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System Dynamics Model of Shanghai Passenger Transportation Structure Evolution

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Abstract

Based on the data from a comprehensive transportation survey of Shanghai in 2004 and 2009, this paper analyzed the evolution of urban passenger transportation structure using the system dynamics approach. A system dynamics model of Shanghai passenger transportation structure evolution is proposed, which consists of setting modeling targets, establishing transportation system boundaries, causality analysis, establishing flow diagram, parameter estimation and model validation.

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Keywords: System dynamics model; Passenger transportation structure; Evolution ; Road traffic status

1. Introduction

Transportation structure, which refers to the mode split of passage trips, can reflect the characteristics of traffic demand and the functional roles of different modes in transportation. It has directly impact on the configuration of the limited transportation resources and determines the efficiency of urban transportation system. With the development of urbanization and motorization, traffic supply and traffic demand become imbalance. The transportation structure becomes more and more inefficient. Energy crisis, traffic congestion and environmental pollution become more and more serious. It has seriously hampered the sustainable development of cities. It is an important experience worldwide to optimize the structure of urban passenger transportation for sustainable development of urban transportation by increasing public transit penetration and guiding the travel behavior of residents. Therefore, in the accelerating adjustment of China's urban passenger transportation structure, research on the evolution of urban passenger transportation structure and guide urban transportation to the sustainable

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development modes, not only has a general role in guiding traffic planning, traffic construction, traffic operation and traffic management, but also has a very important practical significance to improve the efficiency of urban transportation running , alleviate the urban traffic congestion and improve the living standards of urban residents.

Schaeffer and Sclar (1975) explored the relationship between transportation system and urban structure for the first time. They considered that the evolution of the urban structure is directly affected by traffic modes. Thomson (1977) started from the transport development mode, and classified the urban layout as strategy of full development of car, strategy of limiting the city center, strategy of maintaining a strong city center, strategy of low-cost and strategy of limiting transportation. Elkind (1991) thought that a sustainable city must have convenient facilities for pedestrians, non-motorized vehicles and public transport. Centralized public facilities could reduce the trip distance and the proportion of car use. Cameron (2003) pointed out that the influencing factors of private motorized trips were population, urbanization area, posts and road network, but mostly depends on the structure of the city. He proposed a model of calculating the ratio of urban private motorized trips.

Xu (2006) analyzed the external environmental conditions and internal factors that influenced the evolution of urban public passenger transportation structure. Shen (2007) analyzed the characteristics and influencing factors of the transportation structure of typical cities in different periods, and proposed the evolution law of transportation structure. Guo (2008) studied the impact of rail transit on transportation structure and analyzed the evolution law of urban passenger transportation structure in various stages of rail transportation development. Chen et al. (2009) studied the residents travel mode choice from an evolutionary point of view using evolutionary game theory. Liu (2009) analyzed the mechanism of the evolution of urban passenger transportation structure in typical cities worldwide, proposed a system dynamics model of the evolution of urban passenger transportation structure and had an empirical analysis. Ye et al. (2010) analyzed the relationship between the space of ribbon group city and the evolution of the transportation system, and studied the evolution mechanism of city space morphology and traffic patterns in the case of Zhenjiang.

Based on the data from comprehensive transportation survey of Shanghai in 2004 and 2009, this paper analyzed the evolution of urban passenger transportation structure using system dynamics approach. A system dynamics model of Shanghai passenger transportation structure is proposed, which consists of setting modeling target, establishing transportation system boundary, causality analysis, establishing flow diagram, parameter estimation and model validating. The proposed model can be used to predict the future evolution characteristics of Shanghai passenger transportation structure in the future.

2. Applicability analysis of system dynamics

System Dynamics (SD) is a discipline of researching on system information feedback and solving the problems integrated in system. It holds that the behavior patterns and characteristics of system primarily depend on the mechanism of system's internal dynamic feedback structure. It emphasizes that research and analyze problems should in overall, contact, development and movement point of view, using system reasoning and the combination of qualitative and quantitative method to simulate the dynamic development of system and its trend for long-term dynamic strategic quantitative analysis.

Urban passenger transportation system is a complex socio-economic system. There are certain limitations in relying solely on qualitative research methods or purely rational and static quantitative research methods to analyze and solve problems. The system dynamics method can have a good combination of qualitative analysis and quantitative analysis. It also can visible analyze the system behavior, system composition, control mechanism and causality constraints, which are applied to study the evolution of urban passenger transportation system.

