Transport Policy 164 (2025) 104–117

Contents lists available at ScienceDirect

Transport Policy

journal homepage: www.elsevier.com/locate/tranpol

Does vehicle purchase tax effectively restrict car ownership and promote public transport?

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ARTICLE INFO

Keywords:
Vehicle purchase tax
Game-theoretic model
car ownership
Public transport

ABSTRACT

Vehicle purchase tax (VPT) has emerged as an effective fiscal tool to restrict car ownership and is widely deployed in several countries. Though empirical findings show that VPT can reduce the heavy reliance on private cars, the analytical model exploring the impact of VPT on car ownership and subsequent public transport is quite lacking. To address this gap, we develop a game-theoretic model to quantitatively test the effectiveness of VPT in car ownership restriction and public transport promotion. The proposed model derives the optimal strategies of players in the transport market levying VPT and demonstrates the relationship between the tax rate and travel demands/shares. Analytical results verify the advantages of VPT with the modal shift from self-driving to public transport. Policy implications are further discussed concerning how to encourage this modal shift from the perspective of governance.

1. Introduction

The past decades have witnessed an increasing trend of car ownership all over the world along with rapid economic developments. This has resulted in greenhouse gas (GHG) emissions and a series of urban traffic problems such as congestion and accidents. To alleviate these issues, several policy instruments focusing on providing fiscal incentives, particularly through economic tools, have been developed and deployed in many cities. Broadly speaking, fiscal incentives for restricting vehicles can be classified into policies that primarily affect vehicle ownership such as vehicle purchase tax (VPT) and vehicle usage such as the fuel tax (Liu and Cirillo, 2015). In particular, as a one-off charge levied by the government at the percentage of the vehicle purchase price, VPT can be easily implemented through actions or laws. Compared with vehicle usage-related taxes, VPT has a high level of political and public acceptability (Kok, 2015; Barros et al., 2021) and is suitable for densely populated metropolis with low-mileage travels targeting transit-oriented development (TOD) (Lu, 2023). For example, Hong Kong launched the tiered VPT from 40% to 115% of the vehicle purchase price[1] and Singapore levied the VPT in the name of the vehicle registration fee/tax from 100% to 220% of the vehicle price.[2] The high VPT in these two cities effectively contributes to restricting car ownership. This VPT application has also been found in Israel (Israel Tax Authority, 2008), Sweden (The Swedish Tax Agency, 2015), Korea (Ministry of Economy and Finance of the Republic of Korea, 2018), and China (The National People's Congress of the People's Republic of China, 2018), etc.

With a mass of empirical practices, the merits of VPT are identified with several pieces of evidence. For example, Brand et al. (2013) employed the UK Transport Carbon Model to compare various vehicle taxations and found that VPT is the most effective one to contribute to low carbon technology uptaking and GHG emissions reduction. Østli et al. (2017) explored the impact of VPT and fuel tax on automobile purchasing choices and found that VPT is more useful to incentivize low-emission vehicle choices. Based on the empirical evidence from 15 EU countries, Gerlagh et al. (2018) found that VPT outperforms road taxes in terms of reducing GHG emissions. These pieces of evidence highlighted the priorities of VPT among other vehicle-related taxes.

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[1] https://www.gov.hk/sc/residents/taxes/motortax/index.htm.
[2] https://www.income.com.sg/blog/car-cost-in-singapore.

https://doi.org/10.1016/j.tranpol.2025.01.038
Received 8 August 2024; Received in revised form 26 January 2025; Accepted 28 January 2025
Available online 28 January 2025

Intuitively, a higher VPT will motivate the shift from self-driving to public transport. Unluckily, investigations concerning the generalized quantified influence of VPT rate on reducing car ownership and increasing public transport usage are quite limited.

1.1. Literature reviews

We review the related studies to identify the research gaps, where the first stream focuses on the role of VPT and the second stream focuses on the transport modal shift.

i) The role of VPT

Despite the mentioned merits, the VPT studies are much less than those for other fiscal incentives. Among these limited VPT studies, Fridstrøm and Østli (2017) utilized the Nordic data to estimate the environmental influence of VPT and found that this tax was a powerful policy instrument to reduce energy consumption. Ciccone (2018) measured the effects of VPT reform in Norway and identified that the new tax structure contributes to the reduction of the average GHG intensity of new vehicles. Different from these studies focused on the empirical impact on emissions, some studies focused on car ownership impact. For example, Yan and Eskeland (2018) studied the effectiveness of VPT in Norway and found that increasing 1000 NOK tax can reduce at least 1.06% vehicle sales. Liu (2023) studied the impact of VPT exemption on electric vehicle sales in China and found that this exemption increased car sales by 177.3%. This conversely demonstrates the effectiveness of VPT on car ownership restriction, more exactly, the fuel vehicles. Similar results about the role of VPT in reducing car ownership and GHG emissions can be found in Ireland (Hennessy and Tol, 2011), the UK (Cerruti et al., 2019), Italy (Bergantino et al., 2021), and China (Lo et al., 2021), etc. However, current VPT studies mainly adopt econometric approaches or conduct empirical analysis. There is a lack of modeling studies that theoretically examine the effectiveness of VPT except for the limited two works studied by Niu (2021) and Ji et al. (2022). Niu (2021) used a double difference model to analyze the vehicle sales data and found that the small-displacement vehicle sales volume in China was reduced after the implementation of 10% VPT. Ji et al. (2022) proposed a random-coefficients discrete choice model to check how an increase in the rate of VPT affects sales of electric vehicles. Unluckily, no one has ever explored the influence of VPT on public transport, more exactly, the modal shift from self-driving to public transport. As we have mentioned before, a higher cost of VPT rate will motivate more people to switch to public transport but there is a gap in understanding the quantitative impacts of VPT on this modal shift.

ii) Transport modal shift

Though lack of modeling work on the impact of VPT on the modal shift, other related modal shift studies provide fruitful inspirations. This modal shift is a significant task because it creates a greener and more sustainable transport system (Holmgren, 2020). The relationship between car ownership and public transport market share is toughly identified as “good public transport can deter car ownership” or “car ownership restrictions promote public transport”, which is supported by a mass of empirical evidence (Tao et al., 2019; Yao et al., 2021). Focusing on the modeling work to quantify this relation, current studies revealed the effectiveness of different kinds of policies (e.g., congestion charging, parking charges, and public transport service enhancement) in realizing the modal shift. For example, Mulalic and Rouwendal (2020) explored the effectiveness of the public transport service enhancement scheme by developing a model to integrate residential location choice and household car ownership. Bian et al. (2023) investigated the relationship between car ownership, public transport, and ride-hailing usage through a structural equation model and found that TOD design will reduce car ownership and promote alternative modes. Alyavina et al. (2024) studied how Mobility-as-a-Service-enabled measures affect travelers’ intentions to own a car and to substitute public transport trips.

As one of the policy tools to promote the modal shift, VPT is favored by the government because it has fiscal incentive benefits and is easily implemented with a one-off charge. However, the transport market with VPT involves several stakeholders including the car manufacturer, travelers, the government, and the public transport operator. Interactive relationships among them induce complicated decision-making and subsequently the market equilibrium state. This results in a much more complex market compared with the markets under other modal shift policies. One of the feasible approaches to characterize players’ interactive relations is the game-theoretic model (Gorji et al., 2022). It provides a mathematical framework to model and analyze the strategic interactions among different players with various objectives (Mertens and Sorin, 2013) and is widely used in operations management studies such as emission regulations (Zis, 2021), parking operations (Xiao and Xu, 2023), and port operations (Peng et al., 2023). In this way, how to utilize the game-theoretic approach to analyze the complex transport market with VPT and how to quantify the impact of VPT on the modal shift from self-driving to public transport are challenging.

1.2. Main works of this study

To address the aforementioned gaps, this study explores whether levying VPT can encourage car ownership restriction and public transport promotion in a transport market with both private cars and public transport. A game-theoretic model considering the levy of VPT is developed to incorporate the strategies of the mentioned rational players, which provides a comprehensive picture of the interactive relations among them. The demands/shares of the two travel modes, i.e., self-driving and public transport are derived from the proposed model. By comparing the travel demands/shares of the market with and without VPT, we quantify the impact of VPT in reducing private car demand/share and increasing public transport demand/share. A case study based on the data from Beijing verifies theoretical findings and policy implications are discussed. The contributions of this study are summarized as threefold.

- First, we characterize the specific features of the real transport market launching the VPT. The market involves two travel modes, i.e., self-driving v.s. public transport, and four key rational players, i.e., the car manufacturer, the public transport operator, travelers, and the government. A game-theoretic model is developed to identify these players’ interactive relationships at the strategic level, which further derives their optimal strategies.
- Second, we examine the effectiveness of VPT in reducing car ownership and promoting public transport under a game-theoretic framework. Quantitative relationships between the VPT rate and the optimal travel demands/shares are firstly identified by comparing the results with and without VPT via a mathematical modeling approach, which provides a clear implication for the government on how to levy VPT.
- Third, we reveal pathways for the government to realize a quantified target of a certain car ownership demand/share and public transport demand/share, including levying the optimal VPT rate, enhancing public transport services, and optimizing the community layout.

