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System Dynamics Simulation Based Analysis of Effect of Some External Conditions on Development of Natural Gas Vehicles

Xuesong Guo and Zhiping Yuan
School of Management, Xi'an Jiaotong University, 710049, China

Abstract: Auto-station system composed of natural gas vehicles and gas service stations was studied in the research according to the method of system analysis. System dynamics model is developed based on economic relationship between interrelated objects in the model. Principles of effects of policies of price of natural gas to the system and gas service station construction layout modes selected by government to auto-station system are derived from the scenarios generated by system simulation of the system in the future under different external possible conditions. It's proved that government should depend on future information rather than current information in the actual process that layout is worked out by scientific and reasonable forecast.

Key words: Natural gas vehicles, gas service station, system dynamics, simulation

INTRODUCTION

In the past 20 years, compressed natural gas and liquefied petroleum gas etc have been taking the place traditional fuel and playing more and more important roles to settle the pollution problem in Chinese cities, with the index of air pollution descending 60~80%. In recent years, with the rapid progress and improvement of the traffic condition in Chinese cities, gasoline-fueled automobile has become the main factor causing the rapid ascending of the index of air pollution. The government sectors such as National Planning Council and Ministry of Science and Technology, attach importance to the problem and take the scale development of clean fueled automobiles as focal points in the guidance of present prior developing high-tech industries and major fields, among which gas service station is one of the key technologies. How to accelerate the development of popularization work of Natural Gas Vehicle (NGV) is one of the critical problems faced by government. The researchers analyzed the problems from the point-view of economy, policy[1-3] and technology[4-6], etc. But further research in the interactive development from the view of systems engineering and modern IE should be done.

The systems analysis of the question is to be accomplished in the study with System Dynamics theory and method employed.

Because taxicabs play important roles in industry of transportation in cities of China and affect the environment more greatly, taxicab is the main object studied and NGV represents taxicab in the study.

Review of system dynamics: System Dynamics is a science studying information feedback system. It extracts valuable knowledge from theories on control and information. According to the theory, principle and methodology of System Dynamics, questions on system can be analyzed by System Dynamics model with technology of computer simulation employed.

System Dynamics is a laboratory for actual system. More abundant information can be gotten from the results of simulation. The process solving the question is an optimizing process in essence with the final aim to seek better function of the system. One of the significant merits of System Dynamics is good at solving high order, non-linear, stochastic and highly complex questions.

System Dynamics is used to analyze and program behaviors of complex social and economic system in the future.

System Dynamics was founded by Professor Jay. W. Forrester in 1956. In the late of 1950s, System Dynamics began to become a new field in science. In the initial period, it was used to study the questions on management of industrial enterprise, fluctuation of production and employees etc. Having been developed for 15 years, System Dynamics began to be a mature science.

In early of 1970s, the club of Rome was confused by the perspectives of population and problems in resources. Because the tools at that time can't be used to analyze such a complicate question, they turned to the method of System Dynamics and developed World Dynamics Model, with which Population, resources, industry,

Corresponding Author: Xuesong Guo, School of Management, Xi'an Jiaotong University, 710049, China

agriculture, pollution etc and the relationships between them were studied.

After that, a System Dynamics Model composed of about 4,000 equations on the whole America was developed. The economic and social problems in America were taken a whole to be studied and some questions existing in the field of economy having confused economists for a long time were opened out with the model employed[7]. The most valuable production is opening out the internal mechanism of the phenomenon of Long Wave[8], which indicates System Dynamics has get to a more mature level. And lots of economic problems were studied with system dynamics employed[9,10] at the same time.

In 1990s, System Dynamics began to be used more and more widely. System dynamics was applied in the fields of National Model, problems on resources, environments and evolution of city. On the other hand, theories on enterprise management and learning organization[11] have been developed with System Dynamics employed. Simultaneously, theories, methods and tools, such as basic models of System Dynamics, integration of System Dynamics and other mathematics methods, DSS and powerful simulation software etc, have been being developed durably.

SYSTEM ESTABLISHMENT

Because the aim of the system analysis is to explore the internal mechanism of development of NGVs and gas service stations so as to put forward decision support to government, the viewpoint of government is required to make the system definition. The government changes the environments of the system to affect the operation of system and accelerate the interactive development of NGVs and gas service stations. External conditions include the situation of resources, the development of city and policies of government and the effect to the quality of air is one of the important outputs of the system (Fig. 1).

