage of public traffic and development of rail transit [23,24].

China's transportation development process is similar to that of western countries. However, transportation system in China is confronted with greater challenges, not only because of the huge population base, but also due to the rapid urbanization during the past 50 years. The transportation system in developed countries have completed the transformation from non-motor vehicles to motor vehicles in one hundred years, but it took only 50 years in China. Excessive growth of transportation system in China has left many problems.

2.1.2Traffic congestion law in metropolis

Both Chinese and western cities have similar congestion laws, which can be summarized from spatial characteristics, time characteristics, influence of major events and trend of congestion.

Spatial characteristics of congestion

The urban roads are divided into different grades. Road with different grades have different capacity. Traffic congestion usually occurs at the junction of main road and branch road, that is, the junction from the road with large capacity to the road with small capacity [25]. At the same time, affected by left turning vehicles and traffic lights, the traffic capacity of road intersection will be weakened. Once these traffic congestion points are formed, traffic congestion will spread throughout the road network.

Time characteristics of congestion

The main purpose of urban residents' travel is to work and study. There is congestion in the morning rush hour and evening rush hour during weekdays because traffic flow keeps increasing in a short period of time. According to transportation survey data, the peak of traffic volume often appears at 7:00-9:00 a.m. and 17:00-19:00 p.m. during the work days. This kind of congestion is widespread and periodic. With the development of modern urbanization, there is heavy congestion in the direction of entering the city on Monday morning and leaving the city on Friday evening.

Fig 2.1 Traffic congestion in the direction of entering the city [25] (河北十大易拥堵收费站和易堵路段公布！_车流量 (sohu.com))

Congestion caused by major events

There are two kinds of congestion caused by major events. One is predictable congestion, such as congestion caused by holiday travel; The other type of congestion is caused by emergencies, such as bad weather and traffic accidents. For the preventable traffic congestion, it can be alleviated by making emergency plans. Taking national day for example, there were more than 600 million travels during the national day in 2020 but the traffic was in good condition. That is because the transportation department has estimated the number of trips in advance through ticket sales and other channels, and made plans for different situation [26]. Congestion caused by accident is hard to predict and one way to reduce road accidents is to ask drivers to obey the traffic rules.

With the expansion of the city, the growth of population and the change of travel mode, traffic congestion is becoming increasingly serious problem in Chinese society. In recent years, the roads are more and more crowded, the peak hours are longer and longer, the speed is lower and lower, and finding a spot is more and more difficult.

2.1.3 The criterion of congestion

The criterion of congestion in developed countries

According to the brief introduction of foreign traffic congestion definition given by Beijing Transportation Commission, the following index are often used to describe the degree of congestion: roadway congestion index (RCI), lane kilometer duration index (LKDIF), congestion severity index (CSI), average peak travel time (APTT), level of service (LOS). The explanation of these index is shown in Tab. 2.3 [27]:

Tab. 2.3 The criterion of congestion index in developed countries

Region	Index	Explanation	Criteria
Texas, USA	RCI	Weighted average of average daily traffic volume per kilometer	If RCI>1, then it is judged as congestion
California, USA	LKDIF	Ratio of annual average daily traffic volume (AADT) to capacity(C)	If V/C>1 or AADT/C>9, then it is judged as congestion
Highway Capacity manual (USA)	LOS	Level of service based on passenger’s experience	The index divides LOS into 6 levels (A to F). E and F are judged as congestion.
Federal Highway	CSI	Delay time per million	-

Administration		wagon-kilometers	
Washington state, USA	APTT	Average travel time in morning and evening rush hours	-

Among all these indexes, RCI, CSI, APTT and LOS are commonly used to describe traffic congestion. RCI and CSI are based on travel volume, and by comparing the actual traffic volume with the theoretical traffic volume, the degree of congestion can be figured out. While APTT and LOS are based on the traffic condition service of the transportation system. AAPT is based on the delay time during the rush hours while LOS is based on the passengers' experience.

The criterion of congestion in China

According to the 'road traffic operation evaluation index system of urban road traffic management (2012 Edition)', the domestic congestion assessment indexes in China are as follows: average speed of main road, ratio of volume and capacity (V/C), the congestion rate of intersection during rush hour. The criteria of these indexes are shown in Tab. 2.4. [28]

Tab. 2.4 The criteria of congestion index in China

Index		Threshold	Level of congestion
Average speed of main road		⩾ 30	Smooth traffic
		[20,30)	Mild congestion
		[10,20)	Moderate congestion
		<10	Serious congestion
Ratio of volume and capacity (V/C) Based on the level of service		<0.4	Smooth traffic
		[0.4,0.6)	Mild congestion
		[0.6,0.75)	Moderate congestion
		[0.75,0.9)	Serious congestion
Congestion rate of intersection during rush hour	(Signal intersection) number of green lights	⩽1	Smooth traffic
		(1,2]	Mild congestion
		(2,3]	Moderate congestion
		>3	Serious congestion
	(Unsignalized Intersections) queue length (m)	[0,100)	Smooth traffic
		[100,250)	Mild congestion
		[250,400)	Moderate congestion
		⩾400	Serious congestion

2.1.4 Urban transport development mode

Because different countries have different culture, population density, climate and development degree, transportation mode is also different form each other. There are three transportation modes in the West:

Transportation mode in the United States

The American urban transportation system is dominated by cars. The transportation development of metropolis in the United States can be divided into the three stages. In the first stage (1925~1964), private cars became popular all over the country. In 1925, The federal government has designed and built a road network that adapts to car travel. This move has changed the way people live and travel, because with efficient road network, car became a necessity for a family. The public transportation was almost replaced by private cars, it was difficult to continue under the impact of private cars. In the second stage (1964~1980), the public transport policy was emphasized. The urban public transport law encouraged the planning and establishment of urban public transport system, but the effect is not obvious. It was difficult to change the dominant position of cars in the short term; In the third stage (1980~now), Federal highway administration promotes integrated transfer system. The point of this policy is to improve the efficiency of the whole transportation system by building a network that suits all kinds of transportation mode and multi-mode passenger transfer [29].

Los Angeles is a typical city whose transportation system is dominated by cars. The car-retention rate is very high in LA. In 2000 each family owned 1.68 cars on average. However, the proportion of public transportation in the urban area is less than 10 percent and LA is heavily congested. According to the Highway Capacity manual, the LOS in Los Angeles is at E and F, which means that it is one of the most congested cities in the United States. At the end of the 20th century, the city of Los Angeles decided to change its original transportation system to an efficient, intensive and intelligent system.[30]

The facts proved that it is feasible to take cars as the main mode of transportation for a city with a population of 200,000-300,000. Many towns in Europe and the United

States used this system and it worked perfectly. However, when it comes to metropolis with millions of people, the disadvantages caused by this mode is quite obvious, such as traffic congestion, environmental pollution and energy shortage. In fact, American government have spent a lot of money to revive public transportation, but it did not work. Billions of dollars are invested in public transportation construction and it only attracts 2% of the private car owners. It can be seen that once the car dominant mode is formed in metropolis, it is difficult to change in a short period of time.

Transportation mode in Europe

Unlike the United States, many metropolitan transportation systems in Europe are made up of multiple modes, such as bus, metro, private car and bicycle[31]. In order to reduce traffic congestion, the government make a series of specific, targeted measures. London is a good example.

Due to population growth, economic development and tourism boom, the pressure on London's transportation system is increasing year by year. London government has put forward the following strategies to optimize the structure of the transportation system:

- Increase the development of transportation infrastructure to meet the needs of urban development;
- Improve the public transportation system to attract more passengers;
- Strengthen the management of transportation system and improve the level of service.

Many metropolises in Europe have relatively mature public transport system. Almost all intercity railway traffic goes deep into the city. Stations are set at the edge of the central area and passengers can easily go to the central business district. In general, these stations are comprehensive transfer stations, where passengers can transfer to other means of transportation. There are parking lots around the station to facilitate car transfer. In Europe, it is even more convenient for people to travel on public transport so public transport become the main mode of transport.

Transportation mode in Japan

Rail transit is the main part of public transport system in Japan. Although the automobile industry is highly developed and the private car retention is also high, over 60% of the passenger choose rail transit. That is because the Japanese government has pay attention to rail transit and integrated transfer hub for a long time. This kind transportation system generates less traffic volume and traffic pollution. Due to the limitation of the technical and economic characteristics of rail transit, the mode of transportation system is only suitable for large urban areas with high level of economic development, dense population and compact land use.

Transportation mode in Singapore

As one of the richest countries in the world, Singapore is a nation with small land and dense population. Because of the limited land, the Singapore government avoids congestion by strengthening traffic management.

In order to control the retention of private cars, Singapore government makes private cars the most expensive luxury goods by adjusting taxes and fees. In order to protect environment and reduce emissions, Singapore government also stipulates that people's cars must be scrapped after 10 years of use. For the in-use vehicles, Singapore government adjusts the charging standards for different periods to implement the Stagger Shifts. To guarantee the traffic order, punishment of traffic violations is very strict in Singapore.[32]

Transportation mode of metropolis in China

There are various modes of transportation in China's metropolises. However, with the increase of quantity of private cars, people are more likely to use private cars, resulting in a continuous decline in the proportion of public transport and more serious congestion. Based on the experience of other countries, local government plays an important role in balancing the transportation system. In terms of infrastructure construction, the government spent a lot money on building rail transit and comprehensive transfer station to make rail transit more efficient. On the other hand, when the infrastructure is mature, the traffic management strategy has a greater impact on the traffic system.

2.1.5Traffic congestion policies in metropolis

Urban traffic congestion is affected by various factors, such as traffic demand, economy, urban development, laws and regulations, government management and other aspects to make management policies. The experience of developed countries is worth learning.

Table 2.5 Congestion policies in different metropolises

Metropolis	Congestion policy
London, UK	Implementing congestion charges in urban central area Improving transportation system for non-motor vehicles Improving intelligent traffic management system
Paris, France	Improving transportation system for cycling Developing rail transportation system Improving travel information service
Moscow, Russia	Public transport priority development Strengthen traffic demand management Transportation planning leads city planning
New York, USA	Strengthen traffic management Improving public transportation system Improving intelligent traffic management system
Singapore	Implementing congestion charging policy Limiting vehicle purchases Public transport priority development
Seoul, South Korea	Improving the service level of public transport system Implementing traffic demand management Building intelligent traffic management system
Tokyo, Japan	Developing rail transportation system Building intelligent and humanized transportation hub
Beijing, China	Vehicle restriction rule for restricting car driving Public transport priority development License-plate lottery for limiting vehicle purchases
Hong Kong, China	Improving the public transportation system Establishing a city model guided by public transport

	Building intelligent traffic management system
Shenzhen, China	Building a transportation system based on public transit Building more intelligent and humanized transportation hub Improving the transportation system of walking and cycling

By comparing all the experience above, there are different kinds of congestion control measures:

Improving the public transportation system

Public transportation mainly consists of bus and rail transit. Compared to other modes of transportation, public transportation system is more efficient, more eco-friendly and can carry more passengers. For metropolis with high-density of population and high traffic demands, one of the most efficient ways is to give priority to the public transport. In fact, this is the first choice for most cities and this policy includes the following aspects:

- Public transportation system should be given priority in transportation planning and urban planning;
- Take public transport into consideration when making strategies;
- The management of transportation system should take public transit priority as principle.

Build intelligent transportation system (ITS)

Intelligent transportation system is the application of sensing, analysis, control and communications technologies to transportation system in order to improve efficiency, safety and mobility. Intelligent transportation system consists of automated driving system, ecological intelligent transportation system, real-time information publishing system, etc. The application of this measure has been used for a long time so it is relatively mature in western cities. Chinese cities starting to implement ITS a few years ago and now it plays an important role in transportation system.[33]

Strengthen the punishment of traffic violations

In many Chinese cities, drivers do not obey traffic rules. For example, private cars occupy bus lanes during the rush hour and cause chaos on the roads. In this case, government should strengthen supervision and increase punishment to establish a more efficient transportation system.

Combine transportation planning with urban planning

Transportation planning is a part of urban planning. Different from developed countries, for most cities in China, the urban planning is not finished, so it is important to take transportation system into consideration when the government makes urban planning. Efficiency of transportation system is affected by urban planning:

- Urban planning is the basis of road network planning, transportation hub planning, parking planning and even the traffic management;
- Different land use properties lead to different kinds of road network structure and traffic volume. Generally speaking, if the land is zoned for commercial purpose, the traffic volume is heavier.

Transportation demand management

In the previous chapters, the 'Down's law' was introduced.

According to the 'Down's law' mentioned in the previous chapter, the essence of traffic congestion is the imbalance of the demand and supply. Building more infrastructure only works at the beginning and after a while there will be more vehicles so the problem of congestion has not been solved. When the urban construction reaches a certain degree, building new infrastructure is not an option anymore. Since the traffic supply is limited, government makes traffic policies to restrict car usage:

- Control the growth of vehicle retention;
- Equitable distribution of traffic demand in each district;
- Encourage the Stagger Shifts to weaken the travel demand in congested time.

Control traffic volume by congestion pricing

Western cities introduce congestion charging to limit the traffic flow of central road network in peak period. In order to reduce travel costs, people will choose other routes or use public transportation. Congestion charging is an effective measure to reduce congestion. While in Chinese city, the government attracts passengers by reducing the ticket price of the public transport system. Another measure to restrict car usage is increasing parking charges in city center. Metropolises like Beijing, Shanghai, Guangzhou had put forward the idea of congestion charge to sound out the citizens' response but it has not yet been implemented.

2.2 Methodology

This section mainly introduces the theoretical basis and the applicability of the theory. Firstly, the history and characteristics of system dynamics are briefly introduced; then, the modelling process of system dynamics is introduced; Finally, the applicability of the system dynamics method is illustrated based on the characteristics of the system dynamics and traffic congestion in metropolises in China.

2.2.1 Overview of system dynamics

System dynamics was first proposed by Professor Forrester at Massachusetts Institute of Technology in 1958. It was originally called industrial dynamics. However, with the expansion of the application, it has been applied to the other fields, such as political field, economic field, social field, education field, financial field, military field, medical field, etc. Finally, industrial dynamics became a discipline with various research fields and got a new name-system dynamics.[34]

System dynamics is an interdisciplinary subject to solve system problems. It is based on the feedback control theory, system theory, cybernetics and information theory. What's more, it can also use quantitative analysis and qualitative analysis at the same time. There is a software called Vensim which is developed based on system dynamics and can be helpful in decision-making.

2.2.2Characteristics of system dynamics

System dynamics is an effectively method in solving the complex problems. The characteristics are as follows:

Research on complex large-scale system

The system dynamics model can accommodate dozens, hundreds, even thousands of variables, and can describe the complex relationship between different variables in the model.

Research on open system

System dynamics emphasize the development and change of the elements in the system. Researchers are asked to consider the problem in a dynamic way and take the open system as the research object to establish a dynamic structure.

Study the causal relationship between various factors

It is believed that the causal relationship is used as the connection between the elements in the system, and the causal feedback loops are established based on the causal relationship. Vensim can sort out the causal relationship between various factors efficiently.

Qualitative analysis and quantitative analysis

System dynamics model allows qualitative and quantitative analysis by analyzing problems, defining factors, ordering causality, establishing model and entering mathematical formulas.

Policy laboratory

The system dynamics model works as a policy laboratory. Different policies are simulated by adjusting parameters of key factors. The results of system simulation can provide scientific basis for decision-making.

2.2.3 System dynamics modeling steps

The goal of establishing system dynamics model is to establish the 'policy laboratory', which is the simplification of the real world. Therefore, before establishing a model, the research problems and system objectives should be clearly defined which is helpful to clear system boundary. Once the system boundary is set, the factors, causal relationship and mathematical formulas should not exceed the boundary. To ensure the authenticity and effectiveness of the model, it needs to be checked and modified again and again in the process of modeling [35]. It is a spiral process and cannot be completed at one time. It should be noted that there is no ultimate model, a relatively effective model which can achieve the preset goal and meet the requirements of research objective is good enough. The steps of establishing system dynamics model are shown in Fig. 2.2:

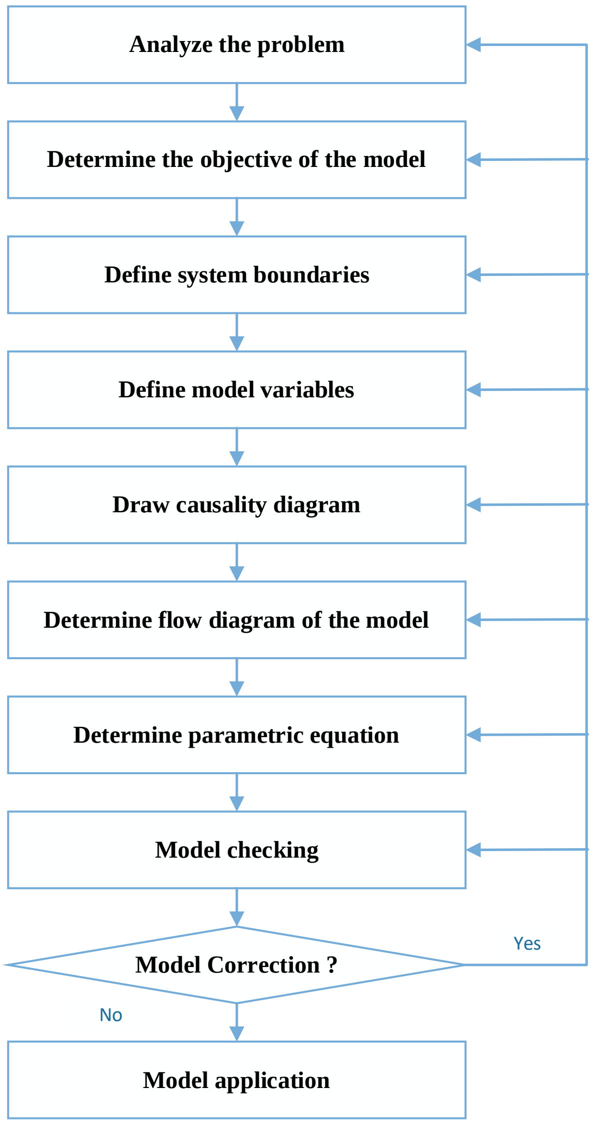

Fig. 2.2 Steps of system dynamics modeling

Analyze the problem

The research object of this paper is to find out efficient measures to reduce traffic congestion. The first step is to analyze the problem, find out the main factors and understand how does transportation system work. When analyzing the problem, it is of great importance to find out the essence of the problem, collect the relevant policies and regulations, understand the objective, and get access to data.

