Hindawi Publishing Corporation
Discrete Dynamics in Nature and Society
Volume 2015, Article ID 769251, 9 pages
http://dx.doi.org/10.1155/2015/769251

Research Article

Research on Congestion Pricing in Multimode Traffic considering Delay and Emission

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Received 18 July 2014; Revised 24 September 2014; Accepted 25 September 2014

Academic Editor: Wuhong Wang

Rapid development of urbanization and automation has resulted in serious urban traffic congestion and air pollution problems in many Chinese cities recently. As a traffic demand management strategy, congestion pricing is acknowledged to be effective in alleviating the traffic congestion and improving the efficiency of traffic system. This paper proposes an urban traffic congestion pricing model based on the consideration of transportation network efficiency and environment effects. First, the congestion pricing problem under multimode (i.e., car mode and bus mode) urban traffic network condition is investigated. Second, a traffic congestion pricing model based on bilevel programming is formulated for a dual-mode urban transportation network, in which the delay and emission of vehicles are considered. Third, an improved mathematical algorithm combining successive average method with the genetic algorithm is proposed to solve the bilevel programming problem. Finally, a numerical experiment based on a hypothetical network is performed to validate the proposed congestion pricing model and algorithm.

1. Introduction

With the development of urbanization and automation, the supply and demand contradiction of urban traffic has become increasingly prominent as well as traffic jam, which has resulted in a series of problems, such as increasing travel delays and traffic emissions, more frequent traffic accidents, and reducing transportation efficiency. The primary reason of urban traffic congestion is the sharp contradiction between urban transport developing and land use. To ease this problem effectively, thousands miles of urban roads have been built in many Chinese cities recently, but this is not the feasible solution to mitigate congestion. For a few decades, congestion pricing has been considered to be an effective way for traffic demand management and revenue regeneration in many cities worldwide. It can balance the spatiotemporal distribution of travel demand by making travelers readjust their travel modes and routes to avoid congested roads. Thus, the traffic congestion can be alleviated and urban traffic system-wide operation efficiency can be improved.

The original motivation of congestion pricing is to reduce traffic congestion [1–5]. Now these corresponding models can generally be classified into two categories, namely, static and dynamic. Waiters proposed an optimal static congestion pricing model according to marginal cost pricing theory, and this model firstly defined that toll charge on each road section was the difference of marginal social cost and marginal individual cost [6]. Dafermos and Sparrow established a road charging model based on marginal charging theory [7], which was applied in multiclass-user transportation network subsequently [8]. Yang and Huang extended to study marginal cost pricing with the constraint of road traffic capacity [9]. In the field of dynamic congestion pricing, Vickrey built a congestion pricing model, considering the departure time of

the travelers at the bottleneck, to make toll pricing equal to queue time cost for system equilibrium [10]. Wie and Tobin developed two types of dynamic congestion pricing models based on the marginal cost pricing theory, and two dynamic charging models were appropriate for a network with stable travel demand and fluctuant travel demand, respectively [11]. Arnott et al. researched the bottleneck charging problem under the condition of random travel capacity and demand for further study [12]. Yang and Huang formulated a time-varying pricing model of a road bottleneck with elastic traffic demand based on optimal control theory [13]. Liu et al. proposed a mathematical programming with equilibrium constraint model for the speed-based toll design [14].

In recent years, given the ever-increasing concern on the sustainability of transportation, travel environments have received much attention and have been comprehensively considered in the travel mode choice. Nowadays, both emissions and other environmental factors are often taken into account in road pricing. It is believed that congestion pricing could lead to emission reduction and urban environment improvement. In this field, Johansson discussed how to apply marginal cost pricing theory to obtain the maximal net social benefit by internalizing marginal emissions and fuel consumption costs [15]. Nagurney et al. carried out a series of pioneering work on market-based policies and proposed a novel charging strategy to keep traffic emission within the limit of an environmental quality standard [16–18]. Yin and Lawphongpanich showed that a traffic flow distribution on a network with minimum emissions can always be induced by a toll charging scheme if link emission functions are increasing [19]. Chen and Yang studied nonnegative link toll schemes and cum rebate schemes for Pareto system optimum of congestion and emissions on a road network using a biobjective optimization approach [20]. Almodóvar et al. proposed a bilevel approach for estimating pollution tax to meet environmental goals [21]. Li et al. designed a road toll model considering congestion and environmental externalities on a congested network with uncertain demand [22]. Yang et al. presented an optimal toll approach for link-based emission pricing [23].

