

## Research Article

# The Traffic Congestion Charging Fee Management Model Based on the System Dynamics Approach

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Received 19 September 2016; Accepted 13 November 2016; Published 15 January 2017

Academic Editor: Nicolas Hudon

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In recent years, the condition of urban traffic congestion in China has become more and more aggravated. Thus, from the social and environmental perspective, this paper has proposed a traffic congestion charging fee (TCCF) management model based on the system dynamics approach, taking Shanghai as a case study. The system dynamics approach applied in this paper focuses on the dynamic interrelations among some major variables in the TCCF management model. Hence, through a detailed discussion on these major variables, which are amount of car trips (ACT), growth of cars (GC), amount of NO<sub>x</sub> generation (ANG), attraction degree of car trips (ADCT), per vehicle area of roads (PVAR), and degree of traffic congestion (DTC), it is discovered that, when TCCF equals 45 yuan/day \* vehicle, the DTC has declined by 67.84% and the ANG by 33.09%, which is a relatively satisfying solution to the traffic congestion problem.

## 1. Introduction

The urban traffic problem (e.g., congestion, exhaust emission, and safety) has become more and more serious. It now has gained world-wide concern. The traffic congestion not only brings bad effect on the traffic safety and causes traffic delays but also leads to severe air pollution. It exerts large adverse impact on human health [1, 2].

Traffic emission is the main source of air pollution in urban areas. NO<sub>x</sub> is the major components in traffic emission as well as PM<sub>2.5</sub> (PM with aerodynamic diameters of 2.5 μm or less) that induces immune-system problems, respiratory and lung disease [3, 4]. The urban traffic congestion frequently occurred in the densely populated regions such as Beijing, Shanghai, Guangzhou, and Wuhan. In particular, the continually increasing motor vehicles have become a significant contributor to the NO<sub>x</sub> emission in these areas [5–7], and the rapid increase of motor vehicles emission in Shanghai has become a more and more important source for the formation of the severe haze [8]. The car ownership has increased rapidly in Shanghai and more than doubled

between 2002 and 2007, reaching its peak in 2011 [9]. In addition, the regional transport had large impacts on the characterization of air pollution (PM<sub>2.5</sub>) in Shanghai from 2011 to 2013 [10, 11]. In the source of PM<sub>2.5</sub> in Huaniao Island (~66 km to Shanghai), the contribution of motor vehicle is ~27% [12]. Hence, the urban traffic congestion is becoming a hot topic and an urgent task in many areas such as Shanghai.

In the past few years, many researchers have established various traffic flow models and obtained some important results [13–16]. Armah et al. (2010) explored the traffic congestion and air pollution link in the city of Accra by the use of systems dynamics [17]. Zhang et al. (2012) studied the traffic congestion evaluation and signal control optimization based on wireless sensor networks and presented a model and algorithms for traffic flow data monitoring [18]. It is helpful to alleviate the urban traffic. Wang et al. (2014) studied the urban traffic congestion pricing model with the consideration of carbon emissions cost and put forward suitable proposals for the implementation of an urban traffic congestion pricing policy in China [19]. Ma and He (2016) researched the effects of the post-Olympics driving restrictions on air quality in

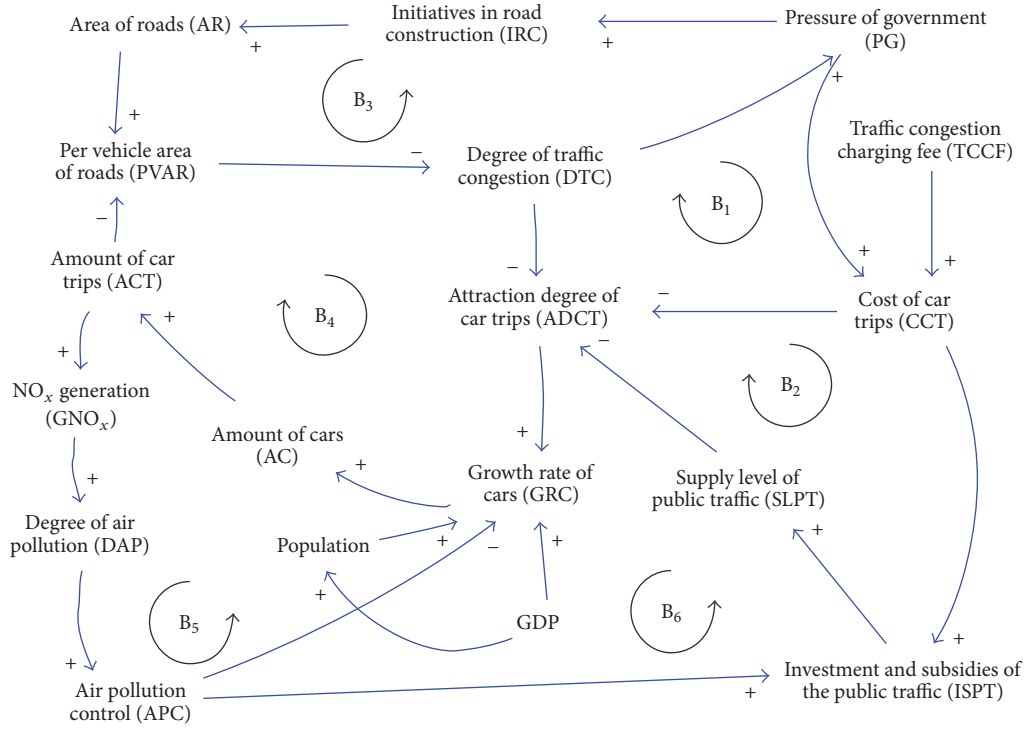


FIGURE 1: The causal-loop diagram of TCCF management model.

Beijing and had implemented a license plate-based traffic control measure, in order to reduce congestion and air pollution [20]. Mei et al. (2012) studied the combination of a guiding parking reliability model and parking choice behavior offering potential for parking guidance and information systems operators, in order to reduce the traffic congestion in central city areas [21]. Sabounchi et al. (2014) set up a dynamic simulation model based on congestion pricing scheme [22], while some scholars adopt the congestion pricing policy and study the traffic congestion problems [23–26].

However, there has been relatively little study on the urban traffic congestion management strategy in system dynamics. To this end, the TCCF management model has been put forward by using system dynamics. A relatively satisfactory solution was found through simulation and policy analysis. The simulation results not only alleviate traffic congestion but also help to reduce the haze pollution.

## 2. Methods

**2.1. System Dynamics Methods.** System dynamics (SD) is a modeling and simulation approach for better understanding the complex system and analyzing its dynamic behavior [27]. The structure of a system in SD is described by causal-loop diagrams [28]; hence, it provides a tool to test the effects of various strategies and policies in a system [29]. The results caused by change of schemes are automatically listed as graphs by the software Vensim® [30].

**2.2. The Causal-Loop Diagram.** Six causal-loop diagrams are delineated and analyzed in Figure 1. In this causal-loop

diagram, the plus sign “+” means that the arrow-tail variable can increase the result to the arrow-head variable while the “-” symbol indicates an inverse relationship. The positive feedback loops would reinforce itself through its positive chain. On the contrary, the negative feedback loops would be relieved.

