University of Groningen

Strategies for applying carbon trading to the new energy vehicle market in China

Nie, Qingyun; Zhang, Lihui; Tong, Zihao; Hubacek, Klaus

Published in:
Energy

DOI:
10.1016/j.energy.2022.124904

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2022

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Nie, Q., Zhang, L., Tong, Z., & Hubacek, K. (2022). Strategies for applying carbon trading to the new energy vehicle market in China: An improved evolutionary game analysis for the bus industry. *Energy*, *259*, Article 124904. https://doi.org/10.1016/j.energy.2022.124904

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Download date: 01-02-2024

Energy 259 (2022) 124904

Contents lists available at ScienceDirect

Energy

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

Strategies for applying carbon trading to the new energy vehicle market in China: An improved evolutionary game analysis for the bus industry

Qingyun Nie [a,b,c], Lihui Zhang [a,b,*], Zihao Tong [a,b], Klaus Hubacek [c]

[a] School of Economics and Management, North China Electric Power University, Beijing, 102206, China
[b] Beijing Key Laboratory of New Energy and Low-Carbon Development, North China Electric Power University, Beijing, 102206, China
[c] Univ Groningen, Integrated Research on Energy, Environment and Society (IREES), Energy & Sustainability Research Institute Groningen (ESRIG), University of Groningen, NL-9747 AG Groningen, Netherlands

ARTICLE INFO

Keywords:
New energy bus
Decision-making behavior
Strategies within the same group
Sustainable transport
Energy transition

ABSTRACT

Application of carbon trading on the consumption-side to subsidize NEVs (called “carbon trading subsidy (CTS)”) is expected to become the successor policy for the phasing-out purchase subsidy, but there is still a gap between practice and theory in how to apply. This study applies CTS to bus industry and addresses the interaction problem between purchase decision of bus operators and policy-implementation decision of the government, and improves evolutionary game theory by considering the incentive effects of strategies within the same group to discuss stable strategies of each parties. Simulation experiments are conducted to validate the correctness of the improved model and investigate the effects of key parameters on the evolution of decision behaviors. The results show that subsidy effect of different carbon prices varies significantly under different cost gaps of new energy buses (NEBs) and fuel buses (FBs), and there is an optimal carbon price range, i.e. 0.163–0.263 CNY/kg in this research. The initial carbon quota less than and close to the carbon emissions of FB can achieve the optimal subsidy effect. Maintaining high-frequency inspections on operators can ensure smooth proliferation of NEBs. Finally, policy recommendations to implement CTS are proposed for different stages of the cost reduction of NEBs.

1. Introduction

With the rapid development of the automobile industry, the problems of environmental pollution and energy supply shortages caused by the widespread use of traditional fuel vehicles (FVs) have become increasingly prominent. Therefore, new energy vehicles (NEVs) with significant energy-saving and emission-reduction benefits are increasingly favored [1]. According to the “China Automotive Industry Development Annual Report 2021″ released by the Chinese Ministry of Industry and Information Technology, there are approximately 4.92 million NEVs and 270 million FVs in China by the end of 2020, with a penetration share of 1.75% for NEVs, with a large potential for growth. In terms of public transportation, electric buses and hybrid buses account for 53.8% and 12.4% of urban public buses and trams respectively [2], but mainly distributed in key regions like Shenzhen, Beijing, Shanghai, Guangzhou, and other municipalities directly under the central government, provincial capitals and planned cities, whereas the bus electrification in some central and western lower-tier cities still needs to be improved. The policies of the central and local governments are still vigorously promoting the application of new energy buses (NEBs) [3] and the smooth replacement of traditional fuel buses (FBs) by NEBs nationwide subsequently.

Since 2010, a purchase subsidy has become the main tool for the Chinese government to support the development of NEVs and has achieved positive results [4]. Benefitting from the incentive of purchase subsidy and the promotion of other government policies, NEBs have been deployed rapidly in key cities in China in the past five years. However, the purchase subsidy policy has led to problems such as ‘subsidy fraud’ [5], a financial burden on the government, and a non-competitive oriented NEV market [6], leading the government to reduce the amount of subsidies each year starting from 2017 with the plan to completely eliminate the subsidy by 2022 [7,8]. According to data from the China Bus Statistics Information Network, under the influence of subsidy retreat, production of NEBs in China continued to decline after reaching a peak in 2016, falling from 135,000 units in 2016 to 61,000 units in 2020. The sluggish market demand for NEBs

---

[*] Corresponding author. School of Economics and Management, North China Electric Power University, Beijing, 102206, China.
E-mail address: zlh6699@126.com (L. Zhang).

https://doi.org/10.1016/j.energy.2022.124904
Received 4 April 2022; Received in revised form 22 June 2022; Accepted 20 July 2022

continued until 2021, with sales falling 25% from January to September in 2021 compared to the same period last year. The question of how the government can promote NEBs nationwide with a better incentive mechanism to ensure the development of energy saving and emission reduction in public transportation is a pressing issue after purchase subsidies continue to be eliminated.

In 2016, the General Office of the National Development and Reform Commission issued a draft of the "Measures for the Administration of Carbon Quotas for New Energy Vehicles", proposing to use the carbon quota transaction as successor policy of the expiring purchase subsidy, which is based on subsidies for the production-side of NEVs, but this new policy has not been successfully implemented. Therefore, some scholars have turned their attention to carbon trading on the consumption-side and demonstrated through market research that it can effectively reduce the negative impact of subsidy withdrawal and promote the development of NEV market [9–11]. In carbon trading subsidy (CTS) on consumption-side, free carbon quota will first be allocated to vehicle owners, who can trade carbon quotas according to the carbon emissions generated by their own driving. For NEVs, their lower carbon emissions will bring subsidy benefits to vehicle owners, and make FV owners bear the corresponding environmental responsibility for their own carbon emissions [9,10,12]. Compared to traditional purchase subsidy, which is the way of "buy-and-get-subsidy", CTS is based on the distance traveled by NEVs, which can promote the actual use of NEVs. Currently Nie has discussed the key issues of carbon trading application in the private vehicle sector [13], while the bus sector, an object with multiple dynamic decisions, has not been targeted for study.

Through this paper, we aim to apply CTS in the bus industry to support further electrification of public transportation by using game theory, explore the implementation details of key parameters such as carbon price, initial carbon quota and government regulation, as well as the impact of vehicle cost on the decision, to further advance the research process of the implementation and application of CTS in the NEV market. Evolutionary game theory can simulate the evolutionary trends of product supply chains and systems in different contexts and has been repeatedly applied to supply chain decision-making problems such as carbon trading [14–16], as well as to explore problems such as the diffusion of EV [17], the construction of EV charging infrastructure [18, 19], and purchase subsidies [20–22]. Evolutionary game theory adopts the assumption of limited rationality for actors with multiple strategy choices, that is, actors' behavior strategies are constantly and dynamically revised and improved under the condition of incomplete information, and finally reach a stable solution [23,24]. Although the Stackelberg game [6,13] has also been used to study issues related to new energy vehicle subsidy policies and supply chain decisions, it makes the assumption of perfectly rational behavior for participating entities, that is, they reach the final decision at once under the condition of complete information. In this study, involving the multi-sectorial and frequency dependent nature of incentives of bus operators and the government, the purchase decision of the former is not seen as a one-time act, but usually a multi-batch procurement iteration until all vehicle purchases are completed, and their decision may change dynamically according to the respective subsidy level in the process of multiple procurements. While government's policy choice will also continuously be improved and refined based on the operator's changing purchase choices, and eventually both parties interact to reach a dynamic and symbiotic optimal decision [25]. Therefore, evolutionary game theory will be more consistent with the properties of the decision process simulated in this study. Furthermore, although a small number of scholars have studied the diffusion of NEVs using different measures using evolutionary game theory [17,25,26], none of them has addressed the topic of carbon trading. Moreover, they did not consider the mutual incentive effect between the strategies within the same group, i.e., herding behavior, which in this study is the imitation behavior of purchasing decisions between different bus operators and imitation behavior between different regional governments. The herding effect in social systems such as markets is widespread [27], and thus would be more accurate to consider such effects in the model. Therefore, this study further considers the incentive effects of the strategies within bus operators and the government, and improves the evolutionary game model to simulate the evolution of the decision-making behavior of both parties under CTS.

This study answers the following questions: (1) In the context of CTS, under what circumstances would bus operators choose to purchase NEBs and under what circumstances would the government choose to implement CTS? (2) How should the government set the carbon price, initial carbon quota, regulation and penalty efforts when CTS is implemented in the bus industry? (3) How to dynamically adjust the CTS implementation strategy when the gap between the total cost of NEBs and FBs is narrowing? Specifically, three steps are adopted: (1) Introduce the incentive coefficients of the strategies within bus operators and the government to build an improved evolutionary game model under the implementation of CTS. (2) Discuss the evolutionary stabilization strategies of the decision-making behavior of bus operators and the government when the parameters in the model satisfy different conditions. (3) Simulate and validate the evolutionary results of bus operators and the government under different parameters with electric buses (EBs) and FBs, and propose corresponding policy recommendations for different stages of the implementation of CTS based on the evolutionary results.

The contributions of this study are as follows: firstly, the constructed general model of the improved evolutionary game under CTS can be used to analyze the evolution of decision-making behaviors of bus operators and the government in different market environments, and this model can also be extended to taxi and similar companies, as well as to the public transport industry in different countries and regions, so as to propose applicable implementation plans for CTS. Secondly, the improved evolutionary game model, which takes into account the herding behavior within the same group, established by introducing the incentive coefficients can more accurately reflect the interaction and evolution of the decision-making behaviors between operators and the government. In the practical application of the model, the incentive coefficients can be adjusted to further investigate the impact of the society's promotion efforts for NEBs and the government's requirements for the implementation of CTS, which provides further value added. Finally, this study proposes policy recommendations for CTS for different cost gaps between NEBs and FBs, which can further promote the application of CTS in the bus industry based on previous research in the private vehicle sector, and provides new ideas for the new policy of NEV subsidy policy after the cancellation of purchase subsidy.

2. Literature review

(1) Incentive policies on NEVs

Purchase subsidy has been used to incentivize the development of NEV market in many countries around the world in the past decade, including the US, Japan, South Korea, UK, Germany, Norway, and other European countries [28–32]. The incentive effect of purchase subsidy on the NEV market has been extensively verified by academics [33–35], which enables NEVs to gain economic competitiveness similar to that of traditional vehicles [36,37], thereby gaining attractiveness to consumers further generating a positive impact on production decisions [38]. However, due to the unsustainable development and non-competitive market-oriented disadvantages of purchase subsidy to the NEV market [6,39,40], many countries have already regressed or even eliminated the purchase subsidy. Including China, the withdrawal of purchase subsidy has had a negative impact on the NEV market. Sheldon proposes that if subsidies are halved without any countervailing measures, the market share of EVs will drop by 21% [35]. Kong and Wang propose that the share of NEVs will drop by 40% and 42% after the cancelation of purchase subsidy, respectively [41,42]. Regarding EBs, Du also believes that the market for normal-charging EBs and light-duty EBs will shrink sharply after subsidies are greatly reduced [43].

In response to the negative impact brought by the retreat, scholars have put forward their policy recommendations. Among them, EV privileges like no restrictions on driving and purchases [39,44], charging infrastructure construction [6], and NEV mandate policy [42] are relatively frequent countermeasures, these studies have verified their positive effects after the retreat of purchase subsidy. Other countries have also adopted measures like reducing car usage costs such as parking fees, charging fees and road registration fees [45,46], access to bus lanes or high-occupancy vehicle lanes [29], which have also been applied in Beijing where there is a high volume of traffic. However, these studies usually focus on the analysis of the market effects of incentives, not on systematic subsidy policies, and cannot be universally applied in China's vast automobile market. There are also some studies on the substitution effect of the dual credit policy (New-Energy Vehicle Credit Program and Corporate Average Fuel Consumption Regulation) [47,48], such as to verify its effect on improving the production willingness of NEV manufacturers based on game theory [49]. This policy implementation of encouraging enterprises to produce NEVs on the production-side has resulted in problems such as supply of points exceeding demand and lower fuel economy of vehicle enterprises. Therefore, Ma proposes to develop a comprehensive policy implementation mechanism and combine it flexibly with other supporting policies to truly bring out the sustainable development of NEVs [50]. Further exploration of incentives on consumption-side to form a policy system that works from the production-side to the consumption-side is expected to achieve more rapid development of NEVs.

(2) Application of carbon trading in the transport sector

Since 2013, the carbon trading mechanism has been piloted in seven provinces and cities such as Beijing and Shanghai in China. Manufacturers involved in carbon trading can obtain low-carbon subsidies by increasing carbon emission reduction, which in turn stimulates them to produce cleaner products [51]. The national carbon trading market officially launched in China in 2021 will expand from key emission units in the power generation industry to key industries such as steel and building materials, and will gradually introduce individuals as trading subjects to form a sound trading market system. Meanwhile, Shenzhen also explored the connection between personal carbon accounts and carbon trading at the end of 2021, and launched the first authorized carbon-inclusive operation platform, which was able to accumulate carbon emission reduction points for energy use and public travel. Some empirical studies have analyzed the impacts of carbon trading schemes on individuals in the last decade, and it is now considered an effective incentive to reduce carbon emissions in the household sector [12,52,53].