Determine the objective of the model

Objective is an important part of system dynamics model. The objective must be determined based on detailed research. All the following steps is to achieve the objective.

Define system boundaries

The definition of model boundary is very important for model construction. There are two principles to define the boundary of the system:

- Seek opinions from various parties, such as people who work in this field, researchers of related subjects and expert in this field. All kinds of opinions should be based on the modeling objectives, and then define the boundary of the system.
- Reduce the system boundary if at all possible while comprehensively considering the factors. Delete irrelevant factors to highlight the focus of the model.

Define model variables

Once the system boundary is defined, variables are selected within the system boundary. The principles are as follows:

- Variables should be closely related to objects and variables that has noting to do with the research question discarded.
- The causal relationship between variables can be described by mathematical formulas;
- Variable data can be obtained

Draw causality diagram

Causality diagram is the basis of the flow diagram. A diagram with clear causality can ensure the rationality of the flow diagram. There are 4 tips when drawing causality diagram:

- In order to facilitate identification, variables should be named with nouns if possible;
- When designing causality, the effect (increase or decrease) of variables on feedback loop should be considered;
- When designing causality diagram, the unit of variable can be determined. For those variables without unit, units can be assumed.
- Both positive feedback loop and negative feedback loop should be closed loop, because the unclosed link cannot reflect the dynamic changes of the system.

Determine flow diagram of the model

The real simulation of the system needs to be realized by establishing the flow

diagram. There are 5 aspects needed to be taken into consideration:
Analyze the model structure from the whole system;
Analyze the model structure from each part of the system;
Identify subsystems and analyze different modules of the system;
Determine the relevant variables in each subsystem;
Based on the causality diagram, the causality between variables is determined, and the system structure flow diagram is drawn.
Determine the causality between variables based on the causality diagram and then draw the flow diagram.

Determine parametric equation

After determining the influence factors in the model, mathematical equations is needed to establish the relationship between factors. The relations between some factors are linear while others are not. Generally speaking, there are two ways to determine the non-linear relationships: one is to use formula from other studies; the other way is to use the look-up function in Vensim.

Model checking

Only the model that has passed the test can be applied to the political experiment. If the model fails to pass the model checking, there might be something wrong with the model in some steps mentioned above. It is important to correct all the mistakes and make sure that the model is efficient.

Model application

The model can be used as a policy laboratory and provide a scientific basis for decision-makers. In this paper, the model can be used to analyze the impact of different congestion policies on transportation system, and then analyze the efficiency of different policies.

2.2.4 Applicability of system dynamics in traffic congestion

The urban transportation system is complex and dynamic while system dynamics emphasizes the integrity and dynamics of the system and the relationship and development between different factors. Therefore, it is feasible to study traffic system with system dynamics. Moreover, the combination of these two has generated some research results.

Urban traffic system is a highly comprehensive and complex system. Urban transportation system is affected by many systems such as population system, pollutant system, economic system and the culture of this city. These relationships can be complex and nonlinear. It is important to study these systems as a whole. The tools provided by system dynamics, such as causal loop, flow graph model, feedback mechanism can analyze the traffic system qualitatively and quantitatively. All these functions can be implemented in Vensim

2.3 Chapter summary

This chapter can be divided into two parts. In the first part, through summing up a large number of literature, this paper discusses the traffic development of different countries, and summarizes different traffic management methods. The second part introduces the theory of system dynamics, modeling steps and the application of the research problem.

3 Congestion characteristics analysis and system dynamic model of transportation system in Chinese metropolis

Chinese first-tier cities, that is Beijing, Shanghai, Guangzhou and Shenzhen, are facing serious traffic congestion nowadays. This chapter first analyzes the traffic situation of these metropolis from different aspects such as traffic supply, traffic demand, congestion, and then summarizes the reasons for congestion; Then, build system dynamic model of the transportation system. The model should be based on the three aspects mentioned above and also taken different policies into consideration.

3.1 Traffic situation in the metropolis in China

3.1.1 Basic situation of metropolis

Beijing is the capital of China. It is located in the north of China. It has a long history and a rich culture. It is the seat of government and large enterprises, especially state-owned enterprise. At the end of 2019, the city had 16 districts under its jurisdiction, with the urbanization level reaching 86.6%. There were 21.536 million people in Beijing, with 7.9 million of them from other provinces.

Shanghai has a history of 1400 years. It is located in the east of China. It is not only the economic and trade center of China, but also the most international city in mainland China. It is a good combination of eastern and Western cultures, and attracts a large number of well-known companies set up branches in Shanghai.

Guangzhou, the capital of Guangdong Province, has a history of more than 2000 years since the Qin Dynasty. It has always been one of the most important port cities in China. During Ming and Qing Dynasties (1368-1911), it was the only port city for foreign trade. It is one of the few large port cities in the world that last for more than 2000 years. Since 1989, Guangdong Province has ranked first in GDP.

Among the two important national policies, one belt, one road strategy and Guangdong-Hong Kong-Macao Greater Bay Area, recently issued by the Chinese government, Guangzhou remains to be one of the core cities.

Shenzhen, founded in 1980, is China's first special economic zone. It is the youngest of the first-tier cities and has been established for only 40 years. Shenzhen plays an important role in China's high-tech industry, financial services, foreign trade and export. It is also known as China's Silicon Valley, the pioneer of various new policies and new technologies. [36-39]

In order to better understand the traffic characteristics of these four cities, there are four aspects that need to be introduced in detail: household registered population, Permanent Population, GDP and per capita GDP. From 1978 to 2019, the changes of the four metropolises are shown in the Fig. 3.1-3.4:

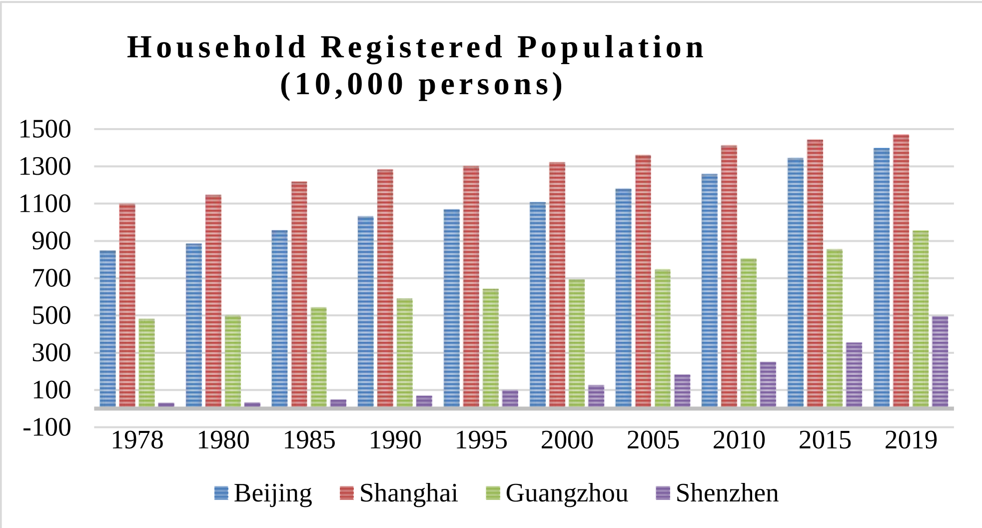

Fig. 3.1 Household Registered Population in metropolises

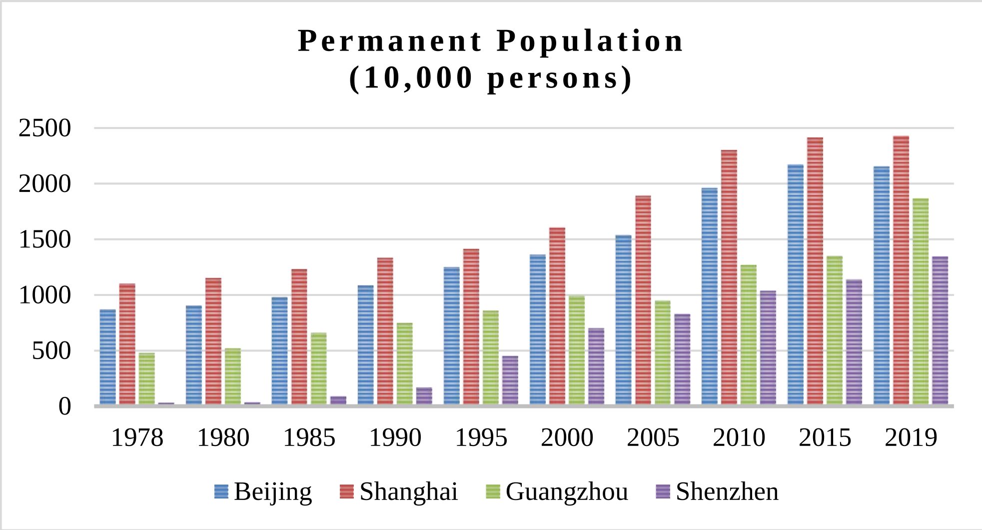

Fig. 3.2 Permanent Population in metropolises

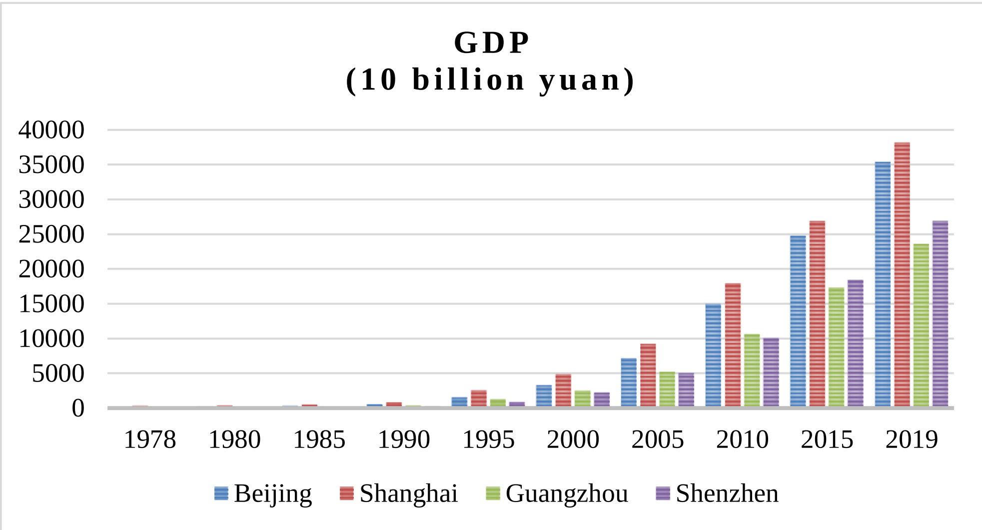

Fig. 3.3 GDP in metropolises

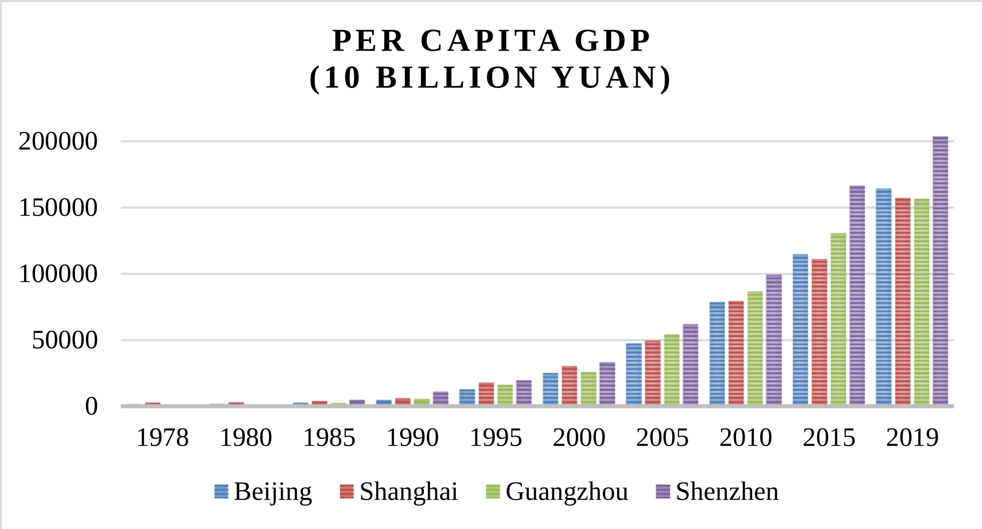

Fig. 3.4 per capita GDP in metropolises

From Fig. 3.1-3.2, it is found that Beijing, Shanghai and Guangzhou have already been metropolises at the beginning of reform and opening up in 1978, especially in Beijing and Shanghai, where the permanent resident population was about 10 million. Guangzhou also has a permanent population of nearly 5 million and it was the largest and most influential city in Guangdong Province. However, in 1978, Shenzhen was only a small village with 310,000 people, which is far behind the other three cities. After 40 years of development, in 2019, the population of the four cities has increased significantly. Beijing and Shanghai is still the two largest metropolises with nearly 15 million household registered population and 25 million permanent population. The household registered population in Guangzhou has increased from 4.8 million to 9.53million, and the resident population has increased from 4.9 million to 18.67 million. The fastest growing city is Shenzhen, by the end of 2019, the household registration population in Shenzhen has reached 4.9 million, 16 times larger than that in 1978, and the permanent population has reached 13.4 million, 43 times higher than that in 1978. By comparing household registered population and permanent resident population in these metropolises, it is realized that the permanent population of these metropolises is 700-1000 million larger than household population. The reason of this phenomenon is that these metropolises can offer many job opportunities and is very attractive to the younger generation.

It can be found from Fig. 3.3-3.4, during the past 40 years, the economic growth of these metropolises is significant. the GDP of Beijing, Shanghai, Guangzhou and

Shenzhen in 2019 are 325 times, 139 times, 548 times and 13,711 times of that in 1978, respectively. It can be seen that although Guangzhou and Shenzhen are not the largest cities, they are the two cities with the fastest growth, especially Shenzhen. Because of the rapid growth of population in these metropolises, the per capita GDP is not as obvious as that of GDP. The per capita GDP of Shanghai in 2019 is 157,279 yuan, only 63 times higher than that of 1978. The per capita GDP of Guangzhou in 2019 is 156,427 yuan, slightly lower than that of Shanghai, 172 times higher than that of 1978. Beijing's per capita GDP in 2019 is 156,220 yuan, 130 times higher than that of 1978. Shenzhen is not only the city with highest per capita GDP, but also the fastest growing city. From 606 yuan in 1978 to 203,489 yuan in 2019, an increase of 335 times. It is seen that the economic development of Guangzhou and Shenzhen is faster than that of Beijing and Shanghai but Shanghai remains to be the metropolis with the largest economy.

3.1.2 Transportation system capacity of metropolis

The transportation system of metropolis is the sum of all the transportation facilities used to meet the travel demands. Generally speaking, it is affected by urban planning and the use of the land, such as roads, subways, stations and other infrastructures. The capacity of transportation system is based on the equipment in the transportation system, such as road capacity, carrying capacity of vehicles and so on. Total capacity can be improved by new construction, reconstruction and expansion of urban roads, overpass and other infrastructures.

