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Effect of personal carbon trading on EV adoption behavior based on a stochastic Petri net

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Abstract: The increasing urgency of environmental issues and maturity of the upstream carbon trading schemes indicate that personal carbon trading (PCT) is likely to be implemented soon, which will significantly affect the green behavior of consumers. In this study, a stochastic Petri net (SPN) model was constructed to analyze the evolution of the residential EV adoption behavior under a PCT scheme and the impacts of the environmental awareness and the PCT scheme on the EV adoption behavior were quantified. The results of this work show that the introduction of PCT does not necessarily positively impact the EV adoption. An emission quota and "cap-and-trade" attributes can significantly increase the environmental awareness of consumers, which is a "double-edged sword" for the EV adoption behavior at this stage. Specifically, it raises questions about the actual low-carbon performance of EVs and changes in travel patterns while increasing the willingness of consumers to pay a premium for the low-carbon products. Therefore, the government should rationalize the strength of PCT policies and traditional incentives to maximize the goal of promoting the EV adoption. The results can aid in gaining a better understanding of the behavioral evolution of the consumer EV adoption under the PCT scheme and provide theoretical support for government policymaking and product design and pricing by EV companies.

Keywords: electric vehicle; environmental awareness; personal carbon trading; Petri net
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1 Introduction

With the increasingly severe environmental issues, the development of new energy vehicles is of great significance in promoting the transformation of China's transportation industry and developing China's transportation powerhouse, and has been elevated to a national strategy. According to the BP Statistical Review of World Energy[1], China has become the country with the largest increase in total carbon emissions worldwide, and has emitted the most greenhouse gases worldwide over the past decade. The contradiction between the growing demand for transportation and resources and environmental pollution is becoming increasingly acute, and that between efficient and green travel is still prominent, putting unprecedented pressure on society. Ecological civilization construction and sustainable development are prominent in China, and the country has undertaken a series of active measures to control environmental pollution while promoting the "transportation powerhouse" and "new infrastructure" construction goals. As a typical emerging industry, the automotive industry is developing in the direction of electric vehicles (EVs), which will significantly impact the national economy, society, the environment, and other elements of sustainable development, which comprehensively reflects the country's scientific and technological strength and management level. China has also implemented a series of measures to support the development of EVs. For example, a new energy vehicle subsidy policy, the "dual-credit" scheme① and the establishment of pilot cities for carbon emissions trading have been proposed. These measures have effectively promoted the development of EVs, and related research has rapidly received great interest in the fields of low-carbon economy and transportation

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① "Dual-credit" is the acronym for the full name "The Passenger Cars Corporate Average Fuel Consumption and New Energy Vehicle Credit Regulation" which was enacted by the Chinese government in 2017 to encourage automakers to produce EVs.

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management.

The acceleration of subsidy rollback in 2019 has revealed that the development of China's EV core market is overly dependent on policy-driven development, and the issue of "barking up the wrong tree" is prevalent, indicating that the phased adjustment of the perception of EVs from economic to non-economic factors and the cultivation of market segments has begun. Previous theoretical studies focused on the economic aspects of the adoption of EVs, with research focusing on the willingness of consumers to adopt EVs[2,3], the market strategies of automobile manufacturers[4-6], and the role of governmental low-carbon policies and implementation strategies[7,8]. Non-economic factors, such as the low-carbon supply-side attributes of EVs and demand-side individual environmental awareness, have received little attention, and a complete system is yet to be formed. Therefore, there is still much room for research exploring the EV adoption behavior in the following areas:

First, environmental awareness is manifested in several dimensions. It can be expressed as a low-carbon preference, that is, the decomposition of consumer environmental responsibility at the level of economic behavior, and the willingness to pay for low-carbon products; that is, consumers recognize the economic value of low-carbon consumption and are willing to pay a premium for low-carbon products. Considering consumers' environmental awareness, the energy efficiency of EVs is not only an economic attribute (it brings the economic utility of travel cost savings to all consumers), but also a non-economic attribute (its low-carbon environmental attributes bring additional utility to environmentally concerned consumers). Therefore, high and low-carbon preferences can significantly influence the perceptions of consumers, effectively translating into the EV adoption behavior. Environmental awareness can also be reflected in the perception of the low carbon levels of green products, as high environmental awareness makes consumers more likely to consider the actual carbon emission levels of products and the full life-cycle carbon emissions of EVs. The actual life-cycle carbon emission levels of EVs are controversial and unrealistic in most countries and regions; therefore, high and low carbon awareness is likely to limit the adoption of EVs.