System dynamics fits for studying the urban passenger transportation structure because of the common characteristics between system dynamics and transportation system. First of all, the research object of system dynamics is the complexity of the social system, economic system, and ecological system. Urban passenger transportation system with complex factors is the system dynamics' ideal research object. Second, system dynamics can be used to study the dynamic development process of the system with the internal factors. So it could be used to simulate the dynamic development of the system and its trend applied to study the long-term development process of the urban passenger transportation system. Third, system dynamics modeling process focuses on the establishment of the system's internal structure. Using the causal relationship between various elements and limited data can do some related projections. It is suitable for studying the urban passenger transportation system with few statistics. Fourth, system dynamics is known as "policy laboratory" which can be used to analyze different impacts on system by different policies. We can simulate different effects of different policy by changing the policy variables and related parameters in the system dynamics model. It can be applied to study the impacts of transportation policy on the evolution of urban passenger transportation structure.

3. System Dynamics Model of Shanghai Passenger Transportation Structure Evolution

We first determined the modeling target and elements of the system that should be considered in the model of Shanghai urban passenger transportation structure evolution. Then we analyzed the causal link between various elements of urban passenger transportation system, and established the flow diagram and structural equation. Using historical traffic data, we calibrated parameters and validated the model. This study uses the dedicated software Vensim PLE (Wang, 2009) for modeling.

3.1. Modeling target and ideas

The modeling target is to establish a real and effective simulation system dynamics model of the evolution of Shanghai passenger transportation structure by studying the causal link between relevant factors of the socio-economic, traffic supply, traffic demand, traffic operations and traffic policies, which can be used to analyze the future development of Shanghai passenger transportation structure.

The modeling ideas began with the composition of urban passenger transportation structure. Transportation structure can be divided into three categories, such as proportion of transit, proportion of non-motorized traffic and proportion of motorized private traffic. Each category can be divided into different subclasses, such as transit can be divided into rail transit, bus and taxi. Subclasses can also be refined for specific trip modes. The influencing factors of the trips of each traffic mode contain socio-economic attributes of the travelers, trip purpose, trip distance, and the choice alternatives. It is difficult to make a quantitative analysis. But it would be easier to calculate the trips volume of each traffic mode through its history supply and demand data. For example, the passenger volume of rail transit is determined by rail mileage and the passenger flow intensity of rail transit, which is determined by statistical analysis of its historical data. Then calculate the specific rail transit trip volumes through the translation of rail transfer rate. This paper is modeling in accordance with this thinking.

3.2. Establish boundaries of system

The first step of the determination of system configuration is to establish the boundaries of system. It needs to define which elements of system are useful based on the modeling target and research objective. The influencing factors of the relationship between the evolution of urban development and urban transportation structure include traffic supply, traffic demand, traffic operation, traffic planning and traffic policy. Combined with the modeling target and the configuration of urban passenger transport system, the boundaries of the model are determined as elements of transportation structure, elements of traffic supply, elements of traffic demand, elements of traffic operations, elements of traffic planning and traffic policy. The specific elements of the system are determined as follows:

(1) The elements of transportation structure, including proportion of motorized private traffic, proportion of non-motorized traffic, proportion of walking, proportion of rail transit in transit, proportion of bus in transit, proportion of taxi in transit, etc.

(2) The elements of traffic supply mainly refers to the supply of road, rail and vehicles, including road grade structure, road mileage, lane capacity, rail mileage, various types of vehicle ownership, etc.

(3) The elements of traffic demand factor mainly refers to the demand characteristics of different trip modes, including urban population (including resident population and floating population), population growth rate, residents' trip rate, daily trips of each kind of motor vehicles, passenger occupancy of each trip of motor vehicles, trip volume of each kind of motor vehicles, passenger occupancy of bus, passenger volume of bus, trip volume of bus, rail transit passenger flow intensity, passenger volume of rail transit, trip volume of rail transit, etc.

(4) The elements of traffic operation mainly refers to traffic load and traffic operation status on road, including daily average travel mileage of each kind of motor vehicles, peak hour traffic factor, peak hour turnover volume, road network capacity, peak hour traffic intensity, peak hour traffic load on road network, peak hour average speed of road network.

(5) The elements of traffic planning and traffic policy mainly refers to the traffic investment policies, traffic demand management policies and the future transportation planning, including the annual average growth rate of rail mileage, road mileage and each kind of motor vehicles, etc.

