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Research Article

Optimization Scheme of Tradable Credits and Bus Departure Quantity for Travelers' Travel Mode Choice Guidance

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To analyze the influence of tradable credits and bus departure quantity on travelers' travel mode choice, this study investigated car travel and bus travel as research objects and established a two-mode day-to-day travel mode choice model based on tradable credits and bus departure quantity. To improve the guiding effect of tradable credits and bus departure quantity, an optimization scheme of tradable credits and bus departure quantity was developed with the goal of minimizing the system total travel time of car travel and the system total comprehensive cost of bus travel. Taking a test transportation network as an example, the influence of no tradable credits scheme, tradable credits scheme, and tradable credits and bus departure quantity scheme on the travelers' travel mode choice behavior was analyzed. The results showed that the tradable credits and bus departure quantity scheme could reduce the saturation of road traffic and improve bus service quality.

1. Introduction

How to alleviate urban traffic congestion has become a popular research topic. Currently, the methods of alleviating urban traffic congestion are mainly divided into traffic supply management and traffic demand management. In terms of traffic supply management, improving the overall supply capacity of the urban road network is the main measure to alleviate the relationship between traffic supply and demand. It mainly includes two aspects, expanding the scale and optimizing the structure of a road network, and dynamically adjusting the supply capacity of a road network based on the temporal and spatial distribution of traffic demand. The finiteness of urban land resources determines that it is unsustainable to continuously expand the scale of a road network. Therefore, optimizing its structure has become an effective way to improve the supply capacity of an urban road network. The theory and method of network design (e.g., Farahani et al. [1], Chen and Xu [2], and Lu et al. [3]) provide strong support for optimizing the structure of an urban road network. In respect to dynamically adjusting network supply capacity, reversible lanes (e.g., Zhang and Gao [4], and Frejo et al. [5]) and ramp metering (e.g., Zhao et al. [6] and Kan et al. [7]) are powerful measures to optimize the network supply capacity, which can effectively alleviate the awkward situation of the coexistence of idle road resources and traffic congestion.

In terms of traffic demand management, the guidance methods of travel mode choice are important ways to alleviate traffic congestion. At present, the research on travel mode choice guidance methods is mainly concentrated on adjusting the proportion of car travel and improving the service quality of public transport. The methods for adjusting the proportion of car travel mainly include congestion pricing (e.g., Cheng et al. [8] and Zhou et al. [9]) and tradable credit schemes (e.g., Wang et al. [10] and Zang et al. [11]). Currently, the implementation of congestion pricing has a solid theoretical foundation and advanced technical

support, including the electronic toll collection systems implemented in cities such as Singapore, London, and cities in Norway (e.g., Mark [12], Prud'homme and Bocarejo [13], and Shao et al. [14]). However, compared with congestion pricing, tradable credit schemes are a fairer and more transparent choice for travelers. Dales [15] first proposed the concept of a tradable credit scheme. Verhoef et al. [16] promoted the concept of tradable credits in traffic demand management. In recent years, the tradable credit scheme has been expanded in different ways. These mainly include heterogeneous users (e.g., Xiao et al. [17] and Wang and Huang [18]), the income effect (Wu et al. [19]), transaction costs (Nie [20]), bottleneck congestion management (Tian et al. [21]), and controlling the dynamic traffic flow evolution (e.g., Guo et al. [22] and Ye and Yang [23]).

The specific measures for improving the service quality of public transport include bus lane construction (e.g., Steiner and Irnich [24] and Zhao and Zhou [25]), urban rail transit network construction (e.g., Li et al. [26] and Wang et al. [27]), and bus route optimization (e.g., Zhang and Xu [28] and Yan et al. [29]). Although these measures can encourage travelers to choose public transport, they also increase the operating costs of public transportation. Ison [30] examined the attitudes of key stakeholder groups with respect to urban road pricing and proved that income distribution to public transport is usually preferable to investment in road infrastructure. Wu et al. [31] believed that the key to an effective travel mode guidance optimization plan is determining the appropriate fuel tax rate and the number of bus departures and then establishing a guidance optimization model based on these.