The rest of this study is organized as follows. Section 2 presents assumptions and problem descriptions. A game-theoretic model for the transport market with VPT is formulated in Section 3, in which the advantages of levying VPT are discussed and identified. Section 4 performed a case study. Discussions for the results are presented in Section 5. Policy implications regarding the measures to encourage the modal shift are proposed in Section 6. Conclusions and future studies are organized in Section 7.

2. Assumptions and problem description

2.1. Multiple players in the transport market

Recall four key players in the transport market are considered. The government is responsible for launching VPT and determining the tax rate $\alpha(\alpha \geq 0)$, i.e., the percentage at which the car is purchased. The car manufacturer will produce cars at a constant car manufacturing cost e_c $(e_c > 0)$ and set the car retail price denoted by f_c to maximize its profit. We assume $f_c \geq e_c$ for operations. The public transport operator sets the public transport service fare f_p measured by \$/km for profit maximization while facing a constant lump-sum generalized cost e_p $(e_p > 0)$ (includes administrative costs, labor costs, operation costs, etc.) covering the bus's life cycle for daily operations. The travelers will decide whether to purchase a car or ride on public transport for daily commuting. Those travelers who choose to purchase cars are assumed to travel by car throughout the car's life cycle and bear an operating cost e_t $(e_t > 0)$ (includes the depreciation cost, the fuel cost, etc.) measured by \$/km while other travelers choosing to ride on public transport should pay the public transport service fare f_p.

Regarding travelers' utilities, we assume for simplicity that commuting travelers in the same city have the same average travel distance per trip, denoted by l, and the same average number of driving trips throughout the car's life circle, denoted by d. In addition, the travelers are heterogeneous concerning the travel utilities derived from a completed trip, which refers to the average utilities of each trip satisfying the travel demands. We use v_i to denote the utility for traveler i if he/she uses a private car per trip and βv_i for traveler i if public transport is used, where β denotes the public transport comfort factor relative to private cars. We have $0 < \beta < 1$ because traveling by public transport is inferior to traveling by car such as less comfort, convenience, and accessibility. For ease of modeling, we follow Li et al. (2020), Pei et al. (2021), and Xiao et al. (2024) to standardize travelers' utilities with a uniform distribution between 0 and 1 and normalize the car's designed number of driving trips[3] and the total number of travelers as 1. Therefore, dv_i represents the total travel utility of traveler i throughout the car's life cycle when traveling by private cars and βdv_i represents the total utility of traveler i when public transport is chosen, where $0 < d \leq 1$. For easy reference, notations throughout the manuscript are listed in Table 1.

2.2. Player interactions and the Nash equilibrium state

Each player in the game is assumed to be self-interested with rational behavior. This behavior specified as the optimal strategy, either the pricing decisions of the public transport operator and the car manufacturer or the choice decisions of travelers, is contingent on the strategies implemented by other players. Among these players, the government acts as the market regulator to launch the VPT rate for restricting car ownership and promoting public transport. Under a certain VPT rate, the car manufacturer and the public transport operator will compete with each other to attract travelers by setting the car retail price and the public transport service fare, respectively, for the profit-maximization target. The VPT rate, the car retail price, and the public transport service fare will jointly affect travelers' utilities and accordingly their choices, i.e., either self-driving or riding on public transport. The travelers' decisions targeted for utility maximization, in turn, affect the demands of the two travel modes and further influence the profits of the car manufacturer and the public transport operator. This prompts all players to consecutively change their strategies until reaching an equilibrium state, in which none of the players can increase their profits/utilities by intentionally changing their strategies when other players' strategies are kept unchanged. In this way, the Nash equilibrium state has been reached. We illustrate the scenario of the transport market in Fig. 1.

[3] The designed number of driving trips throughout the car's life cycle, denoted by the quotient of the total designed mileage (the same for all cars produced by the same car manufacturer) and the average travel distance per trip (assumed the same for all travelers in the same city), is the same for all travelers and is generally not less than the average number of driving trips d.

Table 1
Notations.

Notations	Interpretations
α	The VPT rate
e_c	The car manufacturing cost
f_c	The car retail price
f_p	The public transport service fare
e_p	The lump-sum generalized cost for bus operations
e_t	The operating cost for car operations
l	The average travel distance per trip
d	The average number of driving trips throughout the car's life circle
v_i	The utility for traveler i if he/she uses a private car per trip
β	The public transport comfort factor relative to private cars
U_{ic}	The utility of traveler i who chooses to purchase a car
U_{ip}	The utility of traveler i who chooses public transport
D_c	The travel demands of private cars
D_p	The travel demands of public transport
R_c	The private car share
R_p	The public transport share
Π_c	The profit of the car manufacturer
Π_p	The profit of the public transport operator
TS	The traveler surplus
SW	The social welfare

3. Model formulations and discussions

We first propose a game-theoretic model to characterize the players' behaviors and derive their optimal strategies in Subsection 3.1. Discussions about the role of VPT are presented in Subsection 3.2.

3.1. The game-theoretic model for the transport market

In this subsection, we formulate the transport market with VPT by a game-theoretic model. Kindly note that several approaches such as the game-theoretic model and system dynamics can be adopted to address complex systems but they have different focuses and methodologies. The game-theoretic model focuses more on the equilibrium states of the market (Mertens and Sorin, 2013) while the system dynamics focus more on the evolution of complex markets over time. The transport market considered in this study contains several rational players and we pay close attention to their interactive relationships under the policy of levying VPT. We care more about the strategic interactions among these

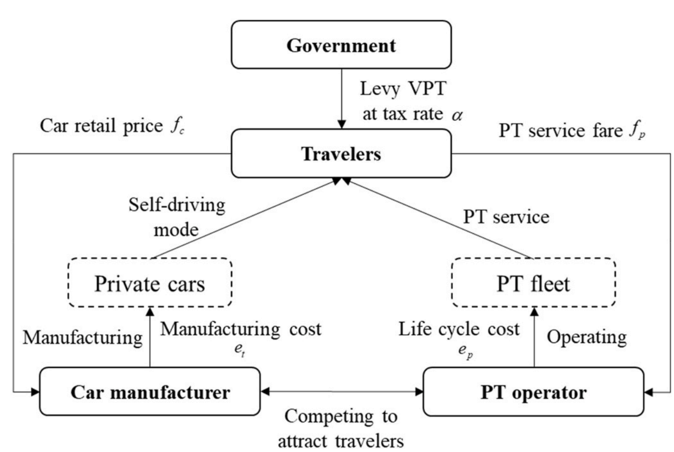


Fig. 1. Illustration of the transport market levying VPT.

players as well as the subsequent equilibrium state rather than the evolution process of the system. Therefore, the game-theoretic model is suitable for this scenario. Following the above descriptions, the utility of traveler i who chooses to purchase a car is given by

$$U_{ic} = d(v_i - le_t) - (1+\alpha)f_c \tag{1}$$

where subscript c stands for traveling by car. Correspondingly, the utility of traveler i who chooses public transport is given by

$$U_{ip} = d\left(\beta v_i - lf_p\right) \tag{2}$$

where subscript p stands for traveling by public transport. Note that both two travel modes satisfy travelers' demands within the car's life cycle, i.e., dv_i for private car driving and βdv_i for public transport riding, and induce usage-related costs within the same time range, i.e., dle_t for private cars and dlf_p for public transport. The choice of private cars, additionally, will induce the property-related cost of f_c and VPT αf_c. Kindly note that Eqs. (1) and (2) are linearly formulated in this study because the relationships between the travel cost and the travel distance in different kinds of travel modes are all found to be quasi-linear in empirical studies (Mathisen, 2015), especially in the long-term range such as the car's life cycle. The linearization of utility functions can be also found in several modeling studies for transport markets (e.g., Jørgensen and Preston, 2007; Adler et al., 2021) considering the simplification contributes to deriving analytic solutions. By enforcing $U_{ic} \geq 0$ and $U_{ip} \geq 0$, the threshold of traveler's utility for participation in the transport market is given by

$$\begin{cases} v_c = (1+\alpha)f_c/d + le_t \\ v_P = lf_p \big/ \beta \end{cases} \tag{3}$$

which means that travelers whose travel utilities are lower than v_c will not choose to purchase cars and whose travel utilities are lower than v_p will not travel by public transport. Based on the above formulations, the threshold travel utility of mode shift is $v = \frac{dl(e_t - f_p) + (1+\alpha)f_c}{d(1-\beta)}$, which suggests any traveler whose travel utility is higher than v will purchase a car, and travel by public transport otherwise. Based on the demand function formulation in general operations management studies (Bian et al., 2021; Tian et al., 2021; Xiao et al., 2023a, 2023b; Li et al., 2024), the travel demands of private cars and public transport can be formulated to be the integral function, which are given by

$$\begin{cases} D_c = \int_v^1 f(v)dv \\ D_p = \int_{v_p}^{v} f(v)dv \end{cases} \tag{4}$$

where $f(v)$ denotes the probability density function of v. Following the probability theory (Walpole et al., 2016), the value of the probability function of the continuous standard uniform distribution is 1. Eq. (4) can be thus calculated to be $D_c = 1 - v$ and $D_p = v - v_P$, respectively, which are presented as follows:

$$\begin{cases} D_c = 1 - \dfrac{dl\left(e_t - f_p\right) + (1+\alpha)f_c}{d(1-\beta)} \\ D_p = \dfrac{dl\left(e_t - f_p\right) + (1+\alpha)f_c}{d(1-\beta)} - \dfrac{lf_p}{\beta} \end{cases} \tag{5}$$

