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Management of Commuters' Travel Behaviors: A Tradable Credits Scheme Approach Based on Commuters' Travel Utilities

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Abstract. A novel Tradable Credits Scheme (TCS) is approached to effectively control the urban commuters' travel behaviors in this study. To analyze the travelers' behaviors affected by the TCS, a residents' travel utility model is established. Under the constraint of travel expenses, we analyze commuters' travel mode and discuss the relationship between supply and demand. The pricing of tickets is then explored for trading market regulation. A numerical example is further preformed to compare different commuters' (characterized as different groups) behaviors. Results show that reasonable price is the premise of the market stability, and the TCS can improve the rate of public transport trip effectively.

Introduction

In recent years, with the rapid development of economy, the increased number of private cars have led to serious traffic jam in metropolis. However, the capacity of existing road network cannot accommodate the number of vehicles in urban areas. As an emerging traffic demand management, Tradable Credits Scheme(TCS) has taken rising attention recently, since it can effectively control the commuters' travel behaviors and mitigate the traffic congestion.

Yang (2005) first proposed the concept of TCS based on the emission trading theory from Dales. At present, there are two main related theoretical researches: 1) one is based on the model of traditional system optimization (SO) that determines the optimal link traffic of urban road network and puts forward various mathematical models and algorithms, then designs the ticket transaction system with the optimal system. 2) Other scholars learned from the individual carbon trading market mechanism [2-3], they focus on establish in a reasonable trading market from the overview of economics, then perfecting the trading strategy and making a reasonable transaction price. Nie [4] proposed an auction and bargaining market in the TCS. Grant-Muller and Xu [5-6] adopted the constant elasticity of substitution(CES) approach to describe residents' travel utilities. In fact, the Cobb-Douglas is the special form of CES utility function. Meanwhile, the CD utility function has often been chosen in consumer's behavior analysis due to its advantageous explanatory, and its consequences on the assumptions with respect to the existence and uniqueness.

Considering the lack of individual travel and trading behaviors of previous works in the TCS, this paper formulates a model to describe commuters' utilities, and compare the general situation with the TCS, A numerical example is performed to analyze different commuters' (characterized as different groups) behaviors

The Explanation of the TCS

The TCS in this study is a traffic demand management policy based on the market mechanism, which controls the residents' travels in urban areas. The TCS can reduce automobile exhaust emissions and mitigate urban road congestion. Under the TCS, the management will issue a certain number of initial road tickets to qualified residents and determine the total amount of ticket distribution and the term of validity. During the TCS period, commuters can choose different trips

for travel and they need to pay appropriate amount of road tickets that can be traded in the competitive market. According to their own situation, travelers choose to buy or sell. The transport management agency or government is not participating in regulation or receive tax benefits. Travelers can accept policy due to less conflict for transaction system.

Under the personal travel utility, the government no longer charges tickets for each road. The mileages of car travel are set as a new road tickets. We assume residents invest a certain fee on trips every month. They can meet their travel in two ways: car or mass. In the TCS, residents need to deliver the ticket in accordance with car travel mileages. All travelers can be divided into two groups, i.e., higher tickets commuters and less tickets commuters. For higher tickets commuters, they use private cars for traveling more frequent so that their car kilometers beyond the initial allocation of mileage. To ensure their own travel demands, they should buy extra tickets. For less tickets commuters, they rarely use a private car to travel, their travel tickets are remaining, they can choose to sell the extra travel tickets and therefore obtain additional subsidies. These two groups establish the relationship between supply and demand, In the trading ticket market, higher ticket commuters are the demand side, and the less ticket commuters are the supply side. They handle the travel transactions at a reasonable price. This paper assumes that there is no reselling behavior in the trading market and the residents can only act as a party in the supply and demand relationship.

Modeling for the TCS Incorporating Commuters' Travel Utilities

In this paper, residents can choose to use a car or use public transport in their daily travel, pursing to maximize their own utilities. And it should be subject to their travel budget. We therefore adopt the Cobb-Douglas (CD) function to describe consumption utility of the individual inhabitants, such as $\max U = x^{a} y^{\beta}$ [7-9], where x and y are two different travel modes respectively, α and β denote the travel preference,.

