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RESEARCH PAPER

System Dynamics Model of Urban Transportation System and Its Application

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Abstract: Urban transportation system is a complex system with multiple variables and nonlinear feedback loops and influenced by transportation, social, economical, and environmental factors. Conventional transportation modeling approaches are unsuitable to simulate and evaluate its performance. This paper presents a system dynamics approach based on the cause-and-effect analysis and feedback loop structures. The proposed SD model comprises 7 submodels: population, economic development, number of vehicles, environmental influence, travel demand, transport supply, and traffic congestion. The model runs in Vensim PLE software using the data from Dalian, China. The coefficient of the intervention policy of vehicle ownership is chosen as the control variable for simulation, and the impacts of different policy scenarios on urban development and transportation system are analyzed. It suggests that Dalian should restrict the total number of vehicles to improve the sustainability of transportation system.

Key Words: urban transportation system; system dynamics; vehicle ownership: intervention policy; sustainability

1 Introduction

The sustainable development of urban transportation system is a key point to strike the resource-saving, environment-friendly, and people-oriented society. The conception of sustainable urban transportation comprises four aspects, namely, economic sustainability, environmental sustainability, social sustainability, and transportation sustainability.

The current research on sustainable urban transportation is mainly focused on the definition, evaluation, realizing way, and countermeasures in China[1,2]. However, urban transportation system is a complex system with multiple variables and feedback loops between subsystems and influencing factors. It is not appropriate to use the ordinary linear quantitative approach to describe the characteristics of this complex system. Therefore, system dynamics (SD) approach is used in this study to simulate the evolution of urban transportation system, specifically the impacts of vehicle ownership policy on urban transportation development in Dalian Central City as an example.

2 Overview of system dynamics

The SD was invented by Forrester from MIT in 1950s. The approach is based on the feedback control theory, equipped with computer simulation technology, and used in quantitative researches of complicated socioeconomics field[3]. The methods of SD are realized by involving feedback loops, variables, and equations. The feedback loop is defined as a closed chain of causes and effects. The variables include (i) level variable, the one that accumulates a flow over continuous time periods; (ii) rate variable, the one that represents a flow during a time period; (iii) auxiliary variable, the one that identifies rate variables. The three kinds of variables are linked by equations taking the form of integral, differential, or other types.

Because urban transportation system is much complex and covers a wide range, it is not suitable to use the traditional approaches to simulate and analyze. Therefore, the SD approach has been applied in complex system analysis. Forresterproposed the first SD model, which is used to simulate the urban system[4]. The SD approach is usually used in evaluating the performance of regional sustainable development[5], analyzing the relationship between transportation and land use[6], and estimating the environmental influences of industrial gardens[7]. The model proposed in this study is to simulate the urban transportation

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system and analyze the driving forces and external influences of the system.

The process of applying a SD approach can be divided into three phases: preliminary analysis, specified analysis, and comprehensive analysis[8]. In the preliminary analysis, with the understanding of the system characteristics deepened, it is necessary to identify the boundary of the system and define the internal and external variables, especially the feedback casual loops of the variables. In the specified analysis, based on the results of preliminary analysis, the system structure is constructed and coefficients and equations are specified to conduct a simulation process quantitatively. In the comprehensive analysis, the simulation results from different scenarios are estimated and compared, and relevant conclusions and policy suggestions are summarized. The flowchart of developing a SD model is shown in Fig. 1.

3 System dynamics modeling

3.1 System structure

As has been mentioned above, urban transportation system is a complex system influenced by economy, population, environment, and transportation sectors. The model of this system consists of seven submodels including population submodel, economy submodel, number of vehicles submodel, environment submodel, travel demand submodel, transport supply submodel, and traffic congestion submodel. Fig. 2 shows the relationships between submodels. In this figure, arrows denote the cause-and-effect relationships, plus and minus signs denote the positive and negative effects, respectively.

In this structure, the population submodel, economy submodel, and number of vehicles submodel play a fundamental role in quantitative analysis and have a great influence on the transportation system and the environment. The congestion submodel is the result of interaction between the transportation demand and supply submodels and feedbacks to economic development submodel. The environment submodel means the major constraint of the urban transportation development and affects the economy submodel and the population submodel.