Overall, adjusting the proportion of car travel can effectively adjust the car travel demand, and improving the service quality of public transport can attract some travelers to travel by public transport, but this may increase the operating cost of public transport. To solve this problem, the suggestions are made for transport managers to levy tradable credits on car travelers and subsidize the new added operating cost of public transport through the total revenue from these tradable credits levied on car travelers. In terms of the tradable credits scheme, Miralarnaghi and Peeta [32, 33] proposed a multiperiod tradable credits scheme to reduce vehicular emissions. Seilabi et al. [34] supposed that the transportation authority distributed travel credits to travelers directly and instantaneously and presented an AV-enabled tradable credits scheme to manage travel demand. Grant-Muller and Xu [35, 36] designed a tradable credits scheme based on economic measure and demonstrated that the tradable credits scheme can affect travelers' mode choice. Shirmohammadi et al. [37, 38] established the identity between congestion pricing and tradable credits scheme in managing network mobility and designed a tradable credits scheme to maintain the queue length of the bottleneck for homogenous travelers. Zang et al. [39] analyzed the management performance of a tradable credits scheme for high-occupancy vehicle lanes and proved that an optimal tradable credits scheme was achievable in the basic system by restricting the traffic flow of general-purpose lanes. Miralinaghi et al. [40] proposed the use of a tradable credit mechanism to manage morning commuter congestion. Tian et al. [41] demonstrated that a tradable mobility credit scheme was fairly efficient and financially sustainable in traffic demand management. These research achievements showed that the tradable credits scheme has good applicability in traffic demand management. Based on this, this study proposed an optimization scheme based on tradable credits and bus departure quantity. In this optimization scheme, the price of tradable credits was determined by the transport managers, and travelers could only purchase additional tradable credits from the transport managers. The total revenue from the scale of tradable credits in that month was used to subsidize the total operating cost of bus departure increment. The free tradable credits determined the car travel demand on the road network and affected the total revenue of transport managers selling additional tradable credits, which meant that they affected the determination of bus departure increment. Moreover, increasing bus departure quantity could improve the bus service quality and decrease the car travel demand, which meant that it affected the determination of the free tradable credits.

The paper is structured as follows. The next section establishes a two-mode day-to-day travel mode choice model based on tradable credits and bus departure quantity. Section 3 constructs an optimization model of tradable credits and bus departures quantity and proposes a solution algorithm for the optimization model. In Section 4, the feasibility of this optimization model and its solution algorithm are verified. In Section 5, the conclusions of this research are drawn.

2. Two-Mode Day-to-Day Travel Mode Choice Model Based on Tradable Credits and Bus Departure Quantity

To analyze the influence of tradable credits and bus departure quantity on travelers' travel mode choice, we divide travelers into car and carless travelers. In the transportation network, we assume that carless travelers can only choose to travel by bus, car travelers can choose to travel by car or bus, and car travelers who choose to travel by car must have a tradable credit on that day. Furthermore, we suppose that q_{ij}^{o} is the travel demand of car travelers on OD pair (i, j), q_{ij}^{n} is the travel demand of carless travelers on OD pair (i, j), M is the number of days in the month, and the transport managers issue $k\,(0 < k \leq M)$ free tradable credits to individual car travelers in that month. In other words, they issue kq_{ij}^{o} is free tradable credits to group car travelers. If a car traveler needs additional tradable credits, he can only purchase tradable credits from the transport managers, and the price of tradable credit is ρ_{tc}. Based on this, it can be determined that the maximum number of group car travelers who purchased tradable credits is $(M - k)q_{ij}^{o}$. For readability, some of the main variables and parameters are listed in Table 1.

Table 1: Main variables and parameters.