DEVELOPMENT OF SYSTEM DYNAMICS MODEL

Economic analysis: As we have known, economic relationship is the main factor harmonizing the behaviors of objects in a market system. In terms of the auto-station system, the behaviors of the objects including the operators of taxicabs and gas service stations are harmonized by economic relationship. So, in order to explore the behaviors of the objects in the system studied in the study, the economic relationship between them must be studied firstly.

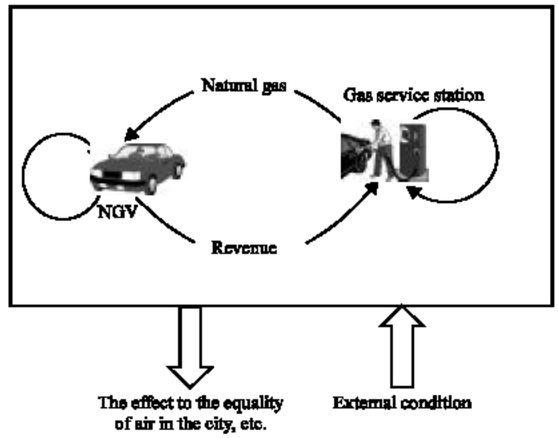

Fig. 1: Figure of system definition

Economic analysis of behaviors of the operators of taxicabs: One of the main behaviors of the operators of taxicabs is the choice between NGV and gasoline-fueled automobile. Because an operator of taxicab is an individual object with the target to make profit maximized, the operators of taxicabs will choose the automobiles being able to make more profit.

Here, some variables are defined to describe the factors affecting the choice of the operators of taxicabs.

C_1: The expense to buy a gasoline-fueled automobile;
C_2: The expense to buy a NGV;
L_1: The time for which a gasoline-fueled automobile can be used in the industry of taxicab;
L_2: The time for which a NGV can be used in the industry of taxicab;
S: Mileage of a taxicab running in a year;
V_{11}: Amount of gasoline consumed by a gasoline-fueled automobile in a year;
V_{12}: Amount of gasoline consumed by a NGV every hundred kilometers;
V_{22} Amount of natural gas consumed by a NGV;
P_1: Price of gasoline;
P_2: Price of natural gas ;
C_0: Other daily payouts of an operator of taxicab in a year;
Gra: The expected probability denoting a NGV runs in natural gas consumed state derived from RoSD.
RoSD: The ratio of the supply and demand of the natural gas.

$$\begin{aligned}\text{RoSD} &= \text{IF THEN ELSE (SoG}\\ &= 0{,}0\text{, IF THEN ELSE (DfG}\\ &\qquad = 0, \tfrac{1}{\text{Eof}}, \tfrac{\text{SoG}}{\text{DfG}}\text{))}\end{aligned} \tag{1}$$

$$\text{Gra} = \begin{cases} 1, & \text{RoSD} \times \text{Eof} \geq 1 \\ \text{RoSD} \times \text{Eof}, & 0 \leq \text{RoSD} \times \text{Eof} \end{cases} \quad (2)$$

Eof is an effect coefficient, where $0 < \text{Eof} \leq 1$.

$$C_{10} = \frac{C_1}{L_1} + S \times V_{11} \times P_1 + C_0 \quad (3)$$

$$C_{20} = \frac{C_2}{L_2} + (1 - \text{Gra}) \times S \times V_{12} \times P_1 + \text{Gra} \times S \times V_{22} \times P_2 + C_0 \quad (4)$$

Since the revenue of a NGV equals to a gasoline-fueled automobile in taxicab operation industry because the passengers don't care about what fuel the taxicab uses, operation cost should be taken into account as the most important factor. The economic condition inducing the operators of taxicabs to choose NGV can be deduced to the following in Eq. 5.

$$C_{10} > C_{20} \quad (5)$$

Economic analysis of gas service station construction: As individual operation entities directed by layout of government, the operators of gas service stations have to take profit into account as the most important factor just like operators of taxicabs. In Chinese cities, a gas service station can't be constructed without the license from the sectors of government. On the other hand, an operator can't invest to any new gas service station unless the expected profit of the new station is more than a certain level, which is assumed to 0 in the study. So, increment of the gas service stations must satisfy the conditions aforementioned on all accounts. Hence, we can introduce some variables to denote related factors affecting construction of the gas service station.

