Incentive Scheme for Low-carbon Travel Based on the Public-private Partnership and Personal Trip Carbon Accounts

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1 INTRODUCTION

The transportation sector accounts for 26% of the total emission worldwide[1]. Continuous growth in vehicle ownership and the inadequate usage of public transit have exacerbated traffic congestion and urban pollution. One solution is to encourage shifts to public transit through congestion pricing and subsidies. However, it may raise fairness disputes and fiscal deficit issues. Recently, Zhang *et al.* (2023) described a novel method to reduce carbon emission with personal carbon accounts. Inspired by that, we introduce personal trip carbon accounts (PTCAs) as an incentive to induce individual low-carbon travel behavior and reduce traffic emission. The idea is that each traveler has a carbon account to store credits awarded for choosing low-carbon travel modes. These credits can then be redeemed for rewards such as coupons and gifts. As far as we know, theoretical analysis of the PTCAs-based incentive scheme in transportation studies remains limited.

This paper proposes a PPP-PTCAs scheme based on the public-private partnership (PPP) where the government and the private sector work together to promote low-carbon travel. The main contributions are as follows. First, results show that a triple-win situation for the government, the private sector, and travelers can be realized, which sheds light on traditional incentives only involving the government/enterprises. Second, heterogeneous travelers and elastic demand are considered. Third, we explore the impact of government budget allocation strategies on the performance of the scheme.

2 METHODOLOGY

The government subsidizes the potential private sector to participate in providing personal trip carbon accounts. The private sector leverages these subsidies to incentivize travelers to adopt low-carbon transportation modes through attractive rewards based on accumulated carbon credits. This collaborative approach forms a PPP-PTCAs scheme. Figure 1 illustrates the framework and the relationships among travelers, the private sector, and the government.

This study examines a single OD system with a total travel demand of N, where travelers choose between high-carbon (e.g., private cars) and low-carbon (e.g., public transit) modes, resulting in distinct emission levels. The government allocates its constrained budget between direct pollution control measures and indirect subsidies to the private sector to minimize the total social cost associated with emission reduction. The private sector, comprising financial institutions, enterprises, and a carbon platform, provides low-carbon benefits B for transit travelers, funded by government subsidies S. The value of B is determined by the service level of financial

[1]https://www.iea.org/reports/co2-emission-in-2023

institutions A, participation level of enterprises p, and development level of a carbon platform q of the private sector. Taking China's Ant Forest as an example, banks (financial institutions) that issue legal qualifications, Alibaba (enterprise) that takes responsibility for green travel initiatives, and Ant Forest (carbon platform) that records and accounts for emission, collaborate to provide PTCAs. Enhancing A, p, and q incurs higher costs but increases low-carbon user engagement and platform usage which can bring potential future benefits to the private sector.

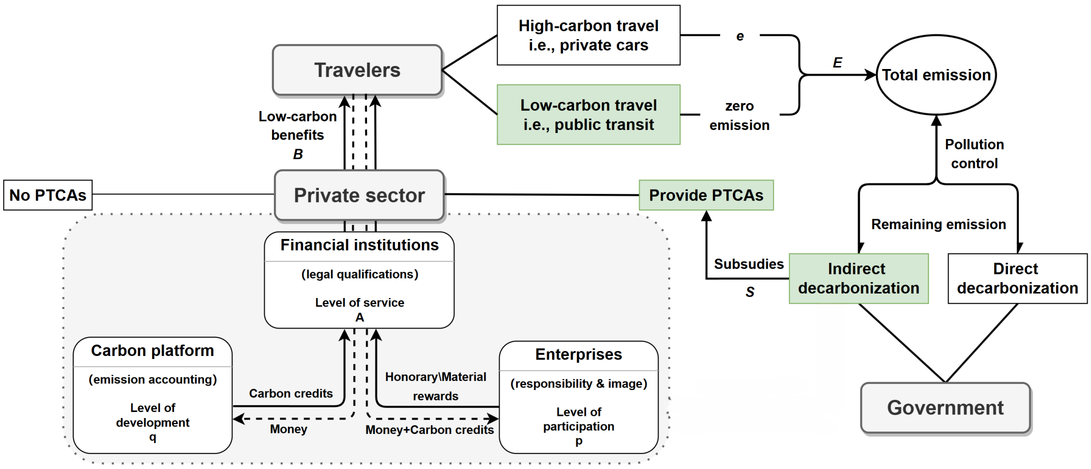

Figure 1 – *Framework of the PPP-PTCAs scheme*

2.1 User equilibrium of heterogeneous travelers

Travel cost generally include time cost and monetary cost. The PPP-PTCAs scheme also considers low-carbon benefits related to carbon credits. The travel cost of the two travel modes can be formulated as follows:

$$TC_{n,1} = \kappa(n)\, t_1 + c_1 - b \tag{1}$$

$$TC_{n,2} = \kappa(n)\, t_2 + c_2 \tag{2}$$

where $TC_{n,1}$ and $TC_{n,2}$ respectively represent the travel cost of the high-carbon trip and the low-carbon trip for the nth traveler with heterogeneous value of time (VOT) $\kappa(n) \geq 0$. Transit travel time t_1 is fixed and the ticket price is monetary cost c_1. Each transit traveler can receive carbon credits b, whose size depends on the number of transit travelers and the private sector's decisions, as shown in Eq.(5). Car travel time t_2 follows the BPR function $t_2(n_2) = t_0\left(1 + \alpha\left(\frac{n_2}{V}\right)^{\beta}\right)$. Fuel and insurance fees are monetary cost c_2. There are no carbon credits for car travelers. n_1 and n_2 are the total number of transit travelers and car travelers, respectively, satisfying fixed travel demand and non-negative constraints: $n_1 + n_2 = N$ and $n_1, n_2 \geq 0$.

Suppose travelers' heterogeneous VOT κ is continuously distributed with a cumulative distribution function, i.e., $\kappa \sim F(\kappa)$. $F(\kappa)$ is assumed to be strictly increasing and differentiable over its support $[\kappa^-, \kappa^+]$. The corresponding probability density function is represented by $f(\kappa) = F'(\kappa)$. Let all travelers be labeled by their VOT in a decreasing order and $\kappa(n)$ denote the VOT of the nth traveler. Assume that $\kappa(n)$ is continuous and differentiable. Clearly, $\kappa'(n) \leq 0$. The relationships between $\kappa(n)$ and $F(\kappa)$, and $\kappa'(n)$ and $f(\kappa)$ are given by: $\kappa(n) = F^{-1}\left(1 - \frac{n}{N}\right)$ and $\kappa'(n) = -\frac{1}{Nf(\kappa(n))}$.

According to Wardrop's principle, travelers always choose the travel mode with the minimum travel cost. When the system reaches user equilibrium, no traveler can reduce their individual travel cost by unilaterally changing their travel behavior. The travel cost of the nth traveler is:

$$TC_n = \min_{i\in\{1,2\}} \{TC_{n,i}\}, \forall n \in [0, N] \tag{3}$$

Eq.(3) is always satisfied in equilibrium. In extreme cases when one travel mode i overweighs another one i', for $\forall n \in [0, N]$, we have $n_i = N, n_{i'} = 0$ and $TC_{n,i} < TC_{n,i'}$.

2.2 The utility of the private sector

Financial institutions, enterprises, and a carbon platform compose the private sector. They share cost of low-carbon benefits $B\left(A,p,q\right)$ and take into account governmental subsidies $S\left(s,n_1\right)$, and potential benefits $G\left(A,p,q\right)$ to maximize the utility:

$$\max_{A,p,q} FU = -B\left(A,p,q\right) + S\left(s,n_1\right) + G\left(A,p,q\right) \tag{4}$$

In Eq.(4), the private sector's low-carbon cost B is the sum of each traveler's credits b. Following the work of Zha *et al.* (2016), the participation level of enterprises $p \in (0,1)$, the development level of the carbon platform $q \in (0,1)$ and the service of financial institutions A are regarded as "inputs", and low-carbon benefits B are regarded as "outputs". Then, a Cobb Douglas production function can be adopted for:

$$B\left(A,p,q\right) = Ap^e q^f = n_1 b \tag{5}$$

where e, f are given parameters. So, credits-based rewards b for each traveler is $b = \frac{B}{n_1}$.

In our framework, the private sector deserves government subsidies which is positively correlated with the number of transit travelers n_1 and the government's unit subsidy s, i.e., $S\left(s,n_1\right) = sn_1$. Besides, the increase in user flow of transit travelers will bring potential benefits $G\left(A,p,q\right) = \frac{KApq}{A+(K-A)e^{-rn_1+h}}$ (Smirnov & Wang, 2020), characterized by an S-shaped growth trend with n_1. Here, K, h, and r are constants. K affects the overall size, h determines the location of the inflection point on the S-shaped curve, and r is the growth rate.

In case of opportunistic behavior, Eq.(4) must satisfy the following constraint expressed in Eq.(6), which ensures that the low-carbon benefits provided by the private sector to each transit traveler exceed the direct subsidies provided by the government:

$$b \geq s \tag{6}$$

2.3 The social cost of the government

The government optimum is to minimize social cost which considers three parts: total travel cost $tt\left(n_1\right)$, subsidies to the private sector $S\left(s,n_1\right)$, and the emission reduction utility $u\left(n_1,\gamma\right)$.