In order to better understand the transportation system of these four cities, there are four aspects that need to be introduced in detail: length of roads, length of subways, number of bus routes and Road area per capita. [40-43] From 2000 to 2019, the changes of the four metropolises are shown in the Fig. 3.5-3.8:

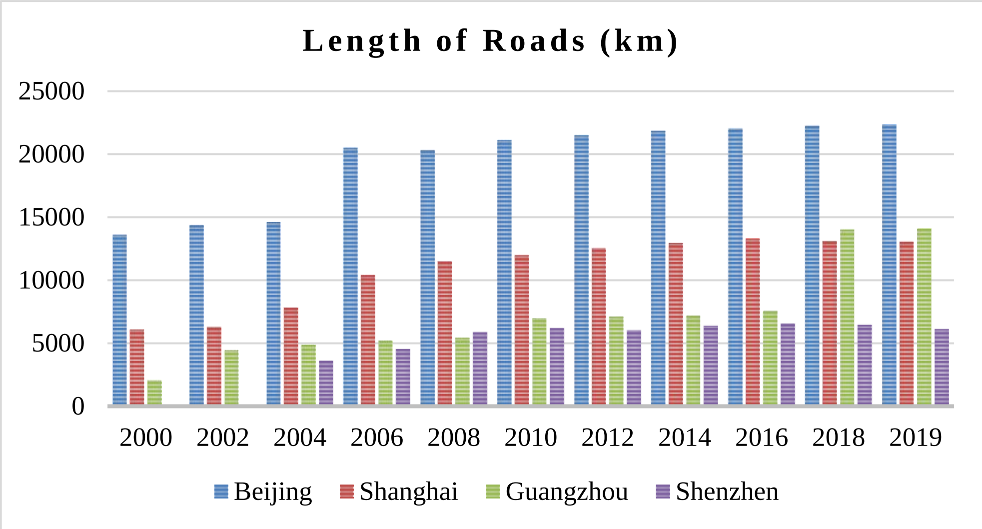

Fig. 3.5 Length of Roads in metropolis

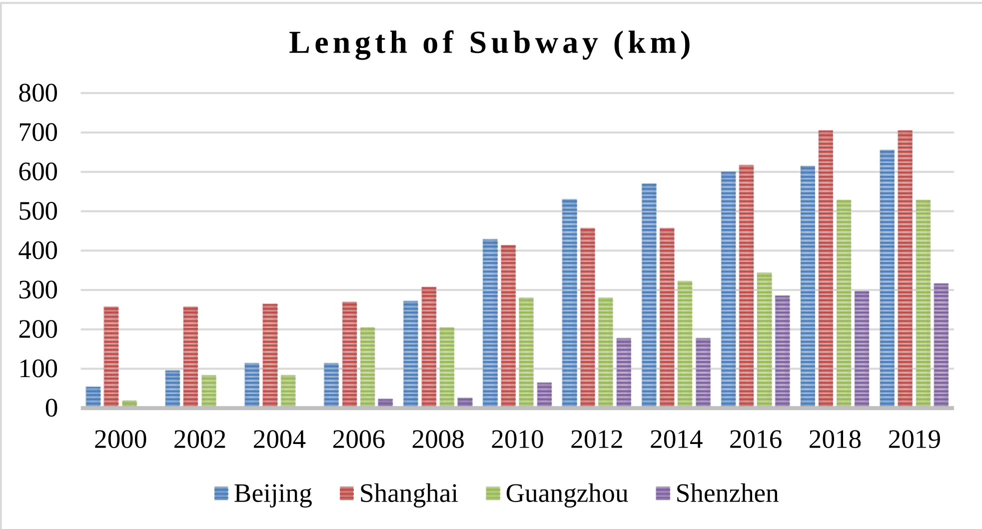

Fig. 3.6 Length of subways in metropolis

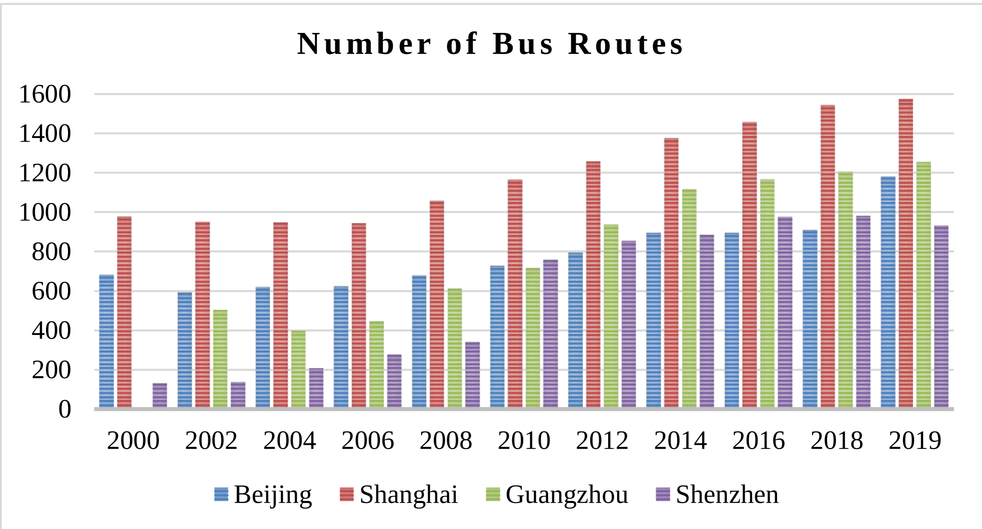

Fig. 3.7 Number of bus routes in metropolis

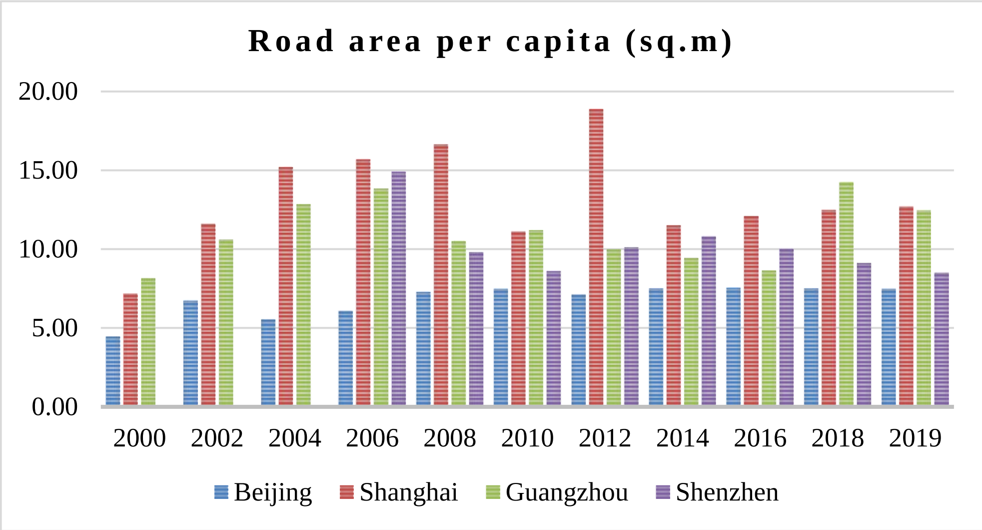

Fig. 3.8 Road area per capita in metropolis

According to Fig. 3.5, Beijing has the longest road network. However, since Beijing has the largest area, this figure is not surprising. The area of Beijing is 16410.54 square meters, which is 2.5 times that of Shanghai, 2.2 times that of Guangzhou and 8.2 times that of Shenzhen. From 2000 to 2018, the length of road network in Shanghai and road area per capita are better than those in Guangzhou, but after 2018, Guangzhou has built a lot of roads, it has greatly improved the traffic condition of Guangzhou. Although Beijing has the longest road network, due to the limited road area and large population base of Beijing's, the road area per capita is the smallest of the four cities.

When it comes to public transportation, it is a different story. In terms of subway construction, these cities are growing rapidly. The length of subway in Beijing and Shanghai are much higher than that of the other two cities. In 2016, Guangzhou opened 108 km subway, and the gap between Beijing and Shanghai was narrowed. The growth of Shenzhen is stable. In terms of bus routes, Shanghai is far ahead of other cities. The growth of bus routes in Guangzhou is the fastest, while the growth of bus routes in Beijing is not obvious.

3.1.3 Travel volume in metropolis

People choose different travel modes to achieve their purpose. Travel volume in metropolis is huge. Different kinds of transportation modes make it possible to meet citizens' travel demand. The study of urban traffic demand involves traffic demand, distribution and structure of traffic system. The distribution of traffic demands consists of spatial distribution and temporal distribution. The structure of traffic demand means the proportion of different modes of transportation.

In order to better understand the traffic composition of these four cities, there are three aspects that need to be introduced in detail: civil automobile, number of passengers carried by bus, and number of passengers carried by subways. In fact, there are other factors that may also influence that may influence traffic demand, such as population and GDP. In this section, these two elements will not be introduced anymore. From 2000 to 2019, the changes of the four metropolises are shown in the Fig. 3.8-3.10:

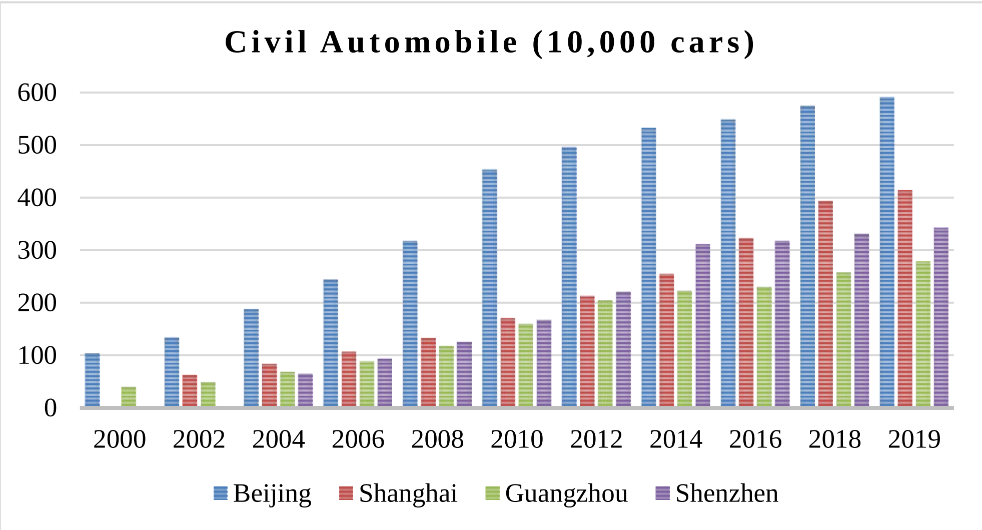

Fig. 3.8 Retention of civil mobile

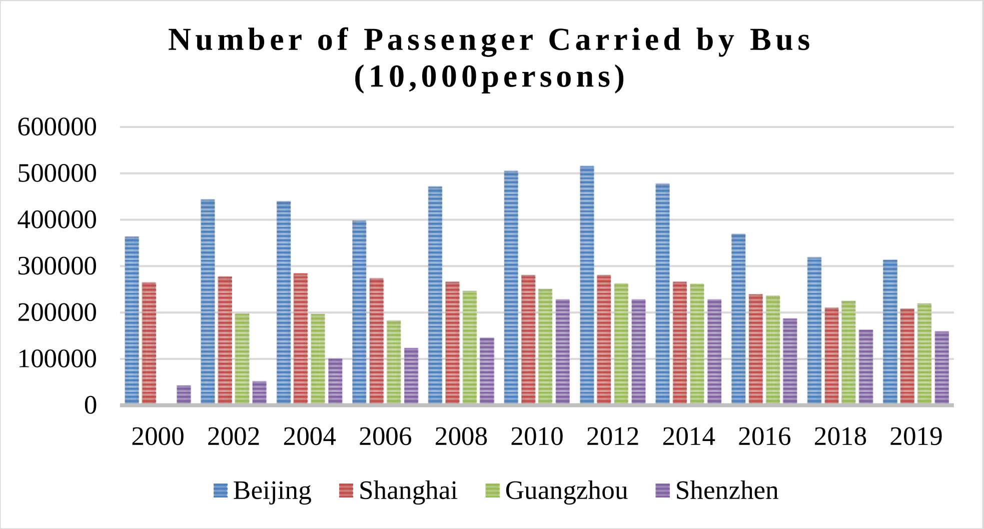

Fig. 3.9 Number of Passenger Carried by Bus in metropolises

Fig. 3.10 Number of Passenger Carried by subway in metropolises

As can be seen from Fig. 3.8, private car retention in these cities has increased rapidly in the past 20 years. Among them, the retention of automobile is the largest and grows faster than the others. On the contrary, Guangzhou has the smallest retention and the lowest growth rate. Beijing has the largest number of passengers carried by both bus and subways. The number of passengers carried by bus reached the peak in 2012 and began decreasing after that. This index showed a similar trend in other cities but not that obvious. The number of passengers carried by subway increase rapidly in these cities.

3.1.4 Traffic congestion characteristics in metropolis

In order to reflect the congestion characteristics of Chinese metropolis in a more intuitive way, this paper will analyze the congestion situation of these cities from three aspects: speed, congestion section and congestion duration.

Vehicle Speed

Vehicle speed is the most intuitive index to reflect the level of congestion. The vehicle speed of Beijing, Shanghai, Guangzhou and Shenzhen in 2021 is shown in the Fig. 3.11-3.14:

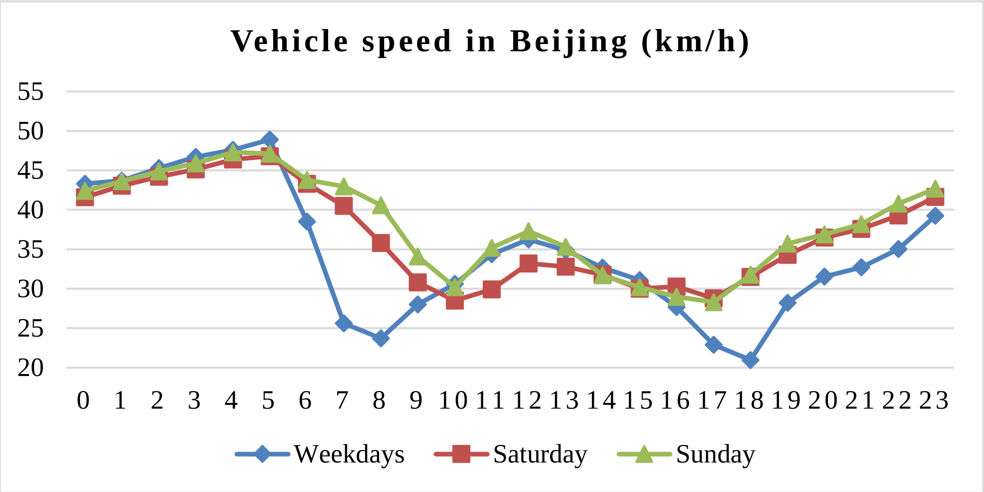

Fig. 3.11 Vehicle speed in Beijing

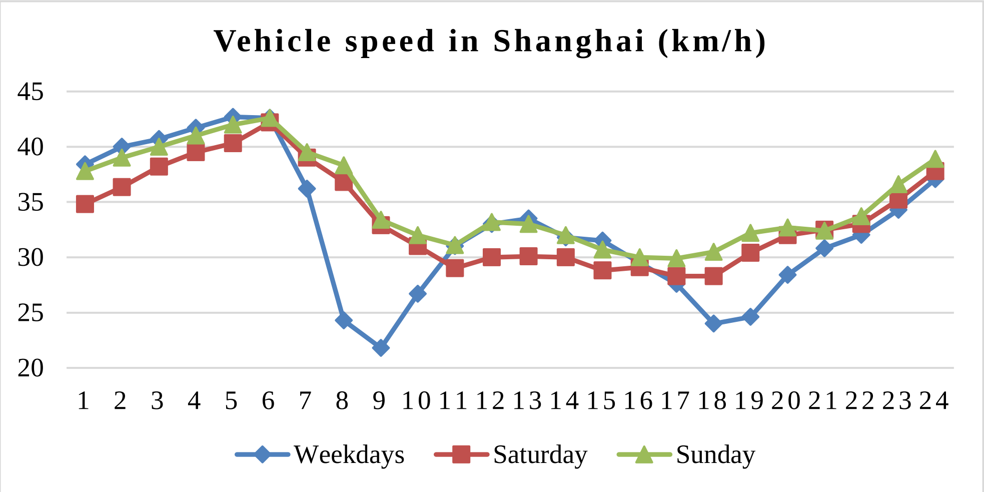

Fig. 3.12 vehicle speed in Shanghai

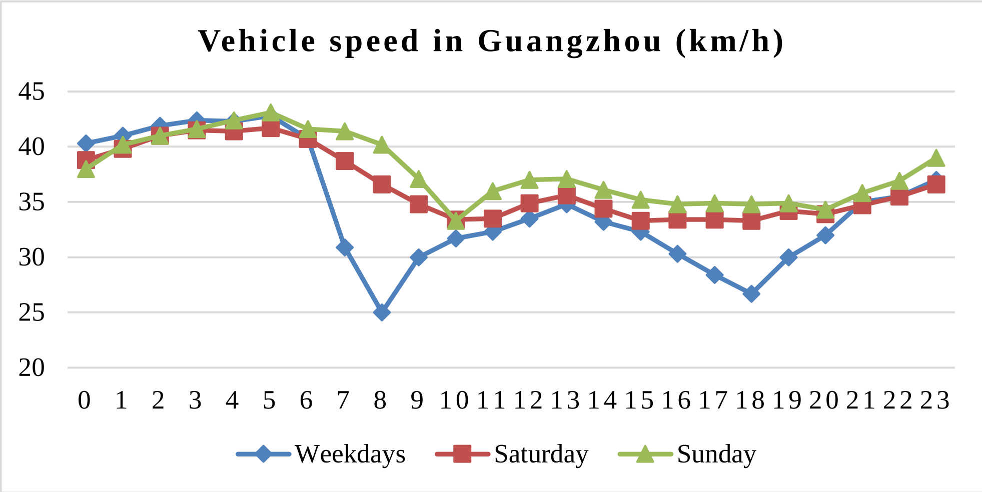

Fig. 3.13 Vehicle speed in Guangzhou

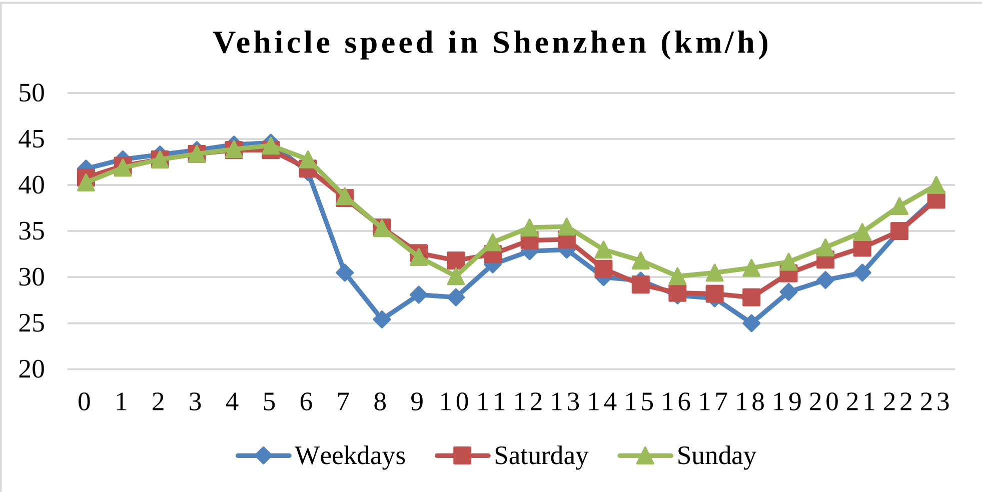

Fig. 3.14 Vehicle speed in Shenzhen

The maximum speed of the four cities usually appears at 3:00 or 4:00 in the morning, and the speed ranges from 42km/h to 46km/h. The free flow speed in Beijing is 46km/h, the highest among all these cities, while the free flow speed in Shanghai is the lowest, which is 42km/h. There are obvious morning and evening peaks in the four cities. The morning peak usually appears at 7:00 am - 9:00 am and the road network is most congested at 8:00. After 1:00 pm, the speed shows a downward trend again until the end of the evening peak. The minimum speed of the day in these four cities appears at 6:00 pm in the evening peak, and the speed is generally between 20 km/h -27 km/h. Among the four cities, The vehicle speed fluctuation in Beijing is the largest. The free flow speed is 47 km/h on weekdays and the minimum speed is 20.97 km/h at 6 p.m., with a difference of 26.03 km/h; The vehicle speed fluctuation in Guangzhou is the smallest. The free flow speed is 42.7 km/h on weekdays and 26.7

km/h at 6 p.m., with a difference of 16 km/h; Compared with weekdays, there is no obvious morning peak on weekends in these cities, and the vehicle speed on weekends is slightly better than that on weekdays.