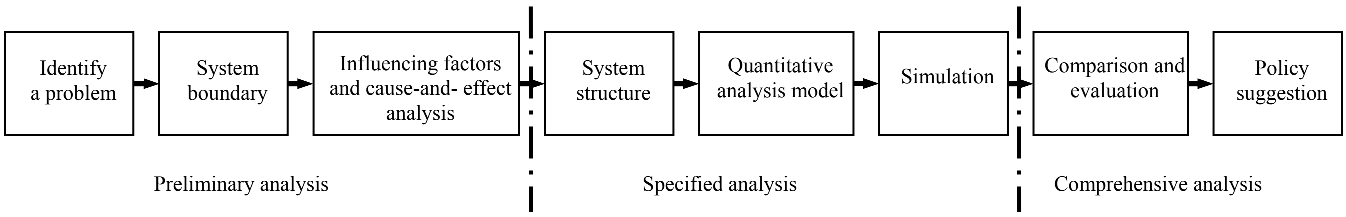

Fig. 1 Flowchart of system dynamics modeling

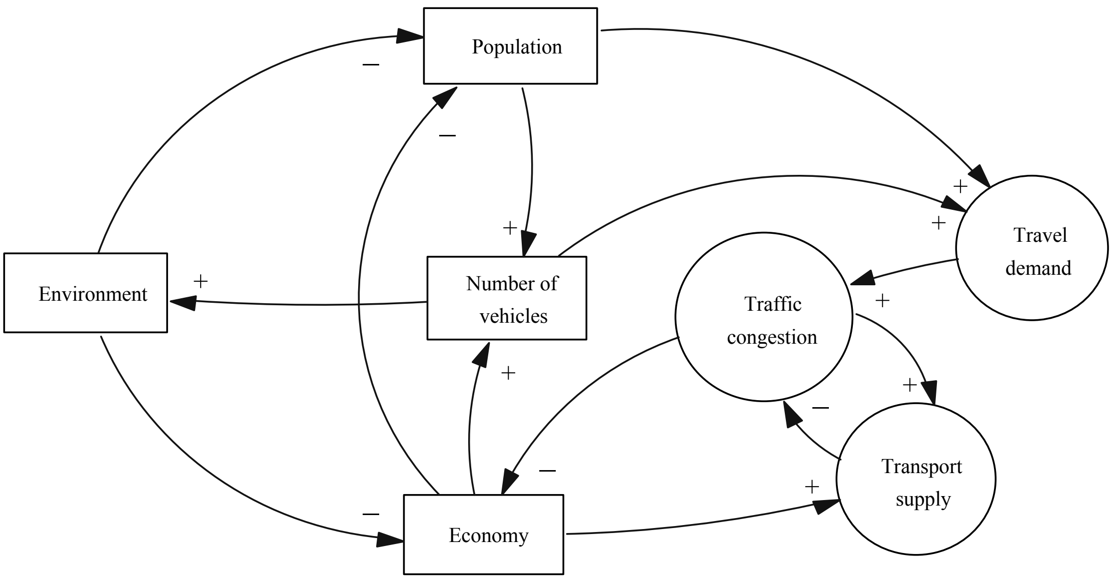

Fig. 2 Relationships among sub-models

3.2 Feedback loops

The main casual loops in this model are listed below:

Economy $\xrightarrow{+}$ Number of vehicles environment $\xrightarrow{-}$ Economy (negative)

Economic development generally urges the demand for mobility and private vehicles. The growth of vehicle ownership leads to an increase in air pollution. The deterioration of the environment has a negative effect on the speed and quality of economic development.

Economy $\xrightarrow{+}$ Number of vehicles $\xrightarrow{+}$ Travel demand $\xrightarrow{+}$ Traffic congestion $\xrightarrow{-}$ Economy (negative)

Economic development results in more vehicles and more demand for mobility. The increasing travel demand leads to more traffic congestion. Serious congestion discourages the motivation of economic activities and results in a decrease in gross domestic production, GDP.

Economy $\xrightarrow{+}$ Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Traffic Congestion $\xrightarrow{-}$ Economy (negative)

Economic development attracts more in-migration population. The growth population generates more travel demand and aggravates the traffic congestion. Serious congestion results in a decrease in economic development.