Second, optimizing low-carbon consumption decisions and proposing strategies to guide policy implementation requires an accurate understanding of low-carbon consumption needs, costs, and benefits[9,10]. As a new carbon trading concept, personal carbon trading (PCT) allows consumers to deeply participate in the carbon trading process, thereby significantly influencing consumers' environmental awareness and willingness to purchase EVs[11,12]. Currently, the main participants in carbon trading in China are governmental agencies, enterprises, and other upstream organizations, and individual consumers are rarely involved as direct buyers or sellers[13,14]. However, individual consumers are always the ultimate executors of all economic activities. With the release of the MEP's Interim Provisions on Carbon Emissions Trading (Draft for Public Comments), it is expected that PCT will likely be rapidly implemented with the continuous increase in the proportion of carbon emissions in residential consumption. With the implementation of PCT, all consumers will face constraints from carbon emission rights similar to companies, and their energy consumption behavior will inevitably be influenced. The outstanding advantages of new EVs, i. e., energy conservation and emission reduction, will become the focus of their competitiveness. The use of EVs will reduce the amount of fuel consumed by the user for the same mileage, lower the level of carbon emissions, and save costs in emission allowances[15]. PCT will be more likely to achieve targeted carbon constraints for all kinds of consumers and guide the demand for low-carbon consumption in the long-term through market supply and demand adjustment than other low-carbon policies, such as the carbon tax[16-18]. Additionally, environmental awareness can be properly incorporated into the EV adoption decision evaluation by considering a PCT scheme.

Only a few studies conducted on EV adoption behavior have discussed the PCT scheme with environmental awareness as the main influencing factor[18,19]. The results of these studies did not consider the structural description of EV adoption behavior under PCT and the equilibrium state variation law of the evolution system. There is a lack of modeling and mechanism analysis of the evolution of EV adoption behavior under PCT from a system perspective. Therefore, in this study, we developed an evolutionary stochastic Petri net (SPN) model of consumer EV adoption under PCT based on the Petri net theory and conducted systematic analysis of the specific consumer EV adoption process. The following mechanisms were investigated through computer simulation: ① the influence of PCT on consumer EV adoption by adjusting the carbon emission reduction level under PCT; ② the influence of changes in environmental awareness of consumers regarding EV adoption. Finally, we summarize the influence factors and processes of the consumer EV adoption behavior under PCT and propose more useful and comprehensive policy recommendations to support the development of a low-carbon economy.

In summary, the structural description of the EV adoption conducted in this study can provide normative guidance for studying the complex and abstract behavioral evolution. Additionally, the proposed evolutionary system, the stochastic Petri Net model, and its isomorphic Markov chain can objectively reflect the influence of PCT on the evolutionary equilibrium state of adoption behavior, which is conducive to the evaluation of the probability of policy failure. At the theoretical level, this study attempts to propose more specific analyses of the equilibrium and regulation problems of the EV adoption from the perspective of systems thinking. At the application level, the findings of this work can provide potential guidance for identifying the critical time at which the PCT scheme distorts the role of the EV promotion, thereby preventing possible policy failures and coordinating various policies.

The remainder of this paper is organized as follows. Section 2 provides a brief review of related literature. Section 3 presents an SPN model to illustrate how the EV adoption behavior of consumers evolves when the PCT scheme is introduced to the market. Several numerical studies are then conducted in Section 4 to determine the effect of substantial factors on EV adoption and policy implications. Section 5 concludes with the main findings of this work and discusses the limitations and potential directions for future studies.

2 Literature review

This study aims to identify and explore the critical mechanisms underlying the effects of PCT on EV adoption behaviors while considering the environmental awareness of consumers. There are three streams of literature closely related to the focus of our study. The first involves the PCT scheme and its impact on consumers, and the second involves consumer EV adoption behaviors.

2.1 Research on personal carbon trading

PCT is a carbon reduction mechanism for the consumer sector based on the principles of fairness and equality, in which all people are given the same carbon allowances. When consumers utilize household energy or vehicle fuel, the corresponding carbon allowance amount is deducted from their personal carbon accounts. In 2006, the UK Environment Secretary Miliband proposed the UK PCT scheme, which, for the first time, extended the carbon trading system from the state and corporations to individuals[20]. To our best knowledge, the evolutionary path of research on PCT over the past 25 years can be divided into the following three main stages.

(Ⅰ) Before 2006: The first phase of study focused on the management of environmental pollution, which led to discussions of the effects of the PCT scheme. Reference [21] analyzed the issue of environmental pollution due to climate change and provided recommendations for governments and enterprises. Reference[22] analyzed the effects of PCT in terms of equity and efficiency, while reference[21] extensively introduced and compared different types of PCT schemes, providing a theoretical basis for the next phase of in-depth research.

(Ⅱ) 2008 - 2014: The second phase of study focused on the implementation details and feasibility of PCTs and comparing them with policies such as upstream carbon trading or carbon taxation. Reference [24] confirmed that a household carbon trading system can more effectively reduce emissions than upstream carbon trading. Reference[11] concluded that the PCT is at least as acceptable as a carbon tax in terms of social acceptability. Reference [25] evaluated the binding effect of PCT on carbon emissions from personal vehicles and its stabilizing effect on gasoline prices, and suggested that it was superior to the carbon tax. References [26-28] and further confirmed the policy advantages of PCT and its positive impact on guiding the transition of consumer energy consumption transition from the perspective of individual and social welfare, providing support for the next phase of carbon pricing research.