- (i) *Loop B<sub>1</sub>*. Degree of traffic congestion (DTC)  $\overset{+}{\rightarrow}$  pressure of government (PG)  $\overset{+}{\rightarrow}$  cost of car trips (CCT)  $\overset{-}{\rightarrow}$  attraction degree of car trips (ADCT)  $\overset{+}{\rightarrow}$  growth rate of cars (GRC)  $\overset{+}{\rightarrow}$  amount of cars (AC)  $\overset{+}{\rightarrow}$  amount of car trips (ACT)  $\overset{-}{\rightarrow}$  per vehicle area of roads (PVAR)  $\overset{-}{\rightarrow}$  degree of traffic congestion (DTC).
- (ii) *Loop B<sub>2</sub>*. Degree of traffic congestion (DTC)  $\overset{+}{\rightarrow}$  pressure of government (PG)  $\overset{+}{\rightarrow}$  cost of car trips (CCT)  $\overset{+}{\rightarrow}$  investment and subsidies of the public traffic (ISPT)  $\overset{+}{\rightarrow}$  supply level of public traffic (SLPT)  $\overset{-}{\rightarrow}$  attraction degree of car trips (ADCT)  $\overset{+}{\rightarrow}$  growth rate of cars (GRC)  $\overset{+}{\rightarrow}$  amount of cars (AC)  $\overset{+}{\rightarrow}$  amount of car trips (ACT)  $\overset{-}{\rightarrow}$  per vehicle area of roads (PVAR)  $\overset{-}{\rightarrow}$  degree of traffic congestion (DTC).
- (iii) *Loop B<sub>3</sub>*. Degree of traffic congestion (DTC)  $\overset{+}{\rightarrow}$  pressure of government (PG)  $\overset{+}{\rightarrow}$  initiatives in road construction (IRC)  $\overset{+}{\rightarrow}$  area of roads (AR)  $\overset{+}{\rightarrow}$  per vehicle area of roads (PVAR)  $\overset{-}{\rightarrow}$  degree of traffic congestion (DTC).

- (iv) *Loop B<sub>4</sub>*. Per vehicle area of roads (PVAR)  $\bar{\rightarrow}$  degree of traffic congestion (DTC)  $\bar{\rightarrow}$  attraction degree of car trips (ADCT)  $\bar{\rightarrow}$  growth rate of cars (GRC)  $\bar{\rightarrow}$  amount of cars (AC)  $\bar{\rightarrow}$  amount of car trips (ACT)  $\bar{\rightarrow}$  per vehicle area of roads (PVAR).
- (v) *Loop B<sub>5</sub>*. NO<sub>x</sub> generation (GNO<sub>x</sub>)  $\bar{\rightarrow}$  degree of air pollution (DAP)  $\bar{\rightarrow}$  air pollution control (APC)  $\bar{\rightarrow}$  growth rate of cars (GRC)  $\bar{\rightarrow}$  amount of cars (AC)  $\bar{\rightarrow}$  amount of car trips (ACT)  $\bar{\rightarrow}$  NO<sub>x</sub> generation (GNO<sub>x</sub>).
- (vi) *Loop B<sub>6</sub>*. Amount of car trips (ACT)  $\bar{\rightarrow}$  NO<sub>x</sub> generation (GNO<sub>x</sub>)  $\bar{\rightarrow}$  degree of air pollution (DAP)  $\bar{\rightarrow}$  air pollution control (APC)  $\bar{\rightarrow}$  investment and subsidies of the public traffic (ISPT)  $\bar{\rightarrow}$  supply level of public traffic (SLPT)  $\bar{\rightarrow}$  attraction degree of car trips (ADCT)  $\bar{\rightarrow}$  growth rate of cars (GRC)  $\bar{\rightarrow}$  amount of cars (AC)  $\bar{\rightarrow}$  amount of car trips (ACT).

Loop B<sub>1</sub> is a negative feedback loop, a change of any variable: for example, DTC would eventually affect itself in a negative way. An increase in the DTC will promote the increase of PG, and larger pressure on the government indicates a severer traffic congestion condition, suggesting a higher TCCF; otherwise, it might be hard to ease the traffic congestion. So, larger PG leads to larger CCT, which finally results in less ADCT. Then decrease of GRC will reduce the AC, which will further reduce the ACT. Finally, less amount of ACT will result in a larger PVAR, which leads to a smaller DTC.

Loop B<sub>2</sub> is also a negative feedback loop; the process of Loop B<sub>2</sub> is similar to the Loop B<sub>1</sub>. Suppose there is an increase in the DTC, the PG and CCT would increase accordingly. This can gradually improve the ISPT. Subsequently, the better SLPT will lead to a decrease in ADCT, and the decrease of GRC will result in a smaller AC. Eventually, less ACT will promote the increase of PVAR and consequently reduce the DTC. Therefore, the variable DTC can affect itself negatively through the chain effects in this feedback loop.

In the same way, it is easy to analyze the loop B<sub>3</sub>–B<sub>6</sub>.

Loop B<sub>3</sub> will largely depend on the road-building policy to solve the traffic congestion problem, but the effect of this policy is only temporary. It cannot fundamentally solve the problem and loop B<sub>4</sub> can demonstrate this phenomenon. Namely, the original efforts committed to an increase of PVAR but the final amount will reduce.

Loops B<sub>5</sub> and B<sub>6</sub> adopt the air pollution control and investment and subsidies of the public traffic, respectively, in order to relieve the traffic congestion through the application of economic measure (such as TCCF) to reduce amount of car trips and NO<sub>x</sub> generation. Hence, to some extent, it can inhibit the haze-fog.

*Assumption 1.* (1) The car which contains less than 7 seats is the major focus in this paper; (2) the NO<sub>2</sub> of car emission is

the main concern due to its harmfulness to human health; (3) the cost of TCCF will be invested in the traffic infrastructure construction and improvements of the public transport; (4) a proper range of TCCF is applied to the next 5 years.

*2.3. The Stock-Flow Diagram.* As noted above, the stock-flow diagram, as shown in Figure 2, is presented by using the Vensim software, and all descriptions of the major variables in the model are tabulated in detail in Table 1.

### 3. Dynamic Simulation and Policy Analysis

#### 3.1. In the Quantification of Major Variables

*Simulation Settings.* Initial time = 2010, final time = 2030, time step = 0.5, and unit of time is year.

(1) Official statistical data such as “Shanghai Statistical Year Book 2015” (method for quantification: Q<sub>1</sub>) is as follows:

- (a) From 2010 to 2014, the AAR in Shanghai are  $2.567e + 008 \text{ m}^2$ ,  $2.6176e + 008 \text{ m}^2$ ,  $2.6813e + 008 \text{ m}^2$ ,  $2.729e + 008 \text{ m}^2$ , and  $2.7918e + 008 \text{ m}^2$ ; therefore, the initial values of AAR and GRRC are  $2.567e + 008 \text{ m}^2$  and 0.0212, respectively. In the same way,  $AC_{\text{initial value}} = 1.7572e + 006$  vehicles,  $AP_{\text{initial value}} = 2.30266e + 007$  persons,  $AGDP_{\text{initial value}} = 1.7166e + 012$  yuan.
- (b) In 2010–2014 years, the BR in Shanghai are 7.13‰, 7.17‰, 8.51‰, 7.62‰, and 8.64‰. So,  $BR_{\text{average value}} \approx 7.82\text{‰} = 0.00782$ . Similarly,  $DR_{\text{average value}} \approx 8.06\text{‰} = 0.00806$ ,  $NRPM_{\text{average value}} \approx 6.6\text{‰} = 0.0066$ , and  $GGDP_{\text{average value}} \approx 0.0855$ .

(2) Existing literature (quantification method: Q<sub>2</sub>): according to Yang et al. (2014), we can obtain the following results [31].

- (a) PVANE = 0.02 ton/day \* vehicle.  
 (b) CRNC = 0.5.  
 (c) DR = 0.2.  
 (d) SR = 0.067.

(3) Estimated value (quantification method: Q<sub>3</sub>) is

- (a)  $(NO_x)_{\text{initial value}} \approx 0.02 \times 175.72 \times 10^4 = 35144$  tons,  
 (b) calculation of ADC.