Congestion area

The congestion area in these cities is shown in Fig. 3.15-3.18. The red area represents the area with serious traffic congestion, the yellow area represents the area with slight traffic congestion and the green area represents the area with good traffic condition.

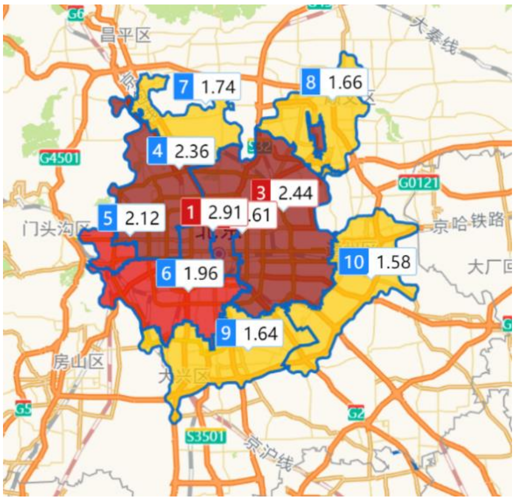

Fig. 3.15 Congestion area in Beijing

Fig. 3.16 Congestion area in Shanghai

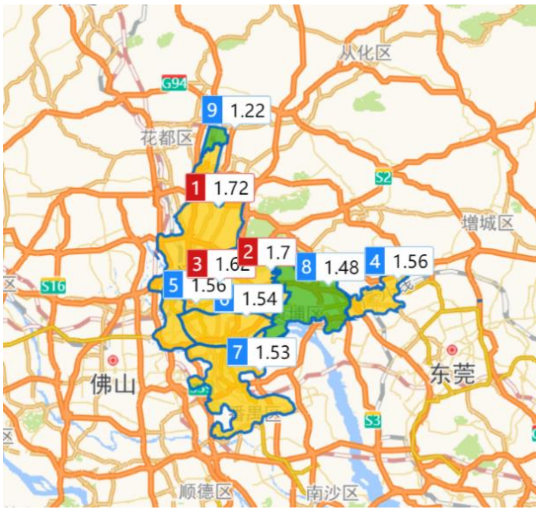

Fig. 3.17 Congestion area in Guangzhou

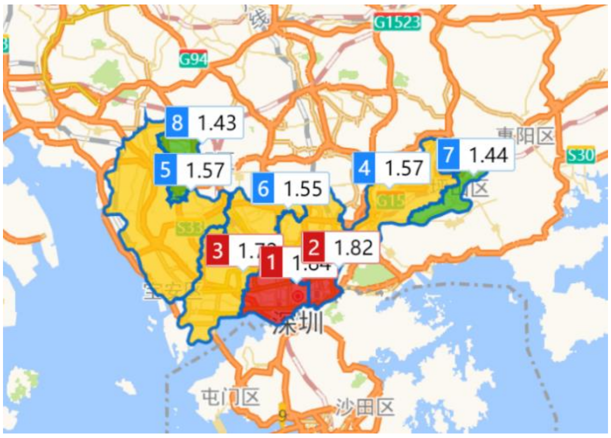

Fig. 3.18 Congestion area in Shenzhen

According to the congestion report of major cities in China, published by amap.com, the industrial layout has great effect on traffic congestion. In central business district, the congestion is more serious. If there are many Internet companies located in this region, the duration of evening peak is longer due to the longer overtime of the Internet company.

According to the above figure, it can be found that the evening peak of CBD in Beijing, Shanghai and Shenzhen are heavily congested, and the area of serious congestion in Beijing is the largest. This is due to the fact that many people need to live far away from their work place, so the congestion spreads widely. The surrounding areas of Beijing are slightly congested areas, and there is no green area in the evening peak. The CBD in both Shanghai and Shenzhen are heavily congested due to the intensive internet and financial industry. In the urban fringe of Shanghai and Shenzhen, there are small number of green areas without traffic congestion. Guangzhou, as the most livable city in these cities, has no serious congestion section in morning or evening peak. This is because the cost of living in Guangzhou is lower compared to the others, and people do not need to live far away from their working place.

Analysis of traffic congestion characteristics in metropolis

It is found that traffic congestion is serious in these cities, especially Beijing and Shanghai. Traffic congestion is influenced by both social development and transportation system.

The impact of social development on traffic congestion is that due to the rapid economy growth after reform and opening, a large number of people move to these cities, the urbanization process is accelerating, the city is gradually expanding so the travel demand increasing dramatically during the past 40 years. However, with the increase of living costs, many people live in cheaper suburban areas while most of their work concentrated in the central area, so the distance between people's working place and their living place is getting longer. On the other hand, economic development also plays an important role in traffic congestion. The per capita GDP of these cities has increased 63 times to 335 times during the past 40 years, which has stimulated people’s passion in purchasing cars.

Transportation system affects traffic congestion from two aspects: imbalance of supply and demand and insufficient management.

The imbalance between capacity of transportation system and citizens’ travel volume means that the traffic capacity provided by the transportation system cannot meet the rapid growth of traffic volume. Traffic capacity is limited by urban planning in these cities and it’s hard to improve, especially in the center area. In fact, this is the main reason for the increasingly serious traffic congestion in recent years.

Inadequate management refers to the management of existing network and commuters is not strong enough. Traffic control in most area with frequent traffic congestion is not strong enough so traffic organization is chaotic. On the other hand, the behavior of commuters needs to be governed. Illegal traffic behavior is one of the main reasons that cause traffic accidents, and lead to traffic congestion. What's more, the government can also encourage commuters to use eco-friendly travel modes such as walking and public transportation.

3.2 Establishment of system dynamic model

3.2.1Modelling objectives

The main objectives of this model are as follows:

- Analyze the causes of traffic congestion and sort out the relationship between various factors by using system dynamics method;
- Draw the causality diagram of the transportation system which includes sub modules such as social development, traffic demand, traffic supply, traffic operation and traffic policy.
- Establish the system dynamic model to predict the trend of urban traffic supply and demand based on the model and data that has been collected.
- Simulate different policies by verifying parameters in the model and analyze the efficiency of different models.
- Put forward feasible policy suggestions for traffic congestion in Shanghai.

3.2.2 Modelling boundaries and factors

Modelling boundaries

To establish the system dynamics model, the system boundary should be defined first, then the factors included can be defined. For the same system, different objectives may end up with different system boundaries. Therefore, the system boundaries are determined by objectives and causality relationship within the system. In fact, the process of determining the system boundary is the same as the process of determining the factors of the system. If the factor is inside the boundary and related to the research objectives, then it should be included, otherwise, it should be excluded. When determining the boundary of the system, these basic principles should be followed:

- Principle of objectives: When establishing a system dynamic model, it is important to focus on specific problems and specific policies, instead of facing a whole system.

- Principle of efficiency: The model should be able to describe the research objective accurately, so that the strategies generated are useful and reliable.
- Principle of simplicity: Narrow the boundary as much as possible. If the objective can be achieved without some factors, then these factors should be excluded from the system boundary.

The steps of setting boundaries are as follows:

- Select relevant state variables;
- Analyze relationships between state variables other variables;
- Identify variables that are useful;
- Adjust and determine the final boundary.

The system boundaries of this study include: population, GDP: resident travel volume, vehicle population, travel volume of various modes of transportation, road network capacity, transportation policy, etc.

Factors

The factors of the model can be divided into three parts, that is, internal factors, external factors and traffic policies. They are shown in Tab. 3.1-3.2:

Tab. 3.1 Internal factors of transportation system

Factors of travel volume	The total amount of residents' travel, motor vehicle retention, the amount of travel by different kinds of transportation modes
Factors of traffic capacity	Length of road network, capacity of transportation infrastructure, public transportation share rate, length of subway
Traffic operation factors	Traffic load, average speed of road network, traffic congestion and the service level of the transportation system, quality of commuters, the level of traffic management.
Traffic policies	control the growth of vehicle retention, restrict the use of cars, congestion charge, public transport priority

Tab. 3.2 External factors of transportation system

Urban development factors	Population, urban industrial structure
Social and economic factors	Urban GDP, per capita GDP, residents' living standards
Resources and environment factors	Urban resources, vehicle emissions, energy supply

There are four policies that are going to be simulated in this research: investment on infrastructure, restriction of car usage, control the growth of cars and stagger shifts.

3.2.3 Causality diagram

Module frames

Transportation system plays an important role in the social system. Transportation system and social system can influence each other. According to Fig. 3.19, there are 4 modules: population and economy, urban development, transportation system capacity and travel volume. They can influence each other both directly or indirectly. There are also intermediary factors like vehicle retention, travel mode, travel distance, investment and traffic situation that are used to connect different modules. Traffic situation has effect on the choice of traffic policies while these policies may change capacity and travel volume.

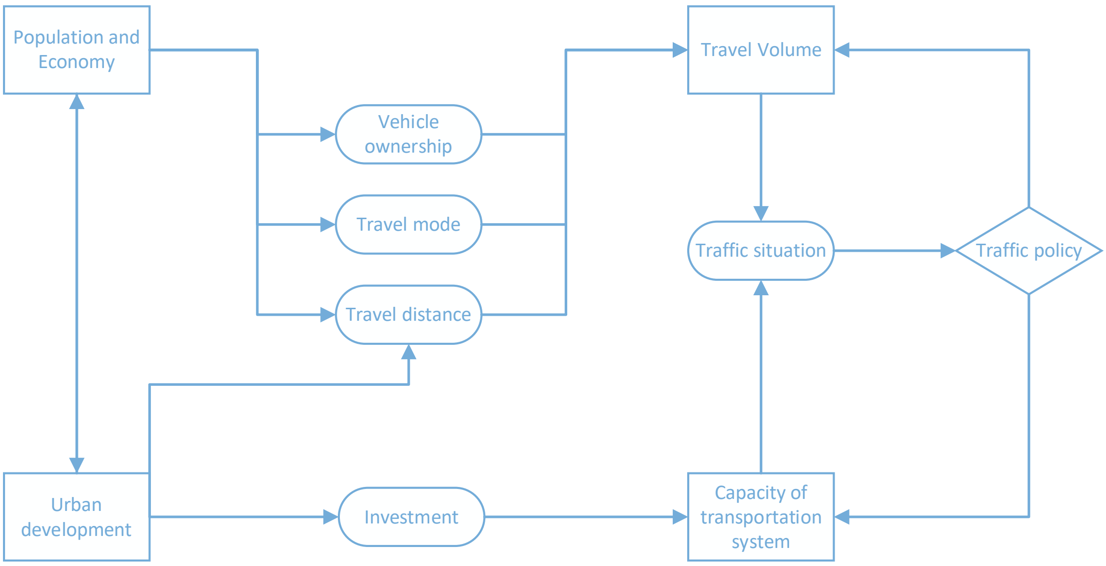

Fig. 3.19 The diagram of module frames

Causal relationship

In order to analyze the relationship between the factors in details, this section will start with the causal relationship of main factors, and then analyzes the causality of the whole model from a systematic perspective.

Capacity of transportation system

As shown in the Fig. 3.20, capacity is mainly determined by the investment on road network, lane capacity, length of road network and road grade. In fact, investment depends largely on the GDP. Those cities with higher GDP are more likely to construct sufficient road network.

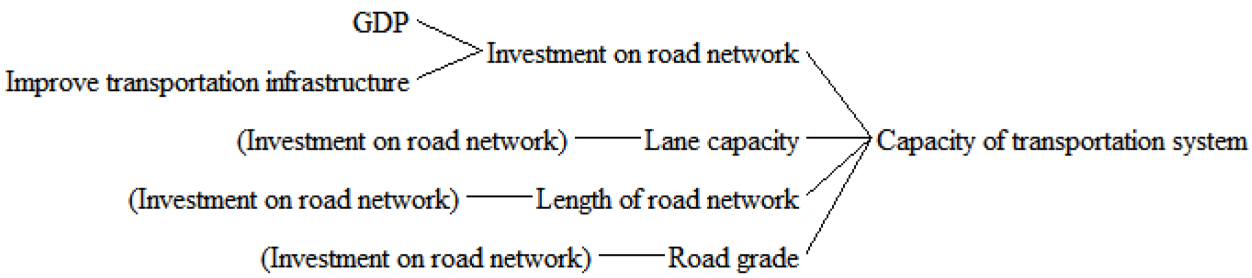

Fig. 3.20. Causal relationship of capacity

Travel volume

Based on the analysis of traffic congestion characteristics, it is known that traffic congestion is most serious around 6:00 p.m. Therefore, total turnover volume in peak hour is used to illustrate traffic demand. As shown in Fig. 3.21, despite the turnover volume of various vehicles, the ratio can also make a difference due to staggered shifts. Staggered shifts can give people more freedom to choose their off-duty time so that they can avoid serious traffic congestion.

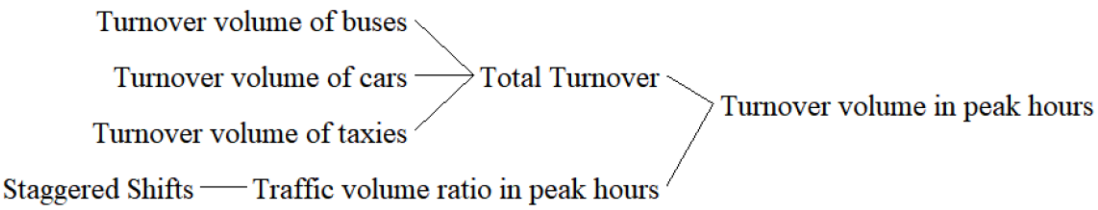

Fig. 3.21 Causal relationship of traffic demand

Level of traffic congestion

For the existing road network, its traffic carrying capacity is fixed, and the degree of road congestion in affected by traffic volume in peak hours. Therefore, the degree of traffic congestion is directly proportional to the turnover volume in peak hours; on the other hand, if the quality of commuters can be improved, there will be less accident, which leads to slighter traffic congestion. Based on ‘road traffic operation evaluation index system of urban road traffic management (2012 Edition)’, level of traffic congestion can be measured by ratio of traffic volume and capacity. When the value is less than 0.4, the road network is slightly congested; When the value is larger than 0.75, the road network is seriously congested. The causal relationship of level of traffic congestion is shown in Fig. 3.22:

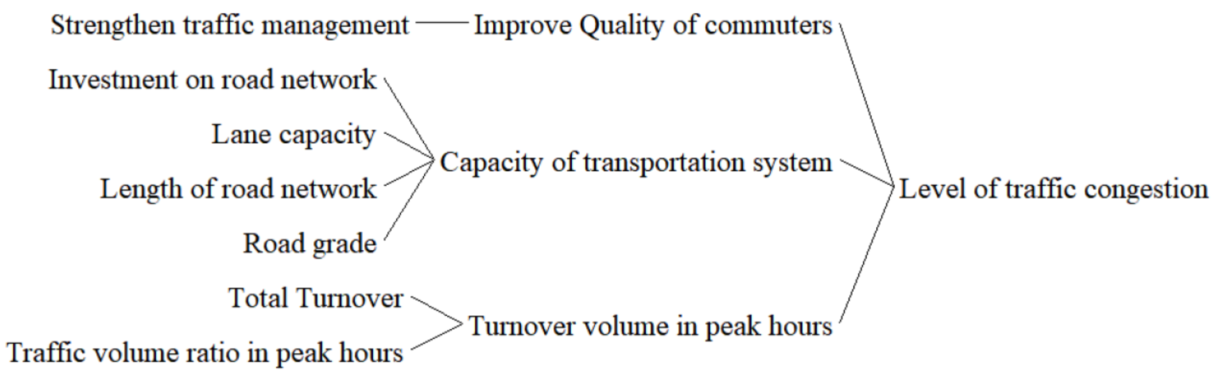

Fig. 3.22 Causal relationship of level of traffic congestion

Traffic policies

Traffic policy is formulated by the government. As shown in Fig. 3.23, the traffic policies in this paper can be divided into the following three types: policy to increase capacity, policy to control the travel volume and other policies. Basically, policy to control the travel volume have two goals, one is to restrict car usage and another one is to control the growth of vehicle retention. The last type of policy is about the management of the transportation system, such as staggered shifts and the improvement of the quality of commuters.