The profit of the car manufacturer Π_c and the profit of the public transport operator Π_p are thus given by

$$\begin{cases} \Pi_c = (f_c - e_c)D_c = (f_c - e_c)\left[1 - \dfrac{dl\left(e_t - f_p\right) + (1+\alpha)f_c}{d(1-\beta)}\right] \\ \Pi_p = dlf_pD_p - e_p = dlf_p\left[\dfrac{dl\left(e_t - f_p\right) + (1+\alpha)f_c}{d(1-\beta)} - \dfrac{lf_p}{\beta}\right] - e_p \end{cases} \tag{6}$$

By enforcing $\partial\Pi_c/\partial f_c = 0$ and $\partial\Pi_p/\partial f_p = 0$, the equilibrium results of f_c^* and f_p^* can be obtained by combining the two differential equations as follows:

$$\begin{cases} f_c^* = \dfrac{2e_c + 2d - 2\beta d - 2e_tdl + \beta e_tdl + 2\alpha e_c}{(4-\beta)(1+\alpha)} \\ f_p^* = \dfrac{\beta(e_c + d - \beta d + e_tdl + \alpha e_c)}{(4-\beta)dl} \end{cases} \tag{7}$$

By substituting Eq. (7) into the demand functions in Eq. (5), we have the equilibrium results of D_c^* and D_p^* as follows:

$$\begin{cases} D_c^* = \dfrac{\beta e_c - 2e_c + 2d - 2\beta d - 2e_tdl + \beta e_tdl - 2e_c\alpha + \beta e_c\alpha}{(\beta-4)(\beta-1)d} \\ D_p^* = \dfrac{e_c + d - \beta d + e_tdl + \alpha e_c}{(\beta-4)(\beta-1)d} \end{cases} \tag{8}$$

Though e_c is considered to be constant in this study, the following mechanism on the side of the car manufacturer still holds. The decrease in the number of sold cars D_c can be attributed to the increase of e_c because it will increase D_p and subsequently decrease D_c, which is verified by the finding that $\frac{\partial D_p}{\partial e_c} = \frac{1+\alpha}{(\beta-4)(\beta-1)d} > 0$ and $\frac{\partial D_c}{\partial e_c} = \frac{(1+\alpha)(\beta-2)}{(\beta-4)(\beta-1)d} < 0$ (see Eq. (8)). This will further motivate the car manufacturer to lower f_c to avoid car sales decline. Kindly note that the car manufacturer will face a profit decline when the generated profit derived from increment demands cannot make up for the total profit loss derived from lowering f_c while will face a profit boost otherwise. Given the equilibrium demands of the two travel modes, the private car share R_c^*, denoted by the percentage of travelers driving by private cars, and the public transport share R_p^*, denoted by the percentage of travelers riding on public transport, are given by

$$\begin{cases} R_c^* = \dfrac{D_c^*}{D_c^* + D_p^*} = \dfrac{(\beta-2)(e_c - 3d + e_tdl + e_c\alpha) + (\beta-4)d}{(\beta-1)(e_c - 3d + e_tdl + e_c\alpha)} \\ R_p^* = \dfrac{D_p^*}{D_c^* + D_p^*} = \dfrac{e_c + d - \beta d + e_tdl + e_c\alpha}{(\beta-1)(e_c - 3d + e_tdl + e_c\alpha)} \end{cases} \tag{9}$$

We can obtain the equilibrium results of Π_c^* and Π_p^* by substituting Eq. (7) into the profit functions in Eq. (6) as follows:

$$\begin{cases} \Pi_c^* = \dfrac{(\beta e_c - 2e_c + 2d - 2\beta d - 2e_tdl + \beta e_tdl - 2\alpha e_c + \alpha\beta e_c)^2}{(\beta-4)^2(1-\beta)(1+\alpha)d} \\ \Pi_p^* = \dfrac{\beta(d - \beta d + e_c + e_tdl + \alpha e_c)^2}{(\beta-4)^2(1-\beta)d} - e_p \end{cases} \tag{10}$$

The traveler surplus can be subsequently calculated based on Eqs. (7) and (8) as follows:

$$TS^{*} = \int_{v_p}^{v} U_{ip} dv_i + \int_{v}^{1} U_{ic} dv_i = \frac{(3\beta-4)e_c^2(1+\alpha)^2 - 2e_c d(1+\alpha)[\beta(\beta-3e_t l+3)+4e_t l-4]}{2(\beta-4)^2(\beta-1)d} - \frac{d^2\left[-5\beta^2+e_t^2 l^2(4-3\beta)+2e_t l(\beta-1)(\beta+4)+\beta+4\right]}{2(\beta-4)^2(\beta-1)d} \tag{11}$$

where the first term $\int_{v_p}^{v} U_{ip} dv_i$ represents the surplus of travelers who choose public transport and the second term $\int_{v}^{1} U_{ic} dv_i$ is the surplus of travelers who choose private cars. Therefore, the social welfare of the transport market SW^* is obtained by summating the profit of the car manufacturer Π_c^*, the profit of the public transport operator Π_p^*, the traveler surplus TS^*, the total VPT $\alpha f_c D_c^*$, and the positive externalities derived from the reduction of private car demands such as the environmental benefits and congestion benefits. In particular, the positive externalities can be characterized to be the product of the reduced private car demands $\Delta D_c = \overline{D}_c^* - D_c^*$ ($\overline{D}_c^*$ can be obtained by setting $\alpha = 0$ in Eq. (8)) and the externality parameter σ, in which the parameter measures the utility increment when one private car is reduced in the market. In this way, the social welfare SW^* is obtained by

$$\begin{aligned} SW^* &= \Pi_c^* + \Pi_p^* + TS^* + \alpha f_c^* D_c^* + \sigma \Delta D_c \\ &= \frac{d\left[13\beta-12+\beta^2-2\beta^3+2e_t l(\beta-1)(5\beta-12)+e_t^2 l^2(\beta(9-2\beta)-12)\right]}{2(\beta-1)(\beta-4)^2} \\ &+ \frac{e_c^2(1+\alpha)[\alpha(4-3\beta)+\beta(9-2\beta)-12]-2e_c\alpha\sigma(\beta-4)(\beta-2)}{2d(\beta-1)(\beta-4)^2} - e_p \\ &+ \frac{e_c(\beta-1)[\beta(5+3\alpha)-4(3+\alpha)]+e_c e_t l\left[(3\beta-4)(3+\alpha)-\beta^2(2+\alpha)\right]}{(\beta-1)(\beta-4)^2} \end{aligned} \tag{12}$$

3.2. Further discussions about the role of VPT

In this subsection, we investigate whether the levy of VPT can encourage the modal shift from self-driving to public transport, which is realized by comparing the equilibrium travel demands/shares in the market with VPT and without VPT. The private car/public transport demand and the private car/public transport share in the market without VPT can be obtained by setting $\alpha = 0$, which are given by

$$\begin{cases} \overline{D}_c^* = \dfrac{\beta e_c - 2e_c + 2d - 2\beta d - 2e_t dl + \beta e_t dl}{(\beta-4)(\beta-1)d} \\ \overline{D}_p^* = \dfrac{e_c + d - \beta d + e_t dl}{(\beta-4)(\beta-1)d} \end{cases} \tag{13}$$

$$\begin{cases} \overline{R}_c^* = \dfrac{(\beta-2)(e_c-3d+e_t dl)+(\beta-4)d}{(\beta-1)(e_c-3d+e_t dl)} \\ \overline{R}_p^* = \dfrac{e_c+d-\beta d+e_t dl}{(\beta-1)(e_c-3d+e_t dl)} \end{cases} \tag{14}$$

The differences between the market with VPT and without VPT in travel demands/shares can be calculated based on Eqs. 8, 9, 13 and 14, which are given by

$$\begin{cases} \Delta D_c = D_c^* - \overline{D}_c^* = \dfrac{\alpha e_c(\beta-2)}{(\beta-4)(\beta-1)d} \\ \Delta D_p = D_p^* - \overline{D}_p^* = \dfrac{\alpha e_c}{(\beta-4)(\beta-1)d} \end{cases} \tag{15}$$

$$\begin{cases} \Delta R_c = R_c^* - \overline{R}_c^* = \dfrac{e_c d\alpha(4-\beta)}{(\beta-1)(e_c-3d+e_t dl)(e_c-3d+e_t dl+e_c\alpha)} \\ \Delta R_p = R_p^* - \overline{R}_p^* = \dfrac{e_c d\alpha(\beta-4)}{(\beta-1)(e_c-3d+e_t dl)(e_c-3d+e_t dl+e_c\alpha)} \end{cases} \tag{16}$$

We first discuss the values of Eqs. (15) and (16) and have the following propositions.