Due to the burden of emission reduction in transport sector and the high suitability of carbon trading system to this sector [54], scholars such as Harwatt [55], Raux [54,56,57], and Wadud [58] have preliminarily explored the scheme to introduce carbon credits and carbon trading on vehicle driving, discussing some practical issues like the implementation potential, cost-effectiveness, acceptability, and equity. The differences and feasibility of implementing this scheme in the upstream (fuel producers) [59,60], midstream (vehicle manufacturers) [61,62] or downstream (vehicle owners) [63–65] of transport sector is another topic of ongoing debate among scholars [66,67]. The oversourcing of downstream users makes its quota trading considered too costly and difficult to implement, but this has been a concern in the past. Due to the ability to cover the widest range of emission sources, as well as direct incentives for vehicle owners and its greater sensitivity to downstream price signals that makes it more effective in reducing emissions [67], there have been many studies have proposed solutions for individuals to trade quotas. Each eligible adult would have a “carbon account”, similar to a bank account, in which the allocated carbon quota would be stored electronically, and people could view changes in their carbon accounts through easy access via their cell phones for energy use and transportation and purchase or sell quotas through banks or relevant government agencies [58,67–70]. This is similar to the operating platform launched in Shenzhen, and the consensus so far is that with the increasing maturity of mobile devices such as smartphones and big data technologies, there are no substantial technical barriers to the introduction of carbon trading for vehicle owners [53].

The Chinese city of Shenzhen first included public transport in its carbon trading system in 2015, promoting the development of NEVs through allocating quotas to buses [66]. Internationally, the practice of allocating quotas to vehicle owners is rare, but scholars have explored the potential for implementation in developed regions such as London [71], France [72], Ireland [73], and less developed countries such as Kenya [68]. In addition, there are some studies focusing on the practical studies of carbon trading in the transport sector, mainly include two aspects, one is the impact on drivers' travel behavior, Raux combined stated preferences survey and utility model on the French driver market to verify that carbon trading can change the travel behavior of drivers and further reduce transportation emissions [12]. The other is the impact on consumers' car purchase choices. Two main approaches have been used in this research area: 1) A combination of discrete choice experiment and random utility model to investigate consumers' purchase choices between NEVs and FVs under the incentive of personal carbon trading [9,10], and many other scholars have used these two methods to discuss the effect of different incentives on EV purchase preferences, such as no purchase restrictions, no driving restrictions, charging discounts, etc. [39,74,75]; 2) Construct an equilibrium model of car purchase under carbon subsidies, and there are still very few studies in this area, with only Fan considers personal carbon trading with the objective of minimizing driver's cost and establishes a purchase decision problem of hybrid vehicle, it is able to calculate the equilibrium price of carbon quota [76]. Although the application of carbon trading in the international transport sector has not yet been promoted to a satisfactory level, as research continues to be conducted and validated, it will provide more references and possibilities to become an incentive mechanism for carbon reduction in the transport sector in the future.

As a prelude to this investigation, Li verifies that carbon trading can effectively change the decision to adopt and encourage the adoption of EVs based on a choice experiment in Jiangsu, China [9], but this approach can only focus on its effectiveness on the market and cannot discuss the details of the implementation of carbon trading in the transportat sector. While Nie takes the lead in discussing the feasibility of carbon trading in private vehicles using a game approach [13], but the fact that bus operators are a sector with multiple dynamic decisions and the more widespread phenomenon of “subsidy fraud” makes its application a more specific problem. Therefore, investigating the application in the bus industry will promote carbon trading to stimulate the electrification of the entire transport sector.

3. Methodology

3.1. Application of the carbon trading subsidy mechanism

This study proposes a subsidy system for NEVs based on carbon trading on the consumption-side, called ‘carbon trading subsidy (CTS)’. By introducing it into the bus industry, based on the egalitarian principle that everyone has the same right to environmental protection [58,77], allocate the same initial carbon quota for free to every bus entity, the bus entity will obtain the corresponding subsidies according to its carbon emission of actual driving [9]. When the carbon emissions are greater than the carbon quota, operators need to pay extra to purchase quotas to meet emission requirements; when carbon emission is less than carbon quotas, operators can sell excess quotas to obtain carbon subsidies. Considering the problems that may arise from an imperfect market mechanism and the large number of potential participants in the early stages of the application of the carbon trading mechanism, the trading in this study would be different from the existing carbon market. The trading would not take place between operators and operators, but between operators and the government, or the government would fund and authorize a designated agent to organize and monitor the quota trading. The management of carbon quotas would not be left entirely to the market, quotas would be sold at a fixed price set by the government and at which the government would buy back unused quotas [56,57]. Consequently, the CTS application mechanism in the bus industry is established (see Fig. 1).

The CTS for individual bus entity is calculated in Eq. (1) as:

$$A = (Q - C)^{*}p = (Q - d^{*}e)^{*}p \tag{1}$$

where A and Q are the subsidies and initial carbon quotas obtained by the bus operator, respectively; d is the mileage of the bus, e is the carbon emission factor per unit of mileage, C is the carbon emissions generated by the mileage d, and p is the carbon price of unit quota. It should be noted that carbon trading in the transport sector only considers emissions from the driving phase, that is, emissions from charging sources is not considered for EVs, as these emissions are already covered by carbon trading in the electricity sector [67].

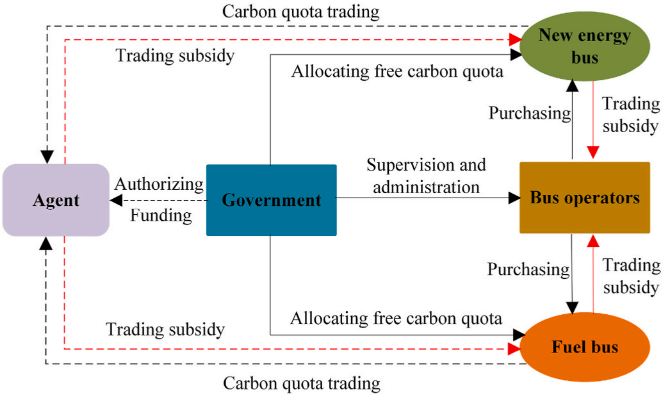


Fig. 1. Diagram of the CTS application mechanism in the bus industry.

3.2. Establishment of the improved evolutionary game model

3.2.1. Model hypotheses

Study of decision-making choices on vehicles usually considers cost and effectiveness throughout their life cycle [78,79], that is, from purchase to retirement, so bus operators will also make decisions on NEB or FB based on the utility during the life cycle. The government chooses whether to implement CTS according to the costs and benefits of the subsidy mechanism. Based on this, the evolutionary game model hypotheses under CTS are constructed as follows:

Hypothesis 1. The two parties of the evolutionary game are bus operators and government, both of which are limited rational groups. In the process of multiple game evolutions, the two parties will adopt corresponding strategies to deal with each other's strategies and constantly seek the optimal strategy to finally reach a dynamic equilibrium.

Hypothesis 2. After introducing CTS mechanism to the bus industry, only two strategies exist for both parties. For bus operators, their strategy set is $\{a_1, a_2\} = \{\text{Purchasing NEB}, \text{Purchasing FB}\}$, and the probability of purchasing NEB and FB are $x(0 \le x \le 1)$ and $1 - x$, respectively. For the government, their strategy set is $\{b_1, b_2\} = \{\text{Implementing CTS}, \text{Not implementing CTS}\}$, the probability of implementing CTS and not implementing CTS are $y(0 \le y \le 1)$ and $1 - y$, respectively.

Hypothesis 3. When bus operators choose to purchase NEB, the purchasing cost is B_e, the charging cost is F_e, the maintenance and repair cost is M_e, the carbon trading subsidy is A_e, and the social and environmental benefit obtained by the government is S; when choosing to purchase FB, the purchasing cost is B_f, the fuel cost is F_f, the maintenance and repair cost is M_f, the subsidy is A_f, and the additional government investments in air pollution control is I. A single bus can realize operating revenue R for operators during its operating cycle (the revenue is the net gain excluding the above cost and benefit items), and the operation of buses can facilitate public travel, and this part of people's welfare W should also be included in government utility.

Hypothesis 4. When the government chooses to implement CTS policy, to prevent 'fraud' phenomenon for bus operators, that is, by using mileage of FB to cheat subsidies by forging license plates and other means. There is a certain probability $\lambda(0 \le \lambda \le 1)$ to check the actual driving situation of the corresponding bus, and the inspection cost is E. If the 'fraud' phenomenon exists, the government will retract the subsidy A_e, issue A_f, and impose penalty P.

Hypothesis 5. When the government chooses not to implement the CTS policy, the willingness of bus operators to purchase NEB in the next stage will be reduced, so that the decline in the number of NEB purchases will lead to a reduction in social and environmental benefits. This study considers this effect in the model and sets the social and environmental benefit obtained by the government when the CTS is not implemented as $f(t)S$, and satisfies $0 < f(t) < 1$.

The above parameters and the meanings of the variables are shown in Table 1.

3.2.2. Utility matrix of bus operators and government

According to the above model hypotheses, there are four strategic combinations in the evolutionary game between bus operators and the government.

(1) When the strategic combination is $\{a_1, b_1\}$, the utility of bus operators is $R + A_e - B_e - F_e - M_e$, and the government may pay inspection cost in addition to the paid carbon trading subsidies, the utility is $W + \lambda(S - A_e - E) + (1 - \lambda)(S - A_e)$.
(2) When the strategic combination is $\{a_1, b_2\}$, the utility of bus operators is $R - B_e - F_e - M_e$. The government does not implement CTS, and its utility is $W + f(t)S$.
(3) When the strategic combination is $\{a_2, b_1\}$, there is a 'fraud' phenomenon for bus operators, the utility of bus operators is $R + \lambda(A_f - B_f - F_f - M_f - P) + (1 - \lambda)(A_e - B_f - F_f - M_f)$. The government may pay inspection cost in addition to the paid subsidies, and the 'fraud' behavior of operators will be found, the

Table 1
Parameters and variable meanings.

Parameters	Meanings
$x, 1 - x$	Probability of bus operators purchasing NEB and FB
$y, 1 - y$	Possibility of the government implementing and not implementing CTS
B_e, B_f	Purchasing costs of NEB and FB
F_e, F_f	Energy costs of NEB and FB
M_e, M_f	Maintenance and repair costs of NEB and FB
A_e, A_f	CTS of purchasing NEB and FB
S	Social and environmental benefits obtained by the government when using NEB
I	Additional government investments in air pollution control when using FB
R	Bus operating revenue
W	People's welfare
E	Inspection cost for the government
P	Fraud penalty of bus operators
λ	Inspection probability of government
$f(t)$	Impact factor of positivity

utility of government is $W + \lambda(P - A_f - E - I) + (1 - \lambda)(-A_e - I)$.

(4) When the strategic combination is $\{a_2, b_2\}$, the utility of bus operators is $R - B_f - F_f - M_f$, the utility of government is $W - I$.

Based on the above strategic combinations, the utility matrix of the evolutionary game is constructed, as shown in Table 2.

3.2.3. Equilibrium points of the improved evolutionary game

For the sake of conciseness, let $M = B_f + F_f + M_f$, $N = B_e + F_e + M_e$, then M and N represent the total cost of purchasing and using FB and NEB, respectively.

For bus operators, the expected utility of purchasing NEB and FB is formulated in Eqs. (2) and (3), the population utility is in Eq. (4) as:

$$U_1 = R + y(A_e - N) - (1 - y)N \tag{2}$$

$$U_2 = R + y\left[\lambda\left(A_f - M - P\right) + (1 - \lambda)(A_e - M)\right] - (1 - y)M \tag{3}$$

$$\overline{U} = xU_1 + (1 - x)U_2 \tag{4}$$

For the government, the expected utility of implementing CTS and not implementing CTS are formulated in Eqs. (5) and (6), the population utility is in Eq. (7) as:

$$\begin{aligned} V_1 = {} & W + x[\lambda(S - A_e - E) + (1 - \lambda)(S - A_e)] \\ & + (1 - x)\left[\lambda\left(P - A_f - E - I\right) + (1 - \lambda)(-A_e - I)\right] \end{aligned} \tag{5}$$

$$V_2 = W + x{\cdot}f(t)S - (1 - x)I \tag{6}$$

$$\overline{V} = yV_1 + (1 - y)V_2 \tag{7}$$

On this basis, the replication dynamic equations are improved by considering the incentive effect of the strategies within bus operators and the government. This is because the probability of a bus operator to purchase NEB can be influenced by the number of other operators in the market to purchase NEB, and whether or not the government implements CTS will likewise refer to the implementation of CTS by other provincial and municipal governments, making this incentive factor an important part of the strategy evolution for both bus operators and the government to consider.