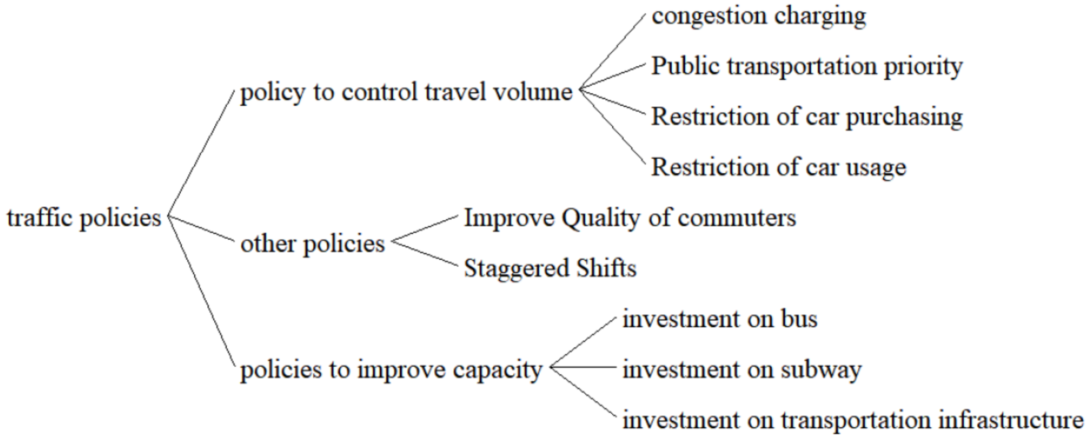

Fig. 3.23 Causal relationship of level of traffic policies

Causality diagram

Based on causal relationship discussed above, the causality diagram is shown in Fig. 3.24， which includes the following feedback loops:

Restriction of car purchasing

GDP - per capita GDP - motor vehicle retention - turnover volume of cars – total turnover volume – turnover volume in peak hours – level of congestion – restriction of car purchasing- motor vehicle retention

This feedback loop indicates that people in developed area with higher GDP are more likely to spend money on private cars and lead to the increase of turnover volume of cars. Once the turnover volume in peak hours exceeds capacity of the road network, there will be traffic congestion. If the congestion is getting more and more serious, the government will find ways to solve it and one of them is restriction of car purchasing to limit motor vehicle retention.

Restriction of car usage

Level of congestion - Restriction of car usage – transportation mode – travel frequency of cars – turnover volume of cars - turnover volume in peak hours – level of congestion. This feedback loop shows that government will put forward policies to restrict car usage based on the level of congestion. This may affect the choice of transportation mode as well as the travel frequency of cars. Therefore the turnover volume of cars is different and results in different level of congestion.

Public transportation priority

Level of congestion – public transportation priority – transportation mode - travel frequency of cars – turnover volume of cars - turnover volume in peak hours – level of congestion

This feedback loop is similar to the last one. The purpose of this policy is to control the usage of cars by changing the transportation mode of citizen.

Investment on transportation infrastructure

Investment on transportation infrastructure – road grade / length of road network / lane capacity – traffic supply – level of congestion – GDP - Investment on transportation infrastructure

This feedback tells the story about the supply side policies. The purpose of these kind of policies is to improve the capacity of road network to reduce traffic congestion. The investment is also influenced by local GDP. Cities with higher GDP are more likely to invest on transportation system.

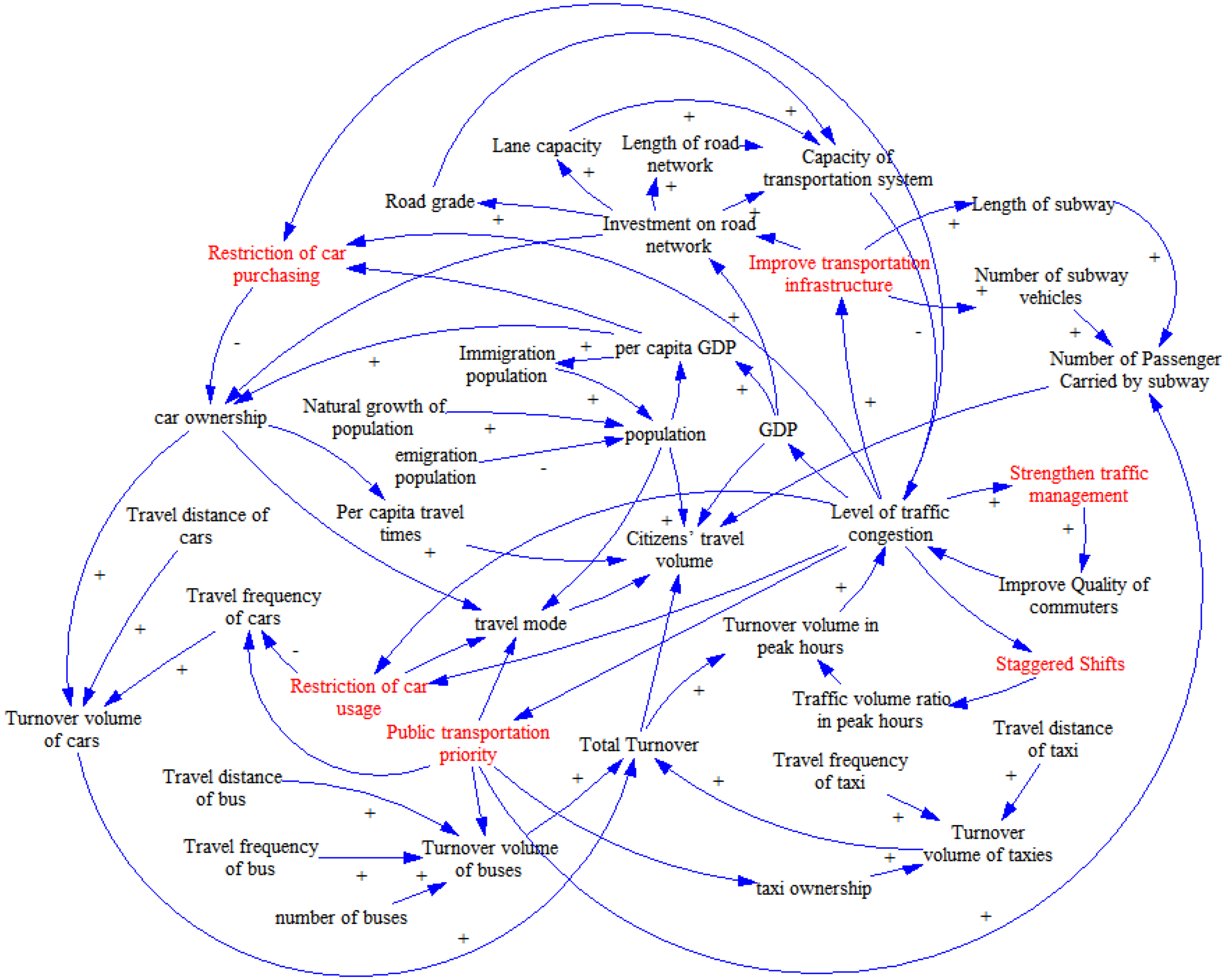

Fig. 3.24 Causality diagram

Improve quality of commuters

Level of congestion - Improve quality of commuters – less car accident – level of congestion

This feedback loop indicates that car accident is one of the congestion reasons and it can be reduced by improving the quality of commuters.

Staggered Shifts

Staggered Shifts - traffic volume ratio in peak hours– level of congestion

This feedback loop illustrates how Staggered Shifts works in the transportation system. It allows people to choose their off hours more flexibly thus reducing the turnover volume during peak hours.

3.2.4 Flow diagram

Causality diagram shows the causal relationship in this system. In order to simulate the efficiency of different policies, flow diagram is needed. The flow diagram of metropolises in China is shown in Fig. 3.23. It will be introduced in details in the next chapter.

3.3 Chapter summary

This chapter includes the following two parts: In the first part, the traffic situation of Chinese metropolis is described from various aspects. Therefore problems faced by the traffic system can be figured out. In the second part, based on system dynamics, the modeling purpose is described, the model boundary and main research elements are determined, and causality diagram and model flow diagram are drawn by analyzing the causality of variables, which is the basis of model simulation in the next chapter.

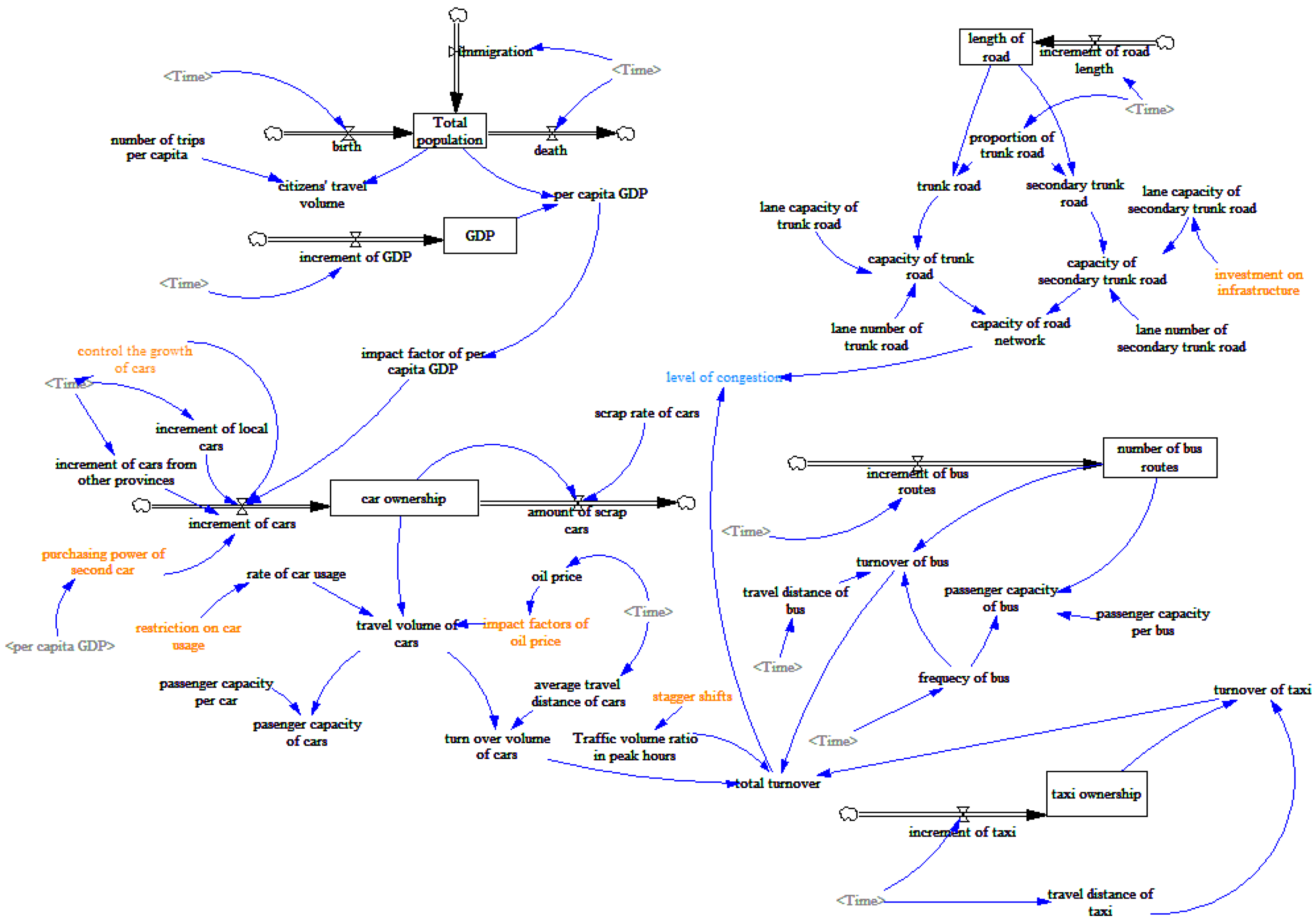

Fig. 3.23 Flow diagram

4 Empirical analysis of traffic congestion policies in Shanghai

This chapter focuses on the establishment of model and simulation of different policies. In order to describe the system, different kinds of data are collected. Once the model is finished, it works as a 'policy lab' to figure out the most efficient policy.

In this study, Shanghai is taken as an example for empirical analysis. Shanghai is one of the economic centers in China. It always held various important conferences and events. Traffic management have great influence on the image and development of Shanghai. On the other hand, most of the developed cities are concentrated in the southeast of China. these cities shared similar culture, development process and urban structure with Shanghai. As the largest and most developed city in the south, Shanghai has a great influence on other cities. From the perspective of urban development, Shanghai has a long history, developed economy and huge population. Due to the long history the road capacity of old town in Shanghai is limited and the demolition is difficult; The developed economy has attracted a large number of talents and companies to settle in Shanghai, which add pressure to the road network in Shanghai. Compared with Shanghai, Beijing is the capital of China, the political，economic center of China, traffic management is different to other cities; The urban development of Guangzhou is similar to that of Shanghai, but the population and travel volume are not as large as that of Shanghai; Shenzhen, on the other hand, is a young city which lacks representativeness.

4.1 Traffic situation in Shanghai

4.1.1 Urban development in Shanghai

Shanghai was founded in 1292 and it has been playing an important role in Chinese history for 700 years, especially in the last 200 years. Since 1949, Shanghai became one of the economic centers in China and has attracted famous companies to open branches in Shanghai. Meanwhile, Shanghai also held international conference in different fields, which gives foreigners opportunities to feel the city. Nowadays, Shanghai is the most important international city in Chinese mainland. In the previous introduction, it is known that Shanghai has achieved outstanding economic increase during the past 40 years. By the end of 2019, there are 24.281 million permanent residents while 9.777 million of them are not local. Shanghai's GDP was 381.55 billion yuan in 2019, 139 times of that in 1978; Shanghai's per capita GDP in 2019 was 157,729 yuan, twice of the per capita GDP in China.

The area of Shanghai is 7262 square kilometers. The construction area is 3171 square kilometers, accounting for 43.7% of the city's land. Among the construction land, residential land is 1123 square kilometers; public and commercial land is 354 square kilometers, land for transportation system is 549 square kilometers, which is shown in Fig. 4.1, the yellow part represents construction land.

According to the urban plan of Shanghai, the population of Shanghai in 2050 will not exceed 25 million. By 2035, public transport will account for more than 50% of all modes of travel. In order to protect the environment and reduce traffic congestion, the proportion of public transportation should be more than 60% and the proportion of private car travel decreased to less than 15%.

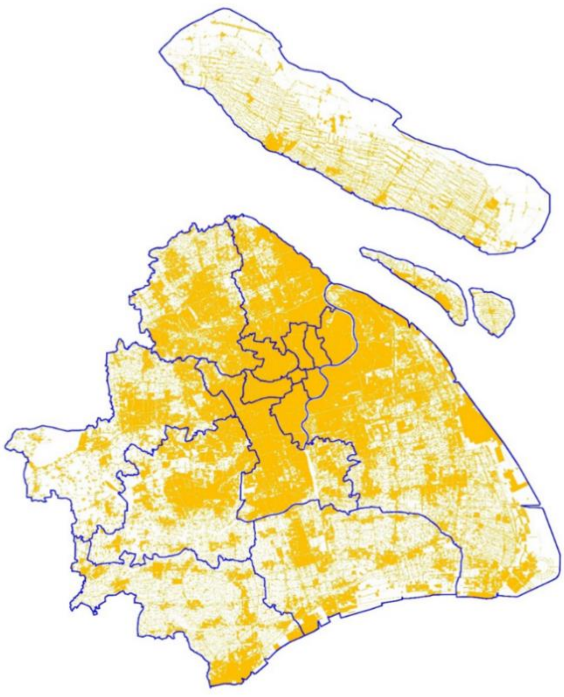

Fig. 4.1 Map of contraction land in Shanghai

4.1.2 Travel volume in Shanghai

The total number of trips in Shanghai keeps increasing. In recent years, the scale of permanent resident population in Shanghai is stable. However, due to the growth of mobile and flow population, the average daily travel volume in Shanghai is 0.5% larger than that of 2018. The average daily travel volume is 57.1 million.

As shown in Fig. 4.3-4.4, in 2019, 48.2% of the citizens travel in motorized mode, while only 44.9% of them choice to motorized travel in 2014. The good news is that the proportion of public transport modes (rail, bus, ferry and bus) increases slightly in 2019, accounting for 22.9%. More and more people choose to travel by cars. In 2014, there are 17% of people travel by cars while the proportion rises to 20.1% in 2019. The proportion of taxi remains to be 4.6% in both 2014 and 2019.