Q: Average amount of natural gas sold by a gas service station per year;
P_c: Price of natural gas paid by gas service station to natural gas company;
C_s: Daily operational cost of gas service station per year;

Then the expected profit of gas service station R can be represented by the following equation

$$R = Q \times (P_2 - P_c) - C_s \quad (6)$$

Besides the factor of expected profit, the other important factor affecting the gas service station construction is layout of government represented by the number licenses provided to investors of gas service station. Here, we assume that if $R > 0$, the increment of gas service station is equal to the layout of government in current year. Otherwise, if $R \leq 0$, the increment of gas service stations is 0 because investors will not invest to the gas service station, even if they can get enough licenses from government.

Let NP be the amount of gas service stations needed in the city, which is estimated by government; let N be the current amount of gas service stations. So, if $NP \leq N$ or $R \leq 0$, the increment of gas service stations is 0; if $NP \leq N$ and $R \leq 0$, the increment is $NP \leq N$.

The increment of gas service station GR can be represented as follows

$$GR = \text{CLIP}(0,1,N,NP) \times \text{CLIP}(0,1,0,R) \times (NP - N) \quad (7)$$

Where, CLIP is a function defined in DYNAMO.

The analysis of causal relation of the system: A Fig. 2 on causal relationship based on economic relationship can be drawn with analysis and it is shown in Fig. 2 with some possible policies incorporated.

Establishment of the system dynamics model: The auto-station system can be divided into 2 subsystems. One is the subsystem of NGV development and the other one is the subsystem of gas service station construction. The 2 subsystems make up the auto-station system being of the character of interactive development of the NGVs and gas service stations with a positive feedback loop shown in Fig. 2. That is, with the increment of the NCV, the demand for natural gas improves and the profit of the gas service station will improve accordingly. On the other hand, with the improvement of the profit of gas service stations, the amount of gas service stations will improve and the number of NGVs will be improved accordingly because of being able to make more profit by having more chances to get cheaper natural gas fuel.

Every taxicab has a certain life cycle, which is represented by fixed number of year regulated by government in Chinese cities, because the sectors of government play an important role in industrial regulation. Now, in the city of Xi'an, the life cycle is 8 years for traditional gasoline fueled automobiles in taxicab industry. So, in order to describe the amount of taxicabs in different life stages, the SD structure shown in Fig. 3 should be applied in the simulation model developed in the study, where level denotes the amount of taxicabs in a certain life stage, rate denotes the transformation rate of taxicabs between different life stages.