These aforementioned methods of urban road pricing mainly focus on single-mode transportation system, which consider environmental factors such as emission. However, few articles have been devoted to focusing on multimode transportation system, particularly on environment and congestion. Hence, a comprehensive congestion pricing approach, under multimode and environmental condition, should be developed to reduce travel delay and pollution emission, for the efficiency and sustainability of entire urban transportation system.

The rest of the paper is organized as follows: Section 2 constructs a bilevel programming model of dual-mode urban traffic congestion pricing considering delay and emissions and then proposes the algorithm combining the successive average method with the genetic algorithm. Section 3 performs a numerical simulation to test the applicability of the congestion pricing method on system operation and performance. Section 4 concludes the paper with a summary of the general findings.

2. Model Construction and Algorithm Solution

2.1. Model Construction. Firstly, the dual-mode pricing model in the paper assumes that the car and bus network are completely separated, and commuters could only transfer within the bus network. Secondly, the ultra-network theory, discussed by Nagurney and Dong [24], is applied in the urban multimode traffic network according to adding virtual nodes and links [25]. In the following network, traveler's cost perceptual psychology is described by proportional expansion and absolute expansion and extended to links and sections [26]. Finally, the Logit-SUE model is applied to analyze route choice behavior in the multimode traffic network.

Based on the above analysis, a dual-mode congestion pricing model considering delay and emission is established for car-commuters in this section. It can be represented by the following bilevel programming model.

2.1.1. The Upper-Level Model. The upper-level model of bilevel programming is the minimum sum of total delay and total emission caused by two modes:

$$\begin{aligned}\min_{\tau} \quad & Z(\tau) = \lambda \cdot vot \cdot \sum_{a \in A} t_a(x_a)\, x_a \\ & + (1-\lambda) \cdot \frac{voe}{100} \\ & \cdot \left(\sum_{a \in A_c} g_a(v_a) \frac{x_a}{N_c} l_a \right. \\ & \left. + \sum_{a \in A_b} \sum_{i \in I} g_a(v_a) \cdot hz_i \cdot \sigma_a^i \cdot l_a \right) \\ \text{s.t.} \quad & 0 \le \tau_a \le \tau_a^+, \quad \forall a \in A_c \\ & \tau_a = 0, \quad \forall a \in A_b. \end{aligned} \tag{1}$$

In this paper, buses and cars are regarded as heavy vehicles and light vehicles, respectively, and their emissions are calculated by (2). In the calculation, the specific parameter values of carbon dioxide, as the only emission gas, are described by Yao and Song [27]. Therefore,

$$g_a(v_a) = \begin{cases} \dfrac{\gamma_c^1}{v_a} + \gamma_c^2 v_a + \gamma_c^3 v_a^2 + \gamma_c^4, & \forall a \in A_c \\ \gamma_b^1 v_a + \gamma_b^2 v_a^2 + \gamma_b^3, & \forall a \in A_b, \end{cases} \tag{2}$$

$$t_a(x_a) = \begin{cases} t_a^0 \left[1 + \alpha \left(\dfrac{x_a}{N_c O_a} \right)^{\beta} \right], & \forall a \in A_c \\ t_a^0, & \forall a \in A_b, \end{cases} \tag{3}$$

in which,

$$v_a(x_a) = \frac{l_a}{t_a(x_a)}, \quad \forall a \in A. \tag{4}$$

The optimization goal of the upper-level model is to minimize the summation of total delay and total emission on the multimode network, where $Z(\tau)$ is the objective function;

λ is the total delay weight of this function, $\lambda \in [0,1]$; *vot* is the monetary cost of unit time (RMB/time); x_a is the commuter flow of link a; $t_a(\cdot)$ is the function of travel time cost on link a; *voe* is the monetary cost of unit emission; $g_a(v_a)$ is the emission function of link a; N_c is the average passengers number by car; l_a is the length of link a; hz_i is the frequency of bus line i; τ_a is the toll charge of link a; τ_a^+ is the upper bound of toll charges on link a; A_c is the set for car routes; A_b is the set for bus paths; γ_c^1, γ_c^2, γ_c^3, and γ_c^4 are the parameters of emission function by car; γ_b^1, γ_b^2, and γ_b^3 are the parameters of emission function by bus; when $a \in A_c$, t_a^0 is the free-flow travel time on link a; when $a \in A_b$, t_a^0 is the average travel time of bus on link a; α, β are the parameters of BPR function; v_a is the average travel speed on link a. Besides, σ_a^i is a 0-1 variable; if bus line i goes through path a, then $\sigma_a^i = 1$; otherwise $\sigma_a^i = 0$.

