A System Dynamics Model for Urban Low-Carbon Transport and Simulation in the City of Shanghai, China

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Abstract

Urban transport plays an important role in low-carbon eco-city and energy conservation and emission reduction in the transport sector. Urban low-carbon transport system is a complex dynamic system including society, economy, motor vehicles, cars, transport infrastructure and other factors. This paper analyzes the complex dynamics relationship through building an urban low-carbon transport system. Taking Shanghai as a case to simulate the urban low-carbon system, and the result suggests rapid increase of private cars is an important driver factor of carbon emissions. So, it is important to strengthen urban transport demand management and improve the urban transport structure in building urban low-carbon transport.

Key words: *Urban Low-Carbon Transportation; System Dynamics; Simulation*

1. Introduction

In the 21 century, the energy consumption and greenhouse gas emissions brought serious test for the sustainable development of human being, the development of low carbon economy has become a consensus all over the world. In 2007, global total traffic oil account for 61.2% of the total oil consumption, and the CO2 emission account for more than 30% of the global greenhouse emissions. Therefore, transportation department becomes the biggest energy consumption and carbon emissions one. The British transport department put forward "low carbon transportation innovation strategy" first in 2007, and in 2009 the book “Low carbon transportation: more green future” was published. China's transportation department, in 2011, announced the "guiding book on the construction of low carbon transportation system”, which formulated relevant policies to support the development of low carbon traffic. Urban transportation energy consumption hold a larger proportion in the transportation department, also is a important driving factor of the city carbon emissions. In last century, there are no more than 20 cities that the population is above one million, but nowadays it exceeds 450 cities. The energy conservation and emission reduction of urban traffic plays a vital role to achieve a low carbon economy and the goals of sustainable development.

Low carbon traffic is a kind of traffic development way, which is energy efficiency, low energy consumption, low pollution and low emission. It’s also a process which is to pursue the balance point among social and economic development, dynamic traffic sustainable development and the low carbon traffic. What’s more, the low carbon traffic is a kind of new industrial development model which is to maximize the effectiveness by lowest carbon intensity and the least amount of greenhouse gas emissions[1]. Urban spatial structure, transportation structure, traffic facilities construction and the traffic operation management are the main influencing factors of the low carbon traffic[2]. With the development of urban economy, all of the problem such as the increasing number of urban population, motor vehicles, urban passenger traffic volume and resident trips, the increasing contradiction between urban traffic demand and supply, and the city traffic management level may cause urban traffic congestion[3]. Frequently, the traditional urban transportation development philosophy tried mostly to solve the traffic problem such as congestion by increasing investment in urban transportation supply. However, the increasing investment will improve the economic development and urban traffic conditions, which finally attract more crowds and traffics. And these will affect the problem including the traffic land resources consumption, energy consumption, air pollution and increase of the carbon emissions.

In recent years, with the advancement of technological and managerial development, the application of low carbon city transportation infrastructure and transportation equipment, as well as the development of the disciplines such as information technology and mathematics, the planning, construction and operation management of the urban transportation is powerfully supported. By using rapid information processing, algorithm design and simulation model optimization, urban transportation research, planning and construction has been well done[4-5]. By using the geographic information system, the urban traffic information has been collected, analyzed, processed. And then the system has developed as intelligent transportation system to improve the city traffic management level [6-8]. IBM first put forward the idea of Smart City. By comprehensive use of the internet of things, sensor networks and information technology on the urban operation management, it improved the city management efficiency entirely and supported the energy conservation and emission reduction of the urban traffic system [9].

However, the urban traffic carbon emissions continue rapid growth. As a matter of fact, the urban traffic carbon emissions are influenced not only by the factors such as the urban population, vehicles quantity, traffic structure, resident trips and urban spatial structure, but also by the constraints of social, institutional and environmental factors[10]. City low carbon traffic construction is a complex system. The internal system contains subsystems like population, vehicles, and the economy. And inside every subsystem, it includes a lot of factors, which exists feedback relations of mutual connection and mutual influence. In this paper, it analyzes the complex dynamics relationship through building an urban low-carbon transport system. And this paper takes Shanghai as a case to simulate the urban low-carbon system, as well as provide the policy support for the urban low carbon transport construction.

2. Urban Low-Carbon Transportation System Model Based on System Dynamics

The urban transportation system is a high order multiple feedback loop and nonlinear characteristics of complex dynamic system. The internal structure of it is complex. It also owns a group of influence factors, which will change and change along with the time development. And at the meantime, the mutual relationship will be constantly changing to more complicated, the system structure and the operation is difficult to fully clear grasp. Therefore, urban low carbon traffic construction system it is difficult to analyze by using accurate mathematical model, but by using half quantitative, half qualitative or qualitative methods. System dynamics in which is complex, multiple feedback loop time-varying, qualitative and quantitative simulation system is a powerful tool.