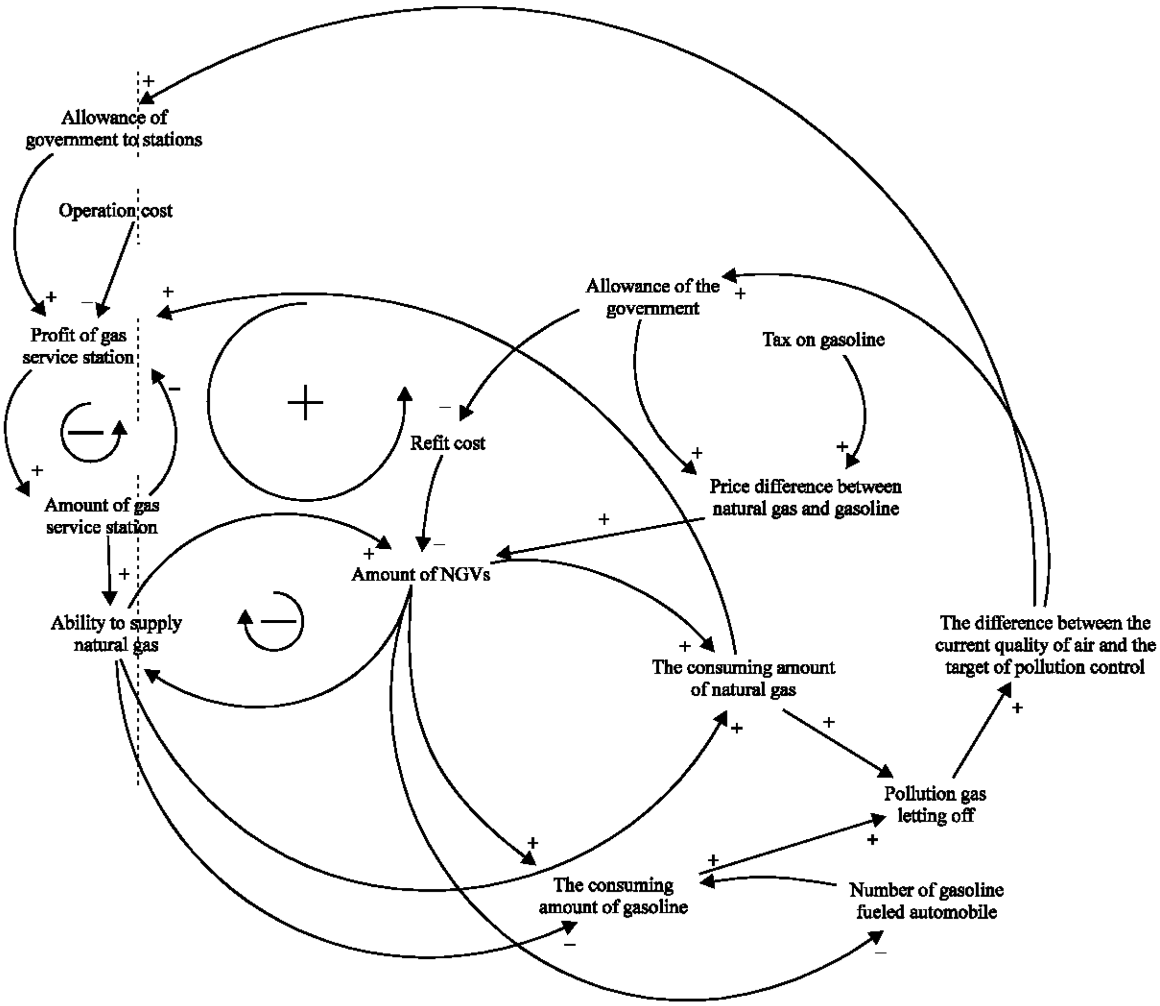

Fig. 2: Causal relation figure of auto-station system

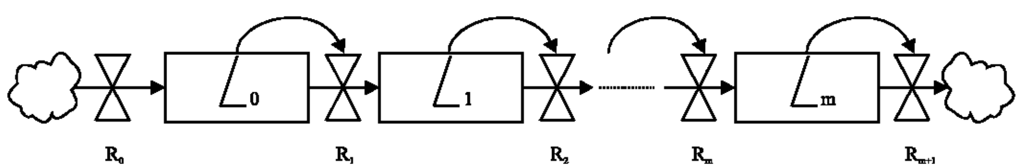

Fig. 3: System dynamics structure describing life cycle

The main equations are as follows, where, L_i denotes the amount of taxicabs which have being used for i years.

$$L_i = \text{INTEG}\,(R_i - R_{i+1}, \text{In}L_i) \quad (8)$$

$$R_{i+1} = L_i \quad (9)$$

where, i = 0,1,2,...,m and INTEG( ) is the function denoting a level in Vensim

Hence, the two kinds of taxicabs can be represented with two structures shown in Fig. 3 and the structure describing choice behavior of operators of taxicabs is shown in Fig. 4.

Where, K_i denotes the amount of gasoline-fueled vehicles which have being used for i years and K_{ia} denotes the amount of NGVs which have being used for i years. C_{10} and C_{20} denote the operation cost of NGVs and gasoline-fueled vehicles, respectively. The module denoting the choice of taxicabs shown in Fig. 4 is called Taxicab Choice Module.