Variables	Description
q_{ij}^{o}	The total demand for car travelers on OD pair (i, j)
q_{ij}^{n}	The total demand for carless travelers on OD pair (i, j)
$q_{ij}^{b}(t)$	The bus travel demand on OD pair (i, j) at day t
$q_{ij}^{c}(t)$	The car travel demand on OD pair (i, j) at day t
$d_{ij}^{c}(t)$	The total demand for car travel on OD pair (i, j) from day 0 to day t
M	The number of days in the month
k	Free tradable credits to individual car travelers in that month, and $0 < k \le M$
y_0	The initial bus departure quantity on OD pair (i, j)
$\Delta y(t)$	The bus departure increment on OD pair (i, j) at day t
$y(t)$	The bus departure quantity on OD pair (i, j) at day t
$f_{ij}^{b}(t)$	The bus flow on OD pair (i, j) at day t
$f_{ij}^{c}(t)$	The car flow on OD pair (i, j) at day t
$f_{ij}(t)$	The total flow on OD pair (i, j) at day t
$c_{ij}^{t}(t)$	The travel time on OD pair (i, j) at day t
$c_{ij}^{cr}(t)$	The in-bus congestion degree on OD pair (i, j) at day t
$c_{ij}^{tc}(t)$	The tradable credits average cost on OD pair (i, j) at day t
$\pi_{ij}^{b}(t)$	The comprehensive cost of bus travel on OD pair (i, j) at day t
$\pi_{ij}^{c}(t)$	The comprehensive cost of car travel on OD pair (i, j) at day t
$\mathrm{ETCQ}_{ij}^{c}(t)$	The excess tradable credits quantity on OD pair (i, j) at day t
$z_{ij}^{b}(t)$	The expected comprehensive cost of bus travel at day t
$z_{ij}^{c}(t)$	The expected comprehensive cost of car travel at day t

2.1. Comprehensive Cost of Bus Travel. Suppose that ς is the conversion coefficient between bus and equivalent car, and $y(t) = y_0 + \Delta y(t)$ is the bus departure quantity on OD pair (i, j) at day t. Then, the bus flow $f_{ij}^{b}(t)$ on OD pair (i, j) at day t can be expressed as

$$f_{ij}^{b}(t) = \varsigma y(t). \tag{1}$$

The total flow $f_{ij}(t)$ on OD pair (i, j) at day t can be written as

$$f_{ij}(t) = f_{ij}^{c}(t) + f_{ij}^{b}(t). \tag{2}$$

Hence, the travel time $c_{ij}^{t}(t)$ on OD pair (i, j) at day t can be written as

$$c_{ij}^{t}(t) = c\left(f_{ij}(t)\right), \tag{3}$$

where $c(\cdot)$ is the traditional Bureau of Public Roads (BPR) link travel time function.

We define the in-bus congestion degree $c_{ij}^{cr}(t)$ as

$$c_{ij}^{cr}(t) = \gamma\left(\frac{q_{ij}^{b}(t)}{y(t)B_b}\right)^{\varpi}, \tag{4}$$

where γ is the conversion coefficient between the degree of bus congestion and the travel time, B_b is the maximum passenger capacity per bus unit, and ϖ is the congestion coefficient.

Suppose that the waiting interval $c_{ij}^{w}(t) = 1/y(t)$, and the comprehensive cost $\pi_{ij}^{b}(t)$ of bus travel on OD pair (i, j) at day t is the weighted sum of travel time $c_{ij}^{t}(t)$, waiting interval $c_{ij}^{w}(t)$, in-bus congestion degree $c_{ij}^{cr}(t)$, and bus ticket price ρ_{ij}^{s}. It can be expressed as

$$\begin{aligned}\pi_{ij}^{b}(t) &= \alpha_1 c_{ij}^{t}(t) + \alpha_2 c_{ij}^{w}(t) + \alpha_3 c_{ij}^{cr}(t) + \alpha_4 \rho_{ij}^{s},\\ &= \alpha_1 c\left(f_{ij}(t)\right) + \alpha_2 \frac{1}{y(t)} + \alpha_3 \gamma\left(\frac{q_{ij}^{b}(t)}{y(t)B_b}\right)^{\varpi} + \alpha_4 \rho_{ij}^{s},\end{aligned} \tag{5}$$

where α_1, α_2, α_3, and α_4 are the conversion coefficients.