Suppose that the number of bus operators that purchase NEB is p_1 and the number of groups that purchase FB is p_2. Then, Eq. (9) is established.

$$x = p_1 / (p_1 + p_2) \tag{9}$$

During the evolution of the group strategy, the rate of change in the number of operators purchasing NEB $p_1{}'$ is positively correlated with the number of operators selecting NEB p_1 and the expected utility U_1, as follows:

$$p_1{}' = \alpha_1 p_1 U_1 \tag{10}$$

where, α_1 ($\alpha_1 > 0$) is the impact factor of the strategy of purchasing NEB, which can be interpreted as the imitation coefficient. A larger α_1 indicates a stronger imitation effect of purchasing NEB among bus operators, when the decision to purchase NEB will promote the decisions of other bus operators to purchase NEB and inhibit the decision to purchase FB.

Derivation of Eq. (9) yields the dynamic replication equation for the bus operator's strategy of purchasing NEB as in Eq. (11):

$$\begin{aligned} x' &= \frac{p_1{}'(p_1 + p_2) - p_1(p_1{}' + p_2{}')}{(p_1 + p_2)^2} = \frac{p_1}{p_1 + p_2}\left(\frac{p_1{}'}{p_1} - \frac{p_1{}' + p_2{}'}{p_1 + p_2}\right) = x\left(\frac{\alpha_1 p_1 U_1}{p_1} - \frac{\alpha_1 p_1 U_1 + \alpha_2 p_2 U_2}{p_1 + p_2}\right) \\ &= x(\alpha_1 U_1 - \alpha_1 x U_1 - \alpha_2(1 - x)U_2) = \alpha_1 x(1 - x)\left(U_1 - \frac{\alpha_2}{\alpha_1}U_2\right) \end{aligned} \tag{11}$$

According to the Malthusian dynamic equation [80], the growth rate of bus operators choosing to purchase NEB and the government choosing to implement CTS is proportional to the difference between the utility obtained by choosing the corresponding strategy and the population utility. Therefore, the replication dynamic equations are given as Eq. (8):

$$\begin{cases} F(x) = \dfrac{dx}{dt} = x(U_1 - \overline{U}) = x(1 - x)\left[\lambda y\left(P + A_e - A_f\right) + M - N\right] \\ F(y) = \dfrac{dy}{dt} = y(V_1 - \overline{V}) = y(1 - y)\left[x\left((1 - f(t))S - \lambda\left(P + A_e - A_f\right)\right) + \lambda\left(P - E + A_e - A_f\right) - A_e\right] \end{cases} \tag{8}$$

Similarly, the dynamic replication equation for the government's strategy to implement the CTS is shown in Eq. (12).

Table 2
Utility matrix of the evolutionary game.

		Government	
		$\{b_1\}$: implementing CTS (y)	$\{b_2\}$: not implementing CTS ($1 - y$)
Bus operators	$\{a_1\}$: purchasing NEB (x)	$R + A_e - B_e - F_e - M_e$, $W + \lambda(S - A_e - E) + (1 - \lambda)(S - A_e)$	$R - B_e - F_e - M_e$, $W + f(t)S$
	$\{a_2\}$: purchasing FB($1 - x$)	$R + \lambda(A_f - B_f - F_f - M_f - P) + (1 - \lambda)(A_e - B_f - F_f - M_f)$, $W + \lambda(P - A_f - E - I) + (1 - \lambda)(-A_e - I)$	$R - B_f - F_f - M_f$, $W - I$

$$y' = \beta_1 y(1-y)\left(V_1 - \frac{\beta_2}{\beta_1}V_2\right) \tag{12}$$

Let $\chi_1 = \frac{\alpha_2}{\alpha_1}$, $\chi_2 = \frac{\beta_2}{\beta_1}$, χ_1, χ_2 represent the incentive coefficients of the strategies within bus operators and the government. $\chi_1 < 1$ indicates that the imitation effect of purchasing NEB is stronger than that of purchasing FB, and purchasing NEB has stronger influence as a dominant decision; $\chi_1 > 1$ indicates that purchasing FB has stronger influence as a dominant decision. $\chi_2 < 1$ indicates that the imitation effect of implementing CTS is stronger than that of not implementing CTS, and that the government's strategy of implementing CTS has stronger influence as a dominant decision; $\chi_2 > 1$ indicates that not implementing CTS has stronger influence as a dominant decision.

Substituting Eqs. (2), (3) and (5)-(6) into Eqs. (11) and (12), respectively, yield the improved two-dimensional dynamical system (L) considering the incentives of the intergroup strategy as shown in Eq. (13).

$$\begin{cases} F(x) = \dfrac{dx}{dt} = \alpha_1 x(1-x)\left[(1-\chi_1)R + \chi_1\lambda y\left(P + A_{\mathrm{e}} - A_{\mathrm{f}}\right) + yA_{\mathrm{e}}(1-\chi_1) + \chi_1 M - N\right] \\ F(y) = \dfrac{dy}{dt} = \beta_1 y(1-y)\left[\begin{array}{l}(1-\chi_2)W + x\left((1-\chi_2 f(t))S - \lambda\left(P + A_{\mathrm{e}} - A_{\mathrm{f}}\right) + (1-\chi_2)I\right) \\ +\lambda\left(P - E + A_{\mathrm{e}} - A_{\mathrm{f}}\right) - (1-\chi_2)I - A_{\mathrm{e}}\end{array}\right] \end{cases} \tag{13}$$

When $\alpha_1 = \alpha_2 = \beta_1 = \beta_2 = 1$, the above dynamical system is consistent with the original replication dynamic equations.

Proposition 1. *There are* 4 *evolutionary equilibrium points in the two-dimensional dynamic system* (L)*, which are* $(0,0)$, $(0,1)$, $(1,0)$, $(1,1)$ *respectively; when* $(S_1 \cup S_2) \cap (S_3 \cup S_4)$ *is satisfied, there is a fifth equilibrium point* (x^*, y^*)*, where*

$$\begin{cases} x^* = \dfrac{(1-\chi_2)W + \lambda\left(P - E + A_{\mathrm{e}} - A_{\mathrm{f}}\right) - (1-\chi_2)I - A_{\mathrm{e}}}{\lambda\left(P + A_{\mathrm{e}} - A_{\mathrm{f}}\right) - (1-\chi_2 f(t))S - (1-\chi_2)I} \\ y^* = \dfrac{N - \chi_1 M - (1-\chi_1)R}{\chi_1\lambda\left(P + A_{\mathrm{e}} - A_{\mathrm{f}}\right) + (1-\chi_1)A_{\mathrm{e}}} \end{cases} \tag{14}$$

$$\begin{cases} S_1 = \left\{(1-\chi_2)W + \lambda\left(P + A_{\mathrm{e}} - A_{\mathrm{f}}\right) - (1-\chi_2)I - A_{\mathrm{e}} > \lambda E > (1-\chi_2 f(t))S - A_{\mathrm{e}}\right\} \\ S_2 = \left\{(1-\chi_2 f(t))S - A_{\mathrm{e}} > \lambda E > (1-\chi_2)W + \lambda\left(P + A_{\mathrm{e}} - A_{\mathrm{f}}\right) - (1-\chi_2)I - A_{\mathrm{e}}\right\} \\ S_3 = \left\{\chi_1\lambda\left(P + A_{\mathrm{e}} - A_{\mathrm{f}}\right) + (1-\chi_1)A_{\mathrm{e}} > N - \chi_1 M - (1-\chi_1)R > 0\right\} \\ S_4 = \left\{\chi_1\lambda\left(P + A_{\mathrm{e}} - A_{\mathrm{f}}\right) + (1-\chi_1)A_{\mathrm{e}} < N - \chi_1 M - (1-\chi_1)R < 0\right\} \end{cases} \tag{15}$$

Proof. When $\frac{dx}{dt} = 0$ and $\frac{dy}{dt} = 0$, system (L) has evolutionary equilibrium points, when $x = 0, 1$ or $y = 0, 1$, the requirements are met. Therefore, $(0,0)$, $(0,1)$, $(1,0)$, $(1,1)$ are the evolutionary equilibrium points. When one of S_1 and S_2 holds, $0 < x^* < 1$; when one of S_3 and S_4 holds, $0 < y^* < 1$, and $\frac{dx}{dt} = \frac{dy}{dt} = 0$ holds at the point (x^*, y^*), so it is the 5th evolution equilibrium point of evolution.

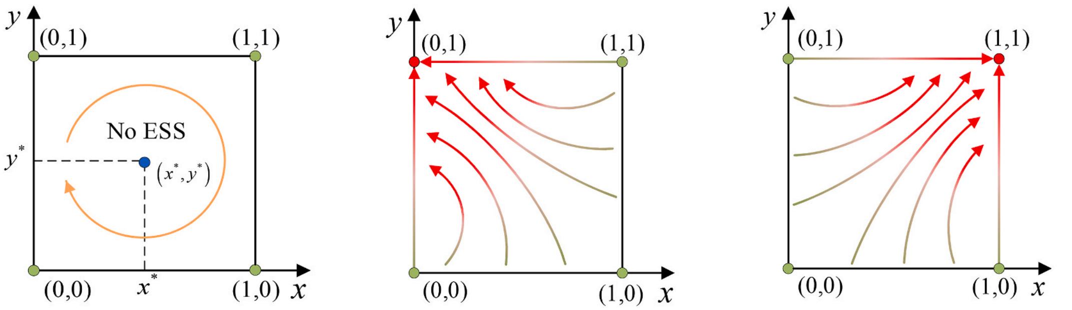
3.2.4. Stability analysis of the equilibrium points

According to the group dynamics of the computational differential equations proposed by Friedman, the stability of its equilibrium point can be obtained by the local stability analysis of the Jacobian matrix of system (L). Find the partial derivatives of x and y sequentially for the differential equations, and the Jacobian matrix can be obtained in Eqs. (16) and (17) as:

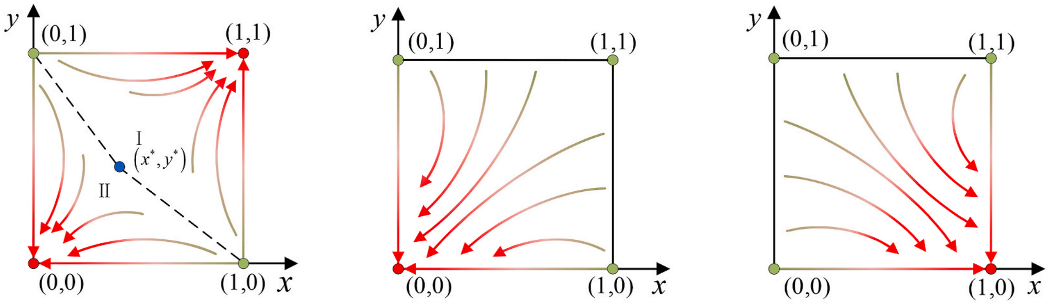
$$J = \begin{bmatrix} \dfrac{\partial F(x)}{\partial x} & \dfrac{\partial F(x)}{\partial y} \\ \dfrac{\partial F(y)}{\partial x} & \dfrac{\partial F(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \tag{16}$$

$$\begin{cases} a_{11} = \alpha_1(1-2x)\left[(1-\chi_1)R + \chi_1\lambda y\left(P + A_{\mathrm{e}} - A_{\mathrm{f}}\right) + yA_{\mathrm{e}}(1-\chi_1) + \chi_1 M - N\right] \\ a_{12} = \alpha_1\lambda x(1-x)\left[\chi_1\lambda\left(P + A_{\mathrm{e}} - A_{\mathrm{f}}\right) + A_{\mathrm{e}}(1-\chi_1)\right] \\ a_{21} = \beta_1 y(1-y)\left[(1-\chi_2 f(t))S - \lambda\left(P + A_{\mathrm{e}} - A_{\mathrm{f}}\right) + (1-\chi_2)I\right] \\ a_{22} = \beta_1(1-2y)\left[(1-\chi_2)W + x\left((1-\chi_2 f(t))S - \lambda\left(P + A_{\mathrm{e}} - A_{\mathrm{f}}\right) + (1-\chi_2)I\right) + \lambda\left(P - E + A_{\mathrm{e}} - A_{\mathrm{f}}\right) - (1-\chi_2)I - A_{\mathrm{e}}\right] \end{cases} \tag{17}$$

When Eq. (18) is met, the equilibrium points of the replication dynamic equations are locally stable, and the equilibrium points are the evolutionary stable strategies (ESS).



(a) Result (1-1)	(b) Result (1-2)	(c) Result (1-3) and Result (3)



(d) Result (2-1)	(e) Result (2-2)	(f) Result (4)

Fig. 2. Dynamic evolutionary game phase diagram of system (L).

$$\begin{cases} trJ = a_{11}+a_{22}<0 \\ detJ = \begin{vmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{vmatrix} = a_{11}a_{22}-a_{12}a_{21}>0 \end{cases} \tag{18}$$

Put five equilibrium points into *trJ* and *detJ* for calculation, discuss the stability of each point and get the ESS of system (L). The results are as follows:

Result (1): When $N-\chi_1 M>(1-\chi_1)R$, $(1-\chi_2)W+\lambda(P-E+A_e-A_f)>(1-\chi_2)I+A_e$:

Result (1-1): If (x^*,y^*) exists, simplify and merge $S_1\cap S_3$. At this time, $\begin{cases}(1-\chi_2 f(t))S-A_e<\lambda E\\ \chi_1\lambda(P+A_e-A_f)+(1-\chi_1)(A_e+R)>N-\chi_1 M\end{cases}$ is satisfied, system (L) has no ESS and (x^*,y^*) is its central point.