Proposition 1. *The levy of VPT can reduce the private car demand and increase the public transport demand.*

Proof. Focusing on the expressions of ΔD_c and ΔD_p in Eq. (15) and follows the constraints of $e_c > 0$, $0 < d \le 1$, $\alpha > 0$, and $0 < \beta < 1$ mentioned in Section 2, we can deduce the results of $\Delta D_c < 0$ and $\Delta D_p > 0$. □

This proposition indicates that the levy of VPT promotes the modal shift from self-driving to public transport and is thus regarded to be a useful policy tool to restrict car ownership and promote public transport. In particular, the absolute decremental private car demand is $|\beta - 2|$ times greater than the absolute incremental public transport demand. Kindly note that the reduction of private car demand may not necessarily imply a decrease in private car share since the total travel demand may vary in the two markets. We then proceed to examine the influences of VPT on travel shares and have the following proposition:

Proposition 2. *The levy of VPT can reduce the private car share and increase the public transport share.*

Proof. Given ΔR_c and ΔR_p in Eq. (16), we can judge their values based on the constraints. Since the private car shares, i.e., R_c^* and $\overline{R}_c^*$, and the public transport shares, i.e., R_p^* and $\overline{R}_p^*$, given by Eqs. (9) and (14) are nonnegative and both $e_c + d - \beta d + e_t dl + e_c\alpha$ and $e_c + d - \beta d + e_t dl$ are positive, the inequalities of $e_c - 3d + e_t dl < 0$ and $e_c - 3d + e_t dl + e_c\alpha < 0$ are deduced. We then have $\Delta R_c < 0$ and $\Delta R_p > 0$. □

This proposition indicates that the levy of VPT reduces private car share and increases public transport share. As expected, the absolute decremental private car share is the same as the absolute incremental public transport share since the sum of the shares of private car and public transport is 1. This proposition also illustrates that there is no conflict in comparing demands and shares in two travel modes, i.e., the decreases in private car demand and the increases in public transport demand will reduce the private car share and increase the public transport share, which further verifies the effectiveness of VPT.

The findings from Propositions 1 and 2 jointly demonstrate that the levy of VPT contributes to the modal shift, which provides sufficient theoretical evidence for the government to launch VPT. Besides, we are concerned about the relationship between the VPT rate and demands/ shares of different travel modes and have the following two propositions.

Proposition 3. *Given the VPT policy, the decreasing trend of the private car demand and the increasing trend of the public transport demand with respect to the VPT rate are linear*.

We prove this proposition in Appendix A.

Proposition 4. *Given the VPT policy, the private car share shows a convex decreasing trend with the increase of the tax rate, while the public transport share shows a concave increasing trend with the increase of the tax rate.*

We prove this proposition in Appendix B.

The findings from Propositions 3 and 4 jointly demonstrate the quantified relationships between the VPT rate and the demands/shares of the two travel modes, which provides interesting implications regarding how to launch the VPT with a certain target. Unlike the previous VPT-related studies to focus on the impacts on car ownership and subsequent GHG emissions, this paper makes the first attempt to explore its impacts on the public transport sector, as outlined in the following proposition.

Proposition 5. *The levy of VPT benefits the public transport operator by inducing a larger public transport demand and a higher service fare and ultimately increasing the profit of the public transport operator.*

We prove this proposition in Appendix C.

The findings from this proposition demonstrate that the levy of VPT can be regarded as an available strategy to benefit the public transport operator. It is of great significance because VPT can lead to a potential advantage benefit, in which the public transport operator has enough earned profit to enhance its service and form a positive loop to attract more travelers.

Without loss of generality, we also investigate the impact of VPT on the travelers' surplus and social welfare and have the following proposition.

Proposition 6. *The levy of VPT reduces the travelers' surplus and social welfare.*

We prove this proposition in Appendix D.

This proposition indicates that the levy of VPT sacrifices travelers' utilities and social welfare because these results under the market with VPT are smaller than those under the market without VPT. This finding is rational since it is consistent with the economic sense that the imposition of a new tax will inevitably cause deadweight losses and other welfare losses associated with microeconomic distortions (Mankiw, 2021).

4. Case study

We conduct a case study based on the data from Beijing in this section. Results of the basic model and the extended models are performed in Subsections 4.1 and 4.2, respectively.

4.1. Basic results

Based on the data from Beijing, key parameters are listed as follows: the VPT rate α is 10% (The National People's Congress of the People's Republic of China, 2018), the public transport comfort factor β of

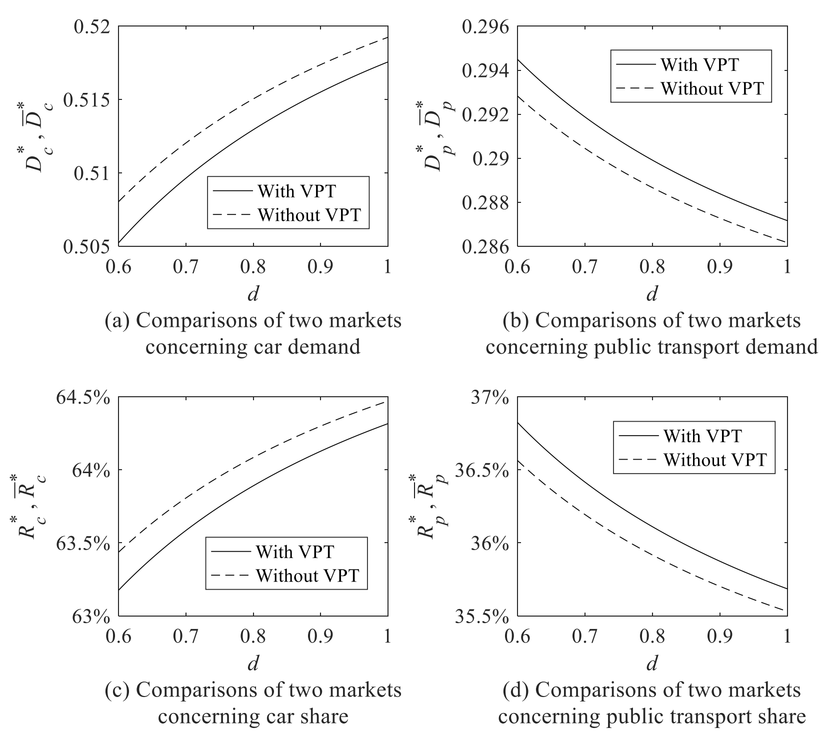
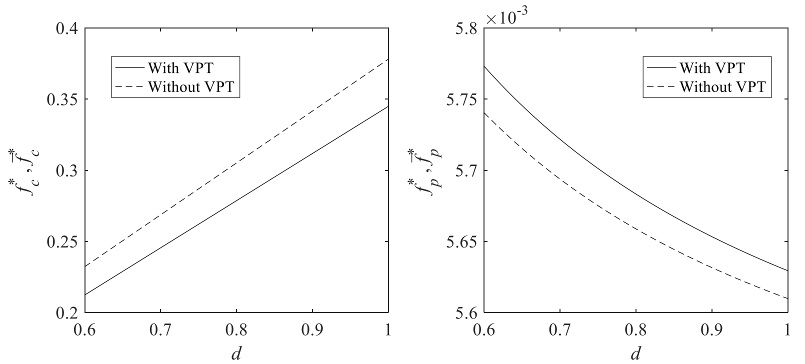


Fig. 2. Comparisons of two markets with and without VPT concerning travel demands and shares.



(a) Comparisons of two markets concerning car retail price

(b) Comparisons of two markets concerning public transport service fare

Fig. 3. Comparisons of two markets with and without VPT concerning the equilibrium price and fare.

Beijing, related to the public transport service level measured by China Academy of Urban Planning and Design (2020), is 32% in 2020, and the average commuting distance l of Beijing is 11.1 km in 2020 (Insight & Info Consulting Ltd, 2020). According to the transport practice in China (Baidu Public Policy Research Institute, 2020), the manufacturing cost e_c is estimated to be $50\% f_c^*$, the operating cost of the car e_t is estimated at around $120\% f_c^*$, the generalized cost of the bus e_p is estimated to be $200\% f_c^*$, and the externality parameter σ is assumed to be $1 \times 10^{-5}\% f_c^*$. Kindly note that we have normalized the average number of driving trips for ease of model building, making the following results have no units.