2.2. Comprehensive Cost of Car Travel. It is known that group car travelers can obtain kq_{ij}^{o} free tradable credits in that month, and the total demand $d_{ij}^{c}(t)$ for car travel on OD pair (i, j) from day 0 to day t can be expressed as

$$d_{ij}^{c}(t) = \sum_{\tau=0}^{t} f_{ij}^{c}(\tau). \tag{6}$$

When $d_{ij}^{c}(t) - \mathrm{kq}_{ij}^{o} \le 0$, the quantity of excess tradable credits $\mathrm{ETCQ}_{ij}^{c}(t)$ on OD pair (i, j) at day t is equal to zero; when $0 < d_{ij}^{c}(t) - \mathrm{kq}_{ij}^{o} \le f_{ij}^{c}(t)$, the quantity of excess tradable credits $\mathrm{ETCQ}_{ij}^{c}(t)$ on OD pair (i, j) at day t is equal to $d_{ij}^{c}(t) - \mathrm{kq}_{ij}^{o}$; when $d_{ij}^{c}(t) - \mathrm{kq}_{ij}^{o} > f_{ij}^{c}(t)$, the quantity of excess tradable credits $\mathrm{ETCQ}_{ij}^{c}(t)$ on OD pair (i, j) at day t is equal to $f_{ij}^{c}(t)$. Thus, the relationship between $\mathrm{ETCQ}_{ij}^{c}(t)$ and $d_{ij}^{c}(t) - \mathrm{kq}_{ij}^{o}$ can be expressed as

$$\mathrm{ETCQ}_{ij}^{c}(t) = \min\left\{f_{ij}^{c}(t),\ \max\left\{d_{ij}^{c}(t) - \mathrm{kq}_{ij}^{o}, 0\right\}\right\}. \tag{7}$$

Considering the complexity of individual car travelers who purchase tradable credits, we propose a concept of tradable credits average cost from the perspective of group car travelers and define the tradable credits average cost $c_{ij}^{tc}(t)$ on OD pair (i, j) at day t as the quantity of excess tradable credits $\mathrm{ETCQ}_{ij}^{c}(t)$ multiplied by the tradable credits unit price ρ_{tc} and divided by the car flow $f_{ij}^{c}(t)$. This can be expressed as

$$c_{ij}^{tc}(t) = \frac{\rho_{tc}\mathrm{ETCQ}_{ij}^{c}(t)}{f_{ij}^{c}(t)}. \tag{8}$$

Suppose that the comprehensive cost $\pi_{ij}^{c}(t)$ of car travel on OD pair (i, j) at day t is the weighted sum of travel time $c_{ij}^{t}(t)$, tradable credit average cost $c_{ij}^{tc}(t)$, and fuel price ρ_{ij}. It can be expressed as

$$\begin{aligned}\pi_{ij}^{c}(t) &= \beta_1 c_{ij}^{t}(t) + \beta_2 c_{ij}^{tc}(t) + \beta_3\rho_{ij},\\ &= \beta_1 c\left(f_{ij}(t)\right) + \beta_2\frac{\rho_{tc}\mathrm{ETCQ}_{ij}^{c}(t)}{f_{ij}^{c}(t)} + \beta_3\rho_{ij},\end{aligned} \tag{9}$$

where β_1, β_2, and β_3 are the conversion coefficients.