2.1.2. The Lower-Level Model. In the lower-level model, (5) is the probabilistic loading equation for Logit-SUE model. Equation (6) is the constraint for travel demand equilibrium. Equation (7) is the nonnegative flow constraint. Equation (8) is link flow conservation constraint. Equation (9) reflects commuters' travel variance of each mode in the relative cost structure and perceived cost:

$$f_k^w = d^w \frac{\exp\left(-\theta G_k^w\right)}{\sum_{r \in K^w} \exp\left(-\theta G_r^w\right)}, \quad \forall k \in K^w,\ w \in W, \tag{5}$$

$$\text{s.t.} \quad \sum_k f_k^w = d^w, \quad \forall w \in W, \tag{6}$$

$$f_k^w \geq 0, \quad \forall k \in K^w,\ w \in W, \tag{7}$$

$$x_a = \sum_w \sum_k f_k^w \delta_{ak}^w, \quad \forall a \in A, \tag{8}$$

where

$$G_k^w = \begin{cases} \sum_{a \in A_c} \left[vot \cdot k_c \cdot t_a\left(x_a\right) + \tau_a + vok \cdot l_a\right] \delta_{ak}^w, \\ \qquad\qquad \forall k \in K_c^w,\ w \in W \\ \sum_{a \in A_b} \left[vot \cdot k_b \cdot t_a\left(x_a\right) + voc_b \cdot h_a\left(x_a\right)\right] \delta_{ak}^w + s_k^w, \\ \qquad\qquad \forall k \in K_b^w,\ w \in W \end{cases} \tag{9}$$

$$h_a\left(x_a\right) = \begin{cases} 0, & \forall a \in A_c \\ \left(\dfrac{x_a}{O_a}\right)^n, & \forall a \in A_b \end{cases} \tag{10}$$

$$s_k^w = sm_k^w + st_k^w, \quad \forall k \in K_b^w,\ w \in W, \tag{11}$$

where f_k^w is the commuters' flow for path k between OD pair w; d^w is the travel demand between OD pair w; θ is the parameter for Logit-SUE model; G_k^w is the total cost on path k between OD pair w; W is the set of OD pairs; K^w is the valid path set between OD pair w, and $K^w = K_c^w \cup K_b^w$; δ_{ak}^w is the incidence matrix of link a, if link a is on the path k, $\delta_{ak}^w = 1$, otherwise $\delta_{ak}^w = 0$; *vok* is the monetary cost of fuel consumption per kilometer; k_c is the travel time perception expansion by car, and assume that $k_c > 1$; k_b is the travel time perception expansion on the bus, and we have that $k_b > k_c$; voc_b is the monetary cost per comfortable degree loss by bus; $h_a(x_a)$ is the function of comfort cost on link a; when $a \in A_c$, O_a is the traffic capacity on link a; when $a \in A_b$, O_a is the average traffic capacity of bus line a; s_k^w is the sum of bus replacement fare and transfer time cost on path k between OD pair w; sm_k^w is the replacement fare on path k; st_k^w is the perceived transfer time cost, which has an inverse relationship with the transferred bus frequency.

Valid path set, as the basic component of Logit-SUE assignment model, has important implications for traffic assignment results. There are a variety of effective path set methods proposed for SUE, such as Dial algorithm [28], full path set [29], and cumulative path set under user-equilibrium condition [30]. For simplicity, the efficient path set of absolute cost constraints is adopted to filter the feasible path. Based on multimode cost function in (9), commuters' preferences, and travel habits, we can obtain valid paths of each mode:

$$K_i^w = \left\{k \in R_i^w : G_{ko}^w \leq (1+\omega)\, G_{io}^{w-}\right\}, \quad \forall i \in \{c,b\},\ w \in W, \tag{12}$$

where R_c^w is the path set between OD pair w on car network; R_b^w is the path set between OD pair w on bus network; G_{co}^{w-} and G_{bo}^{w-} are the total monetary cost (RMB) of any link between OD pair w by car and bus under free-flow state, respectively; G_{ko}^w is the total cost (RMB) of path k between OD pair w under free-flow state.

2.2. The Algorithm. In the paper, the algorithm combining the successive average method (MSA) with the genetic algorithm (GA) is developed to solve the proposed bilevel programming pricing model. It aims to solve the lower Logit-SUE model and then to accurately evaluate the applicability of each chromosome in GA. The detail algorithm solution is shown as follows.