*Definition 2* (see [32]). Assume that the images of zero starting point of the two behavioral sequences

$$\begin{aligned} X_i &= (x_i(1), x_i(2), \dots, x_i(n)), \\ X_j &= (x_j(1), x_j(2), \dots, x_j(n)) \end{aligned} \quad (1)$$

are

$$\begin{aligned} X_i^0 &= (x_i^0(1), x_i^0(2), \dots, x_i^0(n)), \\ X_j^0 &= (x_j^0(1), x_j^0(2), \dots, x_j^0(n)). \end{aligned} \quad (2)$$

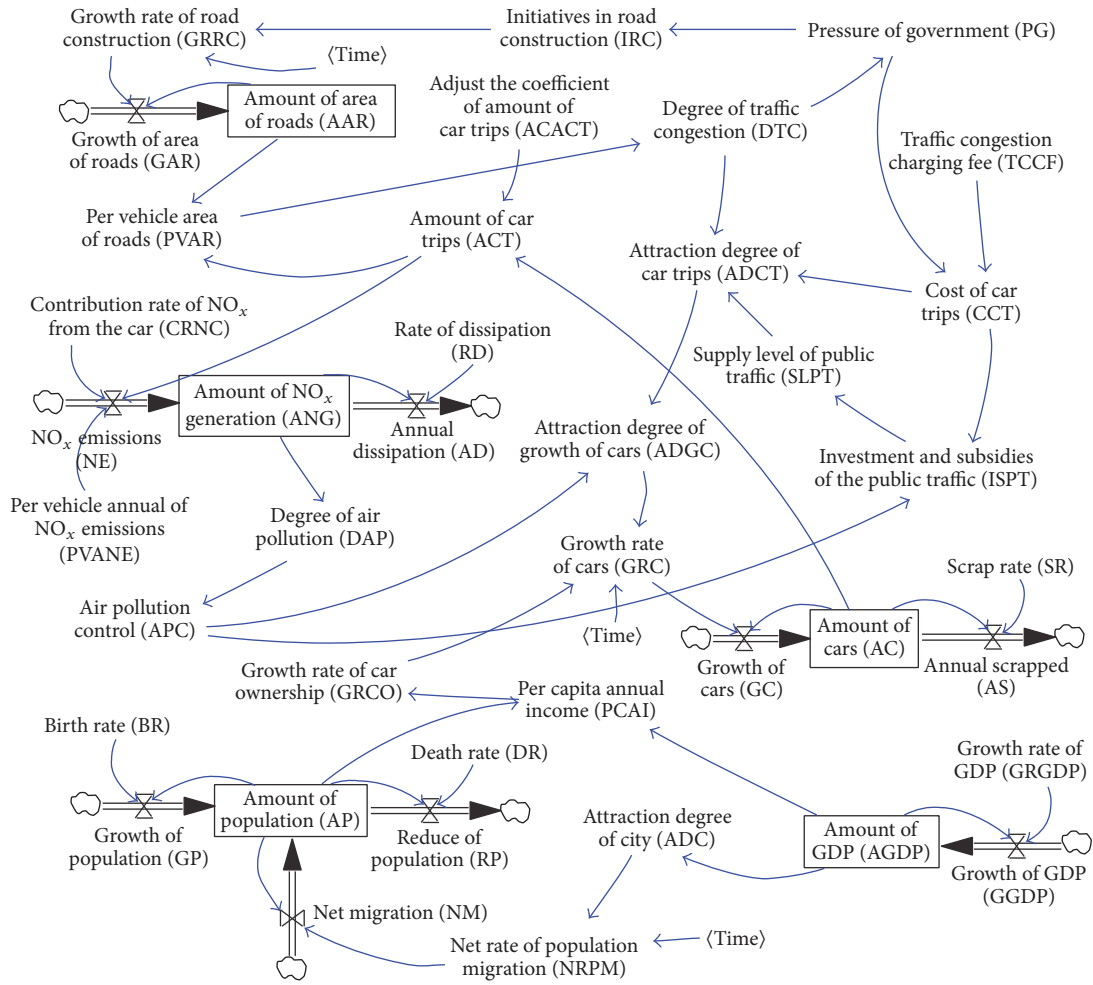


FIGURE 2: The stock-flow diagram of TCCF management model.

Assume that  $X'_i$  and  $X'_j$  are the initial images of  $X_i$  and  $X_j$ , and the images of zero starting point of the two behavioral sequences  $X'_i, X'_j$  are  $X_i^0$  and  $X_j^0$ ; then

$$\begin{aligned} \xi_{ij}^{(1/\sqrt{n},2)} &= \left[ 1 + \left| \sum_{k=2}^{n-1} x_i^0(k) + \frac{1}{2} x_i^0(n) \right| \right. \\ &+ \left. \left| \sum_{k=2}^{n-1} x_j^0(k) + \frac{1}{2} x_j^0(n) \right| \right] \times \left[ 1 \right. \\ &+ \left. \left| \sum_{k=2}^{n-1} x_i^0(k) + \frac{1}{2} x_i^0(n) \right| + \left| \sum_{k=2}^{n-1} x_j^0(k) + \frac{1}{2} x_j^0(n) \right| \right] \quad (3) \\ &+ \left. \left| \sum_{k=2}^{n-1} [x_i^0(k) - x_j^0(k)] + \frac{1}{2} [x_i^0(n) - x_j^0(n)] \right| + \frac{1}{\sqrt{n}} \right. \\ &\cdot \left. \left( \sum_{k=1}^n |x_i^0(k) - x_j^0(k)|^2 \right)^{1/2} \right]^{-1}, \end{aligned}$$

$$\begin{aligned} \gamma_{ij}^{(1/\sqrt{n},2)} &= \left[ 1 + \left| \sum_{k=2}^{n-1} x_i^0(k) + \frac{1}{2} x_i^0(n) \right| \right. \\ &+ \left. \left| \sum_{k=2}^{n-1} x_j^0(k) + \frac{1}{2} x_j^0(n) \right| \right] \times \left[ 1 \right. \\ &+ \left. \left| \sum_{k=2}^{n-1} x_i^0(k) + \frac{1}{2} x_i^0(n) \right| + \left| \sum_{k=2}^{n-1} x_j^0(k) + \frac{1}{2} x_j^0(n) \right| \right] \quad (4) \\ &+ \left. \left| \sum_{k=2}^{n-1} [x_i^0(k) - x_j^0(k)] + \frac{1}{2} [x_i^0(n) - x_j^0(n)] \right| \right. \\ &+ \left. \frac{1}{\sqrt{n}} \cdot \left( \sum_{k=1}^n |x'_i(k) - x'_j(k)|^2 \right)^{1/2} \right]^{-1}, \end{aligned}$$

are, respectively, called the quasi-“Euclidean” absolute degree of incidence (Q-EUGAID) and the quasi-“Euclidean” relative degree of incidence (Q-EUGRID); then

$$\rho_{ij}^{(1/\sqrt{n},2)} = \sigma_1^{(1/\sqrt{n},2)} \xi_{ij}^{(1/\sqrt{n},2)} + \sigma_2^{(1/\sqrt{n},2)} \gamma_{ij}^{(1/\sqrt{n},2)} \quad (5)$$

TABLE 1: Descriptions on the variables quoted in this model.