2.1. System Dynamics Methods on Urban Low-Carbon Transportation Construction

System dynamics, established by Jay W. Forrester in 1956, is a discipline to research system dynamic complexity[11]. It takes the method, which combine qualitative and quantitative research as well as the system synthesis reasoning, to make the analysis of various factors of a feedback loop between cause and effect, from the complex phenomenon in analysis of the phenomenon of the internal causes and its formation mechanism. The system dynamics has the advantages on dealing with nonlinear problem, information feedback, time delay and dynamic complex. Through the development in recent years, it gradually developed as a complete discipline, it can be widely used in various complex system decision experiment and decision making, including social, economic, ecological, enterprise managerial aspects [12-15]. In the other hand, system dynamics is also a powerful analysis and decision making tool in the aspect of urban construction and urban traffic management.

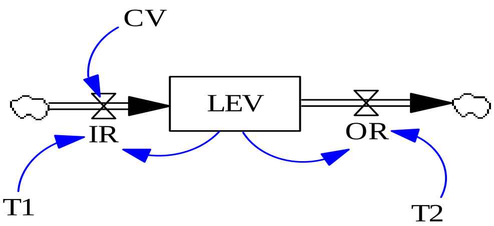

Figure 1. First-order SD feedback loop model

System dynamics uses feedback as elementary unit to describe system, causal relationship to show the relation among the system elements, flow graph to represent the structure and nature of system elements, and difference equation to quantitatively describe the system. It also uses qualitative and quantitative methods to establish the complex system model, quantitatively coordinates and optimizes the relationships of system elements and can use the computer to carry on the simulation analysis. Besides, system dynamics determines the optimal control system implementation and makes policy variables effectively control the development and change of the system state by obtaining the major variable changes of the analytical expression with time[16]. Figure 1 shows a typical system dynamics model of one feedback loop. It is the foundation of how to analyze system dynamics. Through the analysis and combination of this basic mode, the system dynamic model of urban low carbon traffic construction could be built.

According to the flow graph to write about the system state control of spatial expression, there if defined as $X = LEV$,$U = CV$, $\dot{X}$ is derivative to time, then

$$\begin{aligned}\dot{X} &= \frac{d(LEV)}{dt} = IR - OR = \frac{CV - LEV}{T_1} - \frac{LEV}{T_2} \\ &= (-\frac{1}{T_1} - \frac{1}{T_2})X + \frac{1}{T_1}U\end{aligned} \tag{1}$$

Such as

$$\dot{X} = AX + BU \text{ , there, } A = 1/T_1 - 1/T_2 \text{ , } B = 1/T_1 \tag{2}$$

Equation (2) is constant system no homogenous linear equation. When initial time $t = t_0$, initial state is $X(t_0)$, the equation analytic solution as follows

$$X(t) = e^{A(t-t_0)} X(t_0) + \int_{t_0}^{t} \Phi(t-\tau)B \bullet U(\tau)d\tau \tag{3}$$

First paragraph equation (3) is caused by the initial system state free movement, the second is caused by the controlling excitation force movement for homogeneous equation (If the second paragraph does not exist).To equation (1), if $t_0 = 0$, and assume $V = CV$ is constant with time, then has

$$\Phi(t - t_0) = \Phi(t) = e^{At} = e^{(-1/T_1 - 1/T_2)t} \tag{4}$$

2.2. Causality diagram of Urban Low-Carbon Transportation

The interaction relationship of important elements in the system can be described by causality diagram; it is used to design a system dynamics model of the initial stage. The causal chain of causality diagram can indicate its positive and negative effect. The positive sign means variable which arrow point to will increase or reduce with the origin variable of the arrow. And the minus sign shows opposite relation. Urban low carbon traffic construction system is a complex system; the key elements in the system include the level of urban economy, urban population, urban vehicles, rail traffic, urban infrastructure, urban transportation policy and management level. By analyzing the key factors and their mutual relationship of the urban low carbon traffic system and subsystem, the causality diagram has been made. It can be found in figure 2. The development of urban economy expanded the urban scale, increased urban population and improved the income level of resident, so that it also increased urban passenger traffic volume and resident trips, motor vehicle number. Therefore, it induced traffic congestion which will lead to the increase of carbon emissions. The carbon emissions can be influenced by the urban traffic development policy including changing the motor vehicle number, traffic structure and transportation infrastructure. The improvement of urban traffic management operation can optimize traffic network, reduce traffic congestion and reduce the urban traffic carbon emissions.