2.3. Two-Mode Day-to-Day Travel Mode Choice Model. Considering the influence of the travelers' travel behavior and transportation network status at day $t-1$ on the travelers' travel behavior at day t (Liu et al. [42]), we suppose that carless and car travelers choose their travel mode based on their minimum expected comprehensive cost and define the expected comprehensive cost at day t as the weighted sum of the expected comprehensive cost at day $t-1$ and the comprehensive cost at day $t-1$. Then, the expected comprehensive cost $z_{ij}^{c}(t)$ of car travel and the expected comprehensive cost $z_{ij}^{b}(t)$ of bus travel at day t can be expressed as

$$z_{ij}^{c}(t) = \phi z_{ij}^{t}(t-1) + (1-\phi)\pi_{ij}^{c}(t-1), \tag{10}$$

$$z_{ij}^{b}(t) = \varphi z_{ij}^{b}(t-1) + (1-\varphi)\pi_{ij}^{b}(t-1), \tag{11}$$

where ϕ (or φ) denotes a constant weight corresponding to car (or bus) travelers, which reflects the preference between the comprehensive cost of the car (or bus) travel and the expected comprehensive cost of car (or bus) travelers, and $\phi, \varphi \in [0, 1]$.

Suppose that ε_{ij}^{c} is the understanding error of car travel, and ε_{ij}^{b} is the understanding error of bus travel. If ε_{ij}^{c} and ε_{ij}^{b} are independent of each other and obey the Gumbel distribution with zero means, it can be deduced that the travel mode choice behavior of car travelers satisfies the Logit model. Hence, the car travel demand $q_{ij}^{c}(t)$ on OD pair (i, j) at day t can be written as

$$\begin{aligned}q_{ij}^{c}(t) &= q_{ij}^{o}\cdot\Pr\left(z_{ij}^{c}(t) + \varepsilon_{ij}^{c} \le z_{ij}^{b}(t) + \varepsilon_{ij}^{b}\right),\\ &= q_{ij}^{o}\frac{\exp\left(-\theta z_{ij}^{c}(t)\right)}{\sum_{m=\{c,b\}}\exp\left(-\theta z_{ij}^{m}(t)\right)},\end{aligned} \tag{12}$$

where $\theta(\theta > 0)$ reflects the sensitivity of car travelers to the expected comprehensive cost, where a larger value of θ indicates more sensitivity and vice versa. According to Formula (12), the bus travel demand $q_{ij}^{b}(t)$ on OD pair (i, j) at day t can be expressed as

$$\begin{aligned}q_{ij}^{b}(t) &= q_{ij}^{n} + q_{ij}^{o} - q_{ij}^{c}(t),\\ &= q_{ij}^{n} + q_{ij}^{o} - q_{ij}^{o}\frac{\exp\left(-\theta z_{ij}^{c}(t)\right)}{\sum_{m=\{c,b\}}\exp\left(-\theta z_{ij}^{m}(t)\right)}.\end{aligned} \tag{13}$$

Using Formulas (10), (11), (12), and (13), the two-mode day-to-day travel mode choice model can be written as

$$\left\{\begin{array}{l} z_{ij}^{c}(t) = \phi z_{ij}^{t}(t-1) + (1-\phi)\pi_{ij}^{c}(t-1),\\ z_{ij}^{b}(t) = \varphi z_{ij}^{b}(t-1) + (1-\varphi)\pi_{ij}^{b}(t-1),\\ q_{ij}^{c}(t) = q_{ij}^{o}\dfrac{\exp\left(-\theta z_{ij}^{c}(t)\right)}{\sum_{m=\{c,b\}}\exp\left(-\theta z_{ij}^{m}(t)\right)},\\ q_{ij}^{b}(t) = q_{ij}^{n} + q_{ij}^{o} - q_{ij}^{c}(t),\end{array}\right\} \tag{14}$$