General Travel Utility Model

For the N residents, we assume that commuters pursue the greatest travel utility for travel and their travel constraint by the travel cost, the travel utility model as shown in Eq. (1)

$$\begin{aligned} &\max U_i = x_i^{\alpha} y_i^{\beta} \qquad (i = 1, 2, 3...N) \\ &p_1 x_i + p_2 y_i \le I_i \\ &x_i \ge 0 \\ &y_i \ge 0 \end{aligned} \tag{1}$$

Where x_i denotes the mileage of private car, y_i denotes the mileage of mass, I_i denotes the travel expenses, p_1 denotes the unit mileage price of private car, p_2 denotes the unit mileage price of mass, α and β denote the travel preferences of private car and mass respectively. We have $\alpha + \beta = 1$ and $\alpha, \beta \ge 0$.

Eq. (1) is a linear program, the Karush–Kuhn–Tucker (KKT) optimal conditions are shown as:

$$\begin{aligned} &\alpha x_i^{\alpha-1} y_{2i}^{1-\alpha} - \theta_1 p_1 + \theta_2 = 0 \\ &(1-\alpha) x_i^{\alpha} y_i^{-\alpha} - \theta_1 p_2 + \theta_3 = 0 \\ &\theta_1 (p_1 x_i + p_2 y_i - I_i) = 0 \\ &\theta_2 x_i = 0 \\ &\theta_3 y_i = 0 \end{aligned} \tag{2}$$

Where θ denotes the shadow price, θ_1 denotes the unit growth of utility when the cost changes, θ_2 and θ_3 denote the marginal utility of travel mileages respectively. We then obtained:

$$x_i = \frac{I_i}{p_1}\alpha \tag{3}$$

$$y_i = \frac{I_i}{p_2}(1-\alpha) \tag{4}$$

Travel Utility Model of TCS

Compare with the general travel, the commuters have an identity after implementing the TCS. Each commuter can only act as a purchaser or a seller, which indicates that people can only buy or sell. This setting can eliminate the behavior of reselling tickets. For all commuters, besides personal travel consumption expenditures, their tickets must meet their travel demand. According to this rule, for individual commuter of car group, the travel utility function can be expressed as follows:

$$\begin{aligned} &\max U_i = x_i^{\alpha} y_i^{\beta} \qquad (i = 1, 2, 3...N) \\ &p_1 x_i + p_2 y_i + p_e \varphi_i \le I_i \\ &x_i - \varphi_i \le \omega \\ &x_i \ge 0 \\ &y_i \ge 0 \end{aligned} \tag{5}$$

The KKT optimization condition is described as:

$$\begin{aligned} &\alpha x_i^{\alpha-1} y_i^{1-\alpha} - \theta_4 p_1 - \theta_5 + \theta_6 = 0 \\ &(1-\alpha) x_i^{\alpha} y_i^{-\alpha} - \theta_4 p_2 + \theta_7 = 0 \\ &\theta_4 p_e - \theta_5 = 0 \\ &\theta_4 (p_1 x_i + p_2 y_i + p_e \varphi_i - I_i) = 0 \\ &\theta_5 (x_i - \varphi_i - \omega) = 0 \\ &\theta_6 x_i = 0 \\ &\theta_7 y_i = 0 \end{aligned} \tag{6}$$

where ω_i denotes the initial allocation tickets, p_e denotes the trading price, φ_i denotes the trading volume.

$$x_i = \frac{I_i + p_e \omega}{p_1 + p_e}\alpha \tag{7}$$

$$y_i = \frac{I_i + p_e \omega}{p_2}(1-\alpha) \tag{8}$$

$$\varphi_i = \frac{\alpha I_i + [(\alpha - 1)p_e - p_1]\omega}{p_1 + p_e} \tag{9}$$

Commuters who use private car to travel are need to pay attention to the travel ticket situation: i.e., if $\varphi_i > 0$, it denotes these travels belong to the higher ticket commuters, they purchase more travel tickets to meet their travel demand, if $\varphi_i \le 0$, it denotes they belong to the less ticket

commuters and they have remaining tickets, these residents sell excess travel tickets to obtain travel subsidy.

Trading Market

Trading Price. In the ticket market, the key issue is to make clear the supply-demand relationship. The less ticket commuters as the supply side sell the road tickets, the high tickets commuters as the demand side buy the road ticket, the market clearing satisfies that the demand equals the supply.

We assume that there are *n* high tickets commuters and *m* less tickets commuters, it satisfies $\left|\sum_{i=1}^{n}\varphi_i\right| = \left|\sum_{j=1}^{m}\varphi_j\right|$, we can get the equilibrium price in clearing market.

$$p_e = \frac{\frac{\alpha}{N}\sum_{i=1}^{N} I_i - \omega p_1}{(1-\alpha)\omega} \tag{10}$$

Once transaction price is higher than p_e, the supply exceeds the demand. On the contrary, once transaction price is less than p_e, the demand exceeds the supply.