(i) Comparing the results with and without VPT

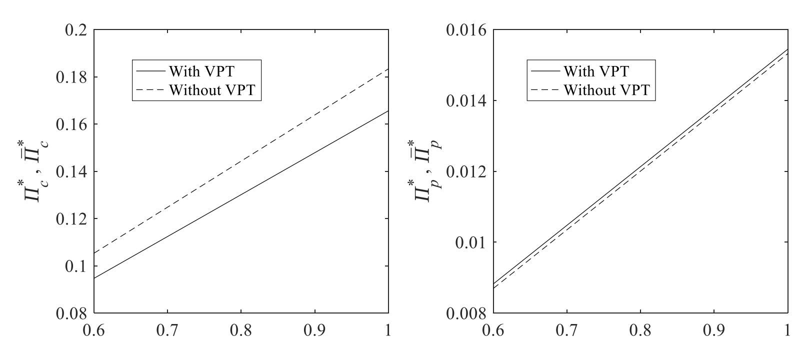
Based on the proposed model and collected data, we present five pairs of equilibrium results, i.e., travel demands D_c^* and D_p^*, travel shares R_c^* and R_p^*, price/fare f_c^* and f_p^*, traveler surplus TS^*, and social welfare SW^*. In particular, these results in the market without VPT can be directly obtained by setting $\alpha = 0$ in Eqs. (7)–(12) and are marked to be $\overline{D}_c^*$, $\overline{D}_p^*$, $\overline{R}_c^*$, $\overline{R}_p^*$, $\overline{f}_c^*$, $\overline{f}_p^*$, $\overline{TS}^*$, and $\overline{SW}^*$, respectively. We also regard the normalized average number of driving trips of cars d as the variable ranges from 0.6 to 1. The larger the value of d, the longer the usage rate or the lifecycle of cars.

We first present the comparison results concerning travel demands and shares in Fig. 2. This result is the most significant one to verify whether the levy of VPT can promote the modal shift. Results from Fig. 2 show that given the same value of d, the market with VPT is found to have smaller private car demand but larger public transport demand than that of the market without VPT. The same trend in travel share can be also found in this figure. This figure also illustrates that both the private car demand/share and the public transport demand/share will be influenced by the value of d. The increase in d will positively affect the private car demand/share, while negatively affecting the public transport demand/share.

We then present the rest of the comparison results of the market, including the equilibrium price and fare, equilibrium profits, the traveler surplus, and social welfare. Fig. 3 illustrates the comparison results concerning the equilibrium price and fare. We can find from this figure that the market with VPT is associated with a smaller car retail price and a larger public transport fare compared with that of the market without VPT under the same value of d. It demonstrates that the levy of VPT will stimulate the car manufacturer and the public transport operator to change their pricing strategies. Similarly, both the car retail price and the public transport service fare will be influenced by d. The increase of d positively affects the car retail price while negatively affects the public transport service fare.

Fig. 4 illustrates the comparison results concerning the equilibrium profits. It can be found that the market with VPT leads to a smaller car manufacturer's profit but a larger public transport operator's profit under the same values of d. We also find from this figure that the value of d will affect the profits. The increases of d will increase both the car manufacturer's profit and the public transport operator's profit.

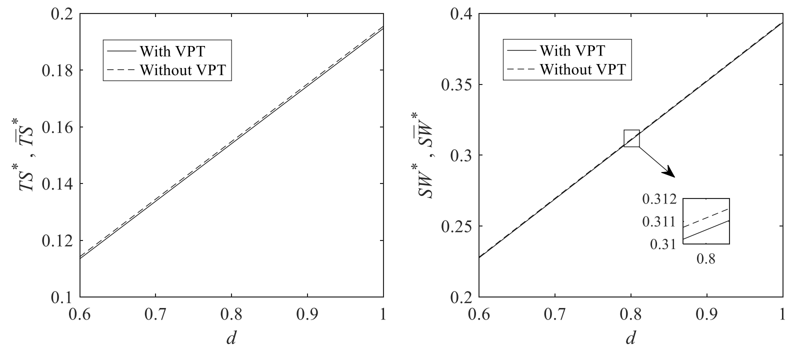
Fig. 5 illustrates the comparison results concerning the traveler surplus and social welfare at the equilibrium state. We can find from this figure that the market with VPT has a smaller traveler surplus and social welfare than that of the market without VPT under the same values of d. The result is consistent with the finding derived from Proposition 6 that VPT sacrifices travelers' utilities and social welfare for the target of car ownership restriction and public transport promotion. Kindly note that



(a) Comparisons of two markets concerning car manufacture's profit

(b) Comparisons of two markets concerning public transport operator's profit

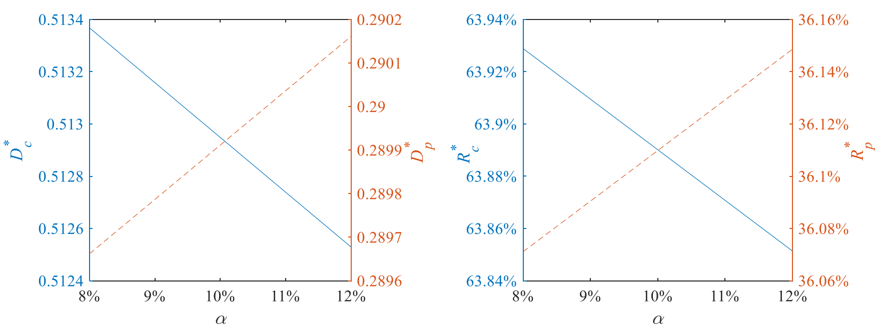
Fig. 4. Comparisons of two markets with and without VPT concerning equilibrium profits.



(a) Comparisons of two markets concerning traveler surplus

(b) Comparisons of two markets concerning social welfare

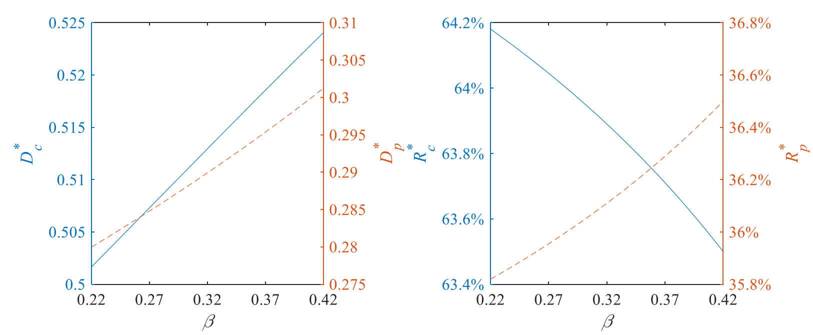
Fig. 5. Comparisons of two markets with and without VPT concerning the traveler surplus and social welfare.



(a) Relationships between the VPT rate and travel demands

(b) Relationships between the VPT rate and travel shares

Fig. 6. Sensitivity analysis of travel demands and shares with respect to the VPT rate.



(a) Relationships between public transport comfort factor and travel demands

(b) Relationships between public transport comfort factor and travel shares

Fig. 7. Sensitivity analysis of travel demands and shares with respect to the public transport comfort factor.

we have normalized some parameters such as the car's designed number of driving trips and the total number of travelers, which leads to the traveler surplus gap and the social welfare gap are not such large in this specific case. Though the experiment differences are small, comparison results supported by both theoretical proof (Proposition 6) and experimental tests (Fig. 5) are still significant because they reveal the side effect of VPT on the traveler surplus and social welfare and subsequently provide potential guidance for the government regarding how to mitigate this negative impact of VPT.

(ii) Sensitivity analysis

This subsection explores ways to achieve the target of reducing private car demand/share and increasing public transport ridership for metropolitan cities that suffer from traffic congestion and emissions. Focusing on the travel demands and travel shares (see Eqs. (8) and (9)), i.e., D_c^*, D_p^*, R_c^*, and R_p^*, we conduct the sensitivity analysis of the two results with respect to some significant parameters, including the VPT rate α and the public transport comfort factor β. Kindly note that we only consider the results under the market with VPT here because the merits of VPT have already been identified.