Step 1. According to (12), find the valid path set K^w between OD pair w.

Step 2. Enter the predetermined model parameters and set the initial path flow $f_k^w = 0, \forall k, w$.

Step 3. Update the link flow and travel cost and calculate and substitute the generalized travel cost G_k^w of each path in the set K^w based on (8).

Step 4. Load network traffic flow with Logit-SUE model and calculate the additional path flow $y_k^{w(n)}, \forall k, w$ according to (2).

Step 5. Calculate $f_k^{w(n+1)}$, according to $f_k^{w(n+1)} = f_k^{w(n)} + (1/n)\left(y_k^{w(n)} - f_k^{w(n)}\right)$, $\forall k, w, n \geq 1$.

Step 6. Examine the astringency, if $\left\| f_k^{w(n+1)} - f_k^{w(n)} \right\| \leq \varepsilon$, then stop; otherwise, set $n = n + 1$ and go to Step 3.

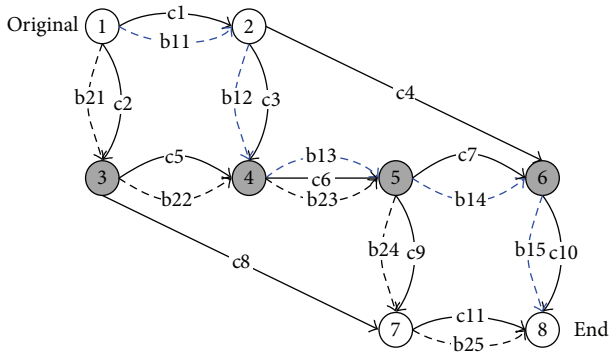


Figure 1: Numerical network including two modes.

3. Experimental Results

3.1. Experimental Road Network. The hypothetical network for numerical test, as shown in Figure 1, consists of two traffic modes: car and bus (c and b, resp.). The label of each link has a unique two-part name, mode-symbols and serial-codes. It is important to note, however, that the serial codes of bus network are the number combination of line and section, for example, b12 represents the second link on bus line 1.

In Figure 1, there are 8 nodes (including 4 grey internal transfer stations of bus) and 21 links. There are 11 links (c1~c11) for the car subnetwork and 2 lines, 11 sections (b11~b15 and b21~b25) for bus subnetwork. The net information is listed in Tables 1, 2, 3, and 4 and all the parameters remain fixed in the following schemes.

3.2. Experimental Parameters and Schemes. The normal values of all parameters in the congestion pricing model are given in Table 5. Suppose the other parameters are fixed when carrying out a parameter sensitivity analysis.

Based on the standard parameter values and (12), the effective path set of the dual-mode network is obtained in Table 6.

As shown in Table 6, there are 12 effective paths between OD pairs, including 6 paths of car network and 6 paths (including 4 transferred paths, which are number 8, number 9, number 11, and number 12) of bus network. Based on the above assumptions and results, two simulated test schemes in Table 7 are set up in this paper, which are the basic test analysis under charge and the analysis under charging or no-charging. Additionally, the corresponding model is the lower Logit-SUE model of the bilevel programming under the no-charging condition.

3.3. Test Scheme 1. To simplify the representation, the additional units are omitted in the following analysis. The results of test Scheme 1 in Table 7 contain two parts. On the one hand, the commuters' flow proportion change of each mode and change of total delay and total emission are shown in Figure 2, when the travel demand under charging increases from 500 to 5000. On the other hand, when the delay weight of the upper objective function increases from 0 to 1, the variations in commuters' flow proportion for each mode are depicted in Figure 3(a), and the variations of total delay and total emission are depicted in Figure 3(b), respectively.

In Figure 2, it shows that (i) commuters' flow proportion of the car has an increasing tendency with the travel demand, but oppositely bus share decreases, particularly when the total travel demand is over 3000. It indicates that the growth of comfort loss cost, due to bus crowding, is higher than growth of car travel time cost, particularly at a high travel demand (Figure 2(a)) and (ii) the total delay and the total emission increase gradually with the travel demand, and the growth rate of the total delay is slightly higher than that of total emissions. It demonstrates that the growth of travel demand, as compared to charging, leads to the deterioration of transportation system performance in Figure 2(b).

In Figure 3, it concludes that when the delay weight of objective function $\lambda \leq 0.4$, the growth of the target delay weight has no significant influence on the commuters'

Table 1: Physical properties of car network.

