On Regulating Transportation Emission via Personal and Corporate Carbon Trading: A Game-Theoretic Approach

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Abstract:

[Objective] The transportation sector is a major contributor to global greenhouse gas emissions, comprising about a quarter of the total global greenhouse gases (Jaramillo et al., 2022). Various technological and policy-based strategies have been employed to reduce carbon emissions in the transportation sector, such as developing green vehicles, promoting the adoption of electric vehicles, encouraging public transit travel, and implementing tolls. Despite these measures, global carbon emissions in transportation persistently increase (IEA, 2023). Therefore, in accordance with the Paris Agreement, some countries leverage market mechanisms to attain their emission reduction objectives. This has led to the establishment of emission trading systems (ETSs), enabling corporations to buy or sell carbon credits for the purpose of offsetting their carbon emissions.

Currently, several countries (e.g., Canada) have incorporated the transportation sector into their ETSs. Within these ETSs, two regimes are proposed to regulate transportation emissions: upstream regime and downstream regime (Matthews, 2010). Under the upstream regime, automotive fuel distributors are responsible for the emissions produced by their products. While, the downstream regime directly regulates the actual end emitters. In practice, the upstream regime is more commonly adopted due to its easier implementation. Nevertheless, the end emitter-based downstream regime could significantly extend ETS entities, expanding beyond transportation service operators to include individual urban commuters, which yields a personal carbon trading scheme and may further facilitates the effectiveness of carbon reduction in the transportation sector (Fuso Nerini et al., 2021).

Existing studies on transportation sector-incorporated downstream ETS mainly focus on evaluation of trading mechanism and policy (Li & Tang, 2017), vehicular emission monitoring and credit charging system design (Lu et al., 2022), and initial allocation strategy for carbon credits (Nie et al., 2022). However, how the introduction of transportation sector-incorporated ETS with personal carbon trading scheme would impact travelers' mobility patterns, operation strategies of transportation service operators, and the overall transportation system performance is still unclear. This study proposes an analytically tractable framework to bridge this gap.

[Method] We model an ETS that includes the transportation sector. Under this ETS, there are two carbon credit trading markets: Personal Trading Market (PTM) and Corporate Trading Market (CTM). Carbon credits are non-transferable between PTM and CTM, and the credit price of each market is governed by its own supply-demand conditions. In the PTM, travelers trade carbon credits that are initially allocated by the government. Travelers are classified into three groups: petrol vehicle (PV) owners, electric vehicle (EV) owners and vehicle-less travelers. PV and EV owners may either choose driving or public transit (operated by one transit operator) based on travel costs of each mode, while the vehicle-less travelers only take public transit. Each PV trip generates carbon emission of E_p kiloton due to direct tailpipe emissions. Each EV trip produces E_e kiloton of emissions resulting from indirect charging and electricity production, with $E_e < E_p$. To engage PV/EV travel, travelers have to offset the associated emission through carbon credits. Taking public transit is considered to produce zero individual emissions, thereby requiring zero credits. However, the transit operator is responsible to offset emissions from transit services.

The CTM only enables companies/organizations to trade their carbon credits allocated by the government. In this study, we specifically examine the participation of the transit operator in the CTM. The carbon emissions of the transit operator arise from the operation of transit fleets. These emissions

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are denoted as $E_t(f)$ and are characterized as an increasing function of the transit service frequency f. The transit operator determines the optimal fare and service frequency in compliance with the emission trading scheme. If the transit operator exhausts its allocated credits for offsetting emissions, it has to purchase additional credits from the CTM. Conversely, if the transit operator possesses excess credits, it has the opportunity to generate additional revenue by selling them in the CTM.