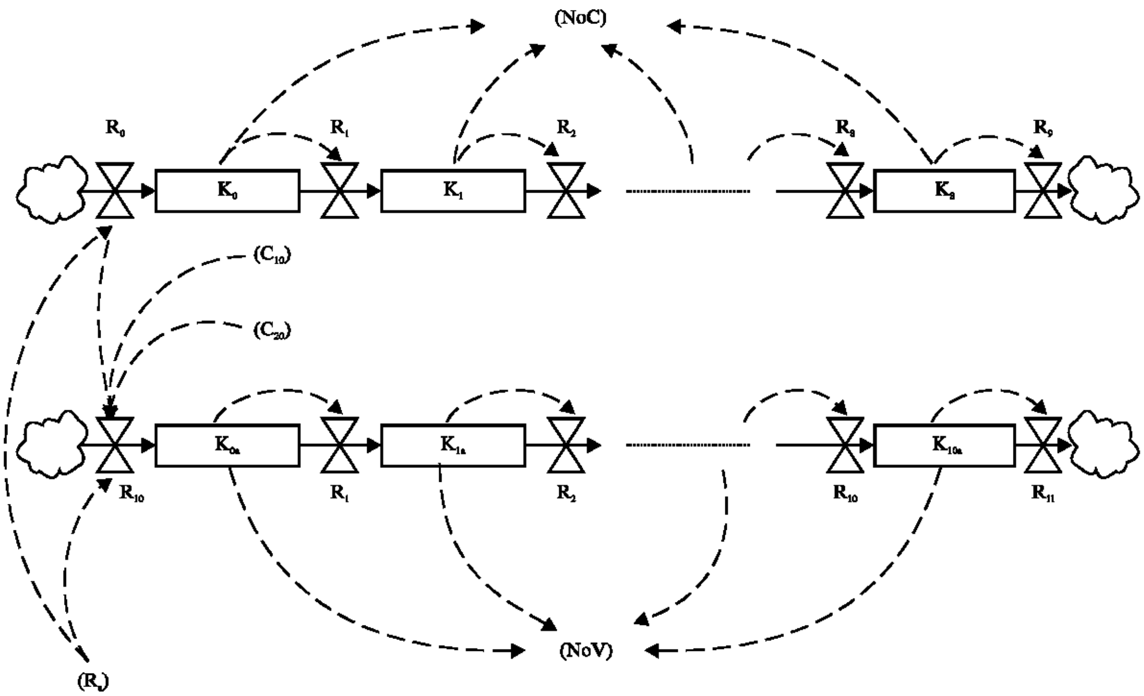

Fig. 4: Structure describing choice behavior of operators of taxicabsv

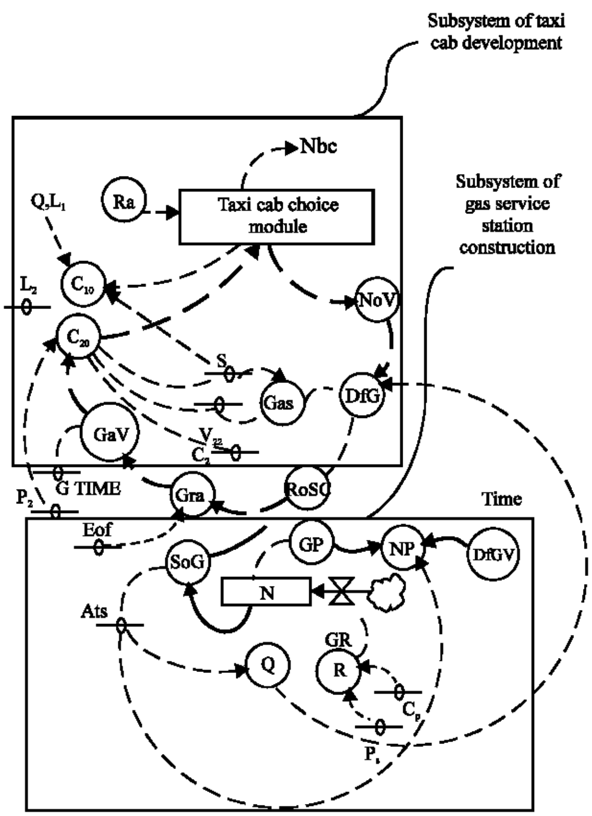

Fig. 5: The simplified flow figure of the model

Main equations are as shown as follows:

$$R_{10} = \text{IF THEN ELSE } (C_{20} < C_{10}, R_a, 0) \quad (10)$$

$$R_0 = R_a - R_{10} \quad (11)$$

$$NoC = K_0 + K_1 + K_2 + K_3 + K_4 + K_5 + K_6 + K_7 + K_8 \quad (12)$$

$$NoV = K_{0a} + K_{1a} + K_{2a} + K_{3a} + K_{4a} + K_{5a} + K_{6a} + K_{7a} + K_{8a} + K_{9a} + K_{10a} \quad (13)$$

The complete system dynamics model can be established based on analysis aforementioned. And the simplified flow figure is shown in Fig. 5.

EFFECTS ANALYSIS

Evaluation index of the system: In order to evaluate the performance of the auto-station system and the effects of policies of government, some indexes should be put forward.

An important aim of NGV development is to take the place of traditional gasoline fuel with clean gas fuel. In terms of auto-station system, it mainly reduces urban pollution percentage of the automobiles. On the other hand, in a market system, in order to accomplish the development of the system in harmony, it is necessary to make the supply and demand of natural gas maintain equilibrium; otherwise the system will not last because the operators of NGV or gas service station can't get essential profit.

Because targets of the system can be divided into environmental target and economic target, the system of the indexes should reflect both of the two aspects aforementioned.

According to the targets aforementioned, two indexes are to be put forward to evaluate the targets of auto-station system.