Result (1–2): If (x^*,y^*) does not exist, when $\chi_1\lambda(P+A_e-A_f)+(1-\chi_1)(A_e+R)<N-\chi_1 M$ is satisfied, the ESS of system (L) is $(0,1)$.

Result (1–3): If (x^*,y^*) does not exist, when $\begin{cases}(1-\chi_2 f(t))S-A_e>\lambda E\\ \chi_1\lambda(P+A_e-A_f)+(1-\chi_1)(A_e+R)>N-\chi_1 M\end{cases}$ is satisfied, the ESS of system (L) is $(1,1)$.

Result (2): When $N-\chi_1 M>(1-\chi_1)R$.

Result (2–1): If (x^*,y^*) exists, simplify and merge $S_2\cap S_3$. At this time, $\begin{cases}(1-\chi_2 f(t))S-A_e>\lambda E\\ \chi_1\lambda(P+A_e-A_f)+(1-\chi_1)(A_e+R)>N-\chi_1 M\end{cases}$ is satisfied, the ESS of system (L) is $(0,0)$ and $(1,1)$, (x^*,y^*) is its central point.

Result (2-2): If (x^*,y^*) does not exist, that is, when $\begin{cases}(1-\chi_2 f(t))S-A_e>\lambda E\\ \chi_1\lambda(P+A_e-A_f)+(1-\chi_1)(A_e+R)>N-\chi_1 M\end{cases}$ is not satisfied, the ESS of system (L) is $(0,0)$.

Result (3): When $N-\chi_1 M<(1-\chi_1)R$, $(1-\chi_2 f(t))S>\lambda E+A_e$, the ESS of system (L) is $(1,1)$.

Result (4): When $N-\chi_1 M<(1-\chi_1)R$, $(1-\chi_2 f(t))S<\lambda E+A_e$, the ESS of system (L) is $(1,0)$.

3.2.5. Evolutionary game results analysis

According to the stability analysis results of the equilibrium points, the evolutionary game process of bus operators and the government can be obtained, and the corresponding dynamic phase diagrams are shown in Fig. 2.

Based on the ESS results and the dynamic phase diagram, the decision-making behaviors of bus operators and the government are analyzed as follows.

Result (1): When $N-\chi_1 M>(1-\chi_1)R$, $A_e<\frac{(1-\chi_2)W+\lambda(P-E-A_f)-(1-\chi_2)I}{1-\lambda}$:

Result (1-1): If $\lambda E>(1-\chi_2 f(t))S-A_e$ and $N-\chi_1 M<\chi_1\lambda(P+A_e-A_f)+(1-\chi_1)(A_e+R)$, as shown in Fig. 2(a), system (L) has no ESS, $(0,0)$, $(0,1)$, $(1,0)$, $(1,1)$ are saddle points, and (x^*,y^*) exists and is an unstable point. There is no stable strategy between bus operators' decision-making behavior and whether the government implements CTS. This situation usually occurs in a transition period after the implementation of the CTS, and the optimal decision-making behavior of bus operators and the government is still in the exploration stage.

Result (1–2): If $N-\chi_1 M>\chi_1\lambda(P+A_e-A_f)+(1-\chi_1)(A_e+R)$, as shown in Fig. 2(b), the ESS of system (L) is $(0,1)$, purchasing FB and implementing CTS will be inevitable choices for bus operators and the government. For bus operators, the total cost of choosing NEB is much higher than FB, even under the incentive of CTS, the utility of purchasing NEB is still less than that of purchasing FB, so bus operators will choose to purchase FB. In addition, CTS is more tempting than the risk cost of 'fraud', and bus operators will take risks and apply for CTS in the face of sluggish market performance. For government, the non-implementation of CTS has a great impact on the enthusiasm of bus operators to buy NEB. Facing severe market environment problems, the government will increase investment to promote the diffusion of NEBs. This situation usually occurs at the beginning of the implementation of the CTS. The cooling effect of the withdrawal of the purchase subsidy on the NEB market continues and the total cost of NEB is relatively high. To ease market performance, the government will implement a large-scale CTS.

Result (1–3): If $\lambda E<(1-\chi_2 f(t))S-A_e$ and $N-\chi_1 M<\chi_1\lambda(P+A_e-A_f)+(1-\chi_1)(A_e+R)$, as shown in Fig. 2(c), the ESS of system (L) is $(1,1)$, purchasing NEB and implementing CTS will be inevitable choices for bus operators and the government. In this case, the total cost gap between NEB and FB is effectively narrowed, and the government's non-implementation of CTS has a great impact on operators' enthusiasm to buy NEB. Moderate carbon trading subsidies play a great role in promoting the NEB market, so the government chooses to implement CTS. Faced with an active NEB market, operators will also choose to purchase NEB to obtain greater benefits. The decisions of these two parties are actual optimal choices, this situation is the first optimal period after the implementation of CTS. As an emerging policy, both bus operators and the government have shown a high degree of enthusiasm for participation at this stage, which can not only promote the improvement of the CTS policy, but also ensure rapid improvement for the electrification level of public transportation.

Result (2):When $N - \chi_1 M > (1 - \chi_1)R$, $A_e > \frac{(1-\chi_2)W+\lambda(P-E-A_f)-(1-\chi_2)I}{1-\lambda}$:

Result (2–1): If $\lambda E < (1 - \chi_2 f(t))S - A_e$ and $N - \chi_1 M < \chi_1 \lambda(P + A_e - A_f) + (1 - \chi_1)(A_e + R)$, as shown in Fig. 2(d), the ESS of system (L) are $(0,0)$ and $(1,1)$, $(0,1)$ and $(1,0)$ are unstable points, (x^*, y^*) exists and is a saddle point, the polyline formed by the two unstable points and the saddle point is the boundary line where the system converges to two stable points, that is, in the region I, system (L) converges to $(1,1)$, bus operators and government choose to purchase NEB and implement CTS, respectively, in region II, system (L) converges to $(0,0)$, bus operators and the government choose to purchase FB and not implement CTS. At this time, the total cost of choosing NEB is slightly higher than that of FB, and the government's non-implementation of CTS has a greater impact on operators' enthusiasm to buy NEB. Faced with this market state, the decision-making behavior of bus operators and the government is uncertain, and the initial state of the system will determine which equilibrium strategy ultimately tend to.

Result (2-2): If $\lambda E > (1 - \chi_2 f(t))S - A_e$ or $N - \chi_1 M > \chi_1 \lambda(P + A_e - A_f) + (1 - \chi_1)(A_e + R)$, as shown in Fig. 2(e), the ESS of system (L) is $(0,0)$, purchasing FB and not implementing CTS will be inevitable choices for bus operators and the government. At this time, the total cost of choosing NEB is much higher than FB; even if the government implements CTS, it is still not enough to make up for this cost gap, bus operators will tend to purchase FB, so the government will not implement CTS policy. In this case, the benefits of both parties are restricted, which is not conducive to the promotion of NEBs. The government should focus on optimizing the upstream and downstream technologies of the NEB industry chain, further reduce its purchasing and using costs, and increase operators' degree of acceptance of NEBs.

Result (3): When $N - \chi_1 M < (1 - \chi_1)R$, $\lambda E < (1 - \chi_2 f(t))S - A_e$, as shown in Fig. 2(c), the ESS of system (L) is $(1,1)$, purchasing NEB and implementing CTS will be inevitable choices for bus operators and the government. At this time, the total cost of choosing NEB is lower than FB, and the government's non-implementation of CTS has a great impact on operators' enthusiasm to buy NEB, bus operators and the government can obtain greater benefits when they choose to purchase NEB and implement CTS. This situation is the second optimal period after the implementation of CTS. With the further reduction in the cost of NEB and the maturity of the NEB market, operators will choose to purchase NEB even if there is no CTS. Therefore, in order to save expenditure at this stage, the government can cancel CTS and promote NEBs to enter the perfectly competitive market as soon as possible.

Result (4): When $N - \chi_1 M < (1 - \chi_1)R$, $\lambda E > (1 - \chi_2 f(t))S - A_e$, as shown in Fig. 2(f), the ESS of system (L) is $(1,0)$, purchasing NEB and not implementing CTS will be inevitable choices for bus operators and government. In this case, the total cost of choosing NEB is lower than FB, even if there is no CTS, the utility of choosing NEB is greater than FB. Regardless of the strength of the incentive policies, operators tend to purchase NEB, and this strategy is stable. Since operators' decision-making behavior does not depend on alteration in government subsidy strategies, the government will gradually withdraw CTS from the NEB market to save investment. This situation usually occurs in the mature period of the NEB market and is the final state of the perfectly competitive market. At this time, the NEB industry chain and supporting facilities are complete. Bus operator's purchase decision considers the maturity and free competition of NEBs and FBs in the market to pursue maximum profits.

Table 3
Cost data initial value of K9 and ZK2.

	K9	ZK2
Purchase costs	$2000/8 = 250$	$600/8 = 75$
Energy costs	$52.67 \times 100.45*0.257/100 = 13.60$	$52.67 \times 34.14*6.47/100 = 116.34$
Maintenance and repair costs	$88/8 = 11$	$278/8 = 34.75$
Total costs	274.6	226.09
Carbon trading subsidies	$56 \times 0.213 = 11.93$	0

4. Numerical experiments

4.1. *Initial data*

The two brands, BYD and Yutong, play an important role in China's NEB and FB markets [17,81], so this study selects BYD K9 (K9) and Yutong ZK6105HNG2 (ZK2) as alternative models for NEB and FB, to perform evolutionary game simulations. K9 and ZK2 are widely used long-axle NEBs and FBs in major cities in China, and they are two bus models with similar size by consulting product descriptions, which can be used as alternatives to achieve the same transportation function in the game simulations. According to the market survey, the price of K9 in China is 2 million CNY and ZK2 is 600 thousand CNY, both of their operating life is 8 years. The residual value of all buses is 0 at the end of their service life [82]. The annual mileage of the bus is taken as the average annual mileage of Beijing buses in 2019, which is 52.67 thousand km [83], and the average daily driving distance is 144.3 km, which meets the K9 battery endurance requirements. The unit energy consumption of K9 and ZK2 is 100.45 kwh/100 km and 34.14 L/100 km, respectively [84]. In order to save energy costs, K9 is charged during the electricity valley period at night, the charging price is 0.257 CNY/kWh [85]; the diesel price is 6.47 CNY/L according to the final oil price in Beijing in 2019. In terms of maintenance and repair cost, the failure rate of NEB is lower, and BYD promises to guarantee the K9 battery and battery core for 8 years, so the maintenance and repair cost of K9 will be lower than for the ZK2. Specifically, the maintenance and repair cost of K9 in the life cycle is 88 thousand CNY, and ZK2 is 278 thousand CNY [86].

The carbon emission factor e_e of K9 is 0, the carbon emission factor e_f of ZK2 is 1.069 kg/km [87], and the carbon price p is 0.213 CNY/kg [88]. According to Ref. [67], the benchmarking method is adopted to determine the initial value of carbon quotas Q, but without considering the emission reduction rate in the base year, which is calculated to be $Q = 56$ t for 1 year. This study takes 1 year as the calculation period, and the cost-related parameter data is shown in Table 3, the units are thousand CNY.

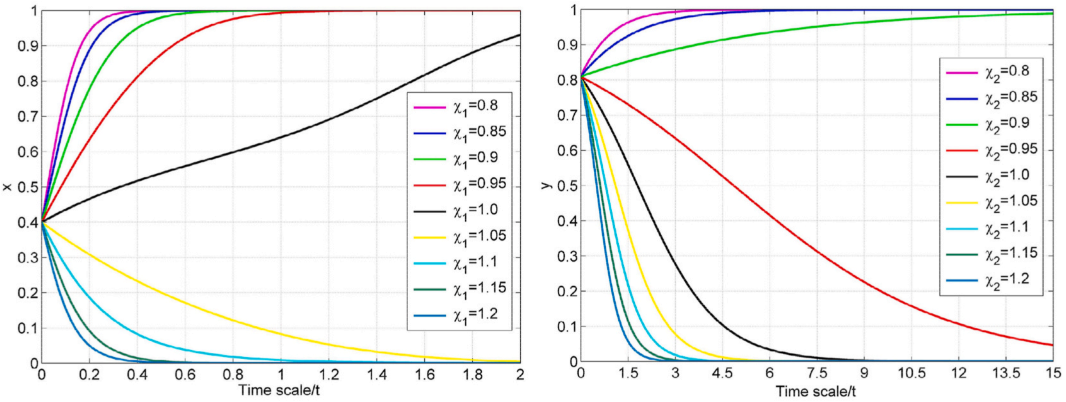
During the implementation of the purchase subsidy, when the 'fraud' phenomenon appears, according to "the Ministry of Finance's New Energy Fraudulent Enterprise Notification Solution", the penalty P will be 50% of the subsidy amount for the enterprise. The initial value of the penalty in this study is set according to the ratio, that is the ratio of 'fraud' fines to subsidy $k = 0.5$ (i.e. $P = kA = 6$). Considering that the existing proportion of EBs in Beijing is about 45%, the initial value of x is set to 0.4. The initial value of y is set to 0.8 due to Shenzhen's development experience of including the public transport sector in carbon trading and China's strong willingness to implement carbon trading in the transport sector. The initial value settings of other parameters are shown in Table 4.