Link number	l_a (km)	Traffic capacity O_a (person/h)	Free-flow time t_a^0 (min)
c1	2	500	1.5
c2	2	500	1.5
c3	4	400	3
c4	12	300	9
c5	4	600	3
c6	6	600	4.5
c7	4	600	3
c8	12	300	9
c9	4	400	3
c10	2	500	1.5
c11	2	500	1.5

Table 2: Physical properties of bus network.

Link number	l_a (km)	Bus capacity O_a (person/h)	Average travel time t_a^0 (min)
b11	2	200	4
b12	4	200	8
b13	6	200	12
b14	4	200	8
b15	2	200	4
b21	2	240	4
b22	4	240	8
b23	6	240	12
b24	4	240	8
b25	2	240	4

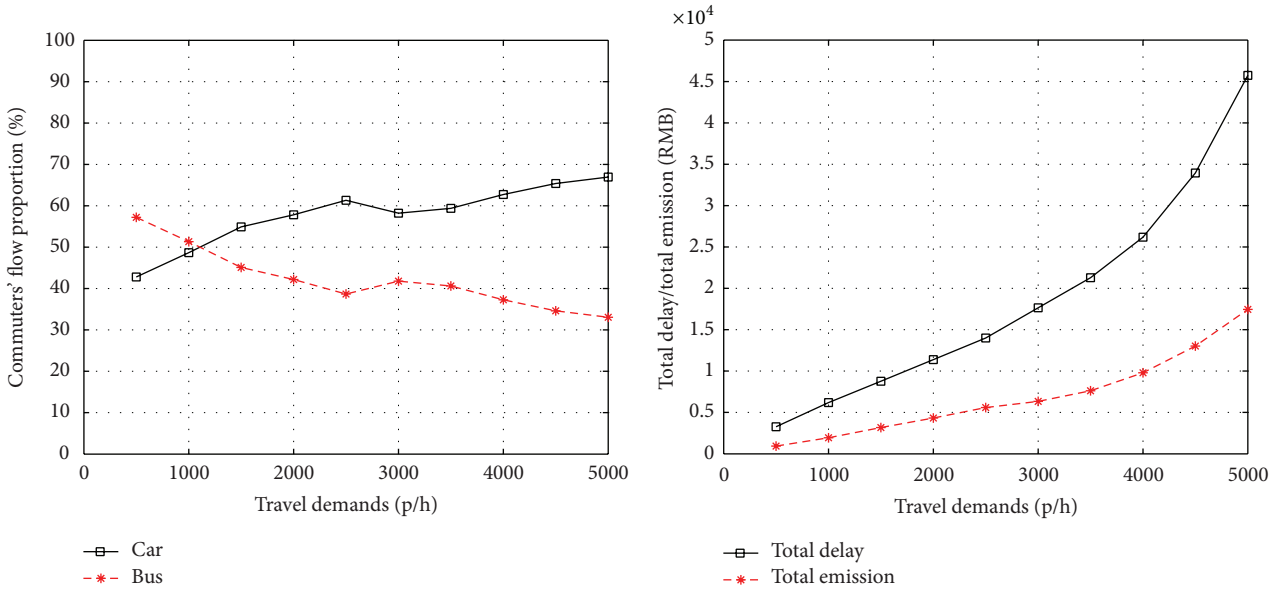
Table 3: Operative information of bus system.

Bus line number	Bus fare (RMB/person)	Frequency (trip/h)	Trip load (person/trip)
Bus line 1	1	5	40
Bus line 2	1	6	40

Table 4: Transfer information of bus system.

Transfer scheme	Replacement fare (RMB/person)	Waking time (min)	Waiting time (min)	Total time (min)
Bus line 1 → bus line 2	1	0	$0.5 \times 60/6$	5
Bus line 2 → bus line 1	1	0	$0.5 \times 60/5$	6