(Ⅲ) 2015-present: The third phase of study focused on the impacts of PCT, such as its impacts on energy markets and consumer decisions. References [7, 26] discussed the buffering effect of PCT on energy prices and its complementary effect on subsidies for energy-efficient vehicles. Reference[29] studied the supply-demand balance in the PCT market and revealed the impact of a critical carbon price on consumer energy choices. References [30, 31] introduced the carbon household theory for studying the application of PCT in transportation planning and provided new suggestions for managing the traffic congestion. Recent studies have begun to examine the role of PCT in influencing the EV adoption attitudes[32] or confirming the advantages of PCT over other mechanisms[18].

2.2 Research on EV adoption

The rapid development of EVs is widely recognized as a key to reducing carbon emissions from transportation and preserving traditional oil resources[33,34], and has been a breakthrough in narrowing the gap between the automotive industries of China and developed countries. References [35, 36] Current research on the EV consumer behavior is mainly focused on the empirical studies on purchase intention and market diffusion models. The research paradigm can be divided into the following:

(Ⅰ) Purchase attitude. Reference[37] established a model reflecting the homogeneous willingness to purchase of consumers based on the logit model and proposed a series of critical decision factors, such as motivation, reliability, cost, and safety, which provided the basis for subsequent research. References [38, 39] reported the positive effects of subjective norms, purchase attitudes, perceived usefulness, and ease of use on the purchase attitudes and willingness-to-pay of residents based on the Technology Acceptance Model (TAM) and Theory of Planned Behavior (TPB).

(Ⅱ) Market diffusion: From a policy perspective, reference [40] investigated the significant impacts of energy efficiency and subsidy policy on EV sales. Additionally, reference [40] further analyzed the main factors influencing the market diffusion of automobiles at different stages based on the whole life-cycle perspective. References [42,43] explored the impacts of the business model innovation and regional differentiation management on market diffusion, respectively. From the infrastructure construction perspective, References [44, 45] used the scenario analysis and the principal-agent approach to optimize the distribution of hydrogen refueling stations on the German Autobahn and charging stations in Shanghai, respectively, to forecast the development of the new-energy vehicle market.

3 Evolutionary model of EV adoption behavior under PCT

3.1 Stochastic Petri Net

In 1963, Carlpetri proposed a Petri net to numerically describe discrete parallel systems, the basic elements of which are places, transitions, directed arcs, and tokens. As it takes time for an event, i. e., a mutation, to occur in the system, time constraints (i. e., time parameters) are often introduced to Petri nets to expand their functionality. Such a Petri Net is called a Stochastic Petri Net (SPN) as they associate a stochastic delay between the implementation ability and implementation of each transition. In a continuous-time SPN, the delay time associated with each transition t has an exponential distribution function with the following Molloy form.

$$\forall t \in T: F_t = 1 - e^{-\lambda_t x} \tag{1}$$

where parameter $\lambda_t > 0$ represents the average implementation rate of the transition t, and the random delay time variable $x \geqslant 0$.

An SPN is typically defined as a directed graph containing six elements, i. e., $\mathrm{SPN} = (P, T, F, W, M_0, \lambda)$. In the residential EV adoption evolutionary system, we have

(Ⅰ) $P = (P_1, P_2, \cdots, P_n)$, which denotes the set of places of the evolving system, and $n > 0$ is the total number of places.

(Ⅱ) $T = \{t_1, t_2, \cdots, t_m\}$, which represents the set of transitions of the evolving system, and $m > 0$ represents the total number of transitions.

(Ⅲ) $F \subseteq I \cup O$, which denotes the set of directed arcs of the transitions, where I is the set of input arcs satisfying $I \subseteq P \times T$ and O is the set of output arcs satisfying $O \subseteq T \times P$. F can contain forbidden arcs, but only arcs with the place points to transition.

(Ⅳ) $W: F \to N^+$, ($N^+ = \{1, 2, 3, \cdots, n\}$), which represents the arc function.

(Ⅴ) $M: P \to N$, which generally represents the mark of the SPN expressed as a vector, where the $i-th$ element of the vector is the number of tokens in the $i-th$ place and M_0 represents the initial mark of the SPN, the initial state of the system.

(Ⅵ) $\lambda = \{\lambda_1, \lambda_2, \cdots, \lambda_m\}$, which represents the set of average implementation rates associated with a transition. Each transition t follows a negative exponential distribution, and $\{\lambda_t \mid t = 1, 2, \cdots, m\}$ is the parameter of the negative exponential distribution function.

Based on the definition of SPN, the modeling and equilibrium solving process for the residential EV adoption evolutionary system can be described as follows.

Step 1 Construct the SPN model of the EV adoption evolutionary system and correlate the delay times of the events that change the system state to the corresponding transitions.