Economy $\xrightarrow{+}$ Number of Vehicles $\xrightarrow{+}$ Environment $\xrightarrow{-}$ Population $\xrightarrow{+}$ Travel Demand $\xrightarrow{+}$ Traffic Congestion $\xrightarrow{-}$ Economy (positive)

Because of the rapid development of economics, the total number of vehicles is increasing and the environment is deteriorating. The attractiveness of the city is lost due to the poor environment and the out-migration increases. The population may keep increasing in a short-term run unless the out-migration is more than the in-migration. Travel demand will continue to increase and traffic congestion level will get worse, having a negative impact on the economic development.

3.3 Flow chart of urban transportation system

On the basis of the above analysis, the flow chart of the urban transportation system is given below, with consideration of system characteristics.

3.4 Submodels

In this section, the variables are identified and relevant equations are established based on the feedbacks and cause-and-effect loops.

3.4.1 Population submodel

The population submodel reflects the developing stage of cities in this model. As people play a dominating role in the city life, the scale of population determines the scale of the city. The total transport demand is influenced by population size and so is the economic development. However, the environmental conditions especially air quality affect the population migration. The total population is chosen as the level variable and birth rate, death rate, and net migration rate as auxiliary variables. The net migration rate is influenced by GDP per capita and environmental quality, the function of which is acquired through correlation analysis.

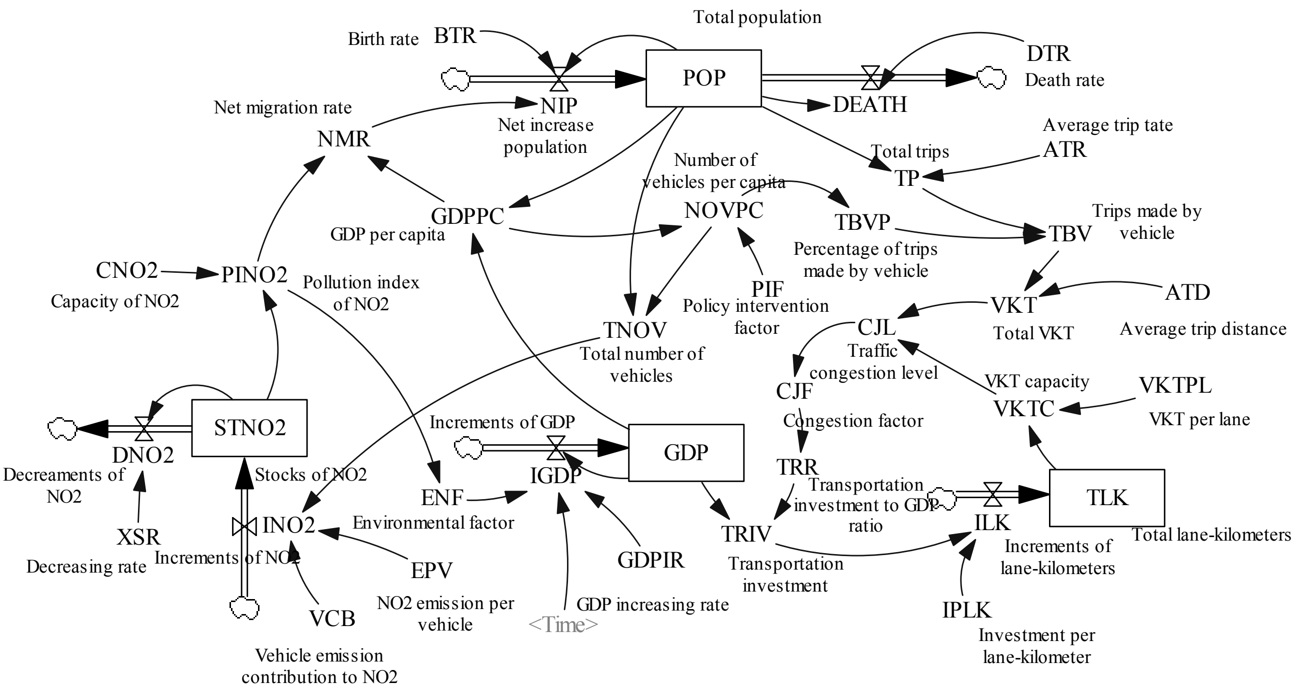

Fig. 3 Flow chart of urban transportation system

The equations of this submodel are listed below:

L POP.K=POP.J+KT*(NIP.JK–DEATH.JK) (1)

R NIP.JK=POP.J*(NMR.J+BTR) (2)

R DEATH.JK=POP.J*DTR (3)