3.3. Causality analysis

Causal relationship is the basis of system dynamics. It is a true portrayal of the internal relations in system. Urban transportation system is a social system accords with causal relationship. System dynamics modeling is based on the causal diagram to illustrate the relationship among the internal elements of the system. Through analyzing the causal relationship among the elements of urban passenger transportation system, the main causal relationships in model include the proportion of each trip mode, trip volumes of transit, trip volumes of motorized private traffic, road network capacity, peak hour traffic intensity, and traffic load in road network. Just take the proportion of each trip mode as an example.

The study object of this paper is urban passenger transportation structure. Transportation structure is mainly divided into three parts based on the historical metropolitan transportation statistics reports, including proportion of motorized private traffic, proportion of transit and proportion of non-motorized traffic. Take the proportion of transit for example, the causal relationship is shown in Figure 1. This paper did not detailed analyze the proportion of non-motorized traffic. One minus the sum of proportion of transit and proportion of motorized private traffic is used to calculate the proportion of non-motorized traffic.

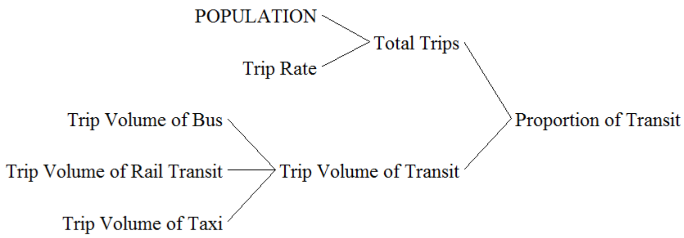

Fig. 1. The impact factors of the proportion of transit

3.4. Establish flow diagram and structural equation

Causal diagram could only describe the fundamentals of the feedback structure and roughly describe the feedback structure of the system. It could not distinguish the nature of each variable and the distinction between material flow and information flow. These will be improved and embodied in the flow diagram.

In order to simplify the complexity of modeling, use decision variables (also known as rate variable) to indicate the impacts of economic development on transportation investment and vehicle ownership, including the growth rate of road mileage, the growth rate of rail mileage, the growth rate of the bus, the growth rate of car, etc. Predetermined population, rail mileage, road mileage, car ownership, coach ownership, motorcycle ownership, taxi ownership, bus ownership as the input variables (also known as state variables or accumulation variables) of the model. Then divided the flow diagram into two sub-modules combined with the causal diagram. One is a flow diagram of urban passenger transportation structure evolution (see Figure 2) and the other is a flow diagram of the traffic state of the road network (see Figure 3).

3.5. Parameter estimation

This paper sets 2004 as the initial year because the Shanghai comprehensive transportation survey data in 2004 and 2009 are more complete. Parameters estimation of the model is based on the data of historical Shanghai comprehensive transportation survey reports, Shanghai comprehensive transportation annual reports and the Shanghai statistical yearbooks.

(1) Population

Urban population includes resident population and floating population. The total travel demand is determined by the city's population in the case of residents' trip rate is fixed. Since from the reform and opening up, a large number of people has moved to Shanghai with a rapid growth rate. There were 13.34 million residents in 1990 and increased to 23.03 million residents in 2010. The average annual growth rate of population is about 500,000 in past two decades (SMSB, 2011). So we adopt 500,000 as the Shanghai population annual growth rate.

(2) Residents' trip rate

Urban residents' trip rate is refers to number of trips per capita per day. It can be used to determine the total travel demand of the city. The residents' trip rate of Shanghai increased from 1.79 times per capita per day in 1986 to 2.23 times per capita per day in 2009 (see Table 1). It had a great influence on the process of the evolution of the transportation structure.