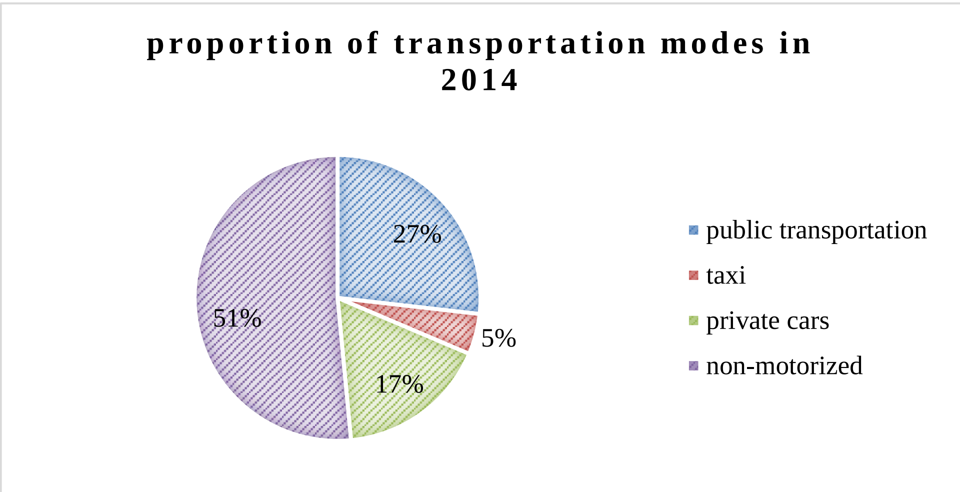

Fig. 4.3 Proportion of transportation mode in 2014

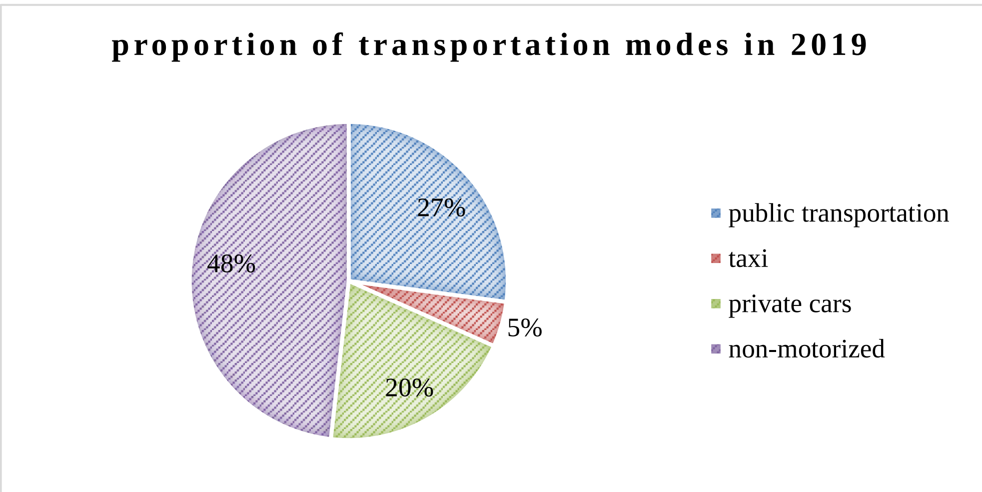

Fig. 4.4 Proportion of transportation mode in 2019

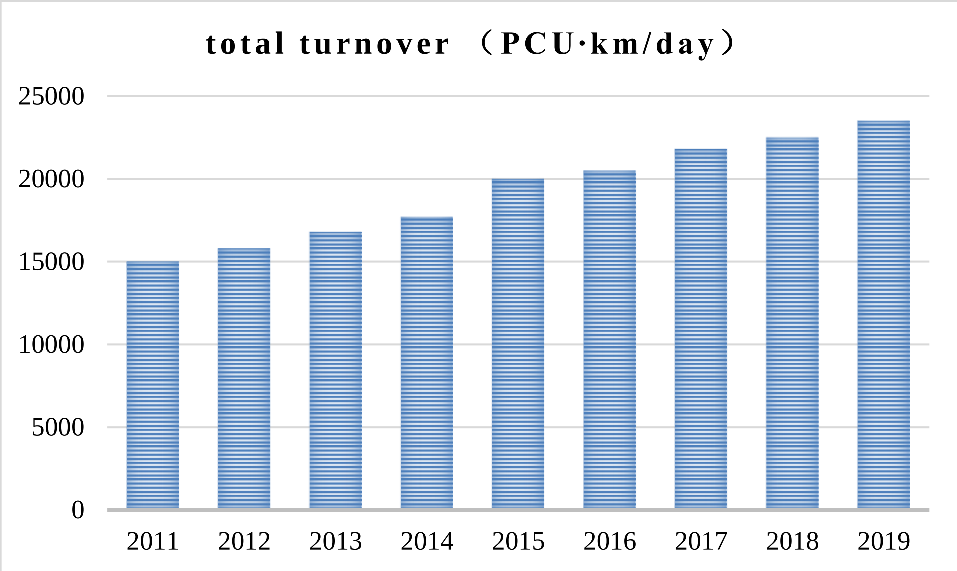

Fig. 4.5 Total turnover

The number of registered motor vehicles continues to grow. The amount of the newly registered vehicles in 2019 is 225,000. By the end of 2019, the total number of registered motor vehicles in Shanghai was 4.438 million, and compared to 2018, the number of vehicles increased by 224,000. When it comes to the number of registered private cars, it is the same story, the number of registered private cars reached to 3.703 million in 2019. However, there are over 1.7 million long-term vehicles that comes from other provinces and it is also increasing.

In 2019, the total turnover volume increased by 7.11 million PCU ·km/Day and reaches 234.91 million PCU ·km/Day. The turnover of motor vehicles in the central city is about 89.3 million PCU ·km/Day, accounting for 38% of the total turnover volume; The turnover of motor vehicles in the suburbs is about 145.61 million PCU ·km/Day, accounting for 62% of the total turnover volume in the whole city. The total turnover volume in different years is shown in Fig. 4.5.

4.1.3 Transportation capacity in Shanghai

Shanghai improves the service level of road network by improving the connectivity of facilities and widening the road. By the end of 2019, the length of road network in Shanghai was 13045 km. The area of urban road network was 121.95 million square meters, an increase of 3.74 million square meters.

There are 728.7 km national roads, 1084.7 km provincial roads, 3155.3 km county roads, 6637.5 km township roads and 1438.5 km village roads. National and provincial roads account for 13.9% of the total mileage, county roads account for 24.2% of the total mileage, and rural roads account for 61.9% of the total mileage. If the road network is divided by technical level, there are 844.7 km of expressway, 553.0 km of first-class highway, 3664.5 km of second-class highway, 2623.0 km of third-class highway and 5359.5 km of fourth-class highway. The road network of Shanghai is shown in Fig. 4.6.

Fig. 4.6 road network in Shanghai

4.2 Estimation of model variables

4.2.1 Assumptions

In this model, the following assumptions are proposed:

Assumption 1: The population in this mode is permanent population;

Assumption 2: In this model, transportation modes refer to taxi, private cars, bus, subway and walking. Ferry is not included.
Assumption 3: When the policy restricts one tail number, the amount of travel by cars will reduce by 10%.

4.2.2 Estimation of model variables

Before the establishment of the model, different kinds of data need to be collected. Based on the flow diagram, data on population, economy, traffic supply and demand are needed. The main sources of data are: Shanghai statistical yearbook, annual transportation report, Shanghai urban planning, etc.

Data on population and economy

Data collection

Data in table 4.1 are used to reflect the social development of Shanghai.

Table 4.1 Social development of Shanghai

Year	Permanent population	Natural growth of population	Mechanic Growth of population	GDP	per capita GDP
Unit	10,000 person	10,000 person	10,000 person	10 billion yuan	yuan
2005	1890	-1.98	9.50	9197.13	49 377
2006	1964	-1.68	9.36	10598.86	54 996
2007	2063	-0.14	10.74	12878.68	63 951
2008	2140	-1.03	12.99	14536.9	69 154
2009	2210	-1.44	10.95	15742.44	72 363
2010	2302	-0.85	12.25	17915.41	79 396
2011	2347	-0.96	7.82	20009.68	86 061
2012	2380	0.37	7.07	21305.59	89519
2013	2415	-0.78	6.06	23204.12	96083
2014	2425	0.46	5.77	25269.75	104205
2015	2415	-1.83	6.29	26887.02	111333
2016	2419	0.72	6.61	29887.02	123551

2017	2418	-0.87	7.68	32925.01	136166
2018	2423	-2.73	9.83	36011.82	148624
2019	2428	-3.38	10.28	38155.32	157147

The natural growth rate of population continues to decline, and the number of immigrants is gradually increasing. In fact, this phenomenon is quite common in Chinese metropolises. Due to the high cost of living and education, birth rate in these cities has been decreasing. On the other hand, these cities is attractive to the younger generation because of the opportunities, so the amount of immigration is much larger than that of emigration. Immigration is the main reason for the increase of Shanghai's population.

According to the experience of developed countries, when the per capita GDP reaches 7,000 yuan, people start buying cars. When it reaches 21,000 yuan to 140000 yuan, there will be a rapid growth of private car retention. This experience also applies to Shanghai, the improvement of GDP and increase of per capita GDP contribute to the rapid growth of cars.

Estimation of variables

According to the flow diagram, the following variables are used to describe the urban development of Shanghai.

- Total population (state variable)

 Total population is a state variable which is affected by birth population, death population and immigration population

$$Total\ population_t = Total\ population_{t-1} + \int_{t-1}^{t}(immigration + birth - death)dt$$

- Birth

 Formula of birth is based on the statistical yearbook of Shanghai.

$$birth = \left\{ \begin{matrix} [(2005,0) - (2025,150000)], (2005,82500), (2006,81200), \\ (2007,100800), (2008,96700), (2009,92300), (2010,100200), \\ (2011,101500), (2012,121100), (2013,108900), (2014,124100), \\ (2015,105900), (2016,130700), (2017,117700), (2018,98400), \\ (2019,91400), (2020,90000), (2025,90000) \end{matrix} \right\} \quad (4\text{-}1)$$

- Death

 Formula of death is based on the statistical yearbook of Shanghai.

$$death = \left\{ \begin{array}{c} [(2005,0) - (2025,130000)], (2005,102300), (2006,98000), \\ (2007,102200), (2008,107000), (2009,106700), (2010,108700), \\ (2011,111100), (2012,117400), (2013,116700), (2014,119500), \\ (2015,124200), (2016,123500), (2017,126400), (2018,125700), \\ (2019,125200), (2020,120000), (2025,120000) \end{array} \right\} \quad (4\text{-}2)$$

- Immigration

  Formula of immigration is based on the statistical yearbook of Shanghai.

$$immigration = \left\{ \begin{array}{c} [(2005,-100000) - (2025,1e+006)], (2005,560000), \\ (2006,740000), (2007,990000), (2008,770000), (2009,700000), \\ (2010,920000), (2011,450000), (2012,330000), (2013,350000), \\ (2014,100000), (2015,-100000), (2016,40000), (2017,-10000), \\ (2018,50000), (2025,40000) \end{array} \right\} \quad (4\text{-}3)$$

- GDP

  GDP is a state variable which is influenced by the increment of GDP.

$$GDP_t = GDP_{t-1} + \int_{t-1}^{t} (increment\ of\ GDP)dt \quad (4\text{-}4)$$

- Increment of GDP

  Formula of Increment of GDP is based on the statistical yearbook of Shanghai.

$$increment\ of\ GDP = \left\{ \begin{array}{c} [(2005,0) - (2025,2e+012)], (2006,1.402e+011), \\ (2007,2.28e+011), (2008,1.658e+011), (2009,1.206e+011), \\ (2010,2.173e+011), (2011,2.094e+011), (2012,1.296e+011), \\ (2013,1.899e+011), (2014,2.066e+011), (2015,1.617e+011), \\ (2016,3e+011), (2017,3.038e+011), (2018,3.087e+011), \\ (2019,3.087e+011), (2024.88,3.109e+011) \end{array} \right\} \quad (4\text{-}5)$$

- Per capita GDP

Formula of per capita GDP is as follows:

$$per\ \ capita\ GDP = \frac{GDP}{Total\ population} \quad (4\text{-}6)$$

Data on traffic demand

Data collection

Data in table 4.2 are used to reflect the traffic demand in Shanghai.

Table 4.2 traffic demand in Shanghai

Year	Vehicle retention	car retention	Taxi retention	Bus routes
Unit	10,000 vehicles	10,000 vehicles	10,000 vehicles	Lines
2005	221.74	95.15	4.7794	940
2006	238.13	107.04	4.8022	944
2007	253.6	119.7	4.8614	991
2008	261.5	132.31	4.8059	1058
2009	285	147.3	4.9111	1129

2010	309.7	170.25	5.0007	1165
2011	329.17	194.96	5.0438	1202
2012	260.9	212.86	5.0683	1257
2013	282.46	235.1	5.0612	1338
2014	304.45	255.19	5.0738	1377
2015	332.35	282.32	4.9586	1429
2016	359.48	322.94	47271	322.94
2017	392.36	361.02	46397	361.02
2018	423.13	393.42	41881	393.42
2019	442.55	413.86	39962	413.86

Estimation of variables

According to the flow diagram, the following variables are used to describe the traffic demand of Shanghai.

- Car retention

  Formula of car retention is based on statistical yearbook

$$Car\ ownership_t = Car\ ownership_{t-1} + \int_{t-1}^{t}(increment\ of\ cars)dt \quad (4\text{-}7)$$

- Increment of cars

  Formula of increment of cars is the combination of both increment of local cars and increment of cars from other provinces:

$$increment\ of\ cars = increment\ of\ local\ cars + increment\ of\ cars\ from\ other\ province \quad (4\text{-}8)$$

- Increment of local cars

  Formula of local cars is based on statistical yearbook

$$increment\ of\ local\ cars = \left\{\begin{matrix} [(2005,0)-(2025,500000)], (2005,0), \\ (2006,118900), (2007,126600), (2008,126100), \\ (2010,229500), (2011,247100), (2012,179000), \\ (2013,222400), (2014,200900), (2015,271300), \\ (2016,406200), (2017,380800), (2018,324000), \\ (2019,204400), (2020,200000), (2025,150000) \end{matrix}\right\} \quad (4\text{-}9)$$

- Increment of cars from other provinces

  Formula of cars from other provinces is based on statistical yearbook

$$increment\ of\ cars\ from\ other\ provinces = \left\{\begin{matrix} [(2005,0)-(2025,200000)], \\ (2005,50000), (2006,50000), \\ (2007,50000), (2008,60000), \\ (2009,60000), (2010,90000), \\ (2011,90000), (2012,80000), \\ (2013,90000), (2014,80000), \\ (2015,80000), (2016,100000), \\ (2017,100000), (2018,120000), \\ (2019,70000), (2025,50000) \end{matrix}\right\} \quad (4\text{-}10)$$

- Amount of scrap cars

Formula of amount of scrap cars is as follows:

$$Amount\ of\ scrap\ cars = \ car\ ownership\ \times scrap\ rate\ of\ cars \qquad (4\text{-}11)$$

- Travel volume of cars

Formula of travel volume of cars is as follows:

$$travel\ volume\ of\ cars = \ car\ ownership \times ate\ of\ car\ usage \times\ impact\ factors\ of\ oil\ price \qquad (4\text{-}12)$$

- Average travel distance of cars

Formula of average distance of cars is as follows:

$$\text{Average travel distance of cars} = \begin{Bmatrix} [(2005,5)-(2025,10)],(2005,6.7),(2008,6.9), \\ (2010,7.5),(2013,8),(2015,8.5),(2018,9.1), \\ (2025,9.5) \end{Bmatrix} \qquad (4\text{-}13)$$

- Number of bus routes

Formula of number of bus routes is as follows:

$$Number\ of\ bus\ route_t = \ Number\ of\ bus\ routes_{t-1} + \int_{t-1}^{t}(increment\ of\ busrout)dt \qquad (4\text{-}14)$$

- Increment of bus routes

Formula of increment of bus routes is as follows:

$$increment\ of\ bus\ routes = \begin{Bmatrix} [(2005,0)-(2025,90)],(2005,0),(2006,4), \\ (2007,47),(2008,67),(2009,71),(2010,36), \\ (2011,37),(2012,55),(2013,81),(2014,39), \\ (2015,52),(2016,28),(2017,39),(2018,47), \\ (2019,32),(2020,30),(2025,30) \end{Bmatrix} \qquad (4\text{-}15)$$

- Turnover of bus

Formula of turnover of bus is as follows:

$$turnover\ of\ bus = \ number\ of\ bus\ routes \times travel\ distance\ of\ bus \times frequecy\ of\ bus \qquad (4\text{-}16)$$

- Taxi retention

Formula of taxi retentions is as follows:

$$taxi\ ownership_t = \ taxi\ ownership_{t-1} + \int_{t-1}^{t}(increment\ of\ taxi)dt \qquad (4\text{-}17)$$

- Increment of taxi

Formula of increment of bus routes is as follows:

$$increment\ of\ taxi = \begin{Bmatrix} [(2005,-5000)-(2025,2000)],(2005,0),(2006,228), \\ (2007,592),(2008,-555),(2009,1052),(2010,896), \\ (2011,431),(2012,245),(2013,-71),(2014,126), \\ (2015,-1152),(2016,-2315),(2017,-874),(2018,-4516), \\ (2019,-1919),(2020,-1000),(2025,-1000) \end{Bmatrix} \qquad (4\text{-}18)$$

- Turnover of taxi

Formula of turnover of taxi is as follows:

$$turnover\ of\ taxi = \ taxi\ ownership \times travel\ distance\ of\ taxi \qquad (4\text{-}19)$$

- Total turnover

Formula of total turnover is as follows:

$$total\ turnover = turnover\ of\ cars + turnover\ of\ bus + turnover\ of\ taxi \quad (4\text{-}20)$$

There are four policy variables in this section:

- Purchasing power of second car

For families who are more dependent on vehicles, they are more likely to purchase a second car to reduce the impact of the number limit. This is influenced by per capita GDP, the formula is as follows:

$$purchasing\ power\ of\ second\ car = IF\ THEN\ ELSE(per\ capita\ GDP > 10000, 1.1, 1\ ) \quad (4\text{-}21)$$

- Restriction on car usage

In this paper, it is assumed that when the policy restricts one tail number, the amount of travel by cars will reduce by 10%. The initial value of this 1, which means there is no restriction.