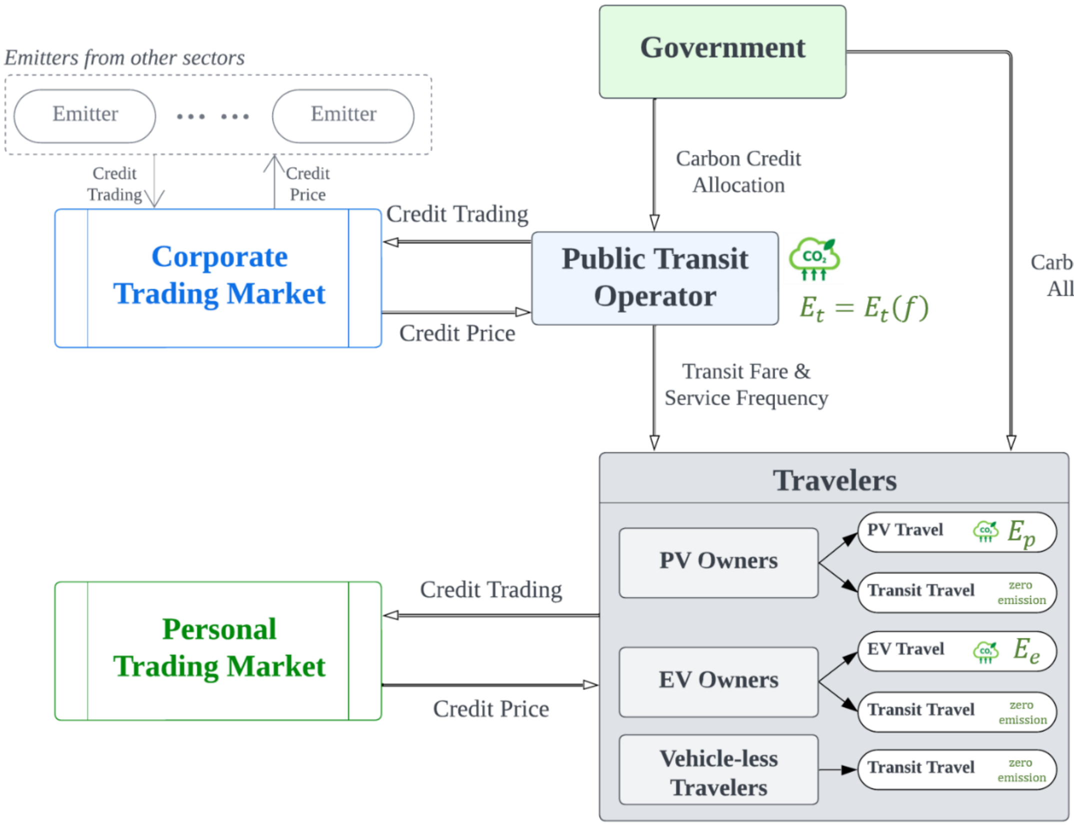

Fig. 1: Model framework

With the aforementioned model framework (visualized in Fig. 1), we formulate a Stackelberg game to examine the strategic interactions among the government, transit operator, and travelers under the ETS. The government firstly determines the credit allocation strategy. Then, the transit operator receives credits and optimizes transit fare and transit frequency accordingly. Following that, the travelers with carbon credits observe transit operators' operation decisions and make mode choice decisions in order to minimize their travel costs. The government's problem is to minimize the overall travel cost of the transportation system, while adhering to an equality constraint that guarantees the total allocated carbon credits are equal to the targeted carbon emissions for the transportation system. The objective of the public transit operator is to maximize its profit which is determined by revenue from fares, operating costs, and revenue/expenditure associated with carbon trading. The mode choice pattern of travelers under equilibrium conditions is determined by solving the variational inequality formulation, while incorporating the equilibrium conditions of the personal trading market. To solve the Stackelberg game analytically, the backward induction approach is applied. Furthermore, we propose an augmented Lagrangian approach to solve the Stackelberg equilibrium under a numerical setting. A series of sensitivity analysis regarding the government's emission reduction goal, travelers' value of times and carbon price in the CTM are also conducted.

As mentioned above, the CTM and PTM are two distinct carbon trading markets. While these markets operate independently, with CTM facilitating trade among companies and PTM allowing individual travelers to trade credits, there is an interplay between them. The interaction between CTM and PTM is explained in detail as follows. Firstly, the supply-demand dynamics in CTM, influenced by the government's emission targets or sector-wide changes in carbon emissions, directly impact the carbon price in CTM. Fluctuations in credit prices have a direct effect on the operational decisions of transit operators, particularly in terms of service frequency. These operational adjustments, in turn, influence the travel costs for transit users and result in shifts in travel preferences and changes in the flows of passenger PV and EV. Consequently, these factors have an impact on the credit price in the PTM and the levels of transportation emissions. Due to space limitations, a comprehensive analysis and discussion of the complex interactions between these two markets will be conducted in the full paper.

[Results] The key results are as follows. (1) With the ETS, more travelers shift to public transit mode. (2) The vehicle-less travelers have the largest number of carbon credits, followed by EV owners and PV owners, because the government may impose more strict restrictions on travelers with greater emissions. (3) The transit operator might decrease the transit frequency to reduce emission and lower the transit fare to enhance the ridership. (4) When the ETS is introduced, the total transportation system travel cost might be increased as more travelers might shift to the public transit mode, but the overall system-wise emission is reduced. The results mentioned above were obtained through a numerical experiment, and it should be noted that the outcomes may vary, depending on different settings of exogenous parameters, such as the capacity of public transit vehicles, road capacity, emission targets, etc. In the full paper, a series of sensitivity analyses will be conducted to further explore these variations and their practical implications.

[Conclusions] The main contribution of this study lies on the exploration of the novel ETS with PTM and CTM that fully leverages market mechanism to achieve transportation emission reduction goals. It differs from the existing roadway-use right schemes (e.g., tradable credits and road permits) that control traffic congestion and emission through solely altering vehicle owners' travel choices. The interaction between the supply-demand conditions of the CTM and the PTM implies that emission levels in other sectors have indirect effects on travelers' travel choices, thereby highlighting the holistic nature of the proposed ETS system in terms of emission reduction.

Keywords: Emission trading system; Personal carbon trading; Carbon emission; Stackelberg game; Hierarchical optimization; Mode choice

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