2.3. Flow Graph of Urban Low-Carbon Transportation

On the basis of causality diagram, the flow graph of urban low-carbon transportation construction can be reached, which shows in figure 3. The flow diagram of urban low carbon traffic system dynamics model contains six accumulated variables, including total urban population, car number, bus number, taxi quantity, commercial vehicles quantity, urban road mileage, bus lines mileage and rail traffic mileage. The total urban population is related with the natural growth rate of the city residents, immigration and emigration the number of residents. The number of motor vehicle constitutes of car, taxi, bus and lorry numbers. The car number is related with per capita income of City residents. And the lorry number is related with city economic aggregate. The bus number and rail traffic mileage are determined by the infrastructure investment, and it is also related with resident trips. The urban traffic carbon emissions are measured by energy conversion method. Different modes of transportation and energy usage use different carbon emissions coefficient. The improvement of urban transportation development and the level of technology will reduce carbon emissions coefficient. The overall urban traffic emissions are related with the numbers of motor vehicles, trip mileage and traffic structure.

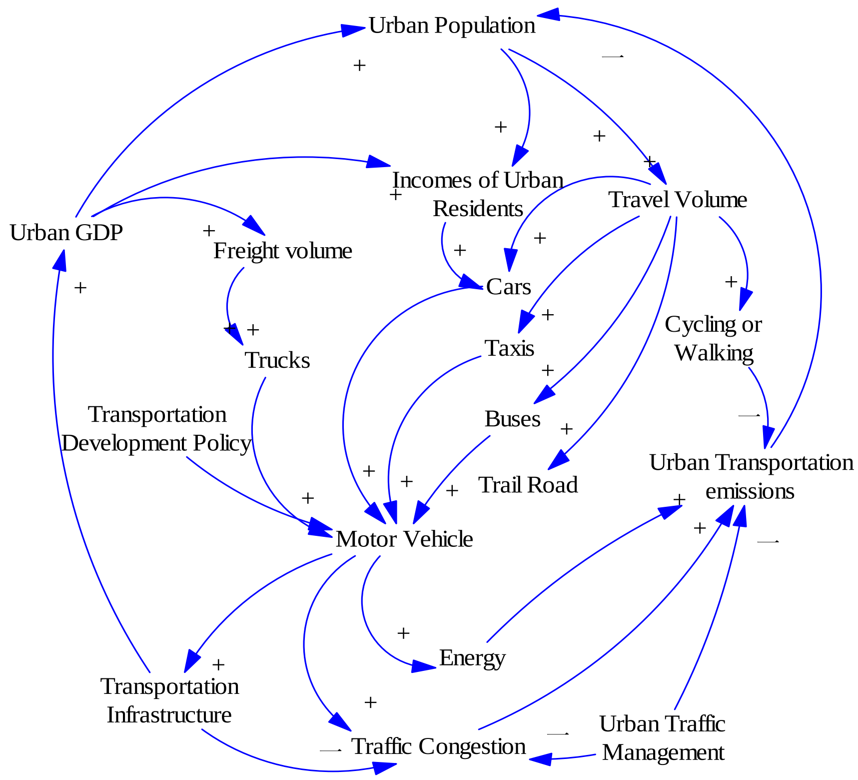

Figure 2. Causality diagram of Urban Low-Carbon Transport

3. Case Study: Taking Shanghai as an example

In order to validate the validity of the urban low carbon transport model, this paper takes Shanghai as a case to simulate the urban low-carbon system. Shanghai covers an area of 6340 square kilometers. In 2010, the economic aggregate reached 1.69 trillion Yuan. Shanghai is China's first biggest city as well as one of the world's most populous city. The permanent population of Shanghai is 23.02 million, which includes 14.12 million of the household register population. In recent years, Shanghai developed so fast that in the process of holding EXPO, urban transportation infrastructure and traffic operation management level are getting great development. Shanghai makes high emphasis on the important role of urban transportation in the construction of low-carbon city and sustainable development. As the population continued growth and urban space developed unceasingly in recent years, Shanghai transportation in travel space and travel methods is greatly changed, while the urban traffic carbon emissions continued to increase.

This paper use Vensim PLE to simulate Shanghai urban low carbon traffic system, analyze the mutual relationship between the factors of the system. And through the simulation, it predict the future trend of development. The parameter values in the model are evaluated by the data from “Shanghai statistical yearbook”, “China's city construction yearbook (2001-2009)” and “Shanghai industrial energy traffic statistics yearbook”. The qualitative variables such as urban traffic management level and urban congestion index are selected from the “Smooth Traffic Project”, which announced by the ministry of public security and rural construction. Then it used the comprehensive evaluation like expert scoring (from 0 to 100). And the relationship between the variables used table function.