Abbreviations	Variable name	Unit	Variable type	Quantification method
AAR	Amount of area of roads	m <sup>2</sup>	Stock	Q <sub>1</sub>
AC	Amount of cars	Vehicle	Stock	Q <sub>1</sub>
ACACT	Adjust the coefficient of amount of car trips	Dmnl	Parameter	Q <sub>3</sub>
ACT	Amount of car trips	Vehicle	Auxiliary variable	
AD	Annual dissipation	Ton/year	Flow	
ADC	Attraction degree of city	%	Parameter	Q <sub>3</sub>
ADCT	Attraction degree of car trips	%	Auxiliary variable	Q <sub>3</sub>
ADGC	Attraction degree of growth of cars	%	Auxiliary variable	Q <sub>3</sub>
ANG	Amount of NO <sub>x</sub> generation	Ton	Stock	
AGDP	Amount of GDP	Yuan	Stock	Q <sub>1</sub>
AP	Amount of population	Person	Stock	Q <sub>1</sub>
APC	Air pollution control	Dmnl	Auxiliary variable	Q <sub>3</sub>
AS	Annual scrapped	Vehicle/year	Flow	
BR	Birth rate	1/year	Parameter	Q <sub>1</sub>
CCT	Cost of car trips	Yuan/day * vehicle	Auxiliary variable	Q <sub>3</sub>
CRNC	Contribution rate of NO <sub>x</sub> from the car	%	Parameter	Q <sub>2</sub>
DAP	Degree of air pollution	Dmnl	Auxiliary variable	Q <sub>3</sub>
DR	Death rate	1/year	Parameter	Q <sub>1</sub>
DTC	Degree of traffic congestion	Dmnl	Auxiliary variable	Q <sub>3</sub>
GAR	Growth of area of roads	m <sup>2</sup> /year	Flow	
GC	Growth of cars	Vehicle/year	Flow	
GGDP	Growth of GDP	Yuan/year	Flow	
GP	Growth of population	Person/year	Flow	
GRC	Growth rate of cars	1/year	Auxiliary variable	Q <sub>3</sub>
GRCO	Growth rate of car ownership	Dmnl	Auxiliary variable	Q <sub>3</sub>
GRGDP	Growth rate of GDP	1/year	Parameter	Q <sub>1</sub>
GRRC	Growth rate of road construction	1/year	Auxiliary variable	Q <sub>1</sub>
IRC	Initiatives in road construction	Dmnl	Auxiliary variable	Q <sub>3</sub>
ISPT	Investment and subsidies of the public traffic	Yuan/day * vehicle	Auxiliary variable	Q <sub>3</sub>
NE	NO <sub>x</sub> emissions	Ton/year	Flow	
NM	Net migration	Person/year	Flow	
NRPM	Net rate of population migration	1/year	Parameter	Q <sub>1</sub>
PCAI	Per capita annual income	Yuan/person	Auxiliary	
PG	Pressure of government	%	Auxiliary variable	Q <sub>3</sub>
PVANE	Per vehicle annual of NO <sub>x</sub> emissions	Ton/year * vehicle	Parameter	Q <sub>2</sub>
PVAR	Per vehicle area of roads	m <sup>2</sup> /vehicle	Auxiliary variable	
RD	Rate of dissipation	1/year	Parameter	Q <sub>2</sub>
SLPT	Supply level of public traffic	Dmnl	Auxiliary variable	Q <sub>3</sub>
RP	Reducing population	Person/year	Flow	
SR	Scrap rate	1/year	Parameter	Q <sub>2</sub>
TCCF	Traffic congestion charging fee	Yuan/day * vehicle	Parameter	

is called the quasi-“Euclidean” synthetic degree of incidence (Q-EUGSID) of  $X_i$  and  $X_j$ , where

$$\begin{aligned}
 \sigma_1^{(1/\sqrt{n},2)} &> 0, \\
 \sigma_2^{(1/\sqrt{n},2)} &> 0, \\
 \sigma_1^{(1/\sqrt{n},2)} + \sigma_2^{(1/\sqrt{n},2)} &= 1.
 \end{aligned}
 \tag{6}$$

This paper adopts the method of Q-EUGSID and assumes that the two behavioral sequences of  $AGDP_{China(2010-2014)}$  and  $AGDP_{Shanghai(2010-2014)}$  are denoted as  $X_0$  and  $X_1$ , where  $X_0 = (408903.0, 484123.5, 534123.0, 588018.8, 636138.7)$  and  $X_1 = (17165.98, 19195.69, 20181.72, 21818.15, 23567.70)$ . Subsequently, calculating the values of Q-EUGAID and Q-EUGRID, we have that  $\xi_{01}^{(1/\sqrt{n},2)} \approx 0.4439$ ,  $\gamma_{01}^{(1/\sqrt{n},2)} \approx 0.8353$ . Finally, let  $\sigma_1^{(1/\sqrt{n},2)} = 0.5 = \sigma_2^{(1/\sqrt{n},2)}$ ; we can gain the value of



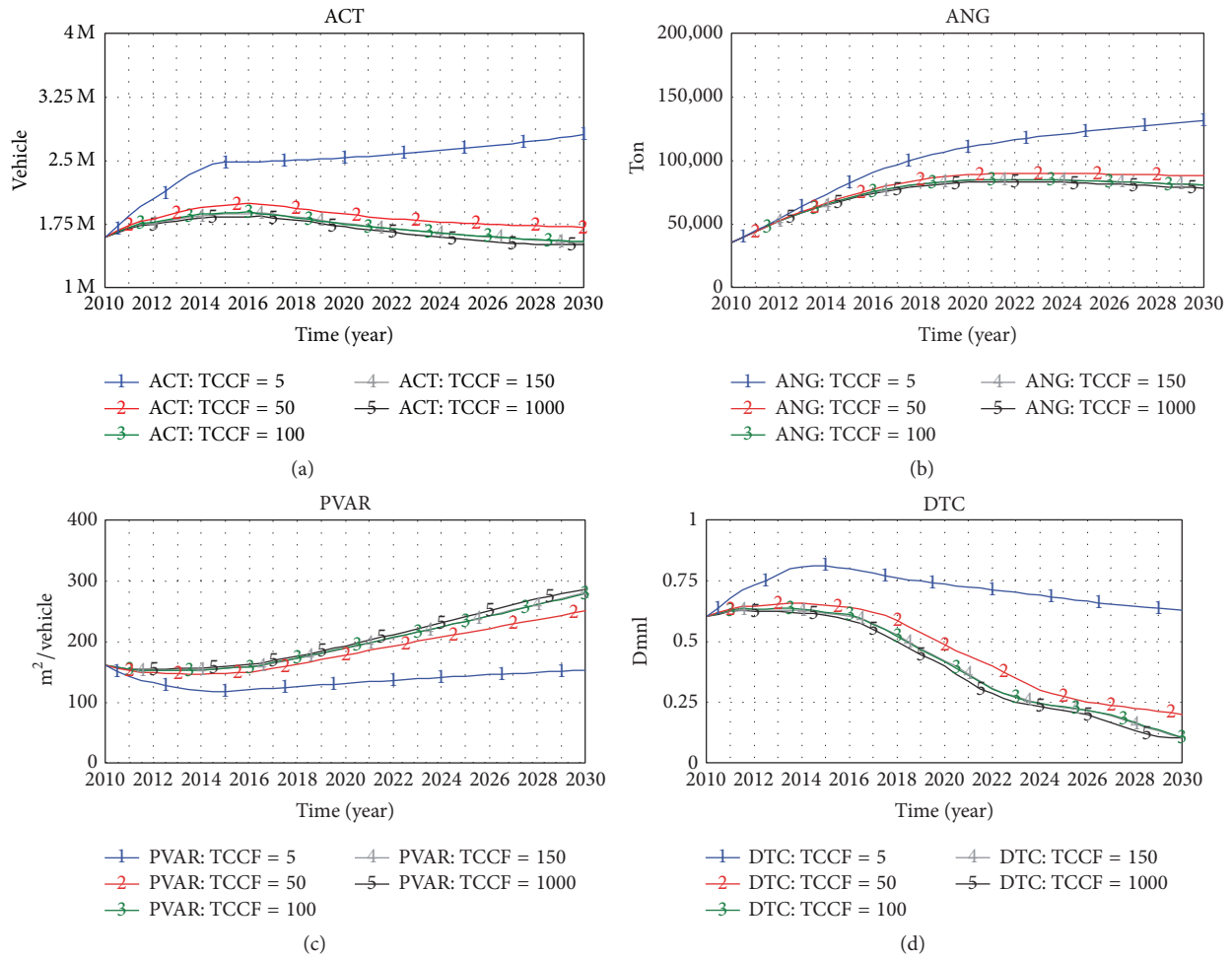


FIGURE 3: Realistic test for the main variables. (a) ACT; (b) ANG; (c) PVAR; (d) DTC.