4.2. *Simulation results and analysis*

Based on the non-rigid differential equation solving algorithm ode45 in Matlab2013 to solve the evolution game model, the results and

Table 4
Initial value settings of other parameters.

Parameter	λ	S	I	R	W	E	$f(t)$	x	y
Value	0.7	20	10	300	10	2	0.2	0.4	0.8
Unit	/	thousand CNY	thousand CNY	thousand CNY	Thousand CNY	thousand CNY	/	/	/



(a)Bus operators (b)Government

Fig. 3. The effect of different incentive coefficients on decision-making behaviors.

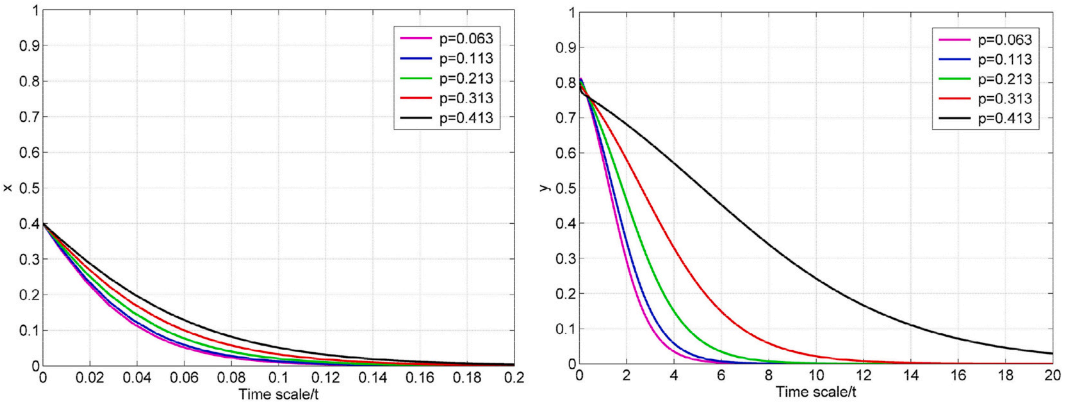


Fig. 4. The decision-making behaviors of bus operators and government under different carbon prices (a).

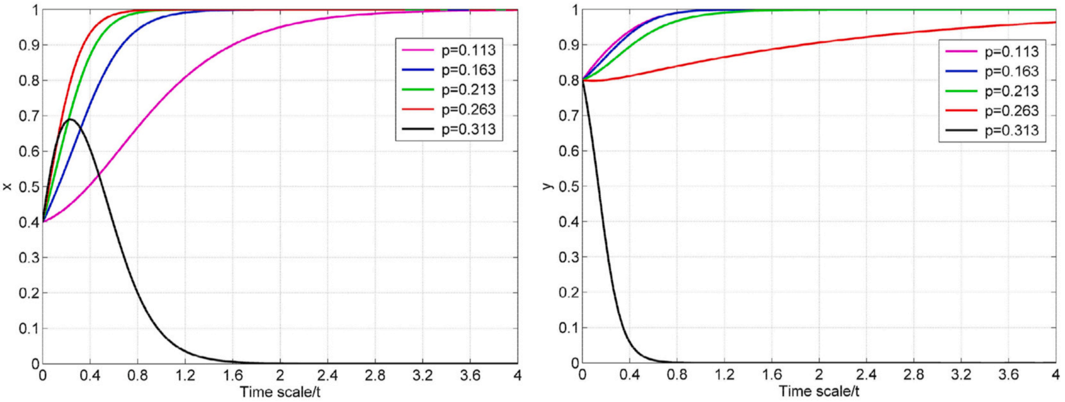


Fig. 5. The decision-making behaviors of bus operators and government under different carbon prices (b).

analysis are as follows. The numerical setting of parameters in the model is chosen with reference to the values of the parameters in practice and with the principle of more validation of the evolution results in Section 3.2.5.

4.2.1. *Sensitivity analysis of the improved evolutionary game model*

This study introduces incentive coefficients of the strategies within bus operators and the government to improve the evolutionary game model. This section will first simulate the effect of incentive coefficients on the evolution of the decision-making behaviors of bus operators and the government to verify the correctness of the model. The simulation results are shown in Fig. 3(a) when the incentive coefficient χ_1 of bus operators is set to 0.8, 0.85, …, 1.15, 1.2, $N = 234.6$, with other parameters unchanged. Resetting the incentive coefficient χ_2 of the government to 0.8, 0.85, …, 1.15, 1.2, with other parameters unchanged, the simulation results are shown in Fig. 3(b) and y are the probability of the bus operator will purchase NEB and the probability that the government will implement the CTS policy, respectively.

As shown in Fig. 3(a), when $\chi_1 < 1$, the smaller χ_1 is, the faster the bus operators' decision converges to 1. This is because the smaller its value, the stronger the decision of imitation effect of the bus operators' decision to purchase EB within the group compared to the decision to purchase FB, that is, the decision to purchase EB has a stronger incentive, so the operator will converge to purchase EB more quickly. When $\chi_1 > 1$, the larger χ_1 is, the faster the bus operators' decision converges to 0. This is because the larger its value, the stronger the imitation effect of the bus operators' decision to purchase FB relative to purchasing EB, so the operators will converge to purchase FB more quickly. As shown in Fig. 3(b), for $\chi_2 \leq 0.9$, the smaller χ_2 is, the stronger the imitation effect of the decision to implement CTS among governments relative to the decision not to implement CTS, and therefore the faster they will converge to implement CTS. For $\chi_2 > 1$, the larger the value, the stronger the imitation effect of the decision not to implement CTS among governments relative to the decision to implement CTS, and therefore the faster they will converge to cancel CTS. when $\chi_2 =\ 0.95$, the imitation effect of implementing CTS, although stronger than the imitation effect of not implementing CTS, does not yet change the government's decision intention to decide not to implement CTS in this market situation, but only makes the process slower, which makes intuitive sense. Therefore, it can be concluded that the effect of the improved evolutionary game model with the introduction of χ_1 and χ_2 on the evolution of the decision of the bus operators and the government is consistent with the assumptions made at the time of model building, so the model is correct.

In the practical application of the model, the different incentive coefficients of bus operators and the government can reflect the effort to promote NEVs by society and the strength of the implementation of the CTS policy required by the upper-level government, which makes the improved model able to analyze the influence of the above factors on the electrification process of buses. In the subsequent simulation, considering that the Chinese government actively promotes the penetration of NEBs, the decision to implement CTS and purchase NEB will have a stronger imitation and incentive effect on other governments and operators, so set $\chi_1 = \chi_2 = 0.95$.

4.2.2. *The impact of a carbon price*

This part discusses the impact of carbon price on the decision-making choices of bus operators and the government. Based on the initial data, setting carbon prices p as 0.063, 0.113, 0.213, 0.313 and 0.413, respectively, we simulate the evolution of the behaviors of both parties. The evolution results are shown in Fig. 4.

The parameter relationships and corresponding ESS results are consistent with Result (2-2). According to Fig. 4, for bus operators and the government, their decision will eventually tend to 0. Increasing carbon prices within this range cannot fundamentally change the negative attitudes of the two parties towards the EB market and can only slow their speed towards final decision-making. This is because the total cost of using K9 is much higher than ZK2. In this case, the increase in subsidies is not sufficient to compensate for the cost gap, that is, $N - \chi_1 M > (1-\chi_1)R + \chi_1\lambda(P + A_e - A_f) + A_e(1-\chi_1)$.

Next, further consider narrowing the total cost gap between EB and FB, and discuss the impact of the carbon price on the results. Based on the initial data, let $N = 234.6$, set p as 0.113, 0.163, 0.213, 0.263 and 0.313, respectively. The evolution results are shown in Fig. 5.

As shown in Fig. 5, when $p =$ 0.113, 0.163, 0.213, 0.263, the parameter relationships and corresponding ESS results are consistent with Result (2–1), and located in region I, the decisions of bus operators and government tend to 1. In this range, bus operators choose EB faster and faster as the carbon price increases, but the financial pressure on the government from the gradually increasing carbon price makes them choose to implement CTS more slowly. Where $p = 0.163, 0.213$ is the optimal carbon price in this case, because at this point, relative to the cost gap between EB and FB, the subsidy amount can effectively stimulate operators to purchase EB, and at the same time, the government also quickly chooses to smoothly implement the CTS policy under this subsidy scale. While when $p = 0.113$, 0.263, although both operators' and government's decisions will tend to be 1, too low subsidy amount of the former will significantly reduce the speed of operators' decision of purchasing EB, and too high subsidy amount of the latter will significantly reduce the speed of government's decision of implementing CTS, the marginal effect brought by this subsidy change keeps decreasing, and the subsidy effect is not ideal. Therefore 0.163–0.263 is the optimal carbon price range. When $p = 0.313$, the parameter relationship satisfies Result (1-1), and the decision-making behaviors of both operators and the government tend to 0. In the face of further increases in the scale of subsidies, operators quickly choose to purchase EB at the beginning,

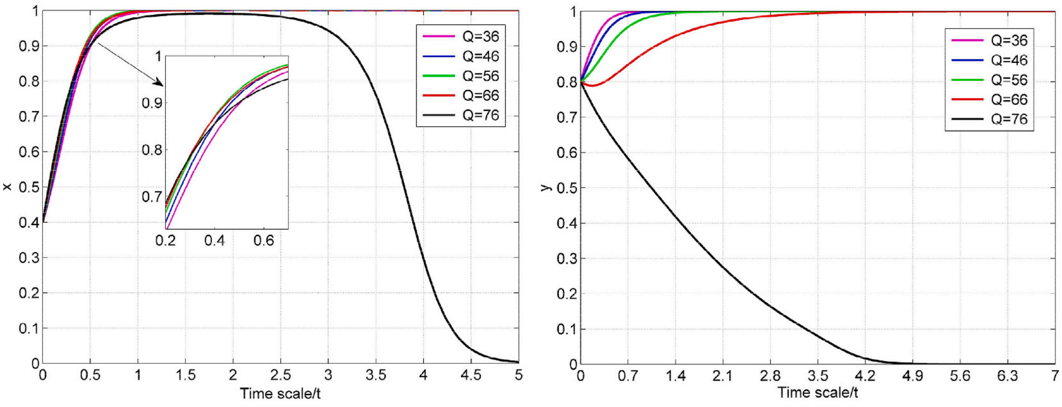


Fig. 6. The decision-making behaviors of bus operators and government under different initial carbon quotas.

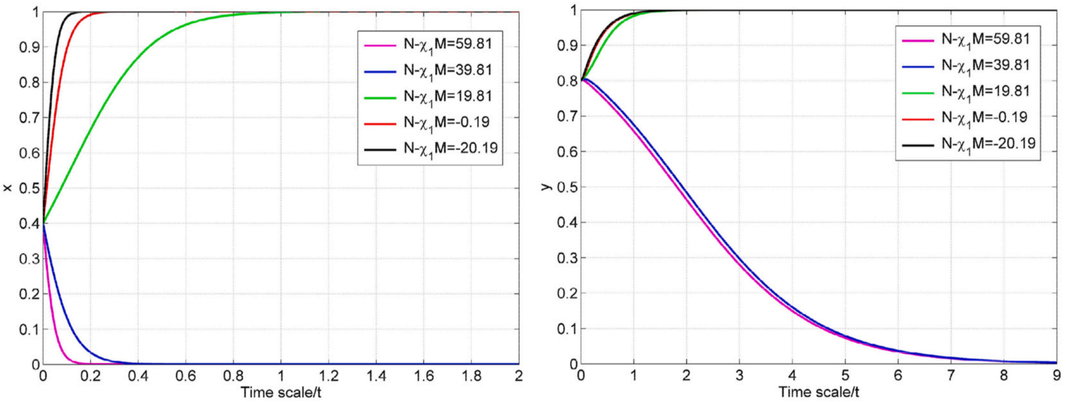


Fig. 7. The decision-making behaviors of bus operators and government under different total cost gap.

but the excessive subsidy amount makes the government's willingness to subsidize gradually weaken, so then the willingness of operators to buy EB also gradually declines, and eventually, as the government cancels the CTS policy, operators will also choose to buy FB.

4.2.3. *The impact of initial carbon quotas*

This part discusses the impact of initial carbon quotas on the decision-making behaviors of bus operators and the government. To avoid the result in Fig. 3 caused by the large gap between the cost of EB and FB, based on the initial data, let $N = 234.6$, set Q as 36, 46, 56, 66, and 76, respectively, and simulate the evolution of the behaviors of both parties. The evolution results are shown in Fig. 6.