3. Optimization Model of Tradable Credits and Bus Departure Quantity

3.1. Model Formulation. The guidance of travel mode choice based on tradable credits and bus departure quantity is expected to guide some car travelers to take the bus by adjusting the quantity of free tradable credits and bus departure and subsidize the total operating cost of bus departure increment with total revenue from the scale of tradable credits in that month. Based on this, an optimization model of tradable credits and bus departure quantity is proposed. It is formulated to comprehensively optimize the system total travel time of car travel and system total comprehensive cost of bus travel. It can be expressed as

$$\min_{k,\Delta y} F = \sum_{t=1}^{M} c_{ij}^{t}(t)q_{ij}^{c}(t) + \sum_{t=1}^{M}\pi_{ij}^{b}(t)q_{ij}^{b}(t) \tag{15}$$

subject to

$$\rho_{tc} \ge 0,\ y_0 \ge 0,\ \Delta y \ge 0, \tag{16}$$

$$\sum_{t=1}^{M}\rho_{tc}\mathrm{ETCQ}_{ij}^{c}(t) \ge \Delta y\sigma, \tag{17}$$

$$z_{ij}^{c}(t) = \phi z_{ij}^{t}(t-1) + (1-\phi)\pi_{ij}^{c}(t-1), \tag{18}$$

$$z_{ij}^{b}(t) = \varphi z_{ij}^{b}(t-1) + (1-\varphi)\pi_{ij}^{b}(t-1), \tag{19}$$

$$f_{ij}^{c}(t) = q_{ij}^{c}(t) = q_{ij}^{o}\frac{\exp\left(-\theta z_{ij}^{c}(t)\right)}{\sum_{m=\{c,b\}}\exp\left(-\theta z_{ij}^{m}(t)\right)}, \tag{20}$$

$$q_{ij}^{b}(t) = q_{ij}^{n} + q_{ij}^{o} - q_{ij}^{c}(t), \tag{21}$$

where F represents the objective function, and σ is the operating cost of the unit bus departure quantity. The first item on the right side of formula (15) is the system total travel time of car travel, and the second item is the system total comprehensive cost of bus travel. Formula (16) is the nonnegative constraint on the price of tradable credit, the initial bus departure quantity, and bus departure increment. Formula (17) is the constraint to ensure that the total operating cost of bus departure increment cannot be higher than the total revenue from the scale of tradable credits in that month. Formulas (18) and (19) are the day-to-day evolution process of the expected comprehensive travel costs of car travel and bus travel, respectively. Formula (20) is the constraint of car travel demand. Formula (21) is the constraint of car travel demand.

3.2. Model Solution. Considering the complexity of the solution process for the optimization model of tradable credits and bus departure, we propose an iterative algorithm in this section. The detailed steps are described as follows:

(i) Step 1 (initialization). The days M of the month, the free tradable credits k of the month, the operating cost σ of the unit departure quantity, and the initial bus departure increment Δy are given.

(ii) Step 2: solve the two-mode day-to-day travel mode choice model, and obtain the value of F and the total revenue $\sum_{t=1}^{M} \rho_{ij} \mathrm{ETCQ}_{ij}^{c}(t)$.

(iii) Step 3: calculate the maximum bus departure increment $\Delta y_{\max} = \mathrm{floor}\,(\sum_{t=1}^{M} \rho_{ij} \mathrm{ETCQ}_{ij}^{c}(t)/\sigma)$. If $\Delta y \le \Delta y_{\max}$, then set $\Delta y = \Delta y + 1$ and go to Step 2. Otherwise, set $\Delta y = \Delta y - 1$ and go to Step 4.

(iv) Step 4: solve the two-mode day-to-day travel mode choice model and obtain the value of F. If $k < M$, then set $k = k + 1$ and return to Step2. Otherwise, record F, k, and Δy.

(v) Step 5: compare the value of F under various numbers of free tradable credits and stop. Finally, $(k, \Delta y)$ is the solution of this optimization model under the minimal F.

Besides, the solving steps of the two-mode day-to-day travel mode choice model are described as follows:

(i) Step 1 (initialization). The total demand q_{ij}^{n} of carless travelers, the total demand q_{ij}^{o} of car travelers, the initial bus departure quantity y_0, the initial car flow $f_{ij}^{c}(0)$, the initial day t, the maximum passenger capacity B_b per bus unit, the bus ticket price ρ_{ij}^{s}, the fuel price ρ_{ij}, the unit tradable credits price ρ_{tc}, and the parameters γ, ϖ, ς, α_1, α_2, α_3, α_4, β_1, β_2, β_3, ϕ, and φ are given.