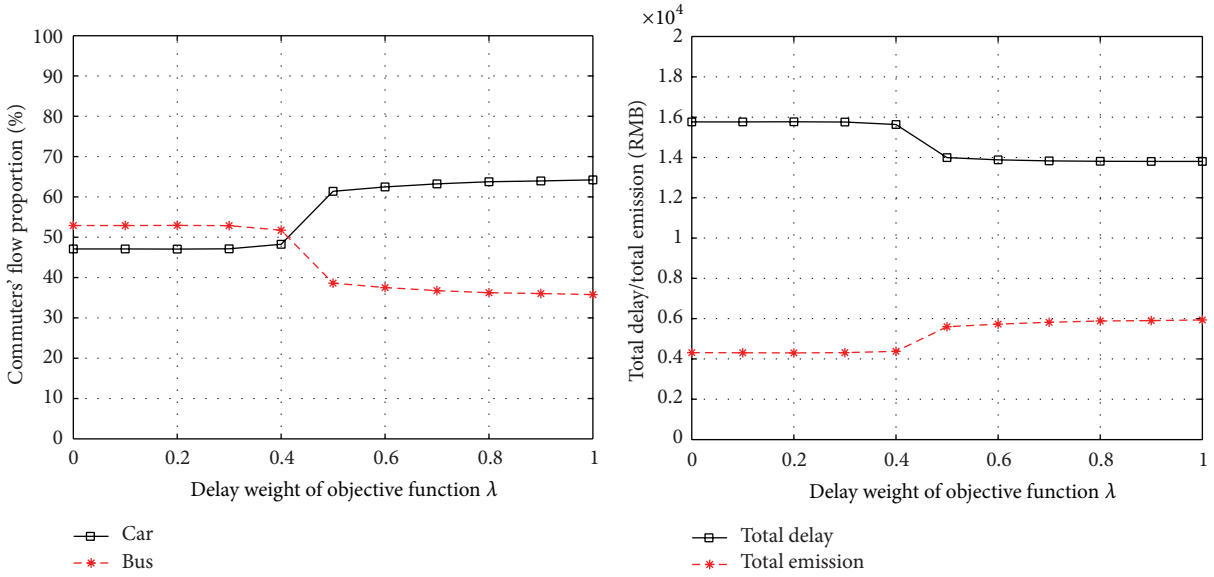
The replacement ticket price equals the bus target line fare, and waiting time is the half of the transferred bus line frequency.



(a) Value of commuters' flow proportion in terms of different travel demands

(b) Value of total delay and total emission in terms of different travel demands

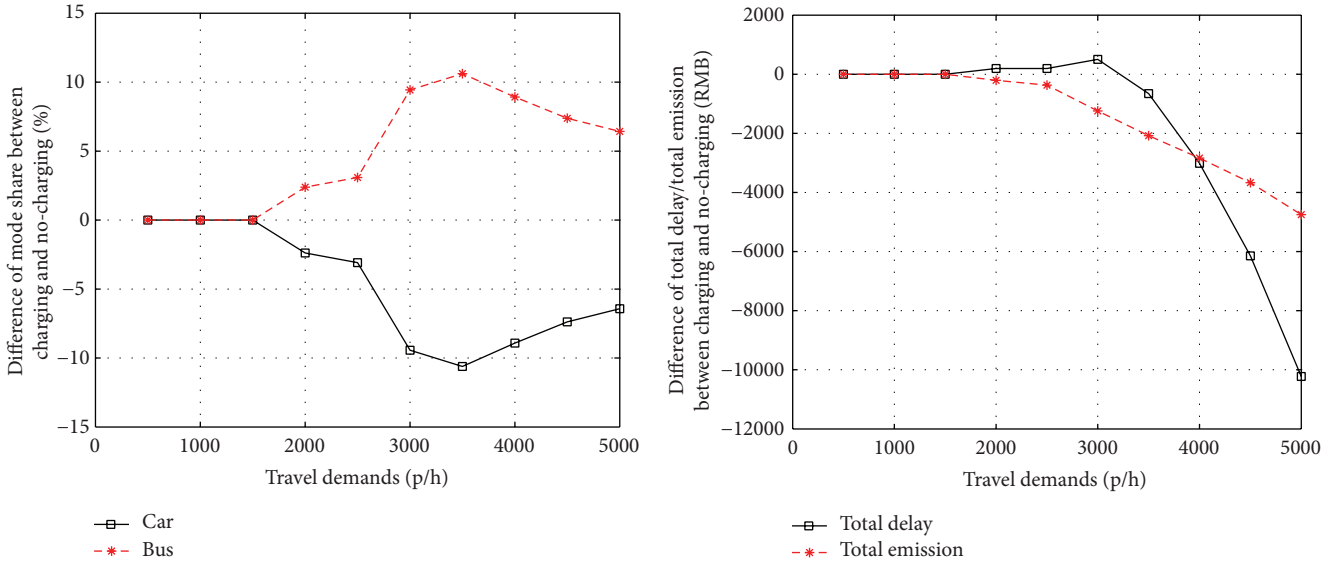
Figure 2: Sensitivity analysis of travel demand underpricing.