According to Fig. 6, When $Q = 36, 46, 56, 66$, the decisions of both the bus operators and the government tend to 1, where the parameter relationships and corresponding ESS results satisfy Result (1–3) when $Q = 36, 46$, and satisfy Result (2–1) and located in region I when $Q = 56, 66$. Specifically, When the initial carbon quota is 56, it is exactly the carbon emission of FB, and FB neither pays for the additional quota nor can they get subsidies, while subsidies obtained by EB have an incentive effect for operators, and operators and the government will ultimately choose to purchase EB and implement CTS, respectively. When the initial carbon quota is lower than FB's carbon emissions, although the subsidies obtained by EB have declined, FB also needs to pay economic costs for its high emission. In this case, operators are more willing to purchase EB with lower subsidies than to purchase FB with paying economic cost, so EB will be the ultimate choice for operators. For the government, in the face of a lower financial burden and the increase in the popularity of the EB market, its decision-making behavior will take priority over operators to approach 1 and will fully cooperate with the market to promote the process of bus electrification. When the initial carbon quota is raised to 66, even though EB acquires higher subsidies at this time and its popularity increases in the short term, the rate at which operators eventually choose EB is still slower than the case when the subsidy is lower. This is because when the carbon quota is higher than the carbon emissions of FB, FB also gains subsidies, and the government's decision tends to 1 at a significantly lower rate under the double pressure of subsidizing EB and FB, thus affecting the speed of operators to choose EB. In this case, the government pays more subsidy expenditure but does not promote operators to accelerate their choice of EB, the subsidy effect is undesirable. When the initial carbon quota is further increased to 76, the parameter relationship and corresponding ESS result satisfies Result (2-2), and both operators and the government's final decision will tend to 0. This is because the excessive initial carbon quota further aggravates the government's subsidy burden, and the government will choose not to implement CTS, and then the operators will also eventually choose the lower-cost FB.

Table 5
The settings of government regulatory scenarios.

Penalty	Inspection		
	Low frequency $\lambda = 0.1$	Medium frequency $\lambda = 0.5$	High frequency $\lambda = 0.9$
Low intensity $k = 0.3$	(L, L)	(M, L)	(H, L)
Medium intensity $k = 0.9$	(L, M)	(M, M)	(H, M)
High intensity $k = 1.5$	(L, H)	(M, H)	(H, H)

4.2.4. *The impact of the total cost of the bus*

The total cost of EB and FB will be an important factor influencing the implementation of CTS, this part will discuss their impact on the decision-making choices of bus operators and the government. Based on the initial data, set the total cost of EB to be 274.6, 254.6, 234.6, 214.6, 194.6 (i.e. $N - \chi_1 M = 59.81, 39.81, 19.81, -0.19, -20.19$), respectively, to simulate the evolution of the behaviors of both parties. The simulation results are shown in Fig. 7.

According to Fig. 7, when $N - \chi_1 M = 59.81, 39.81$, the parameter relationships and corresponding ESS results are consistent with Result (2-2). The subsidy amount is insufficient to close the large cost gap between EB and FB, making the probability of operators buying EB quickly approach 0. Due to the negative performance of the market, the government will also choose not to implement CTS. And as the cost gap narrows, the rate at which operators eventually choose FB becomes slower, but has less impact on the rate at which governments eventually choose not to implement CTS. When $N - \chi_1 M = 19.81$, consistent with Result (2–1), further narrowing of the cost gap enables the subsidies to effectively stimulate the EB market. Operators will gradually choose to purchase EB, and the government will actively respond to the market to ensure the implementation of CTS. When $N - \chi_1 M = -0.19, -20.19$, consistent with Result (3), the full maturity of EB technology makes the total cost less than FB, operators will choose to buy EB. Since the residual heat of CTS has not been dissipated, the government will still implement the policy, but this state will soon end. Subsequently, the impact of CTS on positivity for choosing NEB will gradually decrease, and the EB market will become a perfectly competitive market, and the final state will approach to Result (4).

Therefore, the reduction in the total cost of EBs has a key impact on the implementation of CTS. Combined with the simulation results of Sections 4.2.2 and 4.2.3, it can be concluded that during the implementation of CTS, when the total cost of NEBs is much higher than FBs, the government should not blindly increase subsidies by raising the carbon price or initial carbon quota to stimulate the market in the face of the sluggish NEB market, which will not achieve the expected results and will increase overall costs. Instead, the government should consider how to reduce the total cost of NEBs, make $N - \chi_1 M < \chi_1 \lambda (P + A_e - A_f)$

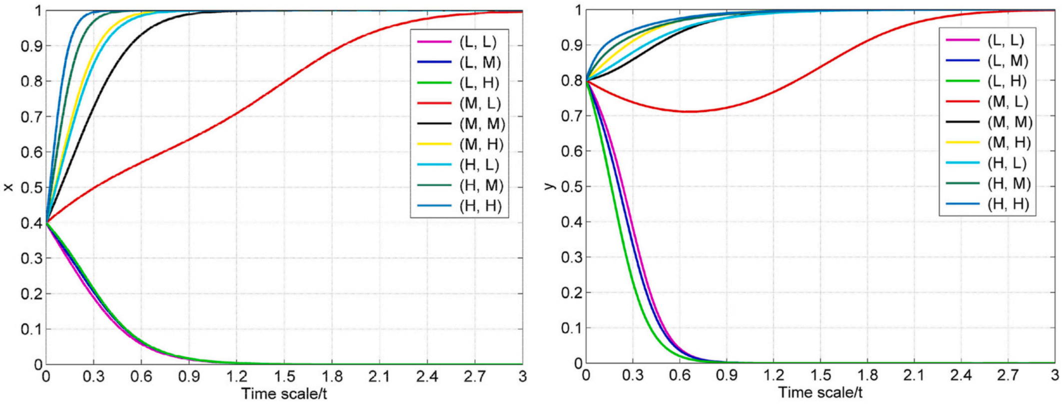


Fig. 8. The decision-making behaviors of bus operators and government under different government regulatory scenarios.

$+ A_e(1-\chi_1) + (1-\chi_1)R$, and promote decision-making behavior gradually approaching bilateral divergence (Result (2–1)) or the first optimal market (Result (1–3)), and finally reach the second optimal (Result (3)) or perfectly competitive market (Result (4)) to achieve the healthy and sustainable development of the NEB market.

4.2.5. The impact of government regulation on CTS

After the implementation of the CTS policy, the effectiveness of the policy will be affected if the operators are subject to 'fraud' similar to the levels observed during the purchase subsidy. In this section, we will investigate the impact of different levels of government regulation on the operators' and the government's strategy. In this model, the two parameters that affect the intensity of government regulation on the CTS policy are the probability of government inspection of bus driving λ and the ratio of fines to subsidies k in the case of 'fraud'. Therefore, the following 9 scenarios are set up in Table 5. To make the simulation results more informative, narrow the EB and FB cost gap, let $N = 234.6$ and simulate the evolution of the behavior of both parties, the results are shown in Fig. 8.

According to Fig. 8, when the regulatory scenarios are (L, L), (L, M) and (L, H), the parameter relationships and corresponding ESS results are consistent with Result (2–1) and located in region II, the risk cost of 'fraud' is very low due to the low inspection frequency, even if a high penalty is taken, the operator will risk applying for subsidies to profit when purchasing FB, so their decisions will soon converge to 0. The government's enthusiasm for CTS policy fades in the face of the negative market performance of EB, and their decision will also quickly converge to 0. When the regulatory scenarios are (M, L) and (M, M), the parameter relationships are consistent with Result (2–1) and located in region I. The increase of inspection frequency raises the risk cost of operators' 'fraud' behavior, and even with the low penalty, operators gradually change their attitude and start to choose EB, and their final decision tends to be 1. The government's willingness to implement CTS decreases in the face of the lower penalty when the EB is not popular enough at the beginning, but as the operators' enthusiasm to purchase EB increases, the government's enthusiasm to implement CTS also increases, and the final decision soon tends to 1. When the medium penalty strength is adopted, the rate at which operators' and government's decisions tend to 1 increases substantially. When the regulatory scenarios are (M, H), (H, L), (H, M) and (H, H), the parameter relationship satisfies Result (1–3), and the higher inspection frequency makes the decision of operators and government transition to a more stable stage. Faced with a more stringent carbon trading regulatory market, the excessively high risk cost prevents 'fraud' phenomenon from occurring, and operators will choose EB that can receive subsidies. The decision of the government implementing CTS will stabilize at 1 after achieving certain effects, forming a benign environment for purchasing and subsidizing for EB. Overall, raising inspection frequency and penalties for 'fraud' will not discourage operators from purchasing NEB but will improve the effectiveness of the subsidy system and drive the long-term application of CTS mechanism in the bus industry. Fig. 8 also shows that raising inspection frequency improves the effectiveness of subsidies more than raising the penalty for 'fraud', therefore, it is necessary to conduct high-frequency inspection on operators during the implementation of CTS to ensure the effectiveness of the subsidy system for NEB diffusion.

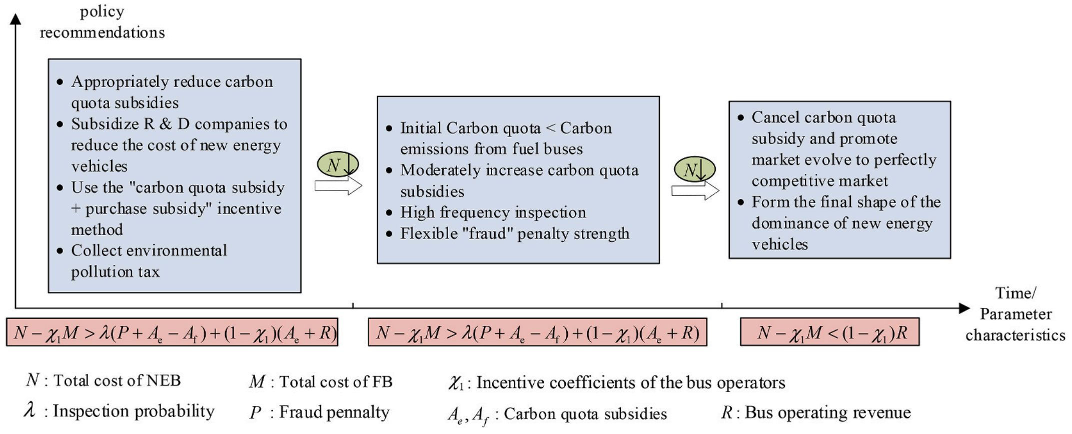


Fig. 9. Policy recommendations for the implementation of CTS in the NEB market.

5. Discussion

The above cases simulate several key issues when using carbon trading as a subsidy mechanism for bus operators.

Firstly, raising the carbon price can increase the subsidy amount of NEBs, but the government should not blindly raise the carbon price to achieve rapid clean transformation for the bus industry. On the one hand, the cost gap between NEB and FB significantly affects the implementation effect of the CTS mechanism, and when the cost gap is relatively large, raising the subsidy will only delay the operators' choice of FB instead of changing the decision to choose NEB. On the other hand, an excessively high carbon price will increase the government's financial burden of implementing CTS and reduce the government's willingness to subsidize, which in turn will affect the operators' decision to choose NEB. According to the result in Section 4.2.2, we conclude that the optimal carbon price in this case is in the range of 0.163–0.263 CNY/kg. A higher price will lead the government to cancel the CTS and lead the operators to choose FB, whereas a lower price will lead to a poor subsidy effect and operators to choose NEB at a slower rate. Compared to the carbon price of China's national carbon market in 2021, the optimal carbon price is higher, which means that with the existing cost gap between EBs and FBs, it is not enough to rely on carbon trading to subsidize EBs, but also needs to be combined with partial purchase subsidies. Unless carbon trading in the transport sector is implemented with a different carbon price system than the general carbon market, and as the cost gap between EBs and FBs decreases, it will then be aligned with the carbon price system of the national carbon market.

Secondly, the initial carbon quota is also a parameter that can be used to adjust the subsidy amount. According to the result in Section 4.2.3, when the initial carbon quota is lower than the carbon emission of FB, the higher the quota, the faster the operator eventually chooses EB, and when the initial carbon quota is higher than the carbon emission of FB, the lower the quota, the faster the operator will choose EB. In the implementation of CTS, the initial carbon quota less than and close to the carbon emission of FB can achieve the optimal subsidy effect.

Finally, high-frequency government inspections on operators are necessary to help increase the government's willingness to implement CTS and thus to ensure operators' willingness to purchase NEB. According to the result in Section 4.4.5, it can be found that increasing the inspection frequency can change the decision choice of both the government and operators, while the difference in the penalty strength will only change the decision speed, but not transform their decision behavior. Therefore, in the implementation of CTS, maintaining high-frequency inspection on operators is the root work, so as to ensure smooth proliferation of NEB, and on this basis, change the decision speed of the government and operators by adjusting the penalty strength, to control the process of clean transformation of the bus industry by regulation of the subsidy system.

Furthermore, the cost gap between NEB and FB is an important factor that affects the implementation of the CTS mechanism, and the trend of cost reduction is inevitable with the continuous improvement of NEV technology [89]. Therefore, in the process of the gradual decrease of the cost of NEVs, different implementation strategies are needed for the CTS mechanism. Based on this, policy recommendations for the implementation of CTS are proposed in the context of the gradual decrease of the cost of NEVs, as shown in Fig. 9.