For the sensitivity analysis with respect to α, we regard α as the variable ranges from 8% to 12%. Other parameters are set the same as in the basic experiment. The relationships between α and D_c^*, D_p^*, R_c^*, R_p^* are illustrated in Fig. 6. It can be found that the increase of α encourages more travelers to shift from self-driving to public transport, though the

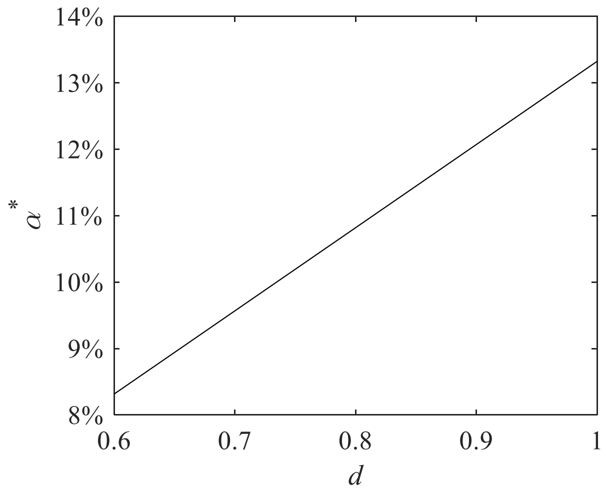


Fig. 8. The optimal VPT rate with the consideration of the endogenized VPT rate.

improvement trend in this case is minor. This finding provides a useful implication regarding further promoting public transport and restricting car ownership, that is, raising the VPT rate appropriately without affecting the auto industries heavily.

For the sensitivity analysis with respect to β, we regard β as the variable ranges from 0.22 to 0.42. Based on the data, the relationship between β and D_c^*, D_p^*, R_c^*, R_p^* are presented in Fig. 7. Results show that the increase of β stimulate the increase of D_c^*, D_p^*, and R_p^*, while lead to the decrease of R_c^*. This indicates that the enhancements of public transport services help to attract travelers to ride on public transport. One worth noting finding is that D_c^* in this case will increase with the increase of β, which seems inconsistent with common sense. However, the increase of D_p^* is attributed to the increased total travel demands derived from the improved mobility services. This finding also provides an implication that the public transport service is encouraged to be improved.

4.2. Extended experiments

In this subsection, we further consider three extended experiments to cover more scenarios, including the endogenized VPT rate, the social welfare maximization target for the public transport operator, and the behaviors of reselling cars.

(i) Considering the endogenized VPT rate

In this case, we consider that VPT is endogenized and determined by the government. The government is included in the market and is requested to set the optimal VPT rate to maximize social welfare. Adopting the same method proposed in Section 3, we can easily obtain the optimal VPT rate, the optimal car retail price, and the optimal public transport service fare by combining $\partial SW/\partial\alpha = 0$, $\partial\pi_c/\partial f_c = 0$, and $\partial\pi_p/\partial f_p = 0$. Other equilibrium results can be calculated subsequently. To focus on the role of VPT, we only present results concerning the optimal VPT and the equilibrium travel demands and shares based on the former settings.

It can be found from Fig. 8 that the optimal VPT rate α^* is affected by the average number of driving trips d. The larger the value of d, the higher the value of α^*. In particular, the optimal VPT at the benchmark environment, i.e., $d = 0.8$, is 10.82%, which is larger than the current VPT rate of 10% in China. This demonstrates that the government is encouraged to mildly raise the VPT rate.

Fig. 9 presents the comparison results of the two markets concerning the travel demands and shares with the consideration of the endogenized VPT rate. Results show that given the same value of d, the market

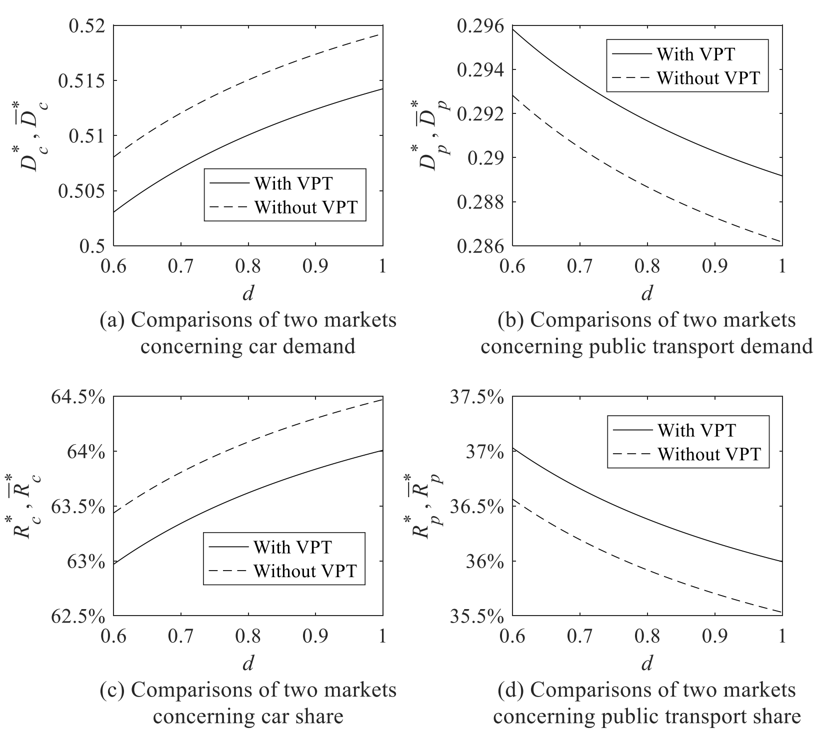


Fig. 9. Comparisons of two markets concerning travel demands and shares with the consideration of the endogenized VPT rate.

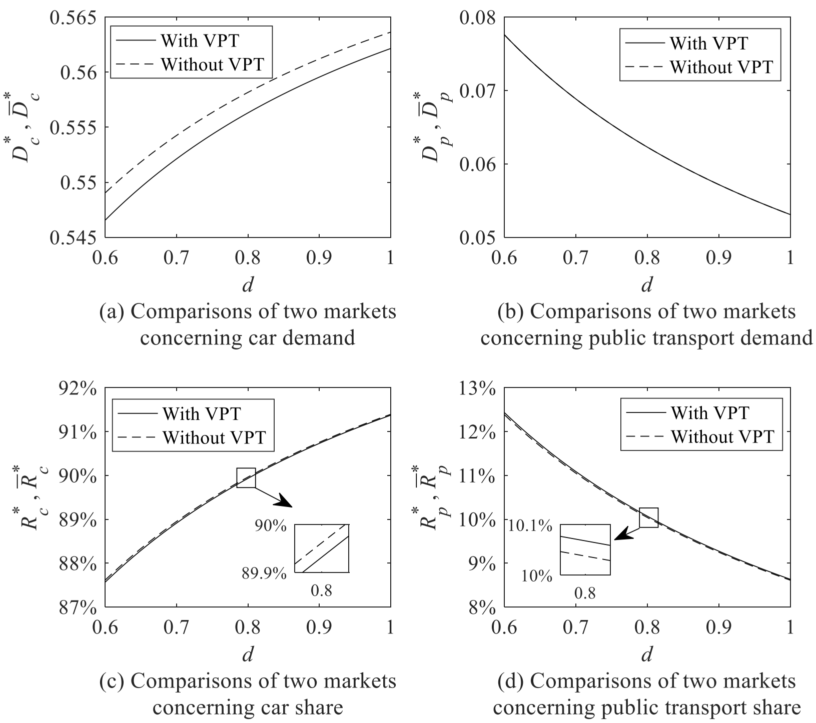


Fig. 10. Comparisons of two markets concerning travel demands and shares with the consideration of social welfare maximization target.

with VPT is found to have a smaller private car demand/share but a larger public transport demand/share than that of the market without VPT. It demonstrates that VPT is still effective and induces a larger growth rate in public transport share and a larger reduction rate in car share. This figure also illustrates that the increase of *d* will positively affect the private car demand and share while negatively affect the

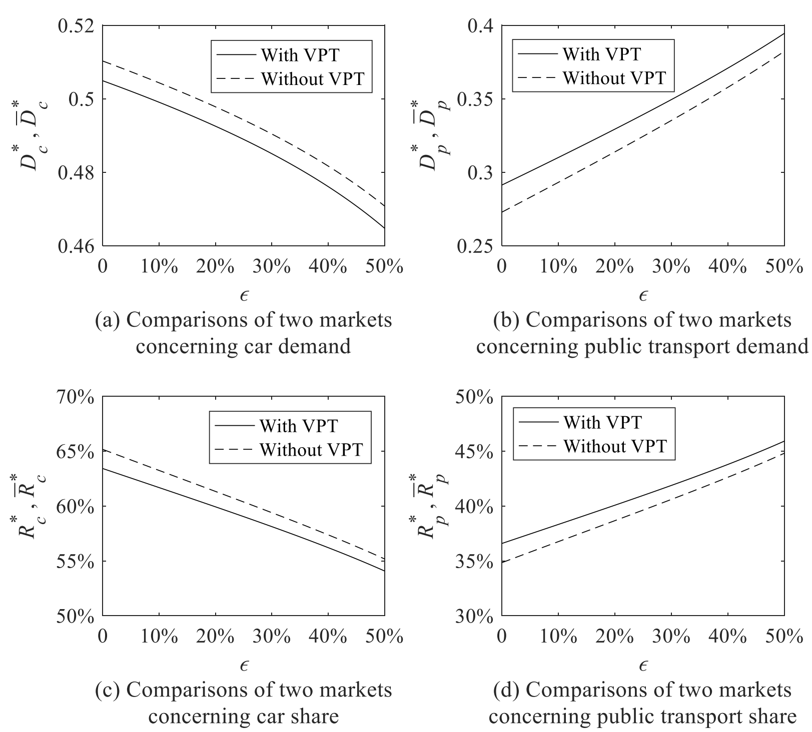


Fig. 11. Comparisons of two markets concerning travel demands and shares with the consideration of reselling private cars.

public transport demand and share, which is the same as the basic experiment.