A NMR.J=*f*(GDPPC.J, PINO2.J) (4)

3.4.2 Economy submodel

The economy submodel reflects the driving forces of the urban transportation development. The level of the economic development is one of the city competitiveness indicators and directly affects the in- and out- migration of people. It stimulates the ownership and utilization of private cars, leading to an increase in the number of vehicles. The economy is also related to transportation investment because government has to increase financial input on transportation infrastructures to maintain good traffic situations. GDP is chosen as a level variable, and annual increment of GDP as a rate variable, and annual increasing rate of GDP, transportation investment rate, and environmental factor as auxiliary variables. The environmental influencing index reflects the influences of environmental quality on GDP development. The equations of this submodel are as follows:

L GDP.K=GDP.J+IGDP.JK (5)

R IGDP.JK=GDP.J*GDPIR.J*ENF.J (6)

A TRIV.K=GDP.K*TRR.K (7)

The variables including annual increasing rate of GDP (GDPIR), transportation investment rate (TRR), and environmental factor (ENF) are estimated by the realistic data from the case city.

3.4.3 Submodel of vehicle ownership

The number of the vehicles submodel is the focus of this study because it is the core interest of the proposed model and related to all other submodels. The increase in the number of vehicles probably results from the development of the economy and transportation demand. However, the traffic congestion and air pollution caused by excessive use of vehicles will react to the economic development and population growth. The total number of vehicles, number of vehicles per capita, and policy intervention factor are chosen as auxiliary variables. The equations of this submodel are as follows:

A TNOV.K=GDP.J+IGDP.JK (8)

A GDPPC.K=GDP.K/POP.K (9)

There is a close relationship between the number of vehicles per capita and GDP per capita[9], and the quantitative relationship is described by the following equation:

A NOVPC.K=γ*EXP(β*EXP(α*GDPPC.K)) (10)

The values of coefficients α, β, and γ are estimated by correlation analysis of urban statistics data. It should be noted here that the number of vehicles per capita is directly related to the policy intervention factor. Therefore, we choose the policy intervention factor as the control variable to examine how intervention policies affect the ownership and utilization of vehicles. The policy intervention factor being incorporated, Eq. (10) takes the form of:

A NOVPC.K=PIF*γ*EXP(β*EXP(α*GDPPC.K)) (11)

3.4.4 Environmental influence submodel

The environmental requirements are the constraints of urban transportation development. The pollutants discharged by vehicles mainly include NO_x (usually NO_2 is used for equivalent), CO, CH, and inhalable particulate matter (IPM). According to the current research, more than 50% of NO_x is discharged by vehicles in large cities of China. Consequently, the emission of NO_2 is used to indicate the level of air pollution. The stocks of NO_2 is chosen as a level variable, the annual increment and decrease of NO_2 as rate variables, and NO_2 decreasing rate, the capacity of NO_2, pollution index of NO_2, annual NO_2 emissions per vehicle, and the environmental factor as auxiliary variables. The equations of this submodel are:

L STNO2.K=STNO2.J+INO2.JK–DNO2.JK (12)

R INO2.JK=TNOV.J*EPV.J*VCB.J (13)

R DNO2.JK=STNO2.J*XSR (14)

A PINO2.K=STNO2.K/CNO2 (15)

The environmental factor is a function of pollution index of NO_2, the form of which is estimated by correlation analysis process.

3.4.5 Transportation demand submodel

Transportation demand is a kind of derived needs and depends on the total urban population, the level of economic development, and so on. The auxiliary variables of this submodel comprise the total number of trips, the average trip rate, the percentage of trips by vehicles, vehicle trips, the average vehicle trip distance, and the total vehicle kilometers having traveled (VKT). The equations of this submodel are:

A TP.K=POP.K*ATR (16)

A TBV.K=TP.K*TBVP.K (17)

A VKT.K=TBV.K*ATD (18)

3.4.6 Transportation supply submodel

Transportation supply reflects the level of urban infrastructure construction and maintains a dynamic equilibrium with the transportation demand side. The level of the transportation supply depends on the investment in infrastructure construction and improvement. The total lane length is chosen as a level variable, the annual increment of the lane length as a rate variable, and the transportation investment, the percentage of transportation investment to GDP, the investment per lane, the VKT capacity per lane, and the total VKT capacity as auxiliary variables. The equations of this submodel are:

$$\text{A} \quad TRIV.K=GDP.K*TRR.K \tag{19}$$
$$\text{L} \quad TLK.K=TLK.J+ILK.JK \tag{20}$$
$$\text{R} \quad ILK.JK=TRIV.J*IPLK \tag{21}$$
$$\text{A} \quad VKTC.K=TLK.K*VKTPL \tag{22}$$

where the calculation of VKT capacity per lane quotes the statistics of the Department of Transportation in the US.