(1) In the early stage of the CTS implementation, the cost of choosing NEB is much higher than that of FB, and the willingness of operators to purchase NEB is still low. To improve the willingness to purchase NEB and prevent the decrease of government's high willingness to subsidize, the government should not blindly increase the scale of subsidies, but should focus on how to reduce the cost of NEB. The recommendations are as follows: reducing the initial subsidies through a low carbon price, and using the saved subsidies to help NEV R&D companies in technological innovation, to accelerate research and economics of scale of automotive batteries to reduce battery cost as soon as possible; introducing CTS at the end of the retreat of the purchase subsidy, reducing the purchase cost of NEB with the incentive method of "CTS + purchase subsidy"; considering imposing proper pollution taxes on operators purchasing FB, increasing operators' willingness to purchase NEB, and gaining time for R&D companies to improve technology and reduce manufacturing costs. After the total cost gap between NEB and FB is narrowed, consider increasing the subsidies to encourage operators to purchase NEB.

(2) During the implementation of the CTS policy, the initial carbon quota should not be higher than the carbon emission of FB; otherwise, there may be an unfavorable situation where operators eventually purchase FB and the government cancels CTS. In order to promote the probability of operators choosing NEB approaches 1 sooner and ensure maximum efficiency of subsidies, the carbon quota should be close to but not exceed the carbon emission of FB.

(3) After the cost gap between NEB and FB is narrowed and the NEB market has heated up, the government should take measures to implement high intensity of CTS supervision, such as establishing a special inspection team to flexibly combine regular inspections and irregular spot checks to carry out high-frequency inspections. It can not only effectively prevent the occurrence of 'fraud', but also allow the government to timely grasp the electrification level of different bus operators, and promote a healthy development of the entire NEB industry. The penalty strength can be used to control the decision-making speed of operators and the government based on high-frequency inspections, and through their combination to form a flexible CTS regulatory system to curb the occurrence of 'subsidy fraud' and establish a healthy environment for NEV subsidies and development.

(4) In the implementation process of CTS policy, the government should timely grasp the changes in the parameters of the NEB market, and apply the seven evolution results in Section 3.2 to implement precise measures for the subsidy market. When the total cost of NEB is higher than FB, the market should be driven to evolve towards bilateral divergence market by setting CTS parameters, and then further driven to evolve to a more stable stage, the first optimal market. When the cost gap between NEB and FB is smaller or already lower, promote the market to evolve to perfectly competitive market. After the NEB market gradually matures and the infrastructure is completed, the government should consider eliminating the subsidy policy. At this point, when considering the technology maturity of NEB and FB in the market and their free competition behavior, operators' vehicle purchase decisions will all tend to NEB, which is the final state of the NEB market.

It is worth mentioning that when applying carbon trading to NEV subsidies, this study takes into account the large number of potential participants and refers to some existing studies that do not consider the interaction between the supply and demand for quotas and carbon prices in the existing carbon market, which is a limitation of this study. We will continue to explore the impact of this interaction mechanism on the application of CTS in future studies.

6. Conclusions

As the purchase subsidy is being gradually phased out, the viability of the NEV market in China is a current key concern of the government and producers. On the empirical evidence that carbon trading on the consumption-side is known to be effective in stimulating the development of NEVs, this study addresses the practical issues of its application in the NEV market, such as the setting of carbon prices and carbon quotas, and regulation, from a new perspective with the help of game theory.

Specifically, this study considers the influence between the strategies within the participating parties in the decision-making process, i.e., the imitation behavior in the herding effect, and introduces incentive coefficients to establish an improved evolutionary game model to calculate the evolution results of the decision-making behavior of the bus operators and the government under CTS mechanism. Numerical experiments are then conducted using examples of EB and FB to verify the correctness of the improved model in two aspects: 1) the simulation results are proved to be consistent with the assumptions after the introduction of incentive coefficients χ_1 and χ_2 in Section 4.2.1; 2) the parameter relationships and simulation results of all cases in Section 4.2 are consistent with the game evolution results in Section 3.2. Then based on the results of numerical experiments, policy recommendations for the implementation of CTS about the key issues of carbon prices, carbon quotas and government regulation are proposed in the context of decreasing cost of NEB. The improved evolutionary game model established in this study can accurately reflect the interaction and evolution of decision-making behavior between the operators and the government under the changing parameters, and it will serve as a reference and basis for the practical application and government decision-making of carbon trading in NEVs on the consumption-side, together with the proposed policy recommendations. Specifically, the model proposed in this paper can simulate the implementation of carbon trading in the bus industry in different countries by changing the initial values of variables according to the current situation of transportation development in the region, and then propose some targeted application strategies. In conclusion, this study will bridge theoretical research and practical application in countries exploring the use of carbon trading for NEV subsidies and will play a role in promoting the research of policy support systems for the future market development of NEVs.

Author contributions

Qingyun Nie: Methodology, Data curation, Writing – original draft, Writing – review & editing. Lihui Zhang: Conceptualization, Supervision. Zihao Tong: Software. Klaus Hubacek: Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the code at 'Attached file' step.

Acknowledgments

This work is funded by the China Scholarship Council (202106730109).

References

[1] Yu X, Lan Y, Zhao R. Strategic green technology innovation in a two-stage alliance: vertical collaboration or co-development? Omega 2021;98:102116. https://doi.org/10.1016/j.omega.2019.102116.

[2] Ministry of Transport of the People's Republic of China. Statistical bulletin on the development of the transport industry in 2020 2021. https://xxgk.mot.gov.cn/2020/jigou/zhghs/202105/t20210517_3593412.html (accessed December 2, 2021).

[3] Tan R, Lin B. Public perception of new energy vehicles: evidence from willingness to pay for new energy bus fares in China. Energy Pol 2019;130:347–54. https://doi.org/10.1016/j.enpol.2019.04.010.

[4] Yang S, Cheng P, Li J, Shanyong W. Which group should policies target? Effects of incentive policies and product cognitions for electric vehicle adoption among Chinese consumers. Energy Pol 2019;135. https://doi.org/10.1016/j.enpol.2019.111009. UNSP 111009.

[5] Zhang X, Bai X. Incentive policies from 2006 to 2016 and new energy vehicle adoption in 2010–2020 in China. Renew Sustain Energy Rev 2017;70:24–43. https://doi.org/10.1016/j.rser.2016.11.211.

[6] Zhu L, Wang P, Zhang Q. Indirect network effects in China's electric vehicle diffusion under phasing out subsidies. Appl Energy 2019;251. https://doi.org/10.1016/j.apenergy.2019.113350. UNSP 113350.

[7] Wang N, Tang L, Zhang W, Guo J. How to face the challenges caused by the abolishment of subsidies for electric vehicles in China? Energy 2019;166:359–72. https://doi.org/10.1016/j.energy.2018.10.006.

[8] Ministry of Finance of the People's Republic of China. Notice on improving the financial subsidy policy for the promotion and application of new energy vehicles. 2020. http://jjs.mof.gov.cn/zhengcefagui/202004/t20200423_3502975.htm. [Accessed 3 December 2021].

[9] Li W, Long R, Chen H, Yang T, Geng J, Yang M. Effects of personal carbon trading on the decision to adopt battery electric vehicles: analysis based on a choice experiment in Jiangsu, China. Appl Energy 2018;209:478–88. https://doi.org/10.1016/j.apenergy.2017.10.119.

[10] Li W, Long R, Chen H, Yang M, Chen F, Zheng X, et al. Would personal carbon trading enhance individual adopting intention of battery electric vehicles more effectively than a carbon tax? Resour Conserv Recycl 2019;149:638–45. https://doi.org/10.1016/j.resconrec.2019.06.035.

[11] Li L, Wang Z, Chen L, Wang Z. Consumer preferences for battery electric vehicles: a choice experimental survey in China. Transport Res Part Transp Environ 2020;78:102185. https://doi.org/10.1016/j.trd.2019.11.014.

[12] Raux C, Croissant Y, Pons D. Would personal carbon trading reduce travel emissions more effectively than a carbon tax? Transp Res Part -Transp Environ 2015;35:72–83. https://doi.org/10.1016/j.trd.2014.11.008.

[13] Nie Q, Zhang L, Li S. How can personal carbon trading be applied in electric vehicle subsidies? A Stackelberg game method in private vehicles. Appl Energy 2022;313:118855. https://doi.org/10.1016/j.apenergy.2022.118855.

[14] Tong W, Mu D, Zhao F, Mendis GP, Sutherland JW. The impact of cap-and-trade mechanism and consumers' environmental preferences on a retailer-led supply Chain. Resour Conserv Recycl 2019;142:88–100. https://doi.org/10.1016/j.resconrec.2018.11.005.

[15] Zhao X, Xue Y, Ding L. Implementation of low carbon industrial symbiosis systems under financial constraint and environmental regulations: an evolutionary game approach. J Clean Prod 2020;277:124289. https://doi.org/10.1016/j.jclepro.2020.124289.

[16] Kang K, Zhao Y, Zhang J, Qiang C. Evolutionary game theoretic analysis on low-carbon strategy for supply chain enterprises. J Clean Prod 2019;230:981–94. https://doi.org/10.1016/j.jclepro.2019.05.118.

[17] Li J, Jiao J, Tang Y. An evolutionary analysis on the effect of government policies on electric vehicle diffusion in complex network. Energy Pol 2019;129:1–12. https://doi.org/10.1016/j.enpol.2019.01.070.

[18] Zhu L, Zhang Q, Lu H, Li H, Li Y, McLellan B, et al. Study on crowdfunding's promoting effect on the expansion of electric vehicle charging piles based on game theory analysis. Appl Energy 2017;196:238–48. https://doi.org/10.1016/j.apenergy.2016.11.060.

[19] Fang Y, Wei W, Mei S, Chen L, Zhang X, Huang S. Promoting electric vehicle charging infrastructure considering policy incentives and user preferences: an evolutionary game model in a small-world network. J Clean Prod 2020;258:120753. https://doi.org/10.1016/j.jclepro.2020.120753.

[20] Tang Y, Zhang Q, Li Y, Li H, Pan X, Mclellan B. The social-economic-environmental impacts of recycling retired EV batteries under reward-penalty mechanism. Appl Energy 2019;251:113313. https://doi.org/10.1016/j.apenergy.2019.113313.

[21] Ji S, Zhao D, Luo R. Evolutionary game analysis on local governments and manufacturers' behavioral strategies: impact of phasing out subsidies for new energy vehicles. Energy 2019;189:116064. https://doi.org/10.1016/j.energy.2019.116064.

[22] Chen W, Zeng Y, Xu C. Energy storage subsidy estimation for microgrid: a real option game-theoretic approach. Appl Energy 2019;239:373–82. https://doi.org/10.1016/j.apenergy.2019.01.232.

[23] Chen W, Hu Z-H. Using evolutionary game theory to study governments and manufacturers' behavioral strategies under various carbon taxes and subsidies. J Clean Prod 2018;201:123–41. https://doi.org/10.1016/j.jclepro.2018.08.007.

[24] Johari M, Hosseini-Motlagh S-M, Rasti-Barzoki M. An evolutionary game theoretic model for analyzing pricing strategy and socially concerned behavior of manufacturers. Transport Res Part E Logist Transp Rev 2019;128:506–25. https://doi.org/10.1016/j.tre.2019.07.006.

[25] Encarnação S, Santos FP, Santos FC, Blass V, Pacheco JM, Portugali J. Paths to the adoption of electric vehicles: an evolutionary game theoretical approach. Transp Res Part B Methodol 2018;113:24–33. https://doi.org/10.1016/j.trb.2018.05.002.

[26] Zhao D, Ji S, Wang H, Jiang L. How do government subsidies promote new energy vehicle diffusion in the complex network context? A three-stage evolutionary game model. Energy 2021;230:120899. https://doi.org/10.1016/j.energy.2021.120899.

[27] Zhao L, Yang G, Wang W, Chen Y, Huang JP, Ohashi H, et al. Herd behavior in a complex adaptive system. Proc Natl Acad Sci USA 2011;108:15058–63. https://doi.org/10.1073/pnas.1105239108.

[28] Breetz HL, Salon D. Do electric vehicles need subsidies? Ownership costs for conventional, hybrid, and electric vehicles in 14 US cities. Energy Pol 2018;120:238–49. https://doi.org/10.1016/j.enpol.2018.05.038.

[29] Figenbaum E. Perspectives on Norway's supercharged electric vehicle policy. Environ Innov Soc Transit 2017;25:14–34. https://doi.org/10.1016/j.eist.2016.11.002.

[30] Lee Y, Kim C, Shin J. A hybrid electric vehicle market penetration model to identify the best policy mix: a consumer ownership cycle approach. Appl Energy 2016;184:438–49. https://doi.org/10.1016/j.apenergy.2016.10.038.

[31] Ma S-C, Fan Y, Feng L. An evaluation of government incentives for new energy vehicles in China focusing on vehicle purchasing restrictions. Energy Pol 2017;110:609–18. https://doi.org/10.1016/j.enpol.2017.07.057.

[32] Palmer K, Tate JE, Wadud Z, Nellthorp J. Total cost of ownership and market share for hybrid and electric vehicles in the UK, US and Japan. Appl Energy 2018;209:108–19. https://doi.org/10.1016/j.apenergy.2017.10.089.