Q-EUGSID. Therefore,  $\rho_{01}^{(1/\sqrt{n},2)} = \sigma_1^{(1/\sqrt{n},2)} \cdot \xi_{01}^{(1/\sqrt{n},2)} + \sigma_2^{(1/\sqrt{n},2)} \cdot \gamma_{01}^{(1/\sqrt{n},2)} \approx 0.6396$ . Namely,  $ADC \approx 0.6396$ .

Other variables can be described by the use of nonlinear function (such as graphical function and logic function), and the major variables and equations are explained in Appendix.

### 3.2. Model Test and Simulation

**3.2.1. Realistic Test.** It can be seen from Figure 3(a) that the ACT gets the minimum value when the TCCF = 1000 yuan/day \* vehicle, while it reaches the maximum when the TCCF = 5 yuan/day \* vehicle. This result is consistent with the reality. All of the curves are rising during the simulation period; however, with the increase of TCCF, ACT declines accordingly. Especially when the TCCF ranges between 5 and 50, ACT declines obviously; however, when the TCCF ranges between 50 and 100, ACT declines slightly. But when TCCF values are more than 100 yuan/day \* vehicle, ACT stays almost unchanged. The varying pattern also applies to Figures 3(b), 3(c), and 3(d). Therefore, the TCCF should not go beyond 100 yuan/day \* vehicle.

**3.2.2. Sensitivity Analysis.** From Figure 4(a), with years increasing, all curves rise first and descend later. For example, curve 5 is rising slowly till 2016; however, it decreases significantly slower during the year 2017 to 2030, even going like a horizontal line. The ACT decreases continuously along with the increase of the TCCF, and the gaps between each curve gradually shrink. Particularly, there is a biggest difference of ACT when TCCF ranges between 5 and 15, and a relatively big difference when TCCF  $\in [15, 45]$ . Nevertheless, there is almost no change in ACT when the TCCF is higher than 45 yuan/day \* vehicle. Hence, the TCCF is not always “bigger means better.” It had better range between 15 and 45 yuan/day \* vehicle.

As is shown in Figure 4(b), all curves continued to rise slowly. However, with the increasing of the TCCF, the gaps between these curves are narrowing. So, the increase of TCCF exerted a marginal decreasing effect on ANG (see curves 1–5). But there are almost no change in ANG when the TCCF is higher than 45 yuan/day \* vehicle; this to a large extent demonstrated that the optimized TCCF should be close to 45 yuan/day \* vehicle.

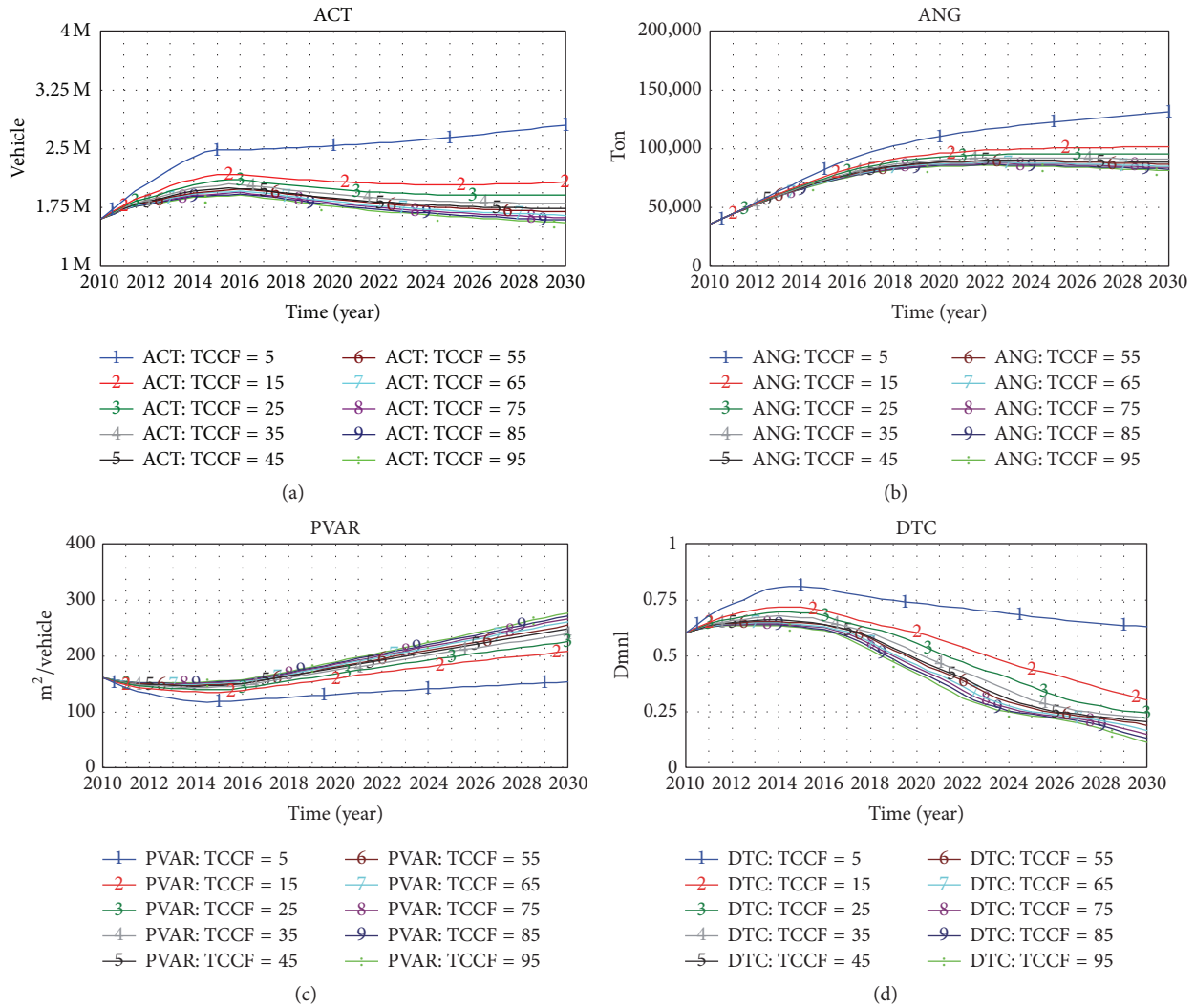


FIGURE 4: The effect of these major variables under different TCCF. (a) ACT; (b) ANG; (c) PVAR; (d) DTC.

On the contrary, Figure 4(c) indicated that all curves descend first and then gradually increase. Other properties are similar to Figure 4(a). Furthermore, the optimal TCCF ( $TCCF \in [15, 45]$ ) results in a significant decline in PVAR; however, the changes are very tiny when the TCCF is more than 45 yuan/day \* vehicle.

From Figure 4(d), we can clearly see that all curves rise slowly first and then descend quickly. Take curve 5 as an example; it rises very slowly from 2010 to 2014; after 2014, it descends quickly. This is probably because of travelers' habit; the effect is not obvious in the early stage of the policy implementation. But in the latter period (2015–2030), the effect is more and more remarkable along with the continuous implementation and improvements of TCCF policy.

To sum up, the reasonable range of TCCT should be [15, 45], which reveals that the TCCF management model is valid and practical to a certain degree.

3.2.3. Sensitivity Test. A rational range between 15 and 45 was divided into sixteen equal portions, so each simulation step

equals 2. Figures 5(a)–5(d) delineated that, although every curve has slight differences, the graphical shapes are almost consistent and did not appear too sensitive or insensitive.

3.3. Results Analysis. To further analyze, we can get Tables 2 and 3. As is shown in Table 2, the ACT has decreased steadily with the increase of the TCCF. In particular, it has decreased most significantly when  $TCCF \in [5, 15]$ ; it decreases relatively significantly when  $TCCF \in [15, 45]$ . It is decreased slightly when TCCF is more than 45 yuan/day \* vehicle. So, the TCCF should range between 15 and 45 yuan/day \* vehicle.