3.4.7 Traffic congestion submodel

Traffic congestion is the result of interaction between transportation demand and supply and is one of the constraints of the urban transportation system.

$$\text{A} \quad CJL.K=VKT.K/VKTC.K \tag{23}$$

4 Case study

The SD model proposed in this study is simulated on Vensim PLE, using the data from Dalian Central City. Dalian City is located in the east part of Liaoning Province, China and is a vice provincial city. Dalian Central City has a total area of 248 kilometers and a population of 1.92 million. The transport structure of Dalian City is dominant by public transport, which had a mode share of 48.96% in all transport modes according to the Personal Trip Survey conducted in 2004. Therefore, it is essential to study the impact of the intervention policy of vehicle ownership on the urban transportation development during the motorization process.

4.1 Parameter estimation

Because the proposed model is very complicated and too many variables are involved, it is crucial to determine the values of variables and coefficients. The estimation of variables and coefficients is made in the following three ways: (i) from statistics data; (ii) from published reports; and (iii) estimation using correlation analysis. The coefficient estimation results for Net Migration Rate (NMT), and Number of Vehicles per capita (NOVPC) are as follows. Other values of coefficients are listed in Table 1.

$$\text{A} \quad NMR.K=0.004435+0.003581*GDPPC.K -0.00564*PINO2.K \tag{24}$$
$$\text{L} \quad NOVPC.K=0.55904*EXP(-4.2324 *EXP(-0.35393*GDPPC.K)) \tag{25}$$

4.2 Model validation

To validate the proposed model, it is applied to simulate the year 2005 output using the time series data from the year 2000 to 2004. It appears unscientific that the validation is based on data from a single point, the year 2005. However, it is due to the difficulty in collecting useful and valid data. The output values of population, GDP, and number of vehicles are compared with the reported data, see Table 2.

Table 1 Values of parameters

Parameters	Value	Unit
Birth rate	0.004	–
Death rate	0.006	–
GDP increasing rate	0.12	–
Average trip rate	2.1	–
Average trip Distance	4.55	kilometer
VKT per lane	800	VKT
Investment per lane-kilometer	10	Million Yuan RMB
NO_x emission per vehicle	20	Kg/vehicle/year
Vehicle emission contribution to NO_x	0.5	–
NO_x decreasing rate	0.2	–
NO_x capacity	75.6	Thousand tons

Table 2 Comparison of model outputs with reported data

Index	Model output	Reported data	Error (%)
Population (million)	1.91669	1.9195	–0.15%
GDP (billion yuan)	34.1735	35.887	–4.77%
Number of vehicles	111402	116650	–4.50%

According to the results, the error terms of population, GDP, and number of vehicles are all less than 5%. It is effective enough to simulate the proposed model.

4.3 System simulation

As mentioned above, this study has focused on the effects of policy intervention on urban development and transportation system. The factor of policy intervention (PIF) has been chosen as the control variable to simulate the proposed model. In the current model, the running time set for the model is 50 years and starts from 2000. The time step for simulation is 1 year. There are five policy scenarios predefined for vehicle development: namely, emphasized encouragement, encouragement, strict restriction, restriction, and no intervention. The respective values of the corresponding control variables (PIF) are 1.5, 1.2, 0.5, 0.8, and 1.0. The results of the number of vehicles, GDP, population, and environment are shown in Figs. 4–7.