Index of Clean Fuel (short for ICF) is used to evaluate environmental target

$$ICF = \frac{NoV \times Gra}{NoV + NoC} \qquad (14)$$

where, ICF, NoV, NoC and Gra are Index of Clean Fuel, the number of NGVs, the number of Gasoline-fueled Vehicles and the probability that the NGVs can get natural gas respectively. The range of the index is from 0 to 1, when it is 1, we can confirm that the taxicabs are all NGVs and they are all of the state of natural gas.

Index of ratio of supply and demand of natural gas RoSD has been described in Eq.1.

In the study, evaluation of the system is accomplished by analysis of the results of simulation. So, the values of indexes are to be derived from the value of the output of the simulation.

Analysis of effects of price of natural gas: In a market system, price is one of the important factors affecting the system. In terms of the auto-station system studied in the research, the price of natural gas plays an important role in harmonizing the objects including operators of NGVs and gas service stations. That is, if the price of natural gas rises, the profit of gas service station will rise accordingly and that of NGV will be reduced; if the price of natural gas is reduced, the objects in the system will be affected on the contrary. So, harmonization policies can't be established correctly unless the principles on variety of the behavior of the system under different scenarios of price of natural gas are mastered. The simulation on the behavior of the system under different conditions is accomplished in this section with some conclusions drawn.

The values of variables are shown in Table 1 and the initial amount of gasoline taxicabs is shown in Table 2.

It's assumed that there are 3 gas service stations in the system at Time 0.

We assume that the upper limit amount of taxicabs that the city can accommodate is 20,000.

The time of simulation is set 20 years. The behavior of the number of taxicabs and T index are shown in Fig. 6.

If the price of natural gas is reduced to 0.8, the results are shown in the following Fig. 7.

Table 1: Value of variables in the model[12]

Variable	Value	Variable	Value
P_1	2.6 RMB Yuan/kg	Ats	$2.16\times10^4 m^3$/Year
P_2	1.5RMB Yuan/m^3	C_2	1.0×10^5RMB Yuan
S	6.0×10^2 100 Km/Year	V_{11}	20 kg/100 Km
V_{12}	21kg/100 Km	Eof	0.8
V_{22}	24m^3/100 Km	C_s	5.0×10^4RMB Yuan
P_c	0.65RMB Yuan/m^3	C_1	9.0×10^4RMB Yuan

Table 2: The initial amount of gasoline taxicabs

	0	1	2	3	4	5	6	7	8
K_i	1.800	1.748	1.697	1.648	1.600	3.432	1.019	0.270	0.500
K_{ia}	0	0	0	0	0	0	0	0	0

Table 3: Table of values of ICF with different extent of increment of the price of natural gas

Extent of increment	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
ICF	0.51	0.54	0.54	0.54	0.54	0.54	0.54	0.54

In order to evaluate the performance under the situation of fluctuate of price, the noise function is introduced to the price P_2

$$P_2 = 0.8 + \text{RANDOM NORMAL} (-0.8, 0.8, 0, \delta, 0) \qquad (14)$$

where, δ is the standard deviation of the noise function and denotes the degree that the price of natural gas fluctuates. The value of ICF auto-station system when δ equals different values is shown in Fig. 8.

On the other hand, the duration that the price remains at a certain level is another factor, affecting the performance of the system. How does the different time the policy executed affect the system is one of the important problems, where

$$P = (1 - \text{PLUSE} (0, \alpha, \delta\times0.7+0.8)) \qquad (15)$$

The Eq. 2 denotes that the price of natural gas remains 0.8 from 0 to the αth year and then come back to 1.5, the results are shown in Fig. 9.

Analysis of the impact of the layout modes of government on the system: Through the simulation in 5.2, we can notice that the ICF reaches only about 0.51 finally (Fig. 7-9), which suggests that there is a large space to improve the index ICF. To improve the value of Gra is a feasible way to improve the value of ICF. In order to improve the value of Gra, the number of gas service stations should be increased. The increment of gas service station can be accomplished by either providing more licenses or improve the price of natural gas according to Eq. 6 and 7. Now, the values of ICF with different extent of increment of the price of natural gas are shown in the Table 3.