Similarly, the ANG and GC are all decreased to some degree, when  $TCCF \in [15, 45]$ .

It is learned from Table 3 that the PVAR increases quickly with the increase of TCCF. But, the TCCF is not always the more, the better, because the PVAR rises most significantly when  $TCCF \in [5, 15]$ , relatively significantly when  $TCCF \in [15, 45]$  and slightly when  $TCCF \in [45, 95]$ . On the contrary, the increase of TCCF promotes the decrease of DTC. Table 3

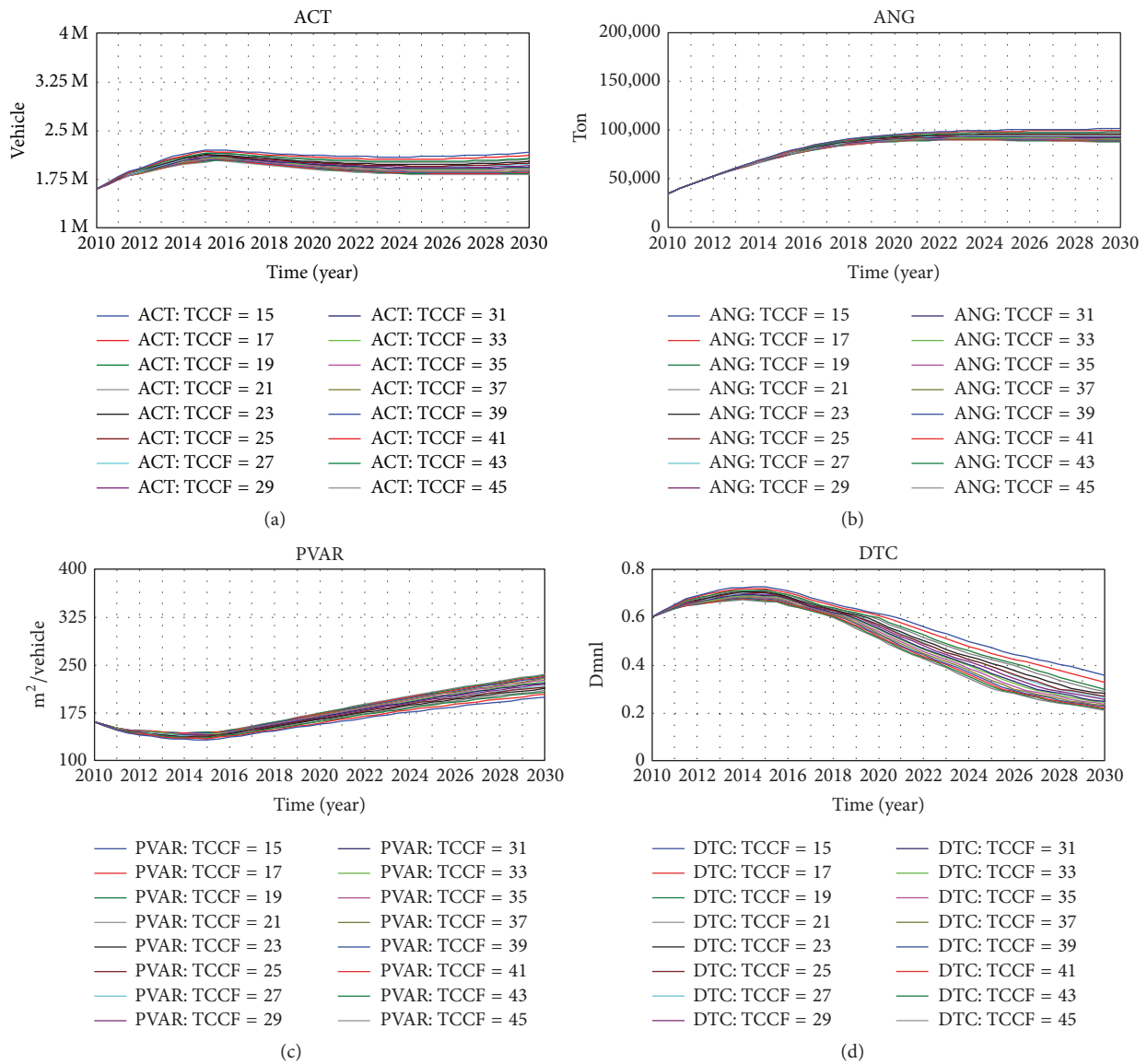


FIGURE 5: Sensitivity test for the main variables. (a) ACT; (b) ANG; (c) PVAR; (d) DTC.

TABLE 2: The influence of ACT, GC, and ANG under different TCCF.

TCCF	ACT	Trend	Variation	GC	Trend	Variation	ANG	Trend	Variation
5	2.80203e + 006	—	—	247932	—	—	131377	—	—
15	<b>2.07151e + 006</b>	↓	<b>-26.07%</b>	<b>170445</b>	↓	<b>-31.25%</b>	<b>101546</b>	↓	<b>-22.71%</b>
25	<b>1.90726e + 006</b>	↓	<b>-7.93%</b>	<b>146902</b>	↓	<b>-13.81%</b>	<b>95044.1</b>	↓	<b>-6.40%</b>
35	<b>1.79831e + 006</b>	↓	<b>-5.71%</b>	<b>131575</b>	↓	<b>-10.43%</b>	<b>90744.4</b>	↓	<b>-4.52%</b>
45	<b>1.72549e + 006</b>	↓	<b>-4.05%</b>	<b>121657</b>	↓	<b>-7.54%</b>	<b>87908.8</b>	↓	<b>-3.12%</b>
55	1.6876e + 006	↓	-2.20%	116650	↓	-4.12%	86584.4	↓	-1.51%
65	1.64308e + 006	↓	-2.64%	112187	↓	-3.83%	84768	↓	-2.10%
75	1.61089e + 006	↓	-1.96%	108625	↓	-3.18%	83487.6	↓	-1.51%
85	1.5791e + 006	↓	-1.97%	105548	↓	-2.83%	82153.2	↓	-1.60%
95	1.55025e + 006	↓	-1.83%	102739	↓	-2.66%	80941.9	↓	-1.47%



TABLE 3: The influence of PVAR, ADCT, and DCT under different TCCF.

TCCF	PVAR	Trend	Variation	ADCT	Trend	Variation	DTC	Trend	Variation
5	153.202	—	—	0.505177	—	—	0.628229	—	—
15	<b>207.299</b>	↑	<b>35.31%</b>	<b>0.473399</b>	↓	<b>-6.29%</b>	<b>0.300347</b>	↓	<b>-52.19%</b>
25	<b>225.075</b>	↑	<b>8.58%</b>	<b>0.444686</b>	↓	<b>-6.07%</b>	<b>0.242404</b>	↓	<b>-19.29%</b>
35	<b>238.71</b>	↑	<b>6.06%</b>	<b>0.422381</b>	↓	<b>-5.02%</b>	<b>0.219207</b>	↓	<b>-9.57%</b>
45	<b>248.785</b>	↑	<b>4.22%</b>	<b>0.406288</b>	↓	<b>-3.81%</b>	<b>0.202066</b>	↓	<b>-7.82%</b>
55	254.37	↑	2.24%	0.397655	↓	-2.12%	0.185433	↓	-8.23%
65	261.264	↑	2.71%	0.392307	↓	-1.34%	0.162455	↓	-12.39%
75	266.484	↑	2.00%	0.386856	↓	-1.39%	0.145053	↓	-10.71%
85	271.849	↑	2.01%	0.383006	↓	-1.00%	0.12717	↓	-12.33%
95	276.907	↑	1.86%	0.379269	↓	-0.98%	0.110309	↓	-13.26%

TABLE 4: A reasonable value is compared with the base run simulation.