- Impact of oil price

This variable refers to the fact that the higher oil price is, the less amount of car travel. The formula of this variable is：

$$impact\ of\ oil\ price = IF\ THEN\ ELSE((oil\ price >= 7, 0.9, 1) \quad (4\text{-}22)$$

- Stagger shifts

This variable works on the traffic volume ratio in peak hours. Assume that when there is stagger shifts, 20% commuters will avoid travelling in peak hours.

Data on traffic supply

Data collection

Data in table 4.3 are used to reflect the traffic supply in Shanghai.

Table 4.3 traffic supply in Shanghai

Year	Length of road	Length of expressive ways	Road area per capita
Unit	km	km	Square meter
2005	8110	77	15.2
2006	10392	77	15.3
2007	15458	77	15.7
2008	11497	114	16.02
2009	11671	114	16.64
2010	11974	196	12.1
2011	12084	194	11.12

2012	12541	199	11.4
2013	12633	199	11.51
2014	12945	187	11.07
2015	13195	197	12.09
2016	13292	207	12.6
2017	13322	207	12.49
2018	13106	207	12.2
2019	13045	207	12.7

Estimation of variables

According to the flow diagram, the following variables are used to describe the traffic supply of Shanghai.

- Length of road

  Formula of length of road is as follows:

$$length\ of\ road_{\ t} = length\ of\ road_{t-1} + \int_{t-1}^{t}(increment\ of\ road\ length)dt \quad (4\text{-}23)$$

- Increment of road length

  Formula of increment of road is as follows:

$$increment\ of\ road\ length = \left\{\begin{matrix} [(2005,-6000)-(2025,6000)],(2005,0), \\ (2006,2282),(2007,2066),(2008,-961), \\ (2009,174),(2010,303),(2011,110), \\ (2012,457),(2013,92),(2014,312), \\ (2015,250),(2016,97),(2017,30), \\ (2018,-216),(2019,-61),(2020,20),(2025,10) \end{matrix}\right\} \quad (4\text{-}24)$$

- Proportion of trunk road

  Formula of proportion of trunk road is as follows:

$$proportion\ of\ trunk\ road = \left\{\begin{matrix} [(0,0)-(3000,10)],(2005,0.1), \\ (2016,0.13),(2019,0.14),(2025,0.15) \end{matrix}\right\} \quad (4\text{-}25)$$

- Trunk road

  Formula of trunk road is as follows:

$$trunk\ road\ = length\ of\ road \times proportion\ of\ trunk\ road \quad (4\text{-}26)$$

- Secondary trunk road

  Formula of secondary trunk road is as follows:

$$secondary\ trunk\ road\ = length\ of\ road \times (1 - proportion\ of\ trunk\ road) \quad (4\text{-}27)$$

- Capacity of trunk road & Capacity of secondary trunk road

  Formula of are as follows:

$$Capacity\ of\ trunk\ road\ = trunk\ road \times lane\ capacity\ of\ trunk \times lane\ number\ of trunk \quad (4\text{-}28)$$

$$Capacity\ of\ secondary\ trunk\ road\ = secondary\ trunk\ road \times$$

$lane\ capacity\ of\ secondary\ trunk \times lane\ number\ of secondary\ trunk\ road$ （4-29）

- Lane capacity of trunk road & Lane capacity of secondary trunk road

  According to the road design specification, lane capacity of trunk road and lane capacity of secondary trunk road are 1400 and 1100 respectively.

- Capacity of road network

  This variable refers to the traffic supply and the Formula is as follows:

$$trunk\ road\ = capacity\ of\ trunk\ road + capacity\ of\ secondary\ trunk\ road \quad (4\text{-}30)$$

- Investment on infrastructure

  This variable refers to the policy that works on traffic supply. Since the trunk road are already good enough in Shanghai, the government has spent a lot of money on improving the lance capacity of secondary trunk road. In this paper, it is assumed that when the government decides to invest, the lane capacity of secondary trunk road will increase by 10%.

  Level of congestion

  This variable refers to the traffic condition of the road network and the formula is as follows:

$$trunk\ road\ = \frac{total\ turnover}{capacity\ of\ road\ network} \quad (4\text{-}31)$$

4.3 Model validation

The comparison between the simulation results of the model and the actual values is as follows:

Tab. 4.4 Comparison between the simulation results and the actual values (2019)

	Unit	Simulation result	Actual result	Error rate (%)
Population	10,000 person	2462	2428	1.400329
GDP	100 million	37415	38155	-1.93946
Car retention	10,000 vehicle	391.8	413.86	-5.3303
Taxi retention	vehicle	41881	39962	4.802062
Length of road	Km	13106	13045	0.467612

Based on the comparison above, all the error rates are less than 10%, so the accuracy of this model meet the requirement.

4.4 Policy simulation

One of the important functions of system dynamics is simulation, that is, by changing the initial input of some key variables in the model and then analyze the results between different policies. There are 5 policies that is going to be simulated in this section, the results are as follows.

4.4.1 Investment on infrastructure

This policy aims to improve capacity of the road network. The per capita road area of Shanghai is 12.7 square meter. Compared with 15 in developed countries, there is still a long way to go. However, when it comes to the city center, it is almost impossible to expand the road due to the large amount of demolition work. Therefore, Shanghai government mainly carries out the upgrading of urban roads to improve the capacity. The capacity of trunk road is already good enough, it is the capacity of secondary trunk road that needed to be improved.

When the capacity of the secondary trunk road increases by 10%, the capacity of road network increases as shown in the Fig. 4.7, and the degree of congestion is shown in the Fig. 4.8:

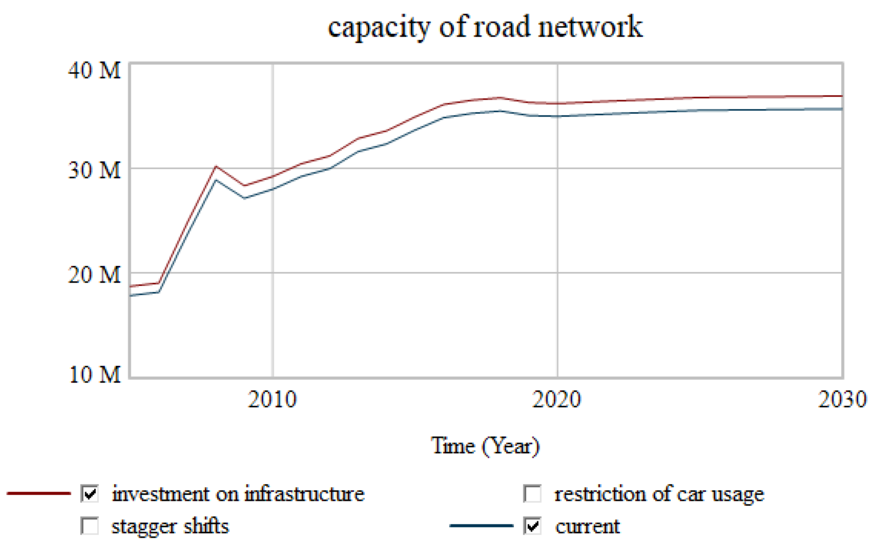

Fig. 4.7 Capacity of road network

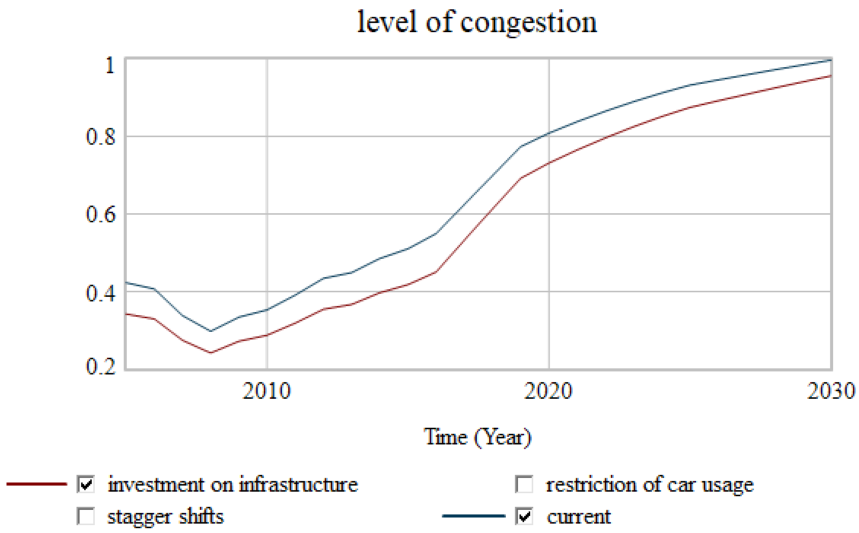

Fig. 4.8 Level of congestion

According to the simulation result, the increase of capacity can solve the traffic congestion at the beginning. However, a growing number of people would like to buy cars when the service level is good. Fig. 4.8 tells the same story. This policy can solve the congestion to a certain degree at first, and when it comes to the long run, this policy is not very efficient.

4.4.2 Control the growth of cars

This policy aims to control the growth of cars. In recent years, Shanghai has implemented a relatively strict policy to control the growth of cars. Assuming that with the further increase of cars, this policy is further tightened by 20%, the car retention and level of congestion are shown in the Fig. 4.9-4.10:

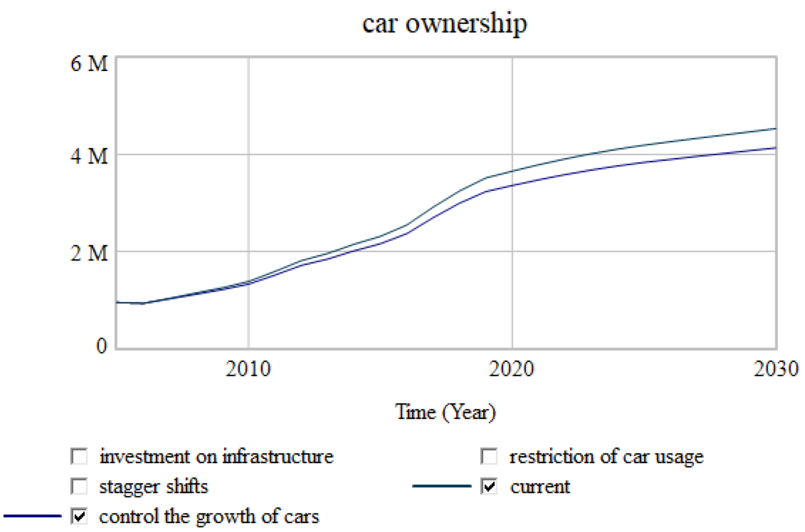

Fig. 4.9 Car retention

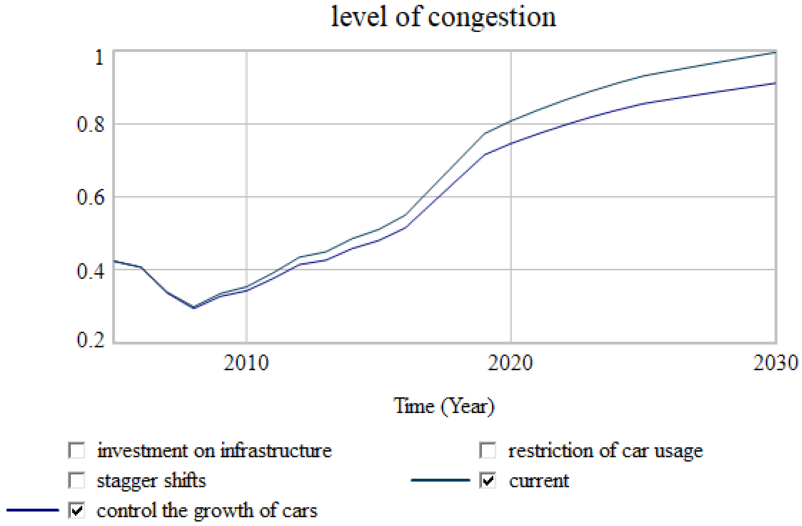

Fig. 4.10 Level of congestion

According to the simulation result, this policy may not be very efficient at first. However, the advantage of is becoming more obvious as time goes on. The efficiency of this policy is related to the level of restriction.

4.4.3 Restriction of car usage

This policy aims to limit the usage of cars. Restriction of car usage is more and more common in Chinese city nowadays. In this paper, it is assumed that two tail numbers are restricted, so 20% cars cannot travel. The turnover of cars and level of congestion are shown in Fig. 4.11-4.12.

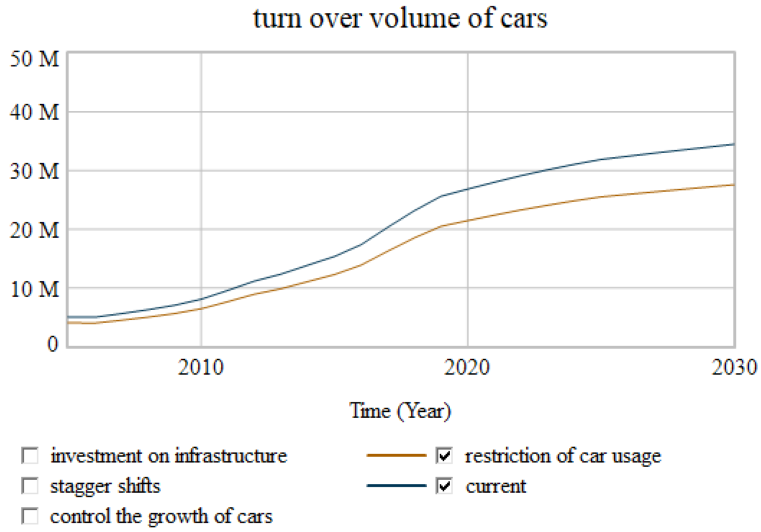

Fig. 4.11 Turnover volume of cars

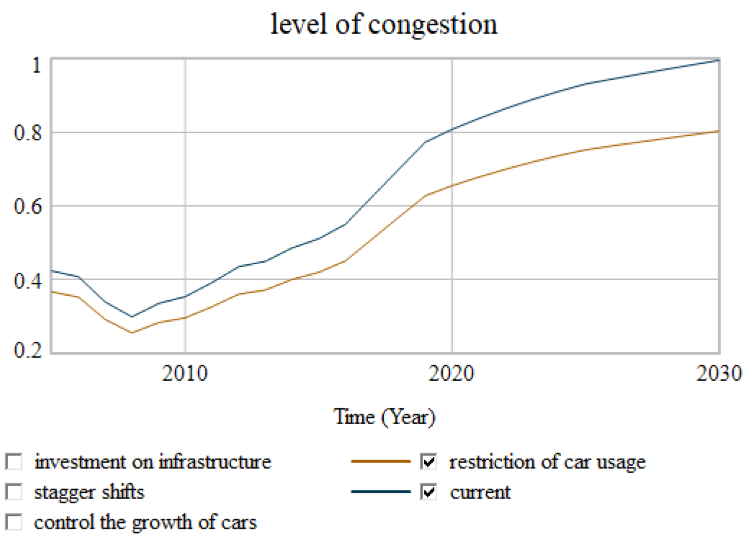

Fig. 4.12 Level of congestion

According to the simulation result, the effect of this policy is lasting and obvious. In addition, this policy is easy to adjust. In fact, many cites restrict more than two tail numbers, especially when there is a holiday or event.

4.4.4 Stagger shifts

This policy aims reduce travel volume during peak hours. In this paper, it is assumed when there is stagger shifts, 15% cars will not travel during the peak hours. The level of congestion is shown in Fig. 4.13.

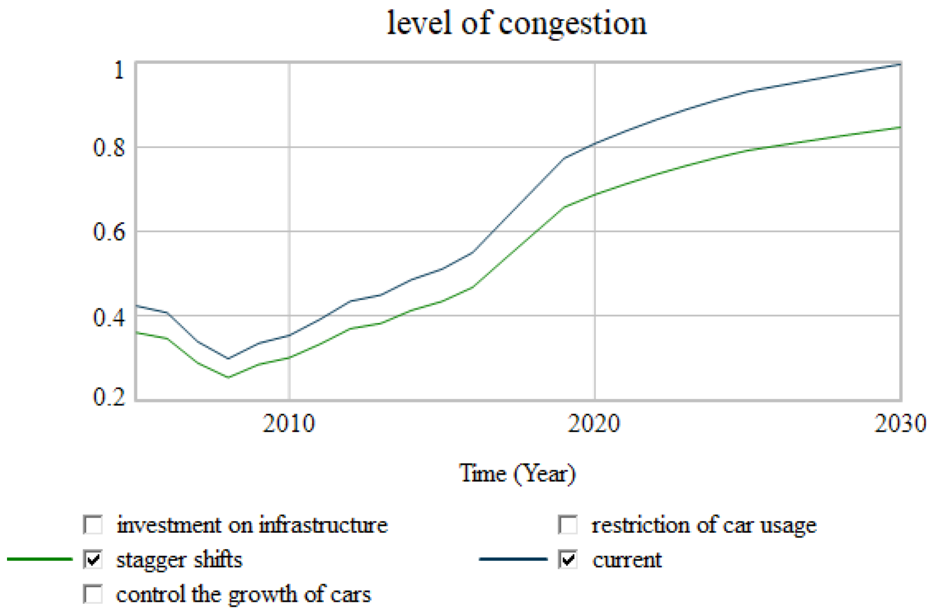

Fig. 4.13 Level of congestion

According to the simulation result, the effect of this policy is similar to that of restriction of car usage. The effect is obvious. However, this policy is hard to adjust, and travel volume is still up to commuters.