(ii) Step 2: calculate the comprehensive cost $\pi_{ij}^{b}(t)$ of the car and the travel comprehensive cost $\pi_{ij}^{c}(t)$ of car travel according to Formulas (5) and (9), respectively.

(iii) Step 3: calculate the expected comprehensive cost $z_{ij}^{c}(t)$ of car travel and the expected comprehensive cost $z_{ij}^{b}(t)$ of bus travel according to Formulas (18) and (19), respectively.

(iv) Step 4: calculate the car travel demand $q_{ij}^{c}(t)$ and the bus travel demand $q_{ij}^{b}(t)$ according to Formulas (20) and (21), respectively.

(v) Step 5: calculate the quantity of excess tradable credits $\mathrm{ETCQ}_{ij}^{c}(t)$ according to Formula (7), and calculate the tradable credits average cost $c_{ij}^{tc}(t)$ according to Formula (8).

(vi) Step 6: if $t \ge M$, then calculate the value of F and the total revenue $\sum_{t=1}^{M} \rho_{ij} \mathrm{ETCQ}_{ij}^{c}(t)$. Otherwise, set $t = t + 1$ and return to Step 2.

4. Calculations and Analysis of Numerical Example

To validate the proposed optimization scheme of tradable credits and bus departure quantity, we suppose that there is a transportation network connecting the living area i to the work area j, travelers have complete traffic information, and travelers can only choose to travel by car or bus in the transportation network. The transportation network will use the traditional BPR link travel time function in the following form:

$$c_{ij}^{t}\left(f_{ij}(t)\right) = c_{ij}^{0}\left[1 + 0.15\left(\frac{f_{ij}(t)}{K_{ij}}\right)^{4}\right], \tag{22}$$

where c_{ij}^{0} is the free flow travel time on OD pair (i, j), and K_{ij} is the road capacity on OD pair (i, j).

In this numerical example, we suppose that the total demand of car travelers $q_{ij}^{o} = 4000$, the total demand of carless travelers $q_{ij}^{n} = 3000$, the fuel price $\rho_{ij} = 20$, the unit of tradable credits price $\rho_{tc} = 200$, the initial bus departure quantity $y_0 = 130$, the conversion coefficient $\varsigma = 2$, the maximum passenger capacity $B_b = 30$, the bus ticket price $\rho_{ij}^{s} = 2$, the free flow $c_{ij}^{0} = 20$, and the road capacity $K_{ij} = 3000$.

4.1. Calculation Results Exhibition. According to the solution algorithm of this optimization model, we select the system parameter $M = 31$, $\alpha_1 = 1$, $\alpha_2 = 7200$, $\alpha_3 = 30$, $\alpha_4 = 1$, $\beta_1 = 2.2$, $\beta_2 = 0.5$, $\beta_3 = 0.5$, $\gamma = 1$, $\theta = 0.03$, $\varphi = 0.5$, $\phi = 0.5$, and $\sigma = 32000$. The calculation results are presented as follows.

In Figure 1, we can observe that the objective function F is the minimum value when the free tradable credits $k = 18$. This means that the solution of the model can be derived from the proposed solution algorithm. When the free tradable credits $k = 18$, the bus departure increment