[33] Hao H, Ou X, Du J, Wang H, Ouyang M. China's electric vehicle subsidy scheme: rationale and impacts. Energy Pol 2014;73:722–32. https://doi.org/10.1016/j.enpol.2014.05.022.

[34] Muenzel C, Ploetz P, Sprei F, Gnann T. How large is the effect of financial incentives on electric vehicle sales? - a global review and European analysis. Energy Econ 2019;84. https://doi.org/10.1016/j.eneco.2019.104493. UNSP 104493.

[35] Sheldon TL, Dua R. Effectiveness of China's plug-in electric vehicle subsidy. Energy Econ 2020;88. https://doi.org/10.1016/j.eneco.2020.104773. UNSP 104773.

[36] Diao Q, Sun W, Yuan X, Li L, Zheng Z. Life-cycle private-cost-based competitiveness analysis of electric vehicles in China considering the intangible cost of traffic policies. Appl Energy 2016;178:567–78. https://doi.org/10.1016/j.apenergy.2016.05.116.

[37] Sheldon TL, Dua R. Measuring the cost-effectiveness of electric vehicle subsidies. Energy Econ 2019;84. https://doi.org/10.1016/j.eneco.2019.104545. UNSP 104545.

[38] Zhang X. Reference-dependent electric vehicle production strategy considering subsidies and consumer trade-offs. Energy Pol 2014;67:422–30. https://doi.org/10.1016/j.enpol.2013.12.028.

[39] Ma S-C, Xu J-H, Fan Y. Willingness to pay and preferences for alternative incentives to EV purchase subsidies: an empirical study in China. Energy Econ 2019;81:197–215. https://doi.org/10.1016/j.eneco.2019.03.012.

[40] Taefi TT, Kreutzfeldt J, Held T, Fink A. Supporting the adoption of electric vehicles in urban road freight transport – a multi-criteria analysis of policy measures in Germany. Transport Res Part Policy Pract 2016;91:61–79. https://doi.org/10.1016/j.tra.2016.06.003.

[41] Kong D, Xia Q, Xue Y, Zhao X. Effects of multi policies on electric vehicle diffusion under subsidy policy abolishment in China: a multi-actor perspective. Appl Energy 2020;266:114887. https://doi.org/10.1016/j.apenergy.2020.114887.

[42] Wang N, Tang L, Zhang W, Guo J. How to face the challenges caused by the abolishment of subsidies for electric vehicles in China? Energy 2019;166:359–72. https://doi.org/10.1016/j.energy.2018.10.006.

[43] Du J, Ouyang M, Wu X, Meng X, Li J, Li F, et al. Technological direction prediction for battery electric bus under influence of China's new subsidy scheme. J Clean Prod 2019;222:267–79. https://doi.org/10.1016/j.jclepro.2019.02.249.

[44] Hu Y, Wang Z, Li X. Impact of policies on electric vehicle diffusion: an evolutionary game of small world network analysis. J Clean Prod 2020;265:121703. https://doi.org/10.1016/j.jclepro.2020.121703.

[45] Langbroek JHM, Franklin JP, Susilo YO. The effect of policy incentives on electric vehicle adoption. Energy Pol 2016;94:94–103. https://doi.org/10.1016/j.enpol.2016.03.050.

[46] Mersky AC, Sprei F, Samaras C, Qian Z, Sean). Effectiveness of incentives on electric vehicle adoption in Norway. Transport Res Part Transp Environ 2016;46:56–68. https://doi.org/10.1016/j.trd.2016.03.011.

[47] Li Y, Zhang Q, Tang Y, Mclellan B, Ye H, Shimoda H, et al. Dynamic optimization management of the dual-credit policy for passenger vehicles. J Clean Prod 2020;249:119384. https://doi.org/10.1016/j.jclepro.2019.119384.

[48] Li J, Ku Y, Liu C, Zhou Y. Dual credit policy: promoting new energy vehicles with battery recycling in a competitive environment? J Clean Prod 2020;243:118456. https://doi.org/10.1016/j.jclepro.2019.118456.

[49] Li Y, Zhang Q, Liu B, McLellan B, Gao Y, Tang Y. Substitution effect of new-energy vehicle credit Program and corporate average fuel consumption regulation for green-car subsidy. Energy 2018;152:223–36. https://doi.org/10.1016/j.energy.2018.03.134.

[50] Ma H, Lou G, Fan T, Chan HK, Chung SH. Conventional automotive supply chains under China's dual-credit policy: fuel economy, production and coordination. Energy Pol 2021;151:112166. https://doi.org/10.1016/j.enpol.2021.112166.

[51] Cao K, Xu X, Wu Q, Zhang Q. Optimal production and carbon emission reduction level under cap-and-trade and low carbon subsidy policies. J Clean Prod 2017;167:505–13. https://doi.org/10.1016/j.jclepro.2017.07.251.

[52] Li J, Wang S, Fan J, Liang L. An equilibrium model of consumer energy choice using a personal carbon trading scheme based on allowance price. J Clean Prod 2018;204:1087–96. https://doi.org/10.1016/j.jclepro.2018.09.040.

[53] Fawcett T. Personal carbon trading: a policy ahead of its time? Energy Pol 2010;38:6868–76. https://doi.org/10.1016/j.enpol.2010.07.001.

[54] Raux C. The use of transferable permits in transport policy. Transport Res Part Transp Environ 2004;9:185–97. https://doi.org/10.1016/j.trd.2004.01.001.

[55] Harwatt H. Reducing carbon emissions from personal road transport through the application of a tradable carbon permit scheme: empirical findings and policy implications from the UK. Inst Transp Stud Univ Leeds 2008; 2008.

[56] Raux C. The potential for CO2 emissions trading in transport: the case of personal vehicles and freight. Energy Effic 2010;3:133–48. https://doi.org/10.1007/s12053-009-9065-7.

[57] Raux C, Marlot G. A system of tradable CO2 permits applied to fuel consumption by motorists. Transport Pol 2005;12:255–65. https://doi.org/10.1016/j.tranpol.2005.02.006.

[58] Wadud Z. Personal tradable carbon permits for road transport: why, why not and who wins? Transport Res Part Policy Pract 2011;45:1052–65. https://doi.org/10.1016/j.tra.2010.03.002.

[59] Grayling T. Tailpipe trading: how to include road transport in the eu emissions trading scheme. 2006.

[60] Sorrell S. An upstream alternative to personal carbon trading. Clim Pol 2010;10:481–6. https://doi.org/10.3763/cpol.2009.0008.

[61] German J. Reducing vehicle emissions through cap-and-trade schemes. In: Driv. Clim. Change. Elsevier; 2007. p. 89–105.

[62] Michaelis P, Zerle P. From ACEA's voluntary agreement to an emission trading scheme for new passenger cars. J Environ Plann Manag 2006;49:435–53. https://doi.org/10.1080/09640560600601686.

[63] Aziz HA, Ukkusuri SV, Romero J. Understanding short-term travel behavior under personal mobility credit allowance scheme using experimental economics. Transport Res Part Transp Environ 2015;36:121–37.

[64] Li Y, Li W, Wei Y, Bao L, Deng H. Using personal carbon dioxide trading to promote cleaner cars. In: Proc. Inst. Civ. Eng.-Transp, vol. 170. Thomas Telford Ltd; 2017. p. 86–98.

[65] Wadud Z, Noland RB, Graham DJ. Equity analysis of personal tradable carbon permits for the road transport sector. Environ Sci Pol 2008;11:533–44. https://doi.org/10.1016/j.envsci.2008.04.002.

[66] Jiang J, Ye B, Ma X, Miao L. Controlling GHG emissions from the transportation sector through an ETS: institutional arrangements in Shenzhen, China. Clim Pol 2016;16:353–71. https://doi.org/10.1080/14693062.2014.1003526.

[67] Li W, Wang L, Li Y, Liu B. A blockchain-based emissions trading system for the road transport sector: policy design and evaluation. Clim Pol 2021;21:337–52. https://doi.org/10.1080/14693062.2020.1851641.

[68] Al-Guthmy FMO, Yan W. Mind the gap: personal carbon trading for road transport in Kenya. Clim Pol 2020;20:1141–60. https://doi.org/10.1080/14693062.2020.1785380.

[69] Fan J, Li Y, Wu Y, Wang S, Zhao D. Allowance trading and energy consumption under a personal carbon trading scheme: a dynamic programming approach. J Clean Prod 2016;112:3875–83. https://doi.org/10.1016/j.jclepro.2015.07.030.

[70] Howell RA. Living with a carbon allowance: the experiences of Carbon Rationing Action Groups and implications for policy. Energy Pol 2012;41:250–8. https://doi.org/10.1016/j.enpol.2011.10.044.

[71] Harwatt H, Tight M, Timms P. Personal transport emissions within London: exploring policy scenarios and carbon reductions up to 2050. Int J Sustain Transp 2011;5:270–88. https://doi.org/10.1080/15568318.2010.506586.

[72] Raux C, Chevalier A, Bougna E, Hilton D. Mobility choices and climate change: assessing the effects of social norms, emissions information and economic incentives. Res Transport Econ 2021;90:101007. https://doi.org/10.1016/j.retrec.2020.101007.

[73] McNamara D, Caulfield B. Examining the impact of carbon price changes under a personalised carbon trading scheme for transport. Transport Pol 2013;30:238–53. https://doi.org/10.1016/j.tranpol.2013.09.017.

[74] Byun H, Shin J, Lee C-Y. Using a discrete choice experiment to predict the penetration possibility of environmentally friendly vehicles. Energy 2018;144:312–21. https://doi.org/10.1016/j.energy.2017.12.035.

[75] Wang N, Tang L, Pan H. Effectiveness of policy incentives on electric vehicle acceptance in China: a discrete choice analysis. Transport Res Part Policy Pract 2017;105:210–8. https://doi.org/10.1016/j.tra.2017.08.009.

[76] Fan J, He H, Wu Y. Personal carbon trading and subsidies for hybrid electric vehicles. Econ Modell 2016;59:164–73. https://doi.org/10.1016/j.econmod.2016.07.005.

[77] Pezzey JCV. Emission taxes and tradeable permits A comparison of views on long-run efficiency. Environ Resour Econ 2003;26:329–42. https://doi.org/10.1023/A:1026393028473.

[78] Zaman H, Zaccour G. Vehicle scrappage incentives to accelerate the replacement decision of heterogeneous consumers. Omega 2020;91:102016. https://doi.org/10.1016/j.omega.2018.12.005.

[79] Moon S, Lee D-J. An optimal electric vehicle investment model for consumers using total cost of ownership: a real option approach. Appl Energy 2019;253:113494. https://doi.org/10.1016/j.apenergy.2019.113494.

[80] Ji S, Zhao D, Luo R. Evolutionary game analysis on local governments and manufacturers' behavioral strategies: impact of phasing out subsidies for new energy vehicles. Energy 2019;189:116064. https://doi.org/10.1016/j.energy.2019.116064.

[81] Ding L, Ye MR, Wu J. Platform strategies for innovation ecosystem: double-case study of Chinese automobile manufactures. J Clean Prod 2019;209:1564–77. https://doi.org/10.1016/j.jclepro.2018.11.139.

[82] Lajunen A, Lipman T. Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. Energy 2016;106:329–42. https://doi.org/10.1016/j.energy.2016.03.075.

[83] Beijing Transport Institute. Annual report-beijing transport institute. 2019. http://www.bjtrc.org.cn/List/index/cid/7.html. [Accessed 18 June 2020].

[84] Wang Z, Chen F, Fujiyama T. Carbon emission from urban passenger transportation in Beijing. Transport Res Part Transp Environ 2015;41:217–27. https://doi.org/10.1016/j.trd.2015.10.001.

[85] The People's Government of Beijing Municipality. Notice of the beijing municipal development and Reform commission on relevant issues concerning the adjustment of electricity prices for general industrial and commercial sales. 2019. http://www.beijing.gov.cn/zhengce/zhengcefagui/201905/t20190531_82985.html. [Accessed 18 June 2020].

[86] Zhou B, Wu Y, Zhou B, Wang R, Ke W, Zhang S, et al. Real-world performance of battery electric buses and their life-cycle benefits with respect to energy

consumption and carbon dioxide emissions. Energy 2016;96:603–13. https://doi.org/10.1016/j.energy.2015.12.041.

[87] Zhang S, Wu Y, Liu H, Huang R, Yang L, Li Z, et al. Real-world fuel consumption and CO2 emissions of urban public buses in Beijing. Appl Energy 2014;113:1645–55. https://doi.org/10.1016/j.apenergy.2013.09.017.

[88] Lu S, Wu Y, Lou S, Yin X. A model for optimizing spinning reserve requirement of power system under low-carbon economy. IEEE Trans Sustain Energy 2014;5:1048–55. https://doi.org/10.1109/TSTE.2014.2325834.

[89] Lajunen A. Energy consumption and cost-benefit analysis of hybrid and electric city buses. Transport Res C Emerg Technol 2014;38:1–15. https://doi.org/10.1016/j.trc.2013.10.008.