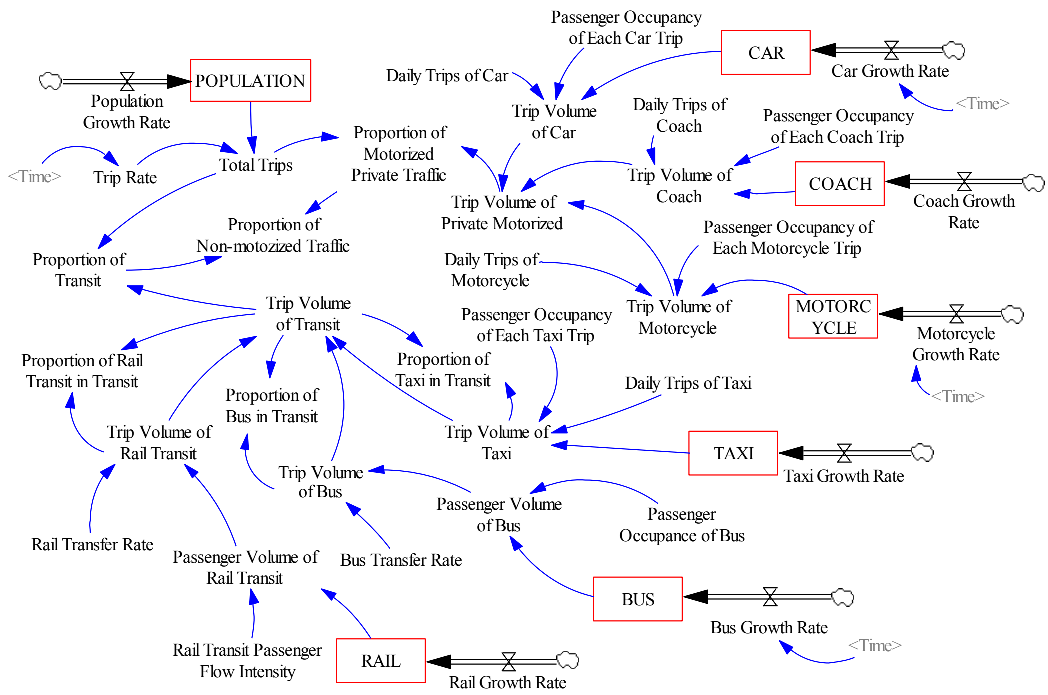

Fig. 2. Urban passenger transportation structure evolution flow diagram

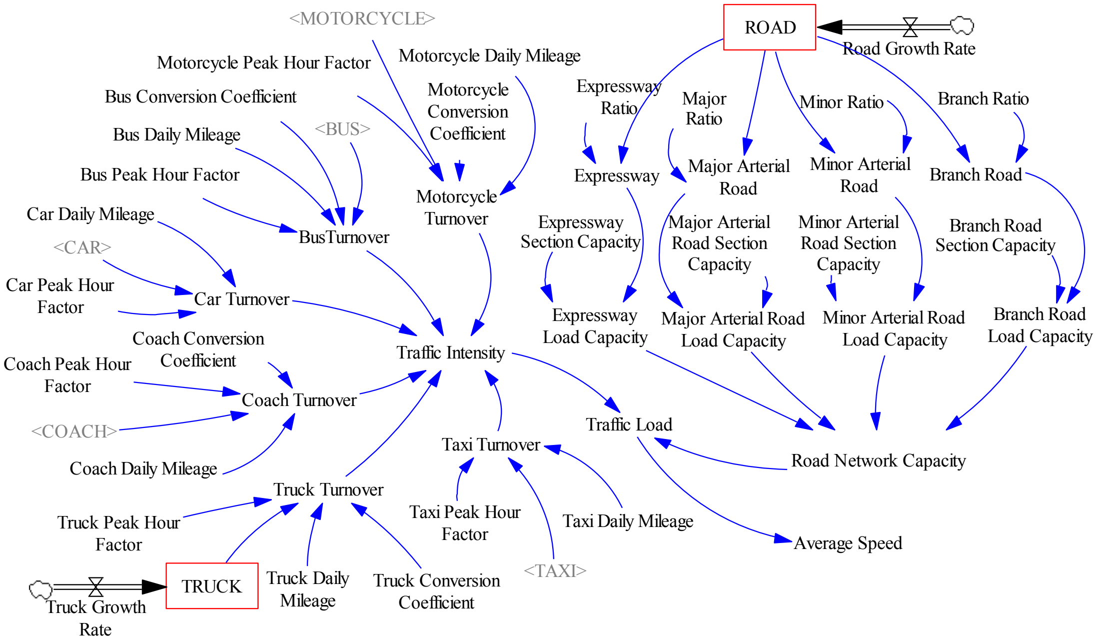

Fig. 3. Traffic state of the road network flow diagram

Table 1. Historical residents’ trip intensity of Shanghai (SCTPI, 2005, 2010a)

year	1986	1995	2004	2009
trip rate (trips/capita/day)	1.79	1.87	2.21	2.23

In addition, the trip rate of floating population, which is only a small part of population, is slightly higher than the resident population. For the ease of calculation, we set the trip rate of floating population equal to that of resident population.