(ii) Considering the social welfare maximization target for the public transport operator

In this case, we consider that the public transport operator is targeted for social welfare maximization. The method to address this case is the same as the basic model except that the optimal car retail price and the optimal public transport service fare are derived from the combination of $\partial \pi_c / \partial f_c = 0$ and $\partial SW / \partial f_p = 0$. Once the two prices are obtained, other equilibrium results can be calculated. The equilibrium travel demands and shares with and without VPT are presented in Fig. 10.

Results demonstrate that given the same value of d, the market with VPT is found to have a smaller private car demand/share but a larger public transport share than that of the market without VPT. The public transport demands in both two markets are the same because the public transport demand in this case is independent with d, but it does not affect the final finding that VPT is effective though it has a smaller effect on the modal shift compared with that in the basic experiment. Similarly, the increase of d will positively affect the private car demand and share while negatively affect the public transport demand and share.

(iii) Considering the behaviors of reselling cars

In this case, we consider that travelers who choose to purchase cars will finally resell the car at a certain point in time. For simplicity, we assume that travelers' behaviors after selling cars are temporarily not considered in this study because the proposed game-theoretic approach focuses more on the equilibrium states of the market rather than the evolution of complex markets over time, the sequential behaviors after selling cars can be better characterized by other approaches and be investigated in future studies. In this study, we assume that travelers will resell cars when the remaining value of the car reaches εf_c, in which ε can be regarded as the resell point ranging from 0 to 1. The larger the value of ε, the earlier for travelers to resell their cars. Therefore, the utility of traveler i choosing to purchase a car modeled in Eq. (1) will be reformulated to be $U_{ic} = (1-\varepsilon)d(v_i - le_t) - (1+\alpha)f_c$. The utility of traveler i choosing public transport modeled in Eq. (2) will be reformulated to be $U_{ip} = (1-\varepsilon)d\left(\beta v_i - lf_p\right)$. The method proposed in Section 3 can be directly adopted here. The equilibrium travel demands and shares with and without VPT are presented in Fig. 11.

Fig. 11 illustrates that VPT is still an efficient policy tool to restrict car ownership and promote public transport with the consideration of reselling private cars, in which the market with VPT is always found to have a smaller private car demand/share but a larger public transport demand/share than that of the market without VPT given the same value of ε. In particular, the increase of ε leads to a decrease in car demand/share and an increase in public transport demand/share.

5. Discussions

In this section, we discuss the results of the case study to derive the potential implications.

5.1. Discussions for the basic results

In the basic experiments performed in Subsection 4.1, we regard the average number of driving trips of cars d as the variable and derive the results regarding the relationship between d and the equilibrium results (travel demands and shares in Fig. 2, prices and fares in Fig. 3, profits in Fig. 4, traveler surplus and social welfare in Fig. 5).

Results of Fig. 2 indicate that the levy of VPT is effective in reducing car ownership and promoting public transport, which verifies the theoretical findings of Propositions 1 and 2 and provides a potential implication that levying VPT is an efficient pathway to encourage the modal shift from self-deriving the public transport. The results of this figure also indicate that the increase in d will positively affect the private car demand/share while negatively affecting the public transport demand/share. This can be explained by the fact that the expected larger number of driving trips will attract more travelers to purchase cars, which leads to fewer travelers for public transport.

Results of Fig. 3 indicate that the increase in d positively affects the car retail price while negatively affects the public transport service fare. The increasing trend of the car retail price is attributed to the incremental vehicle manufacturing cost derived from the improvement of the car's lifecycle, while the decreasing trend of the public transport service fare can be explained by the fact that the lower fare contributes to attracting travelers for the public transport operator given the increased ownership cost of the car. This provides direct guides for both the car manufacturer and the public transport operator regarding how to set their prices/fares in the face of the value changes of d.

Results of Fig. 4 are closely related to the findings from Figs. 2 and 3 because the profit of the car manufacturer/public transport operator is the product of the private car demand/public transport demand and the car retail price/public transport service fare. A smaller private car demand and retail price of cars due to VPT will lead to a lower car manufacturer's profit, while the opposite applies to the public transport operator.

Results of Fig. 5 indicate that the levy of VPT sacrifices travelers' utilities and social welfare. This finding is consistent with the economic sense that the imposition of a new tax will inevitably cause deadweight losses and other welfare losses associated with microeconomic distortions (Mankiw, 2021). Results of this figure also demonstrate that the reduction of the lifecycle of cars (i.e., reducing the value of d) will cause the loss of travelers' utilities and social welfare, which can be regarded as one of the side effects of promoting the modal shift by levying VPT.

In general, discussions of the basic results provide useful research directions regarding how to promote the modal shift from self-driving to public transport under the VPT policy and its related potential side effects, which lays the foundations for policy implications.

5.2. Discussions for the extended results

In the extended experiments performed in Subsection 4.2, we further focus on three specific concerns and derive the related results (the results considering the endogenized VPT rate in Figs. 8 and 9, the results considering the social welfare maximization target in Fig. 10, and the results considering the behaviors of reselling cars in Fig. 11).

Results of Figs. 8 and 9 demonstrate how the value of d will affect the optimal VPT rate and travel demands/shares, in which the optimal VPT rate and the car demand/share will be positively affected by d while the public transport demand/share will be negatively affected by d. This finding is rational because the increase in the car's average number of driving trips will encourage travelers' willingness to purchase cars and thus motivate the government to raise the VPT rate for car purchase restrictions.

Results of Fig. 10 illustrate a similar relationship between d and travel demands/shares compared with the results illustrated in Fig. 9. This indicates that the experiments with two specific concerns, i.e., the consideration of the endogenized VPT rate and the consideration of the social welfare maximization target for the public transport operator, induce similar results derived from the basic experiment, i.e., the car demand/share will be positively affected by d while the public transport demand/share will be negatively affected by d. In other words, the results of the two cases are consistent with rational explanations.

Results of Fig. 11 demonstrate how the value of the car resell point ε will affect travel demands/shares, in which the car demand/share will be negatively affected by ε while the public transport demand/share will be positively affected by ε. This is also rational because a larger ε means less utilization rate of cars and naturally reduces the car demand and share. The public transport demand and share will increase subsequently due to the modal shift.

In general, these results demonstrate pathways to realize the target of the modal shift from self-driving to public transport, that is, increase the value of ε and decrease the value of d.

6. Policy implications

Based on the discussions presented in Section 5, we further summarize detailed measures for restricting car ownership and promoting public transport in this section.

(i) Levy the optimal VPT rate

This insight provides implications for the government regarding how to set the VPT rate. Considering that VPT has been proven to be an effective policy tool to decrease private car demand/share and increase public transport demand/share in various circumstances, the government is encouraged to set the optimal VPT rate derived from the proposed model based on the actual situations, e.g., the public transport service level and average commuting distance of a certain city, etc. The levy of VPT can be regarded as a viable policy tool for metropolitan cities suffering from traffic congestion and GHG emissions since VPT is effective with high public acceptance to promote the modal shift.

(ii) Enhance the public transport services

This insight provides implications for the public transport operator regarding how to attract travelers and improve its profit. Since the proposed model shows that a larger public transport comfort factor helps to increase the public transport demand/share, it is thus imperative to enhance the public transport services for a high public transportation ridership. Detailed measures include improving the internal environment of public transport vehicles by installing amenities, optimizing the public transport station layout and entrance signs, improving reliability and on-schedule rate of the public transport system, improving digital accessibility by installing vehicle-to-everything infrastructures, etc.

(iii) Optimize the community layout

This insight provides implications regarding how to shape the urban structure to stimulate travelers' pro-public transport behaviors. Since the proposed model shows that a small average number of driving trips is encouraged, it is rewarding to optimize community layout by planning a short distance from workplaces to residential areas and providing convenient public transport facilities. This is reasonable because communities are the social units of the city to shape travel behaviors. The optimization of the community layout will help realize the target to promote public transport.