Variable	TCCF (yuan/day * vehicle)		Variation	Trend
	5	45		
DTC	0.628229	0.202066	-67.84%	↓
ANG (ton)	131377	87908.8	-33.09%	↓
PVAR (m <sup>2</sup> )	153.202	248.785	62.39%	↑
ACT (vehicle)	2.80203e + 006	1.72549e + 006	-38.42%	↓
ADCT	0.505177	0.406288	-19.58%	↓
GC (vehicle)	247932	121657	-50.93%	↓

also shows that ADCT decreases steadily with the increase of TCCF.

To some up, the relatively optimized TCCF not only reduces DTC evidently, but also effectively reduces the ANG. So, the reasonable TCCF should range between 15 and 45 yuan/day \* vehicle.

**3.4. Policy Analysis and Optimization.** Table 4 shows that, compared with base run simulation (TCCF = 5 yuan/day \* vehicle), when the TCCF = 45 yuan/day \* vehicle, the DTC, ANG, ACT, ADCT, and GC will reduce by approximately 67.84%, 33.09%, 38.42%, 19.58%, and 50.93%, respectively, and the PVAR will increase about 62.39%. These results reveal that it not only can vastly decrease the DTC, but also can availably control air pollution (especially the “haze-fog” pollution). Hence, the scope between 15 and 45 yuan/day \* vehicle is a satisfied solution.

More specifically, it is quite obvious from Figure 6(a) that the two curves increase initially and decrease afterwards. But the change of curve 2 became more slowly from 2010 to 2014. After 2014, there was a sharp reduction of curve 2 and it dropped by 67.84% in 2030 (compare with curve 1). So, the effect is very obvious. Figure 6(b) shows that the increasing of curve 2 is very tardily and it is inching down like a line after 2020. Particularly, the ANG has dropped to about 87908.8 tons in 2030. Before and after comparative analysis, it has decreased by approximately 33.09% in 2030. As shown in Figure 6(c), after 2014, curve 2 was significantly increased (about 62.39% in 2030) compared with curve 1. Figure 6(d) illustrated that, by 2016, the rising of the ACT is very slow, and

since 2016, it drops year by year. It has reduced about 38.42% in 2030 compared with before.

All of the above reflect essential research value.

**3.5. The Trend of the Main Variables.** As is shown in Figure 7, curve 3 (APC) rises sharply which looks like a jagged line; this phenomenon indicates that the government has strengthened the management of traffic congestion and air pollution. Along with the increase of the APC, we can get the following conclusions:

- (i) *ACT (curve 1)*: the ACT increases in the early stage of simulation period; however it decreases gradually since 2016, and it drops to around 1.7 million vehicles after 2025.
- (ii) *ANG (curve 2)*: the ANG has increased slowly between 2010 and 2022; however, it decreases year by year between 2023 and 2030.
- (iii) *PVAR (curve 5)*: the PVAR increases significantly since 2015, so it has relieved the urban traffic congestion effectively.
- (iv) *DTC (curve 4)*: the significant decrease of DTC has demonstrated that the TCCF management model is flexible and practical to some extent.

## 4. Discussion and Conclusion

Different from the previous researches, in order to relieve the urban traffic congestion and the environmental problems caused by the high-speed urbanization, this paper explored the TCCF management model based on system dynamics approach. It has wide application prospect and significant research value. The major findings are summarized as follows.

- (1) When the TCCF increases, the ACT, GC, ADCT, and DTC decrease accordingly; however, the PVAR increases with the increase of the TCCF. In particular, the DTC decreases around 67.84% in 2030 when the TCCF equals 45 yuan/day \* vehicle. Hence, it can effectively alleviate the traffic congestion in Shanghai.
- (2) There is a steady decline of the ANG with the increase of the TCCF. Particularly, it has declined by nearly 29.87% in 2030. This result indicates that it reduces

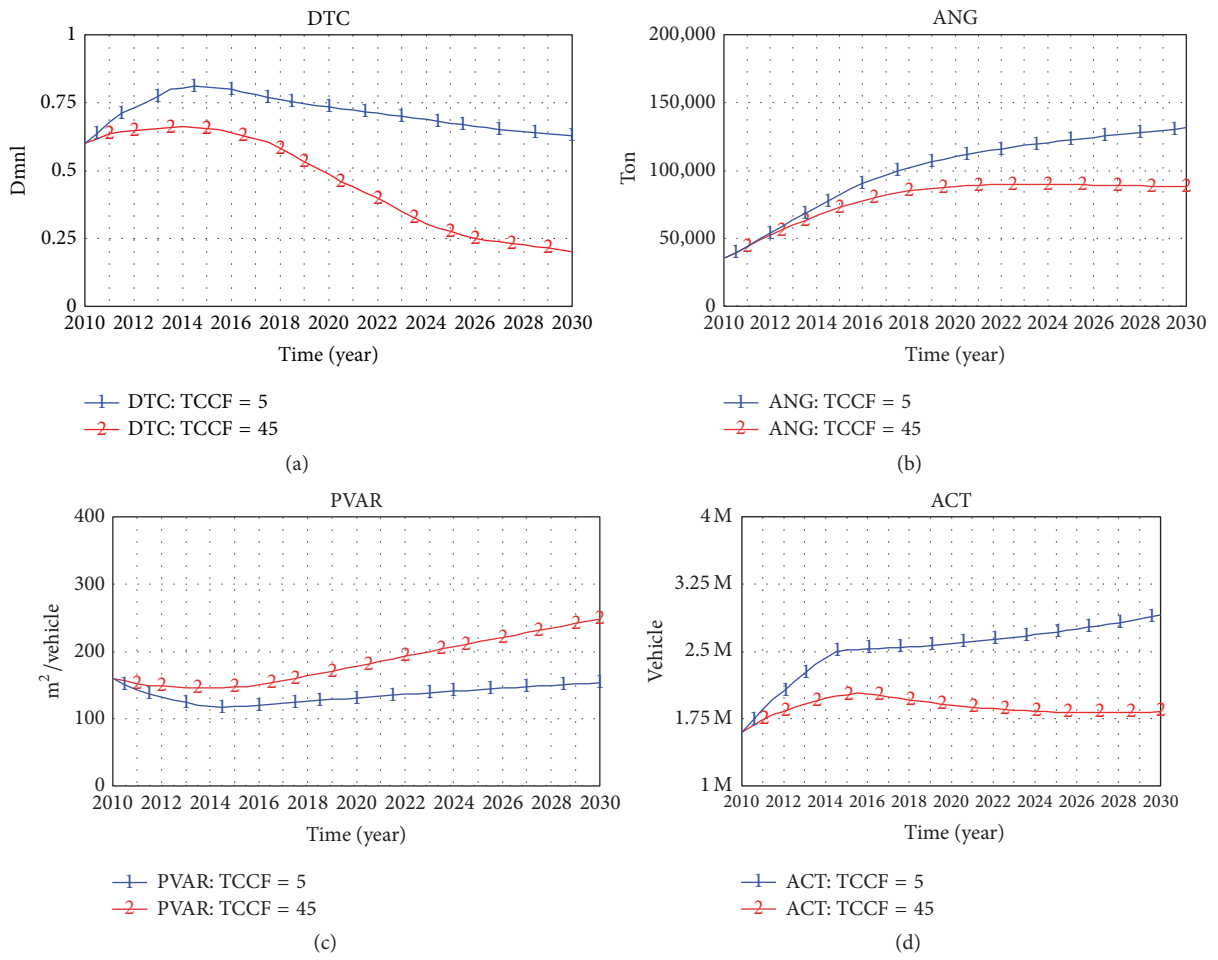


FIGURE 6: The influence of the major variables under different TCCF. (a) DTC; (b) ANG; (c) PVAR; (d) ACT.