Step 2 Introduce Isomorphic Markov chains (MC) for constructing this SPN model. Analyze the reachable set $R(m)$ of the SPN model and label each arc with the average implementation rate of the transition corresponding to that arc. Further, construct MC that are isomorphic to the SPN model and determine their activity and boundedness. All marks or states in the system are labeled as $M_1, M_2, \cdots, M_n$, where n represents the number of marks or states.

Step 3 Compute the steady-state probability of the evolving system and solve the equilibrium result. In a MC, for any mark $M_t \in [M_0>$, $M_j, M_k \in [M_0>$, $M_t[t_j>M_j$, and $M_k[t_k>M_t$ (where $[M_0>$ represents the reachable set of marks and $M_t[t_j>M_j$ represents the mark M_t undergoing a transition t_j to reach mark M_j), if $\{P(M_i) \mid i = 1, 2, \cdots, n\}$ denotes the probability of every steady state of an MC, then all equilibrium equations can be listed out according to the smooth distribution theorem of MC, as follows

$$\left(\sum_j \lambda_j\right) P(M_t) = \sum_k (\lambda_k P(M_k)) \tag{2}$$

Then, combined with the equation $\sum_t P(M_t) = 1$, we can determine the probability of a steady-state for each reachable mark of the system.

Step 4 Analyze the system performance of EVs using the evolved system SPN model, and propose improvement suggestions and control mechanisms based on numerical simulation.

3.2 Evolutionary model and solutions

Based on the existing literature related to residents' adoption behavior, we summarized and sorted out the different states of the EV adoption process and their relationships, added emotional factors such as the emotional contagion and group polarization, and environmental factors such as carbon emission level, personal carbon trading, and emission performance concern, enriched the existing literature, and finally formed the EV adoption behavior evolution system, as shown in Figure 1. Based on the SPN model, each part of the evolutionary system was then converted into a corresponding place or transition, as shown in Table 1, and the evolutionary SPN model was obtained, as shown in Figure 2. The accessibility and likelihood of each place are reflected by the delay time or average implementation rate of its associated transition.

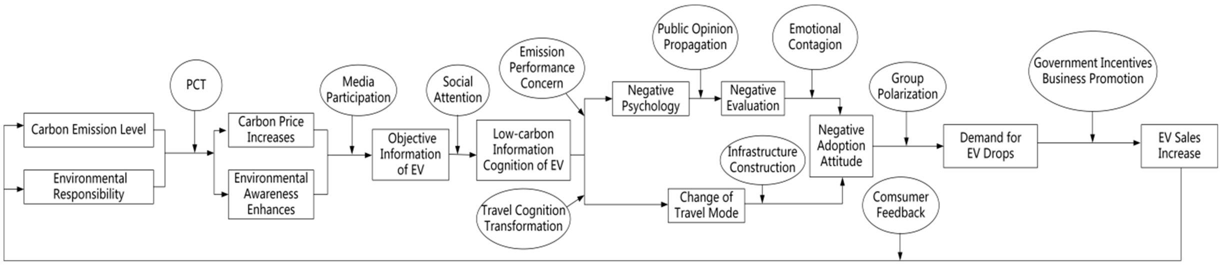

Figure 1. Evolution system of the EV adoption behavior of residents

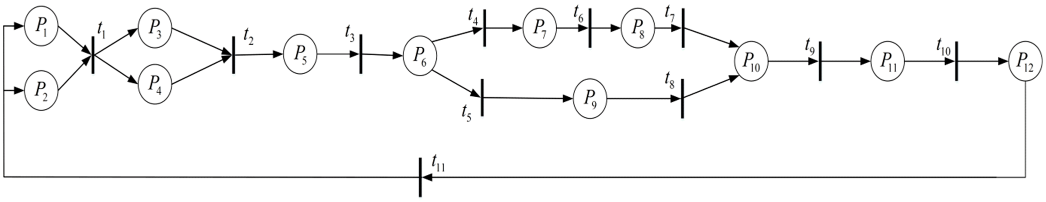

Figure 2. SPN model of the evolution of residential EV adoption behavior

Table 1. Symbolic definitions for the SPN model of the adoption behavior evolution

Place	Description	Transition	Description
P_1	Carbon emission level	t_1	Personal carbon trading
P_2	Environmental responsibility	t_2	Media participation
P_3	Carbon price increases	t_3	Social attention
P_4	increases in environmental awareness	t_4	Emission performance concern
P_5	Objective EV information	t_5	Travel cognition transformation
P_6	Low-carbon information cognition of EV	t_6	Public opinion propagation
P_7	Negative psychology	t_7	Emotional contagion
P_8	Negative evaluation	t_8	Infrastructure construction
P_9	Change in travel mode	t_9	Group polarization
P_{10}	Negative adoption attitude	t_{10}	Government incentives, business propositions
P_{11}	Demand for EV drops	t_{11}	Consumer feedback
P_{12}	EV sales increase	—	—

[Note] "—" indicates that the item does not exist.