$$\min_{\gamma,s} SC = tt\left(n_1\right) + S\left(s,n_1\right) - u\left(n_1,\gamma\right) \tag{7}$$

where $tt\left(n_1\right) = \int_{n_2^*}^{N} TC_{n,1} dn + \int_0^{n_2^*} TC_{n,2} dn$ and n_2^* is the total number of car travelers in the equilibrium travel flow. Total travel cost is an integral of the heterogeneous travelers' travel cost. The emission reduction utility is the net benefit arising from the difference between the increase in social welfare due to improved air quality and the cost incurred by pollution control, formulated as $u\left(n_1,\gamma\right) = m\varDelta E - \pi\gamma E$. Here, $\varDelta E$ is the total emission reduction (g) through direct and indirect measures, m is the value of emission reduction (RMB/pkm) and π is the unit pollution control cost (RMB/g). It is related to the number of transit travelers n_1 and the level of government commitment to direct pollution control $\gamma \in [0,1]$. Let E represents the total carbon emission. Suppose public transit in this article is a zero-emission travel mode. Then, the total carbon emission in equilibrium is only related to cars, which is denoted by a separable emission function (g/veh) (Yin & Lawphongpanich, 2006, Chen & Yang, 2012):

$$E = e\left(n_2\right) \cdot n_2 = 0.2038 \cdot t_2\left(n_2\right) \cdot \exp\left(0.7962 \cdot \frac{l}{t_2\left(n_2\right)}\right) \cdot n_2 \tag{8}$$

Let $\bar{E}$ be the total carbon emission without the intervention of the government or the private sector. Denote $\rho \in (0,1]$ as the emission reduction goal set by the government. The larger ρ is, the higher the cost. Considering the remaining emission must be less than that without the intervention and the government budget is limited in reality, Eq.(7) has two constraints: $E - \gamma E \leq \bar{E} - \rho\bar{E}$ and $0 \leq \pi\gamma E + S \leq C_{bgt}$. Here, $E\gamma$ is the amount of the emission realized by the government pollution control and C_{bgt} is the upper limit of the government budget.

3 NUMERICAL STUDY & DISCUSSION

This section compares and analyzes the results of four schemes to demonstrate the superiority of the proposed PPP-PTCAs.

The benchmark scheme p_0 has neither low-carbon benefits nor subsidies, the government-led scheme p_1 only has traveler-targeted subsidies, the private sector-led scheme p_2 only has low-carbon benefits, and the PPP-PTCAs scheme p_3 has both low-carbon benefits and subsidies. Supposing the emission reduction goal is $\rho = 50\%$, the results of demand $N = 1000, 1500, 2000$ are shown in Table 1.

Table 1 – *Results of Four Schemes for Different Demands*

Demand	1000				1500				2000			
Scheme	p_0	p_1	p_2	p_3	p_0	p_1	p_2	p_3	p_0	p_1	p_2	p_3
n_1	213.7	270.7	529.3	562.3	386.1	572.6	1001.6	1081.9	656.5	970.2	1353.6	1458.0
b	-	0.5	2.5	3.1	-	1.1	3.5	3.9	-	1.8	3.5	4.0
A	-	0.0	1298.7	1520.8	-	0.0	3491.1	4216.9	-	0.0	4752.6	5736.1
p	-	0.0	1.0	1.0	-	0.0	1.0	1.0	-	0.0	1.0	1.0
q	-	0.0	1.0	1.0	-	0.0	1.0	1.0	-	0.0	1.0	1.0
s	-	0.5	0.0	2.1	-	1.1	0.0	2.7	-	1.8	0.0	2.8
γ	-	46.0%	0.0%	0.0%	-	39.3%	0.0%	0.0%	-	32.5%	0.0%	0.0%
FU	0.0	0.0	17620.1	18360.7	0.0	0.0	23156.1	25964.5	0.0	0.0	30520.4	34365.6
SC	26208.0	26202.7	25217.0	26185.2	39789.3	39603.2	36901.6	39387.4	53942.2	53266.9	49198.2	52576.4
ΔE	0.0(0.0%)	3604.9(50.0%)	2918.2(40.5%)	3705.0(51.4%)	0.0(0.0%)	5231.4(50.2%)	5879.3(56.4%)	6612.7(63.5%)	0.0(0.0%)	6492.4(50.1%)	7047.2(54.4%)	8008.1(61.8%)

Results show that: The PPP-PTCAs scheme p_3 achieves a win-win-win outcome. Specifically, it balances suboptimal social costs, maximizes private sector profits, and attracts the most low-carbon travelers, thereby delivering the highest emission reduction rate. The government prefers to subsidize the private sector over direct pollution control, as it reduces social cost compared to the p_1 scheme. Collaboration with the government boosts the private sector's utility FU, surpassing the p_2 scheme. Low-carbon travelers under p_3 also receive the highest carbon credits rewards. Overall, the PPP-PTCAs scheme benefits all stakeholders, making it the most effective approach.

This study proposes a PPP-PTCAs scheme where the private sector provides PTCAs to attract travelers to choose public transit and help the government reduce emission while receiving subsidies. The results show that all stakeholders are better off, which provides inspiration on how to design incentives for low-carbon travel and avoid speculation on fraudulent subsidies. Future studies will explore the PPP-PTCAs scheme from a long-term perspective and incorporate travelers' other choices, such as route choice, car ownership, and vehicle types, into the analysis.

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