It used the statistics from 2000 as the initial value of state variables. The time of simulation model is from 2000 to 2015, set DT=0.25, so that we got the changing trend of the main factors such as the urban traffic carbon emissions, the urban population, private car quantities and the urban management level (see figure 4-7). As the result of simulation can be seen, though the urban traffic management level continues to rise recently, Shanghai's carbon emission is still increasing, especially from 2003 to 2008. It is mainly because of the private auto possession, and the increase of city permanent population also increased carbon emissions. This trend will be kept in the future 5 years. As a result, the urban traffic demand should be managed and the traffic structure should be improved so that the carbon emission could be well controlled.

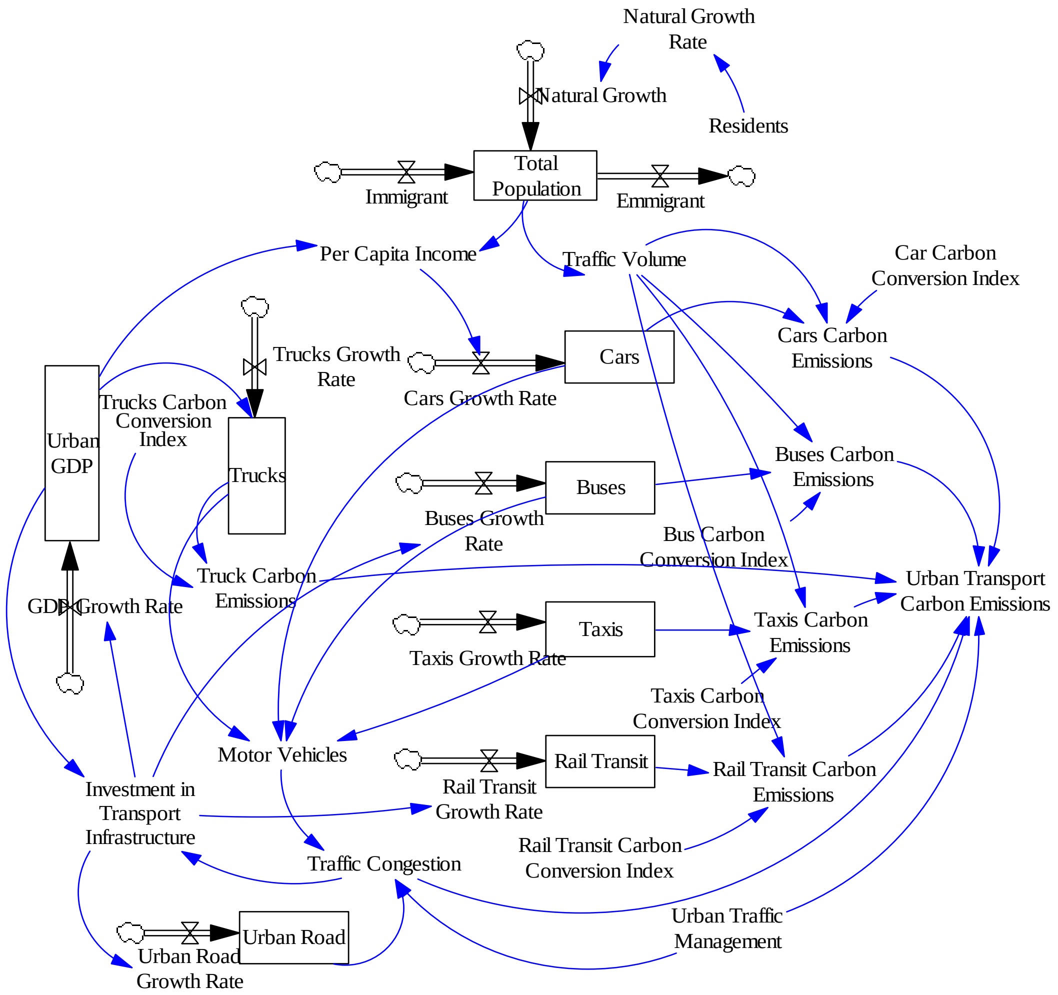

Figure 3. Flow Graph of Urban Low-Carbon Transport

4. Conclusions and Future Research

By analyzing the key influence factors of the urban traffic carbon emissions, this paper build an system dynamics model of urban low-carbon transportation and describe the dynamic relationship among the urban economy, urban population, Urban vehicles (civilian traffic and public transportation), urban transportation infrastructure, city traffic management level and urban transportation carbon emissions. Taking Shanghai as an example, the paper simulate the urban low-carbon traffic system and find out that the major reason of increasing carbon emission is urban