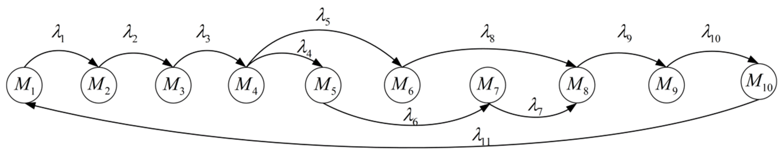

Figure 3. Markov chains of residential behavior evolution

The initial mark of the SPN model for the evolution of the residential EV adoption behavior is$M_1 = (1,1,0,0,0,0,0,0,0,0,0,0)$. P_1 and P_2 contain a token. Therefore, we can obtain the reachable set triggered by different transitions, leading to the following identities

$$\left.\begin{aligned}
M_1 &= (1,1,0,0,0,0,0,0,0,0,0,0)\\
M_2 &= (0,0,1,1,0,0,0,0,0,0,0,0)\\
M_3 &= (0,0,0,0,1,0,0,0,0,0,0,0)\\
M_4 &= (0,0,0,0,0,1,0,0,0,0,0,0)\\
M_5 &= (0,0,0,0,0,0,1,0,0,0,0,0)\\
M_6 &= (0,0,0,0,0,0,0,0,1,0,0,0)\\
M_7 &= (0,0,0,0,0,0,0,1,0,0,0,0)\\
M_8 &= (0,0,0,0,0,0,0,0,0,1,0,0)\\
M_9 &= (0,0,0,0,0,0,0,0,0,0,1,0)\\
M_{10} &= (0,0,0,0,0,0,0,0,0,0,0,1)
\end{aligned}\right\} \tag{3}$$

$\{M_i \mid i=1,2,\cdots,10\}$ are the ten marks in the SPN model for the evolution of the EV adoption behavior. As a continuous-time SPN is isomorphic to a continuous-time MC, the identity of the SPN is isomorphic to the state space of the MC, where the firing time of the inter-place conversion is a random variable subject to exponential distribution, and the average implementation rate of the transition $\{t_i \mid i=1,2,\cdots,11\}$ is $\{\lambda_i \mid i=1,2,\cdots,11\}$. Therefore, if the transitions between different marks or states are represented by directed arcs, an MC equivalent to the above-mentioned SPN model can be obtained, as shown in Figure 3.

If$\{P(M_i) \mid i=1,2,\cdots,10\}$ is the probability of the stability of M_i in equilibrium of MC, then we can obtain the following set of equations:

$$\left.\begin{aligned}
\lambda_1 P(M_1) &= \lambda_{11} P(M_{10})\\
\lambda_2 P(M_2) &= \lambda_1 P(M_1)\\
\lambda_3 P(M_3) &= \lambda_2 P(M_2)\\
(\lambda_4 + \lambda_5) P(M_4) &= \lambda_3 P(M_3)\\
\lambda_6 P(M_5) &= \lambda_4 P(M_4)\\
\lambda_8 P(M_6) &= \lambda_5 P(M_4)\\
\lambda_7 P(M_7) &= \lambda_6 P(M_5)\\
\lambda_9 P(M_8) &= \lambda_7 P(M_7) + \lambda_8 P(M_6)\\
\lambda_{10} P(M_9) &= \lambda_9 P(M_8)\\
\sum_{i=1}^{10} P(M_i) &= 1
\end{aligned}\right\} \tag{4}$$

By solving the set of linear equation (4), we can determine the stable probability of the evolving state of the EV adoption behavior. Furthermore, we can regulate some aspects of the process to drive the eventual adoption of EVs.

4 Simulation and discussions

The scenario analysis involves the analysis of different evolutionary states of an event. The scenario state of the system is derived from various average implementation rates of MC transitions.

We set the average implementation rate of the transitions $\{\lambda_i \mid i=1,2,\cdots,11\}$ based on the temporal development of the evolutionary process, as shown in Figure 3. In line with reference [46], this paper determines the values of λ_i according to the length of time that each influencing factor plays a role in the evolutionary system, thus converting the time parameter into a weight parameter. Specifically, the longer the time, the greater the effect on the whole evolutionary system and vice versa. As the transitions of the evolutionary model are still under theoretical study, we set the benchmark values of the average implementation rate and unit of change to 1, and then set specific values according to the stage of information evolution and psychological change state of the population to study the effects of different implementation rates on the evolution of EV adoption behavior. We set the average implementation rate of PCT (t_1) to $\lambda_1 = 1$. Owing to the increasing degree of informatization of social media, media reports have a great impact on people's lives, and it takes time for society to respond to an event after it is quickly reported by the media. Thus, we set media participation (t_2) and social attention (t_3) to be $\lambda_2 = 4$ and $\lambda_3 = 2$, respectively. The rate of the public opinion propagation (t_6) is slower than that of social attention (t_3), $\lambda_6 = 1$, and the rates of emotional contagion (t_7) and group polarization (t_9) are equal to that of the social attention, with $\lambda_6 = 2$, $\lambda_9 = 2$.