(a) Value of commuters' flow proportion in terms of different objective delay weight

(b) Value of total delay and total emission in terms of different objective delay weight

Figure 3: Sensitivity analysis of objective delay weight underpricing.



(a) Value of difference of mode share in terms of different travel demands

(b) Value of difference of total delay/total emission in terms of different travel demands

Figure 4: Comparative sensitivity analysis of travel demand between pricing and no-pricing.

Table 5: Normal value of the numerical parameters.

Parameter	Value (Unit)
vok	0.8 (RMB/km)
vot	0.25 (RMB/min)
voc_b	0.5 (RMB/comfort loss)
voe	0.15 (RMB/emission)
N_c	1.5 (person/pcu)
$\gamma_c^1, \gamma_c^2, \gamma_c^3, \gamma_c^4$	(3952.113, −3.061, 0.029, 223.289)
$\gamma_b^1, \gamma_b^2, \gamma_b^3$	(−20.024, 0.154, 951.390)
(α, β)	(0.15, 4)
ω	0.25
d_w	2500 (person/h)
τ_a^+	5 (RMB)
λ	0.5
k_c	1.0
k_b	1.15
θ	0.1
n	2

flow proportion of each mode and the total delay and total emission; but when $\lambda \geq 0.4$, it causes an increase of car commuters' flow proportion, the decline of bus share, the reduced total delay, and the increased total emission, and these effects will be smaller and smaller until disappearing along with increasing λ. Those indicate that (i) although the increase of delay weight is of benefit for reducing system-wide total delay, it leads to the decline of bus share and increasing total emissions and (ii) to promote low-carbon travel, bus service level also should be improved to reduce travel cost and further to promote system efficiency and travelers' benefits. In addition to the improvement of bus performance, the measures, including increasing bus frequency and reducing transfer cost, also should be taken in time by the authorities.

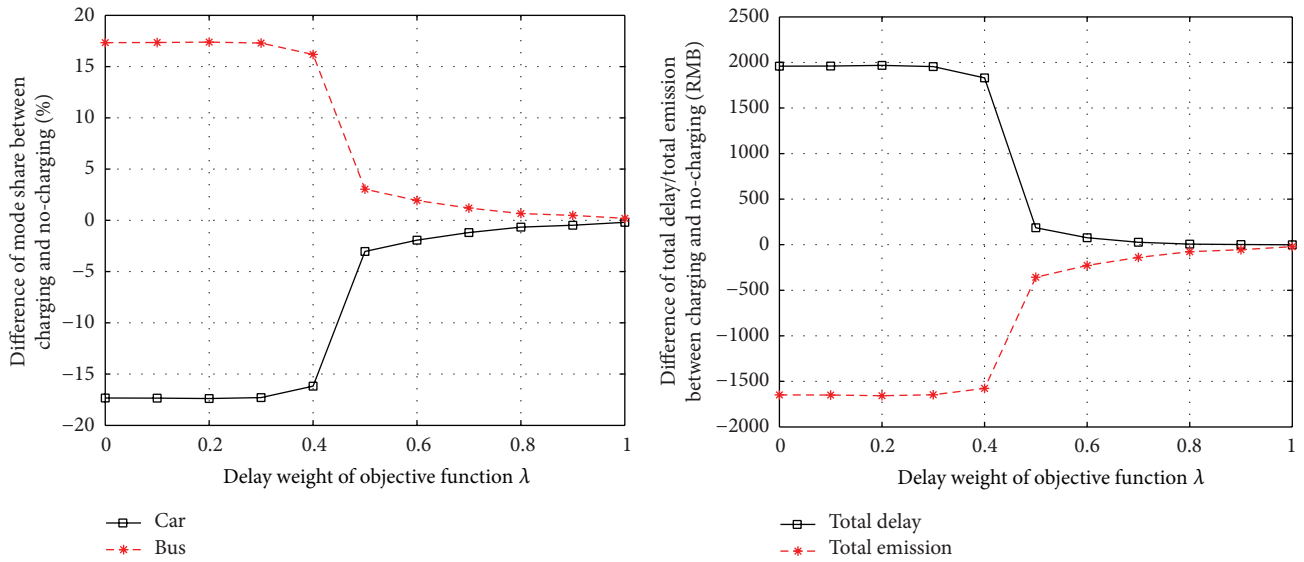
3.4. Test Scheme 2. In this section, the results of test Scheme 2 in Table 7 contain two parts. Firstly, when the travel demand increases from 500 to 5000, the commuters' flow proportion change of each mode and the change of the total delay and the total emissions between pricing and no-pricing can be shown in Figure 4. Secondly, when the delay weight of the upper objective function increases from 0 to 1, the commuters' flow proportion change of each mode and the change of total delay and total emission between pricing and no-pricing are shown in Figure 5. In this case, ordinate values in Figures 4 and 5 are equal to the difference of the corresponding values between toll charging and no-charging.