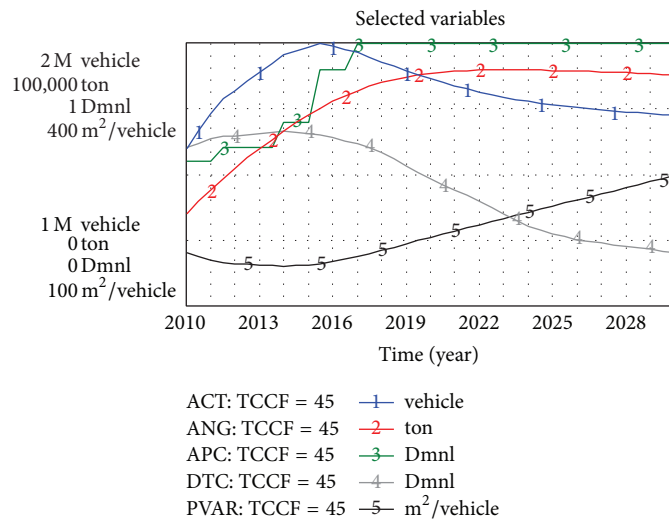


FIGURE 7: The trend of the main variables (when TCCF = 45 yuan/day \* vehicle).

car emission as well as the “haze-fog” pollution significantly.

- (3) But it does not mean that the TCCF is the bigger, the better; it had better range between 15 and 45.

Above all, when the TCCF rises, on the one hand, the PVAR has a dramatic increase (see Figures 4(c) and 6(c), Tables 3 and 4) and the DTC has a sharp decrease (see Figures 4(d) and 6(a), Tables 3 and 4); these results revealed that the TCCF management model is reliable and valid. On the other hand, the simulation and policy analysis has testified its practicability and rationality: the ANG has gradually declined (see Figures 4(b) and 6(b), Tables 2 and 4).

However, due to limited data, the model still has some limitations. (a) During the early stage of implementing the policy, the increase in the TCCF might weaken the public support, which may load more burdens on the government somehow. Therefore, sufficient publicity is necessary during the implementation to raise the public awareness that the traffic congestion charging fee policy aims at easing the urban traffic congestion and reducing environmental pollution. With a better understanding of the policy and its intention, the public support would be maintained through eliminating cognitive conflicts caused by the ignorance and stereotypes, relieving the burden on the government. (b) The range 15–45 yuan/day \* vehicle is not the perfect scheme; it is a relatively satisfying solution. When the living standards should be noticeably raised, the pricing range might be adjusted based on the actual conditions. (c) CCT and ISPT are increased with the increase of TCCF, so it will alleviate the traffic congestion to some degree, but the effects are still limited. From this perspective, we should take other policies into full account, including increasing the parking fee and the government subsidies on public transport, enhancing the trip of public transport, improving the quality of public transport services, and using alternative-energy cars (such as hydrogen fuel-cell buses and all-electric buses).

## Appendix

### Summary of the Major Variables and Equations

- (1)  $AAR = \text{INTEG}(GAR, 2.5607e + 008).$
- (2)  $AC = \text{INTEG}(GC - AS, 1.7572e + 006).$
- (3)  $ACACT = 1/2.5.$
- (4)  $ACT = AC * (1 + ACACT) * 0.65.$
- (5)  $AD = ANG * RD.$
- (6)  $ADC = 0.6396.$
- (7)  $ADCT = 0.3 * (1 - DTC) + 0.45/\text{LN}(CCT) + (1 - \text{SLPT}) * 0.25.$
- (8)  $ADGC = (1 - APC) * 0.45 + ADCT * 0.55.$
- (9)  $ANG = \text{INTEG}(NE - AD, 35144).$
- (10)  $AGDP = \text{INTEG}(GGDP, 1.7166e + 012).$
- (11)  $AP = \text{INTEG}(GP + NM - RP, 2.30266e + 007).$
- (12)  $APC = \text{IF THEN ELSE}(DAP \geq 0.85, 1, \text{IF THEN ELSE}(DAP \geq 0.8, 0.9, \text{IF THEN ELSE}(DAP \geq 0.7, 0.8, \text{IF THEN ELSE}(DAP \geq 0.6, 0.7, \text{IF THEN ELSE}(DAP \geq 0.5, 0.6, \text{IF THEN ELSE}(DAP \geq 0.4, 0.55, \text{IF THEN ELSE}(DAP \geq 0.3, 0.4, 0.3)))))))).$
- (13)  $AS = AC * SR.$
- (14)  $BR = 0.00782.$
- (15)  $CCT = TCCF * (1 + PG).$
- (16)  $CRNC = 0.5.$
- (17)  $DAP = \text{IF THEN ELSE}(ANG \geq 80000, 0.9, \text{IF THEN ELSE}(ANG \geq 75000, 0.8, \text{IF THEN ELSE}(ANG \geq 65000, 0.65, \text{IF THEN ELSE}(ANG \geq 55000, 0.55, \text{IF THEN ELSE}(ANG \geq 45000, 0.5, \text{IF THEN ELSE}(ANG \geq 35144, 0.4, \text{IF THEN ELSE}(ANG \geq 30000, 0.35, \text{IF THEN ELSE}(ANG \geq 25000, 0.3, \text{IF THEN ELSE}(ANG \geq 20000, 0.25, \text{IF THEN ELSE}(ANG \geq 10000, 0.2, 0.1)))))))).$
- (18)  $DR = 0.00806.$
- (19)  $DTC = \text{WITH LOOKUP}(PVAR, ((60, 0) - (280, 1)), (90, 0.9), (120.22, 0.8), (127.56, 0.75), (138.43, 0.7), (147.55, 0.65), (160.53, 0.6), (183.27, 0.45), (192.54, 0.4), (207.28, 0.3), (220.61, 0.25), (250, 0.2), (280, 0.1))).$
- (20)  $GAR = AAR * GRRC.$
- (21)  $GC = AC * GRC.$
- (22)  $GGDP = AGDP * GRGDP.$
- (23)  $GP = AP * BR.$
- (24)  $GRC = 0.6 * ADGC^2 + GRCO * 0.4.$
- (25)  $GRCO = \text{WITH LOOKUP}(PCAI, ((65000, 0.06) - (100000, 0.2)), (66367, 0.1038), (69164, 0.1149), (76074, 0.1929), (82560, 0.1095), (83486.2, 0.0918), (90993, 0.1045), (97370, 0.0855))).$
- (26)  $GRGDP = 0.0855.$
- (27)  $GRRC = 0.026.$
- (28)  $IRC = \text{WITH LOOKUP}(PG, ((0, 0) - (1, 1)), (0, 0), (0.1, 0.11), (0.2, 0.22), (0.3, 0.34), (0.4, 0.46), (0.5, 0.58), (0.6, 0.67), (0.7, 0.75), (0.8, 0.83), (0.9, 0.91))).$
- (29)  $ISPT = CCT * (APC)^{0.5}.$
- (30)  $NE = PVANE * ACT * CRNC.$
- (31)  $NM = AP * NRPM.$
- (32)  $NRPM = 0.0066.$
- (33)  $PCAI = AGDP/AP.$
- (34)  $PG = \text{EXP}(DTC - 1).$
- (35)  $PVANE = 0.02.$
- (36)  $PVAR = AAR/ACT.$
- (37)  $RD = 0.2.$
- (38)  $SLPT = \text{WITH LOOKUP}(ISPT, ((0, 0) - (180, 1)), (5, 0.2), (10, 0.3), (15, 0.4), (20, 0.5), (30, 0.6), (40, 0.65), (60, 0.75), (80, 0.8), (100, 0.85), (150, 0.95))).$

$$(39) RP = AP * DR.$$

$$(40) SR = 0.067.$$

$$(41) TCCF = x.$$

## Competing Interests

The authors declare that they have no competing interests.

## Acknowledgments

This work has been partially supported by the Hujiang Foundation of China (A14006) and Shanghai First-Class Academic Discipline Project (S1201YLXK).

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