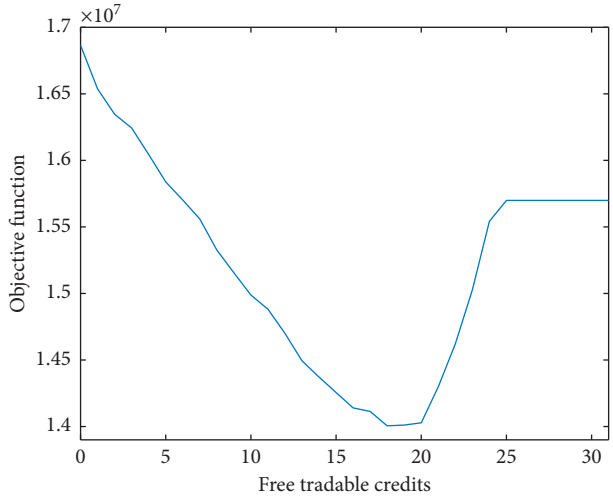

Figure 1: The process of objective function changing with free tradable credits.

$\Delta y = 37$. It should be noted that there is no excess quantity of tradable credits and the objective function when $k \geq 24$; that is, all travelers who choose to travel by car have free tradable credits.

The system performance before and after optimization of the tradable credits and bus departure quantity are listed in Table 2. Compared to the system performance before optimization, the system total comprehensive cost $\sum_{t=1}^{M} \pi_{ij}^{b}(t) q_{ij}^{b}(t)$ of bus travel has decreased by 7.5%, and the system total travel time $\sum_{t=1}^{M} c_{ij}^{t}(t) q_{ij}^{c}(t)$ of car travel has decreased by up to 26.4%. This also reflects the important role of the proposed optimization scheme in traffic demand management.

4.2. Scheme Comparison and Analysis. In this section, we will compare and analyze the three schemes of no tradable credits scheme (NTCS), tradable credits scheme (TCS), and tradable credits and bus departure quantity scheme (TC-BDQS). We select $k = 31$ and $\Delta y = 0$, $k = 18$ and $\Delta y = 0$, and $k = 18$ and $\Delta y = 37$ to represent the above three schemes, respectively. The results of the calculation are listed in Table 3.

In Table 3, we can observe that the road saturation under TCS and TC-BDQS is lower than that of NTCS. Compared with NTCS, road saturation under TCS has decreased by 7.7%, but the saturation in buses has increased by 6.7%. This shows that TCS can reduce road saturation, but it may lead to a decrease in bus service quality. Compared with TCS, road saturation under TC-BDQS has decreased by 9.3%, and the bus travel demand has increased by 8.9%, but the saturation in buses has decreased by up to 15.1%. This also reflects that TC-BDQS can not only guide some car travelers to take the bus but also improve the bus service quality.

Table 2: The system performance before and after optimization.

Optimization scenario	$\sum_{t=1}^{M} c_{ij}^{t}(t) q_{ij}^{c}(t)$	$\sum_{t=1}^{M} \pi_{ij}^{b}(t) q_{ij}^{b}(t)$	F
Before optimization	2.46×10^6	1.32×10^7	1.56×10^7
After optimization	1.81×10^6	1.22×10^7	1.40×10^7

Table 3: The results of the calculation under three schemes.

Scheme	Total flow	Road saturation	Bus travel demand	Saturation in buses
NTCS	3409	1.136	3851	0.988
TCS	3145	1.048	4115	1.055
TC-BDQS	2851	0.950	4483	0.895

5. Conclusions

This paper established a two-mode day-to-day travel mode choice model based on tradable credits and bus departure quantity, designed an optimization scheme for these, and proposed an iterative algorithm for this scheme. Numerical examples verified the effectiveness of the proposed optimization scheme and its solution algorithm and showed the influences of NTCS, TCS, and TC-BDQS on the travelers' travel mode choice behavior. The results showed that TCS and TC-BDQS could reduce the saturation of road traffic, but TCS may lead to a decrease in bus service quality, whereas TC-BDQS could improve the bus service quality.

Beyond the above preliminary research work, there are many interesting avenues for further study. An ongoing extension of this study is to introduce the transportation condition of multiple vehicle types and multiple OD pairs in the optimization model of tradable credits and bus departure

quantity. Another future research direction is to consider the heterogeneity of travelers' travel model choice behavior in travel demand management.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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