7. Conclusions

In this study, we first try to quantify the impact of VPT on car ownership restriction and public transport promotion by the mathematical modeling approach. A game-theoretic model is developed to incorporate the interactive relations and optimal strategies of key transport players. The government is in charge of launching the VPT policy, the car manufacturer and public transport operator determine the car retail price and transport public service fare respectively to maximize their profits, and travelers choose their transport mode, i.e., self-driving and public transport riding, based on their utilities. Several equilibrium results, especially the demands and shares of the two travel modes, are derived from the proposed model. By comparing the travel demands and shares of the market with and without VPT, we find that VPT is an effective tool to reduce private car demand and share and in return increase public transport demand and share. Three kinds of extended experiments are further conducted to cover more scenarios. Viable policy measures to further realize the target of car ownership restriction and public transport promotion are proposed, including levying the optimal VPT rate, enhancing public transport services, and optimizing the community layout.

Despite its achievements in identifying the impact of VPT on car ownership restriction and public transport promotion, this study has still some limitations. First, the game-theoretic model relies on the assumption that all players in the transport market are rational and act in their self-interest. It may not always hold in reality because players may have other motivations or biases that influence their decisions. Second, the scenario considered in this study is ideal with limited and deterministic decisions. More nonlinear behaviors such as the complex relationship between the car manufacturing cost and car retail price and the sequential behaviors of travelers after selling cars are temporarily not considered.

Accordingly, we list the following potential aspects for future studies. First, we can relax the economic assumptions to consider more influence factors to affect players' decisions, e.g., travelers' decisions under bounded rationality and travelers' heterogeneous preferences derived from their incomes. Second, we can extend the scenario to a more complex environment approached by other methods such as system dynamics. Third, the dual policy combining VPT and other car restriction/public transport promotion measures is interesting to explore. Fourth, short-term decisions regarding the day-to-day mode choice are encouraged to be explored through collaboration with the local government.

CRediT authorship contribution statement

Haohan Xiao: Writing – original draft, Resources, Methodology, Conceptualization. **Min Xu:** Writing – original draft, Supervision, Methodology, Conceptualization. **Shuaian Wang:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization.

Acknowledgements

This work was supported by the National Natural Science Foundation of China [Grant No 72361137006 and 72401109].

Appendix A. Proof of Proposition 3

Proof: The relationship between the travel demands and the VPT rate can be obtained by taking the first derivatives of Eq. (8) with respect to α as follows:

$$\begin{cases} \dfrac{\partial D_c^*}{\partial \alpha} = \dfrac{e_c(\beta-2)}{(\beta-4)(\beta-1)d} < 0 \\ \dfrac{\partial D_p^*}{\partial \alpha} = \dfrac{e_c}{(\beta-4)(\beta-1)d} > 0 \end{cases} \tag{A1}$$

where the inequalities are obtained based on the constraints of $e_c > 0$, $0 < d \le 1$, $\alpha > 0$, and $0 < \beta < 1$. This indicates that the private car demand/public transport demand will linearly decrease/increase with the increase in the VPT rate. □

Appendix B. Proof of Proposition 4

Proof: The relationship between the travel shares and the VPT rate can be obtained by taking the first derivatives of Eq. (9) with respect to α as follows:

$$\begin{cases} \dfrac{\partial R_c^*}{\partial \alpha} = \dfrac{(4-\beta)e_c d}{(\beta-1)(e_c - 3d + e_t dl + e_c\alpha)^2} < 0 \\ \dfrac{\partial R_p^*}{\partial \alpha} = \dfrac{e_c}{(\beta-1)(e_c - 3d + e_t dl + e_c\alpha)} - \dfrac{e_c(e_c + d - \beta d + e_t dl + e_c\alpha)}{(\beta-1)(e_c - 3d + e_t dl + e_c\alpha)^2} > 0 \end{cases} \tag{B1}$$

The inequalities of this equation follow from the identified relationships of $e_c - 3d + e_t dl < 0$ and $e_c - 3d + e_t dl + e_c\alpha < 0$ as well as the ranges of preset values (i.e., $\alpha > 0$, $0 < \beta < 1$, $0 < d \le 1$, $e_c > 0$, and $e_t > 0$), which indicate that the private car share/public transport share will decrease/increase with the increase of the VPT rate. To explore the concavity or convexity of the two curves, we further have the following results by taking the second derivatives of subfunctions in Eq. (9) with respect to α as follows:

$$\begin{cases} \dfrac{\partial^2 R_c^*}{\partial \alpha^2} = \dfrac{2e_c^2 d(\beta-4)}{(\beta-1)(e_c - 3d + e_t dl + e_c\alpha)^3} < 0 \\ \dfrac{\partial^2 R_p^*}{\partial \alpha^2} = \dfrac{2e_c^2(e_c + d - \beta d + e_t dl + e_c\alpha)}{(\beta-1)(e_c - 3d + e_t dl + e_c\alpha)^3} - \dfrac{2e_c^2}{(\beta-1)(e_c - 3d + e_t dl + e_c\alpha)^2} > 0 \end{cases} \tag{B2}$$

Again, the inequalities of the above equation are derived from $e_c - 3d + e_t dl < 0$ and $e_c - 3d + e_t dl + e_c\alpha < 0$ as well as the aforementioned preset values. This indicates that the curve for the relation between the tax rate and the private car share/public transport share is convex/concave. □

Appendix C. Proof of Proposition 5

Proof: By enforcing $\alpha = 0$ in Eqs. (7) and (10), the equilibrium transport public service fare $\overline{f}_p^*$ and the equilibrium public transport operator's profit $\overline{\Pi}_P^*$ without VPT are given by Eqs. and respectively:

$$\overline{f}_p^* = \frac{\beta(e_c + d - \beta d + e_t dl)}{(4-\beta)dl} \tag{C1}$$

$$\overline{\Pi}_P^* = \frac{\beta(e_c + d + e_t dl - \beta d)^2}{(\beta-4)^2(1-\beta)d} - e_p \tag{C2}$$

The comparisons of the two markets with and without VPT concerning the two items are given by

$$\Delta f_p = f_p^* - \overline{f}_p^* = \frac{\alpha\beta e_c}{(4-\beta)dl} > 0 \tag{C3}$$

$$\Delta \Pi_P = \Pi_P^* - \overline{\Pi}_P^* = \frac{\alpha\beta e_c[2d(\beta - 1 - e_t l) - e_c(2+\alpha)]}{(\beta-4)^2(\beta-1)d} > 0 \tag{C4}$$

Based on the aforementioned constraints, both Δf_p and $\Delta \Pi_P$ are positive, indicating that the levy of VPT leads to a larger demand, a higher fare, and accordingly a higher profit to benefit the public transport operator. □

Appendix D. Proof of Proposition 6

Proof: By enforcing $\alpha = 0$ in Eqs. (11) and (12), the travelers' surplus $\overline{TS}^*$ and social welfare $\overline{SW}^*$ under the market without VPT are given by

$$\overline{TS}^* = \frac{(3\beta-4){e_c}^2 - 2e_c d[\beta(\beta - 3e_t l + 3) + 4e_t l - 4]}{2(\beta-4)^2(\beta-1)d} - \frac{d^2\left[-5\beta^2 + e_t^2 l^2(4-3\beta) + 2e_t l(\beta-1)(\beta+4) + \beta + 4\right]}{2(\beta-4)^2(\beta-1)d} \tag{D1}$$

$$\overline{SW}^* = \frac{d\left[13\beta - 12 + \beta^2 - 2\beta^3 + 2e_t l(\beta-1)(5\beta-12) + e_t^2 l^2(\beta(9-2\beta)-12)\right]}{2(\beta-1)(\beta-4)^2} + \frac{e_c^2[\beta(9-2\beta)-12]}{2d(\beta-1)(\beta-4)^2} - e_p + \frac{e_c(\beta-1)[5\beta-12] + e_c e_t l\left[3(3\beta-4) - 2\beta^2\right]}{(\beta-1)(\beta-4)^2} \tag{D2}$$

The comparisons of the two markets with and without VPT concerning the two items are thus given by

$$\Delta TS = TS^* - \overline{TS}^* = \frac{\alpha e_c[e_c(2+\alpha)(4-3\beta) + 2d(e_t l(4-3\beta) + (1-\beta)(4+\beta))]}{2d(\beta-4)^2(\beta-1)} < 0 \tag{D3}$$

$$\begin{aligned}\Delta SW &= SW^* - \overline{SW}^* \\ &= \alpha e_c \frac{e_c[2(\beta-3)\beta + \alpha(3\beta-4)] - 2\sigma(\beta-4)(\beta-2)}{2d(\beta-4)^2(1-\beta)} \\ &+\alpha e_c \frac{2d[(3\beta-7)\beta - 4 + e_t l\beta(\beta-3)]}{2d(\beta-4)^2(1-\beta)} < 0\end{aligned} \tag{D4}$$

Based on the aforementioned constraints, both ΔTS and ΔSW are negative, indicating that the levy of VPT leads to smaller travelers' utilities and social welfare. □

Data availability

Data will be made available on request.

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