Furthermore, the transitions $\{t_i \mid i=4,5,8,10,11\}$ were in the key scenario of cognitive formation and change in the EV adoption, so we assumed that the average implementation rate of $\{t_i \mid i=4,5,8,10,11\}$ was $\lambda_4 = 1$, $\lambda_5 = 1$, $\lambda_8 = 2$, $\lambda_{10} = 2$, and $\lambda_{11} = 3$, respectively.

In the evolutionary system of residential EV adoption behavior, PCT (t_1) is the source of the evolution, and the emission performance concern (t_4) is the key parameter in the psychological changes that occurs in low-carbon perceptions. Furthermore, travel cognition transformation (t_5) is an important cause of travel behavior change, emotional infection (t_7) is an important factor influencing the adoption behavior, and government incentives and business propositions (t_{10}) is an important driver of the adoption behavior. Therefore, we analyzed regulatory mechanisms and sub-scenario studies based on the above four transformations. We define λ_1 to vary and $\{\lambda_i \mid i=2,3,\cdots,11\}$ to remain unchanged in scenario 1, λ_4 to vary and $\{\lambda_i \mid i=1,2,3,5,\cdots,11\}$ to remain unchanged in scenario 2, λ_5 to vary and $\{\lambda_i \mid i=1,\cdots,4,6,\cdots,11\}$ to remain unchanged in scenario 3, λ_7 to vary and $\{\lambda_i \mid i=1,\cdots,6,8,\cdots,11\}$ to remain unchanged in scenario 4, and λ_{10} to vary and $\{\lambda_i \mid i=1,\cdots,8,10,11\}$ to remain unchanged in scenario 5. Based on this, we obtained the simulation results for each scenario.

4.1 PCT Implementation efforts

Figure 4 shows that, as λ_1 increased (degree of PCT increased), the probability of the carbon emission level and environmental awareness decreased rapidly, while that of the negative adoption attitude $P(M_8)$ and a drop in EV demand $P(M_9)$ increased significantly. PCT is a "double-edged sword" in the evolution of residential EV adoption behavior. Specifically, the increasing degree of PCT can aid in reducing carbon emissions and improving the environmental awareness of residents; however, as PCT develops to a higher degree, the total amount of carbon quotas becomes limited and the regulation becomes much stronger, leading to a significant increase in carbon trading costs and a gradual increase in the residents understanding of the low-carbon attributes of EVs. As the carbon emission level of EV is not always lower than that of the conventional vehicles, there is a negative intention toward the adoption of EV as residents can compare their real carbon emission performances from a full life cycle perspective. Additionally, as the residents' understanding of the low-carbon attributes of EVs and environmental awareness increases, they may select more low-emission modes of travel, such as bicycle sharing, subways, and other forms of public transportations after reaching a certain level. With the improvement of public transportation infrastructure, residents will gradually abandon their consideration of EVs, reducing their demand for EVs and leading to the emergence of a negative adoption attitude. Therefore, PCT plays a very important role in the evolution of the residential EV adoption behavior. The government should either maintain the total amount of carbon constraints at a moderate level to control transaction costs, or improve the flexibility of PCT by optimizing the PCT mechanism to maintain the degree of PCT at a moderate level to not only raise the residents' environmental awareness and reduce carbon emissions, but also maintain the residents' positive attitude toward EVs and prevent excessive carbon constraints from having a series of negative impacts on residents' willingness to adopt EVs.

4.2 Emission concern

Figure 5 shows that, as λ_4 increased (degree of emission performance concern increased), the probability of people's doubts regarding low-carbon levels increased, and the probabilities of negative psychology ($P(M_5)$), negative evaluation ($P(M_7)$), and decreased EV demand ($P(M_9)$) increased rapidly. The probabilities of a high level of carbon emissions, environmental responsibility ($P(M_1)$), EV objective information ($P(M_3)$), EV low-carbon information awareness ($P(M_4)$), and travel mode change ($P(M_6)$) decreased, while the carbon price increased, environmental awareness was enhanced, and negative adoption attitudes did not significantly change. Figure 5 shows that the doubt of low-carbon level greatly

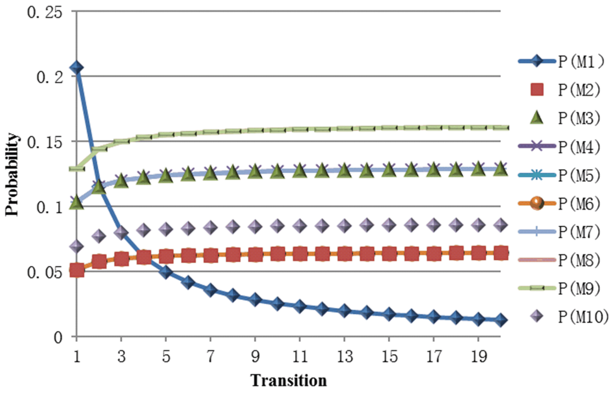

Figure 4. Changes in evolutionary equilibrium for EV adoption behavior with λ_1.