Table 4: Scenarios of the system in the future with m is evaluated different values

m	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
ICF	0.51	0.51	0.51	0.51	0.51	0.53	0.51	0.51	0.51	0.51	0.51
RoSD	0.64	0.64	0.64	0.64	0.64	0.66	0.64	0.64	0.64	0.64	0.64

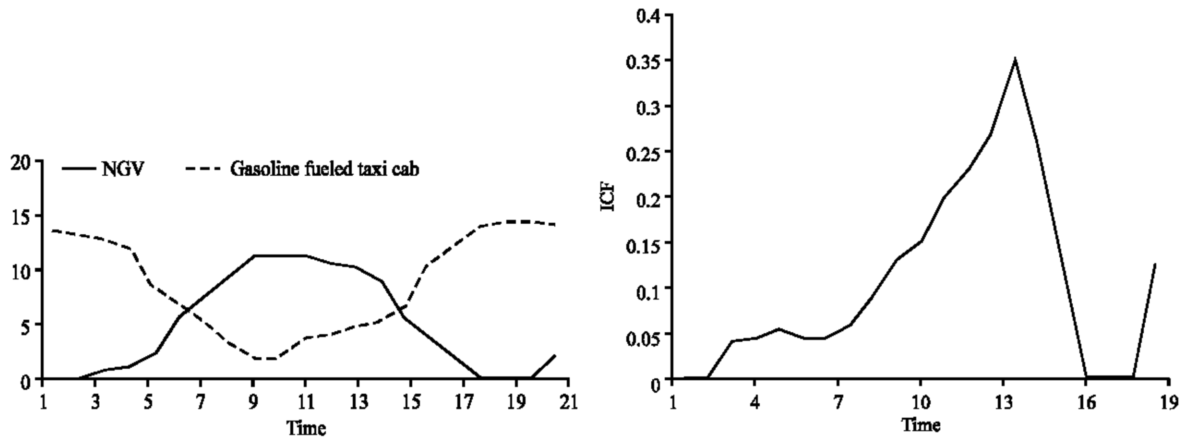

Fig. 6: The behavior of the No. of NGV, No. of taxi and ICF

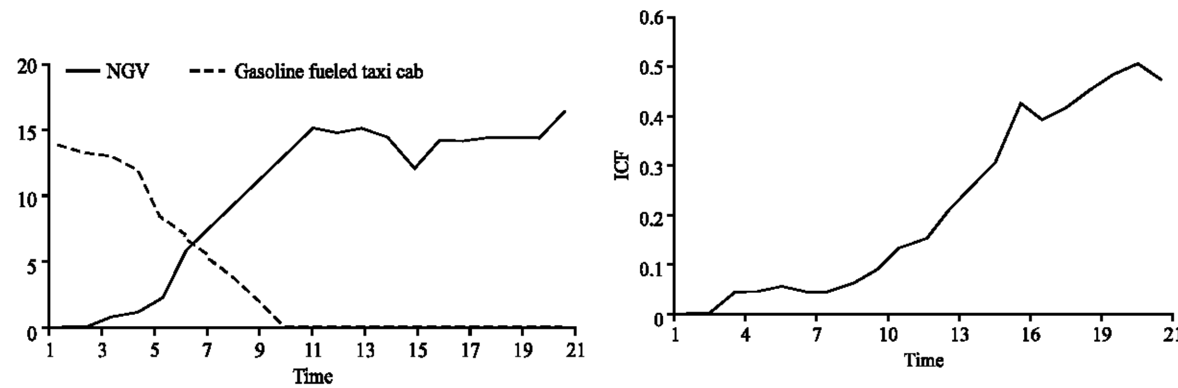

Fig. 7: The behavior of the No. of NGV, No. of taxi and ICF

The result of simulation illustrates the impact is not evident enough. Because in the SD model, government determines the increment of gas service station when the expected profit of gas service station is more than 0. Hence, to increase the licenses for gas service station construction is another feasible method.

The decision of government is a complicate process. If the number of licenses is more than actual requirement, the profit of the gas service stations will be reduced. So, the problem on decision mode selection is one of the key problems faced by government in system optimization.

Government makes decisions on gas service station construction with the information from current system. Equation 17 is modified to the following Eq.16 to represent the increment licenses of government based on current information.

$$GR = \text{Integer}(\text{CLIP}(0, 1, N, NP) \times \text{CLIP}(0, 1, 0, R) \times (NP-N) \times (1+m)) \quad (16)$$

Where, m denotes ratio of increment extent.

The scenarios of the system in the future with m is evaluated different values will be generated with simulation model employed, which are shown in Table 4.

It can be concluded that the supply of natural gas is less than demand for natural gas under the decision mode in initial development stage though m reaches 1 finally.

The decision modes selected by government can be divided into 2 modes according different types information depended on by government, that is, decision based on current information having been studied and decision based on future information.