Initial Ticket Allocation. The initial allocation mode is the foundation of the tickets mechanism, and the reasonable distribution pattern is related to the effectiveness of TCS. In this paper, we use the average allocation mode, it takes the total mileage of the private car that traveled by all residents as the total historical data of the TCS. Each resident obtains the same amount of allocation and the initial ticket is equal distribution. The formula is as follows.

$$\omega = \frac{\lambda Q}{N} \tag{11}$$

Where Q denotes total car mileage in general situation, λ denotes the target ratio.

Numerical Examples

In this section, we provide a numerical example to analyze the results of the preceding context. According to the studies[7,9], $p_1 = 1(¥/km)$, $p_2 = 0.5(¥/km)$, α=0.9, β=0.1. It is assumed that 400 people are divided into three groups based on travel expenses: A (300 ¥), B(600 ¥), C(800 ¥). We obtain the mileages of general as shown in Table 1.

Table 1 The travel of residents in general condition

Group	$x_i(km)$	$y_i(km)$	$\mu = \frac{y_i}{x_i + y_i}$
A	270	60	0.18
B	540	120	0.18
C	720	160	0.18

By calculating, we get $Q = 207000(km)$. We control 90% of the car mileages amount in general, so λ=0.9, here $\omega = 466(km)$, Once the market clearing is finished, the trading price is equal to $p_e = 1.11(¥)$. The commuters travel mileages and trading volume as shown in Table 2.

Table 2 The travel of residents in Tradable Credits Scheme

Gourp	$x_i'(km)$	$y_i'(km)$	$\mu=\frac{y_i'}{x_i'+y_i'}$	$\varphi_i(km)$
A	349	164	0.32	-117
B	476	224	0.32	10
C	562	264	0.32	96

From Table 2, Group A as the supply side in the market sell their spare tickets for subsidies, Group B and C as high tickets commuters, they purchase extra tickets to meet their own travel and as a demand side in market, C needs to buy more tickets than B.

Table 3 Comparison of results

Group	$\Delta x_i(km)$	$\frac{\Delta x_i}{x_i}$	$\Delta y_i(km)$	$\frac{\Delta y_i}{y_i}$	$\Delta x_i+\Delta y_i(km)$	$\frac{\Delta x_i+\Delta y_i}{x_i+y_i}$
A	79	29%	104	173%	183	55.5%
B	-64	-11.9%	104	86/7%	40	6.1%
C	-158	-22%	104	65%	-56	-6.4%

From Table 3, we indicate that group A's travel mileage is increased more obvious, because they sell the ticket in exchange for additional subsidies and take the income for travel, then they can use car more. While B and C are constrained by ticket, they take bus more frequently instead of car travel. Meanwhile, the mass rate of three groups increased from 0.18 to 0.32, which conforms to Tradable Credits Scheme that encourage commuters to travel by public transport.

Through deduction and analysis, we found that the transaction price determines the market supply and demand. When $p_e=1.11(¥)$ that means the market clearing, Once the market price is below p_e, high tickets commuters maintain the original travel, and that lead to increasing requirement and demand exceeds supply on the ticket market. While the price is higher than p_e, commuters can sell tickets to bring more subsidies. The less tickets commuters try to sell more tickets in return for extra income, and some high tickets commuters reduce ticket expenses due to the increasing travel costs, they take bus or subway for travel rather than car. It leads to the ticket hoarding and supply exceeds the demand. Therefore, a reasonable trading price can not only guarantee the balance between supply and demand in transaction market, but also effectively control the choice of urban residents' trip mode, and fundamentally realize the management of traffic travel demand.

Conclusion

As a novel way of traffic demand management, the TCS approached in this paper extends the current theoretical researches. We discussed the effects of distribution pattern based on travel mileages, we further analyzed the results through a numerical example and find that:

(1) The commuters' travel choices are constrained by travel costs, and different travel costs can determine different travel mode choices.

(2) The initial ticket allocation is related to the transaction behavior for different travel groups, and further determines their role orientation.

(3) Reasonable ticket pricing determines the balance between travel supply and travel demand, i.e., lower price can lead to increased demand and insufficient supply for road tickets, and excessive pricing prompt a large number of tickets to enter the market that affecting market operation.

Making an appropriate pricing strategy can not only improve the mechanism, but also effectively control urban residents' travel. For future works, we will consider mixed traffic mode, more flexible trading behaviors, more reasonable ticket allocation strategies and pricing mechanisms.

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