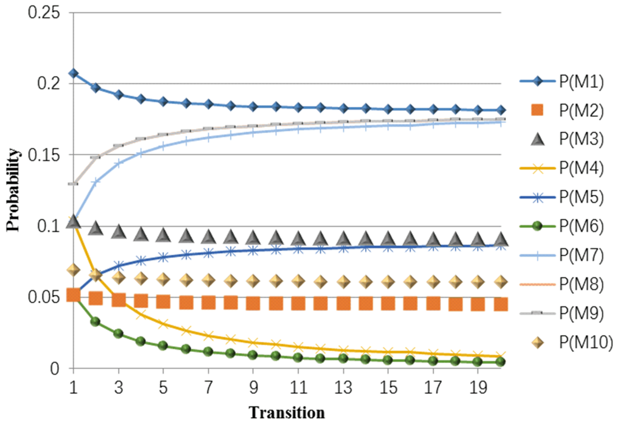

Figure 5. Changes in evolutionary equilibrium for EV adoption behavior with λ_4.

influenced the effectiveness of low-carbon information perceptions regarding EVs and had an important impact on environmental awareness. Additionally, as the doubt of low-carbon level increased, the probability of the adoption of most of the behaviors in the behavior evolution system decreased, while the probability of negative psychology, travel mode change, and negative evaluation increased, indicating that the degree of doubt regarding low-carbon level greatly influenced the perception of and demand for EVs. People base their initial judgments on their perceptions of EV information. In the process of identifying, understanding, and familiarizing themselves with EVs, they think about whether or not the choice is suitable for them, and the doubt of the low-carbon level becomes the main reason for negative psychology and evaluation, leading to negative adoption attitudes and decreased demand for EVs. Under the above situation, the government and relevant authorities must pay attention to the direction of socially relevant information when low carbon levels are not yet appropriately recognized by people. Additionally, the questions due to early ignorance and deep thinking may cause negative public evaluation; therefore, the government and enterprises should respond to the market or consumers in a timely manner to maintain the public's doubts at a reasonable level.

4.3 Traveling demand

Figure 6 shows that, as λ_5 increased, the probabilities of travel cognition transformation, modal shift ($P(M_6)$), and an increase in EV sales ($P(M_{10})$) increased, assuming the average implementation rate of the remaining changes remains the same. Additionally, the probabilities of EV low-carbon information awareness ($P(M_4)$), negative psychology ($P(M_5)$), and EV demand decline ($P(M_9)$) decreased. Figure 6 shows that, when people's travel cognition transformation increases rapidly at a certain EV information perception level, there is a probabilistic travel mode shift. This is because, when cognition transformation and some trips can be completed at home or online, people often consider mode and travel characteristics when making final travel decisions. For example, during the COVID-19 pandemic, controlling the movement of people became the most effective method of controlling the epidemic, which directly led to a decline in the travel demand and frequency, with people choosing to walk and travel by bike or car more frequently. With the rapidly decreasing travel demand, the perceived need for EVs and their benefits may be stronger, and people may not be interested in EVs as they do not require them for their own living situation, thereby affecting the demand for and likelihood of adopting EVs. The evolutionary system suggests that the EV demand is less likely to decline, indicating that market demand and ownership levels will be in relative equilibrium and increase as government incentives and the energy mix change. Additionally, as cognition transformation continues, the probabilities of carbon emission level and environmental responsibility increase; therefore, it is important to focus on the causes and direction of change as the travel demand continues to decline, identify the direction of change in carbon emissions resulting from the shift in travel patterns, and provide guidance and advocacy for government incentives and energy restructuring policies.

4.4 Emotional infection among residents

Figure 7 indicates that, as λ_7 increased (degree of residents' emotional contagion increased), the probability of the negative evaluation $P(M_7)$ decreased continuously, while the probabilities of negative adoption attitude $P(M_8)$ and a drop in EV demand $P(M_9)$ continued to increase following the initial decrease. When λ_7 was taken in a small range, the probabilities of both the negative evaluation and the adoptive attitude decreased; however, as λ_7 increased, the probabilities of the negative evaluation decreased and the negative adoptive attitude increased, following

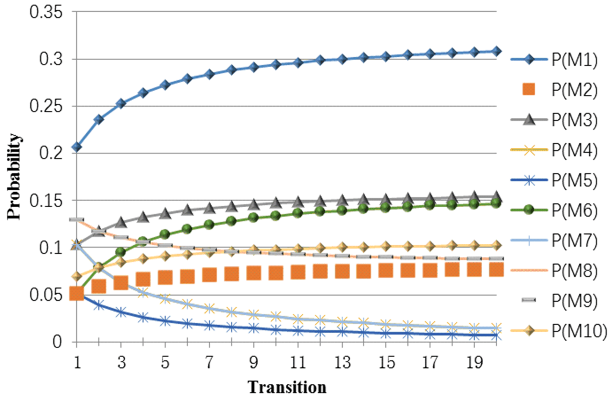

Figure 6. Changes in evolutionary equilibrium for EV adoption behavior with λ_5.