(3) Passenger volume of transit

- Passenger volume of rail transit

According to the fourth Shanghai comprehensive transportation survey in 2009, the average carrying rate of rail transit was 14,300 passengers per kilometer per day. It was closed to the rail transit passenger intensity of Tokyo, which consisted of 15,000 passengers per kilometer per day. So we adopt 14,300 passengers per kilometer per day as Shanghai rail transit passenger intensity. Gets the product of rail mileage and rail transit passenger intensity is the approximate passenger volume of rail transit.

- Passenger volume of bus

Passenger occupancy of bus maintenances 430 passengers per bus per day (SCTPI, 2010b) based on the statistical analysis of the number of passengers and the number of buses over years. Therefore, adopt 430 passengers per bus per day as Shanghai passenger occupancy of bus. Take the product of passenger occupancy of bus and ownership of bus as the approximate passenger volume of bus. Set the growth rate of buses as -380 vehicles per year based on the number of bus reduces year by year from 2004 to 2009 (SCTPI, 2010b).

(4) Annual average growth rate of road mileage and each kind of motor vehicles

The road mileage and vehicle ownership of Shanghai had a greatly growth in recent years based on the statistics from 2000 to 2009 (SCTPI, 2010b). That includes bus, taxi, truck had an average growth rate of 3,000, 1,500, 6,400 vehicles every year, and regard them as the same growth rate in future. Motorcycle had an average decrease of nearly 40,000 motorcycles annual from 2004 to 2009. So regard the future annual growth rate of motorcycle in model as 40,000 motorcycles every year. In considering the average annual growth rate of road mileage was over 800 km from 2004 to 2009, this model take 800 km as the average annual growth rate of road mileage. Shanghai has carried out the new private car license auction policy in 2000, takes the growth rate of car in the model as 110,000 cars every year based on the average annual growth rate of car is 110,000 cars from 2004 to 2009.

(5) Traffic load

In urban road network, traffic load equals to the ratio of traffic volume to capacity is a key parameter of road network service level. The service level of the road network in accordance with the different traffic load and traffic flow state is divided into six levels of A to F. A–level refers to traffic load <0.4 when vehicles are running smoothly on road network without delay. B–level refers to traffic load <0.6 when traffic flow is stable on road network with a little delay. C–level refers to traffic load <0.7 when traffic flow is stable on road network with some delay but most drivers can endure. D–level refers to traffic loads <0.8 when traffic flow is close to unstable with more delay, only few drivers can endure; E–level refers to traffic load <0.9 when traffic flow is unstable with traffic congestion happens in large-scale regional, most drivers cannot endure the large traffic delay. F–level refers to traffic load <1.0 when traffic flow is compulsory on road network with near-constant traffic gridlock (Li, 2008).

3.6. Model validation

This model set 2004 as the initial year and used the third Shanghai comprehensive transportation survey data in 2004 as the model input. Since the purpose of this model was to simulate the evolution of transportation structure, select the proportion of each mode as the consistency test indicators of the model. The transportation structure in 2004 and 2009 output by model simulation were compared with the real value to make error test in order to verify the consistency of the simulation model. Model validation results are shown in Table 2.

Table 2. Model validating results (%)

The main test indices	Actual data	Model simulation data	Error	Relative error
proportion of motorized private traffic in 2004	17.8	17.3	-0.5	-2.8
proportion of transit in 2004	24.6	24.5	-0.1	-0.4
proportion of non-motorized traffic in 2004	57.6	58.2	0.6	1.0
proportion of motorized private traffic in 2009	20.0	20.0	0	0
proportion of transit in 2009	25.2	26.0	0.8	3.2
proportion of non-motorized traffic in 2009	54.8	54.0	-0.8	-1.4

Through comparing the transportation structure results in 2004 and 2009 by model simulation with the real value, the main indicators of the relative errors are within 5%. The consistency of the model meets the requirements of test and the accuracy of the model corresponds to actual simulation analysis. Therefore, this model is in line with the actual quantitative analysis of the evolution of Shanghai urban passenger transportation structure. It can be used for quantitative analyzing Shanghai passenger transportation structure in the long-term dynamic strategic research.

4. Conclusions

This paper proposed a system dynamics model of Shanghai passenger transportation structure in the methods and steps of system dynamics research. Using statistical methods to calibrate the parameters and validate the model. This model is practical in actual quantitative analysis of the evolution of Shanghai passenger transportation structure. The next step is to apply this model to simulate the dynamic development trend of Shanghai urban passenger transportation structure for long-term dynamic strategic quantitative analysis.

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