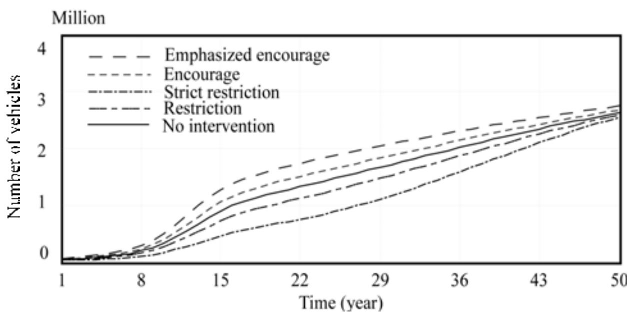

Fig. 4 Effect of policy intervention on number of vehicles

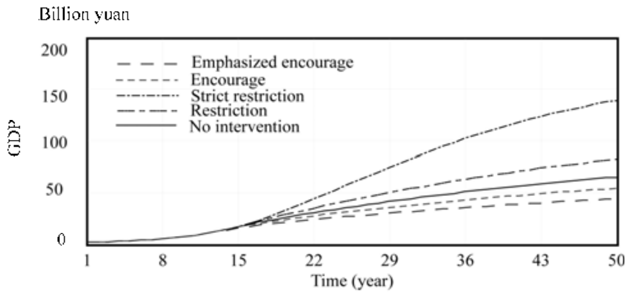

Fig. 5 Effect of policy intervention on GDP

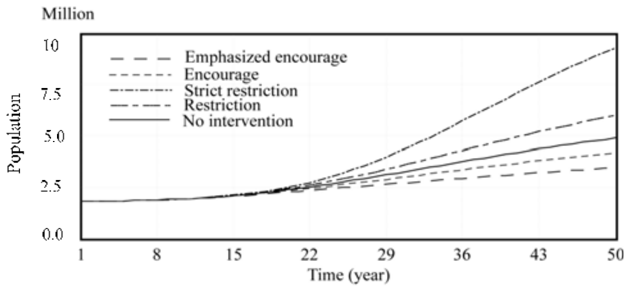

Fig. 6 Effect of policy intervention on population

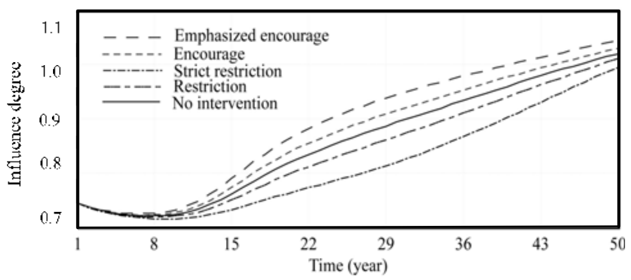

Fig. 7 Effect of policy intervention on environment

As shown in Fig. 4, the number of vehicles increases as an "S curve" during the time period. However, the factor of policy intervention plays an important role in the vehicle development process. The distinguishing effect is that the curve varies slowly as the policy intervention changes from encouragement to restriction. For example, the number of vehicles increases fast in the beginning 20 years and then slows down under the emphasized encouraging policy, whereas under the strict restriction policy, it grows slowly at first and speeds up in 30 years.

The effect of vehicle policy intervention on GDP becomes distinct as time passes. GDP grows much faster under the strict restriction policy than under other policy scenarios. The best way to restrict the ownership and use of vehicles is to improve the service level of public transport. Given that the mode share of public transport in Dalian has been up to 50%, there might not be much space left.

The policy effect on population is in the same way as GDP. The strict restriction on vehicles makes people shift from private vehicles to public transport. Consequently, the urban density increases rapidly, and it is not sure whether it is good or not for urban development.

Air pollution is closely linked with vehicle emissions. To reduce the negative impact on environment and urban development, it is advisable to take the restriction policy on vehicle ownership.

4.4 Results and suggestions

According to the analysis above, it is appropriate to take flexible restriction policy on vehicle development so that the development of GDP and population will be increasing reasonably, and the environment problems will not become serious in a short-term run. Otherwise, the balance of transportation, population, economy, and environment will be destroyed.

The suggestions to the policy on vehicles include three aspects: (i) restrict the ownership and use of vehicles in an acceptable way; (ii) restrict private vehicles and simultaneously improve the service level of public transport; (iii) implement the restriction policy and simultaneously put emphasis on the research and development of emission-reducing technologies.

5 Conclusions

This study is an attempt in using the SD approach to model the urban transportation system. The proposed model considers Dalian City for case study to examine the effects of vehicle policy intervention on urban development and population, GDP, and environment aspects.

However, this study is still preliminary and has its limitations. Further study will be pursued in three directions. First, the model should be more accurate by in-depth selection of variables and parameters. Second, the model should incorporate other related aspects, i.e. energy. Third, the policy scenarios should be more realistic and easier to implement.

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