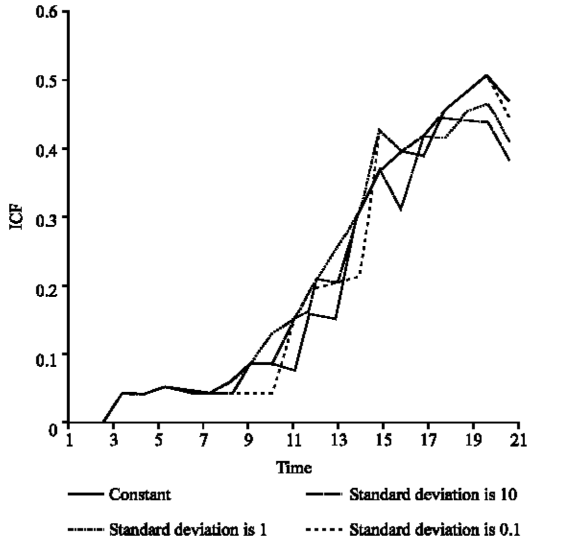

Fig. 8: The value of ICF when δ equals different values

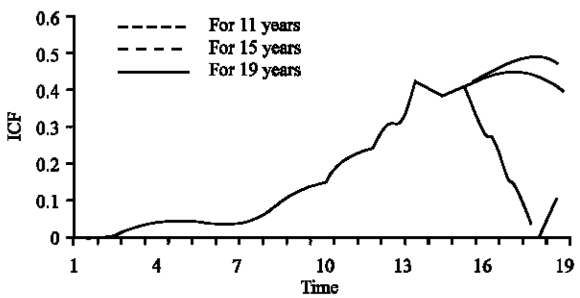

Fig. 9: Behavior of ICF for different duration of policy

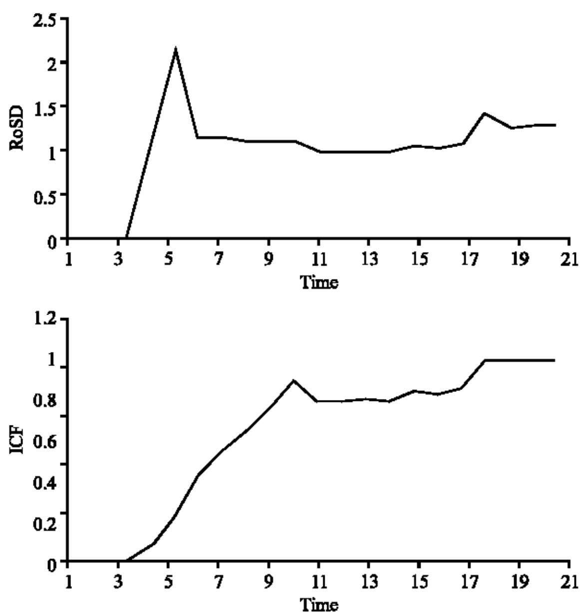

Fig. 10: Behavior of RoSD and ICF

It's assumed that government can work out the increment of the demand for gas service stations exactly, though it's impossible in actual system. Then government can make out the layout based on future information.

In order to simulate the impact of the decision mode based on future information, the structure of the SD model should be modified. The number of the gas service stations to be constructed in the next year is determined by government based on future incomplete information. In the model, the future information on demand for gas service stations is stored in function LooKup ( ). of Vensim.

The tendencies of RoSD and ICF are perfect enough to the system when the layout based on future information is implemented. The complete future information can't be gotten exactly actually, but the results of simulation shown in Fig. 10 suggest that government should take emphasis on the work of forecast and depend more on future information worked out by scientific and reasonable forecast rather than increase the number licenses of gas service stations simply.

CONCLUSIONS

The system dynamics model is established in the study with the system analysis method employed. With the data and actual condition in Xi'an, the popularization policies and the effect of the variety of price of natural gas to the behavior of system etc are analyzed with the method of simulation employed. The results of simulation show effects of different variety of price of natural gas on the system and suggest that government should take emphasis on the work of forecast and depend more on future information worked out by scientific and reasonable forecast rather than increase the number licenses of gas service stations simply. But in fact, the number of licenses is not only determined by the desirability of the government, but also the actual restriction conditions. The conditions include the information depended by government which has been analyzed in the study and the layout of gas service station construction. How to make more gas service stations constructed with scientific programming is one of the key questions to be studied in the future.

There are other external conditions affecting the system such as price of gasoline, Price of natural gas paid by gas service station to Natural Gas Company etc. Because they affect behavior of auto-station system by affecting only one factor I n the system, it's easy for researchers to understand their effects on the system and they are not analyzed in detail in the study.

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