In Figure 4, it implies that (i) when the travel demand is less than 1500, road congestion pricing has little effect on commuters' share of car; (ii) when the travel demand is between 1500 and 3000, road pricing causes a slight increase of total network delay with the growth of travel demand; (iii) when the travel demand is equal to 3500, road pricing reaches to the maximum; (iv) with the travel demand over 3000, congestion pricing can effectively reduce the total delay of network and gradually increase with the growth of travel demands; and (v) no matter how much travel demand is, the implementation of road congestion pricing can reduce the total emission.

The aforementioned test addresses that, when the delay weight is equal to the emission weight, congestion pricing at medium travel demands can effectively affect commuters' travel mode choices and improve the bus share. The reason can be explained as that road pricing is the most conducive to exert the cost advantages of bus at medium travel demands. Meantime, road pricing promotes the increasing of bus users

Table 6: Information of the effective paths.

Traffic mode	Path number	Path info.	Initial total cost (RMB)
Car	1	c1 → c4 → c10	15.8
	2	c1 → c3 → c6 → c7 → c10	17.775
	3	c1 → c3 → c6 → c9 → c11	17.775
	4	c2 → c5 → c6 → c7 → c10	17.775
	5	c2 → c5 → c6 → c9 → c11	17.775
	6	c2 → c8 → c11	15.8
Bus	7	B11 → b12 → b13 → b14 → b15	11.8
	8	B11 → b12 → b13 → **b24** → b25	14.3625
	9	B11 → b12 → **b23** → b24 → b25	14.3625
	10	B21 → b22 → b23 → b24 → b25	11.8
	11	B21 → b22 → **b13** → b14 → b15	14.675
	12	B21 → b22 → b23 → **b14** → b15	14.675



(a) Value of difference of mode share in terms of different objective function delay weight

(b) Value of difference of total delay/total emission in terms of different objective delay weight

Figure 5: Comparative sensitivity analysis of objective delay weight between pricing and no-pricing.

Table 7: Numerical simulation scenarios.

Parameter variation	Test scheme		
	Scheme 1: basic test	Scheme 2: charging or not	
		No charging	Charging
Travel demand: $d^w = [500:1500:5000]$	Change of commuters' flow proportion by car and bus; change of total delay and total emission		
Objective delay weight: $\lambda = [0:0.1:1.0]$			

and plays a key role in sustained environmental improvement. However, it should not be implemented from the perspective of relieving congestion when travel demand is at a low level, because the average travel time of bus is longer than that of car. Instead, when travel demand is at a high level, pricing can significantly improve network performance due to apparent cost advantages of car.

According to Figure 5, it deduces that (i) no matter how much the target delay weight is, congestion pricing can not only improve the bus share and reduce the total emissions but also increase the total delay; (ii) when $\lambda \leq 0.4$, pricing has maximum effects on each parameter, and this effect has small relevance to the target delay weight in this range; and (iii) when $\lambda \geq 0.4$, with the increase of delay weight, the congestion pricing decreases positive effect for car commuters' proportions and the total emissions and weakens the negative impact of the total delay. The above results indicate that, when the traffic demand is at the medium level (travel demand is equal to 2500), there is a significant conflict between the optimization of travel mode share and relieving traffic congestion, even through congestion pricing.

4. Conclusions

Compared with the existing studies, this paper investigates the congestion pricing for dual-mode urban traffic network (car mode and bus mode) at first. Second, a traffic congestion pricing model based on bilevel programming with Logit-SUE is established for the bimode traffic network considering delay and emission. Third, an improved GA embedded MSA is presented to resolve the optimal pricing strategy. Finally, a numerical example is presented to illustrate the capabilities of the methodology and further indicates that (i) congestion pricing can increase the mode share of bus and thus contributes to reduce the total network emission and improve urban environment; (ii) when the travel demand is at a low level, it is difficult to make a tradeoff between reducing emission and relieving congestion; (iii) when the travel demand is at a high level, congestion pricing could raise bus share and reduce total emission.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

This study is supported by Shan Dong Transport Science and Technology Program (no. 2012A43).

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