private car possession. What's more, the expansion of the scale of urban population also increases urban carbon emissions. Therefore, the model and reality has certain alignment. At the meantime, the paper predicts the carbon emission of Shanghai in the future 5 years. It shows that urban traffic carbon emission will continue to increase and urban car numbers and population are still the important driving factors. To achieve the urban low-carbon transportation, the urban traffic demand should be well managed, the private car numbers should be controlled and the urban traffic structure should be improved. In fact, the urban carbon emissions are also close related with the city location features, industrial structure and the function of the city layout. The good application of new energy, new material and energy conservation technology into urban transportation infrastructure and transportation methods can reduce the carbon emission greatly as well. Whether these factors can change the structure of urban carbon traffic system, how is the mutual relations with other factors and whether they influence the urban carbon emissions need to be further researched.

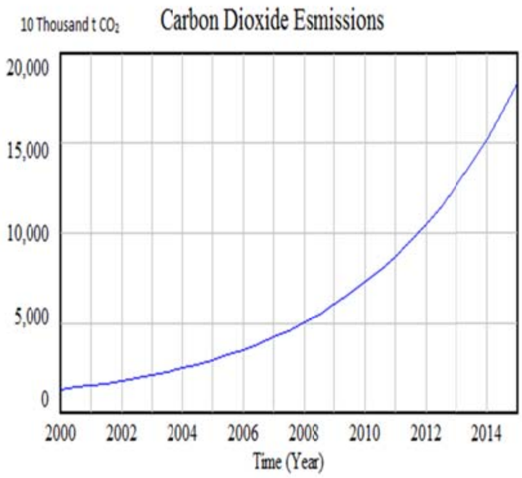

Figure 4. Carbon Dioxide Emissions in Shanghai

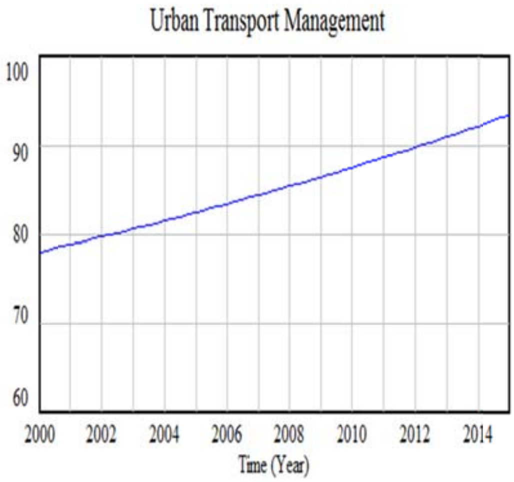

Figure 5. Transport Management in Shanghai

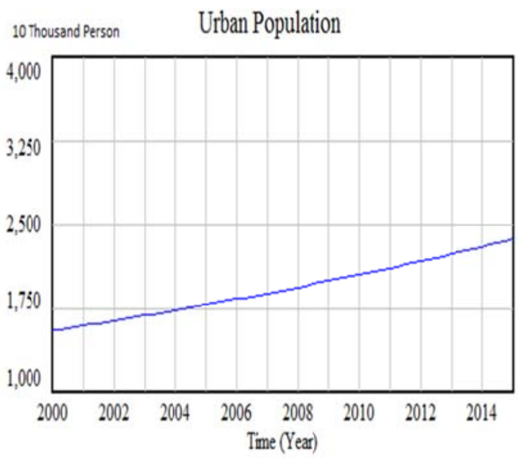

Figure 6. Urban Population in Shanghai

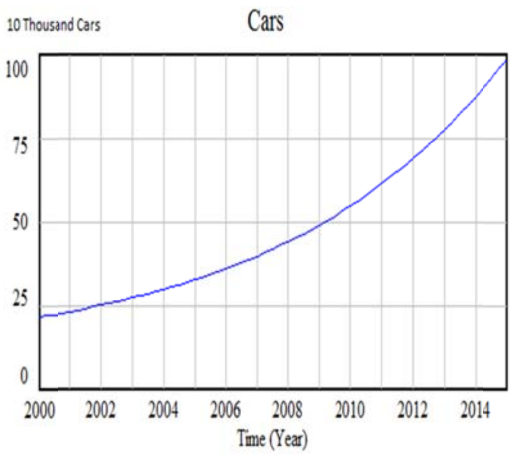

Figure 7. Cars in Shanghai

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