4.5 Comparison of different policies

This section will evaluate the effectiveness of different policies. The following figures show the simulation results of different policies.

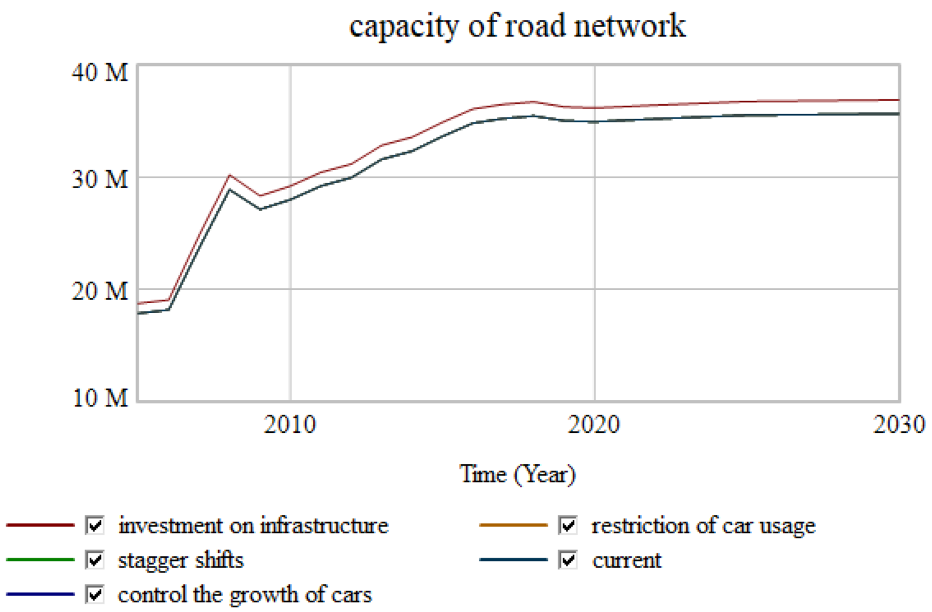

Fig. 4.14 Capacity of road network of different policies

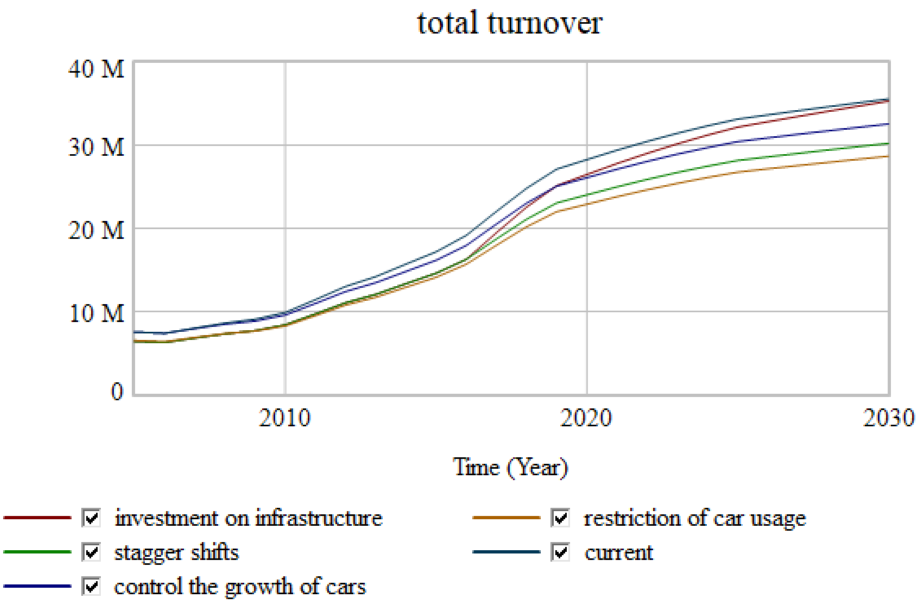

Fig. 4.15 Total turnover of different policies

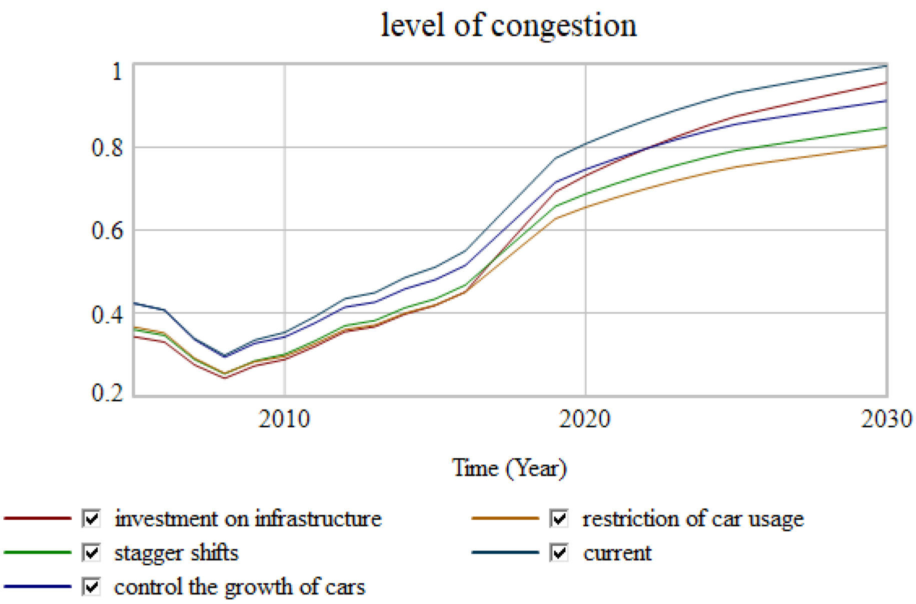

Fig. 4.16 Level of congestion of different policies

In this paper, four policies have been simulated. Investment on infrastructure focused on improve the capacity of the road network, and the other three policies focused on limit the travel volume. Through Fig. 4.14, it is known that investment in infrastructure can improve the capacity of road network while the others cannot; From Fig. 4.15-4.16, it can be found that the demand side policies can reduce the total turnover to a certain degree, thus reducing the degree of congestion. Among them, the effect of restriction of car usage is the most obvious, followed by stagger shifts, and the effect of control the growth of cars is the weakest. Compared with the policy on the demand side, the policy on the supply side is not so effective. According to Fig. 4.16, the improvement of road supply capacity can only reduce the degree of congestion in the early stage, and with the growth of car retention, the impact on traffic congestion is gradually decreasing.

4.6 Measures to control traffic congestion in Shanghai

According to the simulation result of the model, it is found that different congestion control policies have a significant impact on travel volume、 capacity of the road network and level of congestion. To solve the congestion problem, it is needed to make specific policies from the following aspects:

Control the growth of motor vehicles

In recent years, motor vehicles maintain a rapid growth, if it cannot be effectively controlled, congestion will be more and more serious. The specific measures are as follows:

Control the number of vehicles by controlling the growth of motor vehicles. However, the number of ambulances, fire engines, buses and other socially necessary vehicles should not be controlled. On the other hand, vehicles with long service life and substandard emissions should be scrapped. This controls the number of vehicles and reduce environmental pollution as well.

Guide citizens' travel mode:

Through the traffic situation in Shanghai in recent years, it can be found that more and more people choose motor travel, and the proportion of private car travel continues to rise. The government can take a variety of measures like reducing the ticket price, improving the service level and reducing the waiting time to encourage citizens to use public transport or non-motorized travel mode. On the other hand, government can conduct propaganda to improve the quality of travelers and encourage citizens choose non-motorized mode of travel.

Another way is to control the number of travel volumes by limiting usage of private cars. Firstly, the usage of cars can be controlled by tail numbers. If the measure is not efficient enough, government can limit more tail numbers. Secondly, government can charge for congestion. This measure worked well in Singapore. Thirdly, the increase of parking charges in central urban areas can also influence citizens' travel mode. Last but not least, policies such as stagger shifts can reduce the number of travel volume in peak hours.

Improve capacity of transportation system:
From the perspective of urban traffic resources, increasing the length of the road and improving the carrying capacity of the road network can only reduce traffic congestion in the short term. With the growth of road mileage, the travel volume and travel distance of residents will increase, which will lead to a new round of congestion. Therefore, for the old towns of Shanghai, as the road network has been basically formed, it is important to connect the whole road network as soon as possible.

For the new towns, the urban traffic construction should be scientifically planned. when plan the new towns, it is necessary to reduce the residents' dependence on private cars, improve the service level of public transportation system, control the travel distance, reduce the travel cost, and avoid the traffic congestion caused by the long travel distance.

Improve management of transportation system:
The traffic management department has a direct impact on the construction, operation and development of the traffic system. The decision made by management department has a great influence on the performance of road network. At present, all kinds of transportation facilities in Shanghai central area are almost complete. In order to further improve the management level, it is needed to build an intelligent transportation system. Intelligent system includes many aspects, vehicle control system, traffic monitoring system, vehicle management system. By collecting traffic information, these systems can accurately analyze and publish the traffic situation in the road network, and help drivers choose the best path to reduce the load of the road network.

On the other hand, the quality of traffic participants has a great impact on urban traffic. Good traffic habits can reduce congestion. Drivers should strictly implement traffic laws and regulations, be polite to pedestrians and not park vehicles disorderly; Pedestrians should also follow traffic laws and regulations, do not run stop lights, do not cross the road in disorder, and ride in a civilized way. Buses should started on time, ensure the vehicles are clean and tidy, maintain a positive and enthusiastic service attitude, and maintain good riding order, so that people are more inclined to choose bus travel.

4.7 Chapter summary

This chapter analyzes the Shanghai transportation system based on the system dynamic model. Different policies such as investment on infrastructure, restriction of car usage, control the growth of cars and stagger shifts have been simulated by vensim. The effects of different policies have been analyzed suggestions, which have been made based on the simulation results.

Conclusion

The conclusion of this research are as follows:

Factors that cause congestion can be divided as external factors and internal factors. External factors refer to traffic congestion caused by social and economic development. These changes lead to the increase of travel volume, travel distance and also affect travel mode. Internal factors refer to the traffic congestion caused by the poor management of the transportation system.

Based on the system dynamic model and Shanghai Statistical Yearbook, transportation system is simulated. According to the research result, the increase of capacity can only solve the traffic congestion at the beginning, when it comes to the long run, this policy is not efficient anymore. Control the growth of cars and restriction of car usage are efficient and flexible. Stagger shifts is also efficient but hard to apply.

Based on the simulation results, specific measures to control traffic congestion in Shanghai are proposed. These measures are focused on four aspects: control the growth of motor vehicles, guide citizens' travel mode, improve capacity of transportation system and improve management of transportation system.

The urban system and transportation system are very complex, but the model is simplified, some factors are not taken into account, such as the weather factors in the north and south, the influence of culture on driving habits and so on. This paper mainly consider the congestion situation of urban peak hours, and does not discuss the congestion of highways during holidays.

In the follow-up study, the traffic system is simulated in more detail such as environment, cultural differences, road network conditions and climate.
On the other hand, traffic congestion not only exists in the city center, but also in the express ways. This kind of congestion is often caused by major holidays or trade between cities. Finally, in the follow-up study, in order to make the loss of congestion straight forward, congestion can be quantified from different aspects: economy,

emission and influence on health. Efficiency of different policies can also be evaluate from these perspectives.

Reference

[1] National Bureau of statistics of the people's Republic of China. China Statistical Yearbook [G]. Beijing: China Statistics Press,2013

[2] Li Hui. Research on Shenzhen traffic congestion management from the perspective of collaborative governance [D]. Shenzhen: Master's thesis of Shenzhen University，2017.

[3] Yang Yang, he Defang, Tong Hefeng, Qu Weishuang: Construction of urban transportation system dynamics model for policy scenario simulation: a case study of Beijing. China Science and Technology Forum, 2013 (11): 32-44

[4] Feng Xiangzhao, et al. External cost estimation of urban traffic congestion [J]. Environment and sustainable development，2009(3): 1-4

[5] Xie Xuxuan, Zhang Shiqiu, et al. Social cost analysis of traffic congestion in Beijing [J]. China's population, resources and environment，2011(1)：28-32.

[6] Liu Zhiyan, Yue Xiaoyan, Zhao Rui. Causes and Countermeasures of urban traffic congestion in China[J]. Urban social management,2011,18(11):90-96

[7] http://news.xinhuanet.com/auto/2013-01/10/c_124210781.htm

[8] Chen Yanling. Comparative study on travel cost of public transport and car [D]. Nanjing: Master's thesis of Nanjing Forestry University, 2009.

[9] Liu Hui, Guo Huaicheng, Yu Yajuan, et al. Study on Optimization of urban passenger transport environment system based on travel [J]. Journal of Peking University，2010（01）：121-128.

[10] Small Kenneth. Economics and urban transportation policy in the United States[J]. Regional cience and Urban Economics,1997,27 (6).

[11] Hook Walter. Role of nonmotorized transportation and public transport in Japan's economic success [J]. Trasnportation Research Recond. 1994(1441)

[12] Huang Xinhua:《Public sector economics》[M], Fuzhou: Fujian people's publishing house, 2008
[13] Xu Feng. Analysis of urban traffic congestion based on supply and demand [J]. Logistics engineering and management,2012,34(10):83-84

[14] Mei Zhenyu, Wang Wei, Chen Jun, Ge Hongwei. Research on urban traffic demand management in China [J]. Research on modern city , 2004,(4):49-53

[15] Sun Huijuan. Research on intelligent control of traffic signal at intersection [J]. Transportation technology and economy, 2008,(01)

[16] Zhang Lei Yuan. Intelligent traffic management system and its present situation [J]. Intelligent Transportation,2010,(6):49-51

[17] Zhu Minghao. Analysis of social and economic impact of urban traffic congestion [D]. Beijing: Doctoral Dissertation of Beijing Jiaotong University，2013.

[18] Liu Ying, Yun Jun, Li Mingwei. Economic benefit analysis of Urban Rail Transit Based on system dynamics: a case study of Shanghai rail transit [J]. Practice and understanding of Mathematics. 2016 (19):125-132

[19] Wei Xianpeng, Chao Lu, Zhan Qiuyan, Han Hao. Study on urban road traffic pollution control based on system dynamics [J]. Practice and understanding of Mathematics. 2017,23.

[20] Greater London authority(GLA), office of National Statistics (ONS). Focus on London 2001 [R]

[21] Li Bin, he Ning, Wei Chang. Comprehensive analysis model and application of passenger transport mode in big cities [J]. Journal of Chongqing Jiaotong University,1997,16(2):65-70

[22] Lin Zhen, Yang Hao, optimization model analysis of urban traffic structure [J], Chinese Journal of civil engineering, 2005,38 (5):100-104

[23] Liu Shuang, Zhu Xiaoning, Jia Shunping, review of urban traffic structure optimization, transportation system engineering and information [J], 2009.9（1）：1-11

[24] Lu Jian, theory and method of sustainable development planning of urban transportation system, Doctoral Dissertation of Southeast University,2003

[25] https://www.sohu.com/a/290560025_417119

[26] Chu Qin, Gao Yong, Zhang Xin, Feng Xuesong, rational development of urban motor vehicle traffic [J], Analysis of urban public traffic,2004(2):11-14

[27] Chen Chunmei, Ren Futian, review of road network capacity.[J] Highway transportation technology , 2002.19(3):97-101

[28] Lu Shen, Tian Feng, Li Xuhong, research on the development mode of passenger transport structure in big cities of China: Application of AHP-PCA combination evaluation method [J]. Journal of Civil Engineering, 2003,36 (1):30-35

[29] World Bank, unimpeded City: evaluation report on urban transportation strategy of city bank [R] Beijing: China finance and economy press,2006

[30] Xu xunchu, research on determining the structure of urban traffic mode [J], urban planning forum,2003(1):13-15

[31] National conditions analysis and research group, Chinese Academy of Sciences. Opportunities and challenges: A Study on China's economic development strategic objectives and basic development strategies towards the 21st century [M] Beijing, Science Press,1995

[32] Liu Shuang. Evolution mechanism and Empirical Study of urban traffic structure

based on system dynamics [J]. Doctoral Dissertation of Beijing Jiaotong University，2009

[33]https://theconstructor.org/transportation/intelligent-transportation-system/1120/#:~:text=Intelligent%20transportation%20system%20is%20the%20application%20of%20sensing%2C,in%20order%20to%20improve%20safety%2C%20mobility%20and%20efficiency.

[34] Yang Yang. Traffic policy simulation and empirical research based on system dynamics model [D]: Master's thesis. Nanjing: Nanjing University，2014

[35] He Zheng. Study on system dynamics model of urban traffic congestion [J]. Modern economic information,2014(11):383-386

[36] Beijing Bureau of Statistics. Beijing Statistical Yearbook [G]. Beijing: China Statistics Press, 2000-2019

[37] Shanghai Bureau of Statistics. Shanghai Statistical Yearbook [G]. Beijing: China Statistics, Press 2000-2019

[38] Guangzhou Bureau of Statistics . Guangzhou Statistical Yearbook [G]. Beijing: China Statistics, Press 2000-2019

[39] Shenzhen Bureau of Statistics. Shenzhen Statistical Yearbook [G]. Beijing: China Statistics, Press 2000-2019

[40] Beijing transportation development annual report, Beijing Transportation Development Research Institute, 2008-2019.

[41] Shanghai transportation development annual report, Shanghai Transportation Development Research Institute, 2008-2019.

[42] Guangzhou transportation development annual report, Guangzhou Transportation Development Research Institute, 2008-2019.

[43] Shenzhen transportation development annual report, Shenzhen Transportation Development Research Institute, 2008-2019.