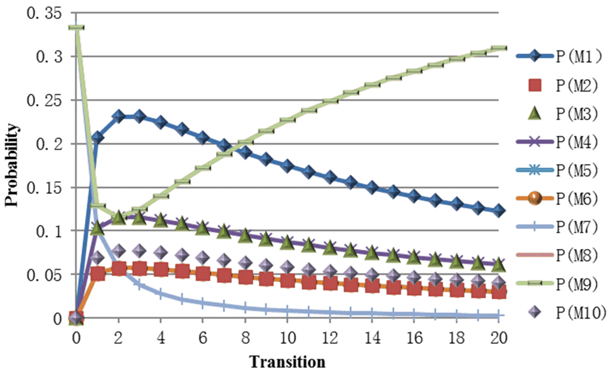

Figure 7. Changes in evolutionary equilibrium for the EV adoption behavior with λ_7.

two opposing trends, indicating that the decrease in negative evaluation does not mean that the residents are optimistic about EVs from now on; however, residents are often more passive toward EVs due to the emotional contagion. The more resolute opinions and attitudes that are driven by the EV adoption may shift from the negative evaluation to a more negative adoption attitude, thereby reducing the demand for EVs. Therefore, during the evolution of the residential EV adoption behavior, an increase in the degree of emotional contagion among residents may inhibit the occurrence of the adoption behavior. The government should not ignore the generation and dissemination of residents' opinions toward EVs, and should always maintain an understanding of the public situation. The government should understand the causes of the residents' negative adoption attitudes deeply through the solicitation of the public opinion and visits, responding to public concerns in a timely manner, actively guide and improve their perceptions of EVs, and drive their EV adoption behavior.

4.5 Government EV incentives

Figure 8 shows that, as λ_{10} increased (degree of government incentives and business promotion increased), the probability $P(M_9)$ of EV demand decreased rapidly. In contrast, the probability $P(M_{10})$ that an increase in EV sales increased. Therefore, the result shows that government incentives and business promotion can significantly promote EV adoptions. According to reference [46], financial policies (subsidies) and publicity policies (environmental awareness campaigns) have the most significant impact on the evolution of EV adoption behavior, but their effect may not always be consistent. At the beginning of the market development, as the publicity efforts increase, the residents' environmental awareness increases, and people have more objective information about EVs, which can effectively improve the willingness to adopt. In the long term, however, residents' environmental awareness continues to increase when publicity efforts are further increased, making their low-carbon awareness of EVs grow. In this case, the negative effect of the publicity policy may eventually offset the positive effect of the subsidy policy. According to our model, the residents' willingness to adopt may instead decline at that time. Consequently, the publicity policy has the opposite effect of the subsidy policy in this situation. Therefore, while the government should actively introduce policies to promote and subsidize EVs, it should also pay attention to policy amendment and coordination to ensure the policies' effectiveness. Besides, the government should stimulate the demand for EVs by supporting corporate promotions to promote EVs' adoption by residents.

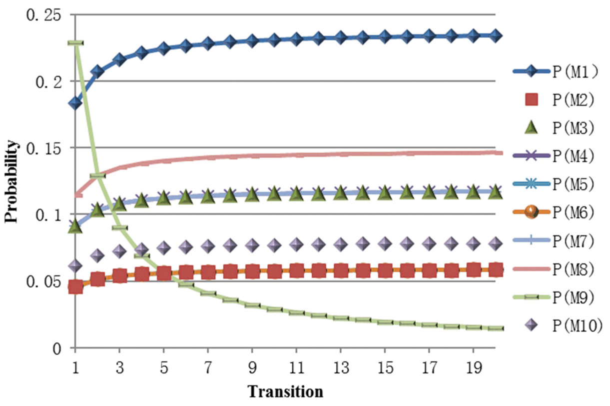

Figure 8. Changes in evolutionary equilibrium for EV adoption behavior with λ_{10}.

5 Conclusions

The implementation of the "dual-credit" scheme indicates the era of the carbon quota trading is approaching. As a downstream "cap-and-trade" policy, the PCT scheme is likely to move from the theoretical stage to the implementation stage shortly. Under the PCT scheme, green consumers can receive the economic benefits of trading the additional carbon emission allowances they save with the following green behaviors. Therefore, as a new type of emission policy, its outstanding advantages lie in total volume control and behavioral guidance. After introducing a reasonable PCT mechanism, the environmental awareness of the population will gradually become significant. However, the results of previous studies seldom considered the structural description of environmental awareness and equilibrium state variation of the evolving system, and little modeling and mechanistic analysis of the impacts of PCT on EV adoption behaviors have been conducted from a system perspective. This study investigated the influence of the PCT scheme on residents' willingness to adopt EVs through a stochastic Petri Net model, which quantitatively revealed the dual path of the impact of PCT. The main findings of this study are as follows:

First, increased environmental awareness is not necessarily conducive to the short-term EV adoption. While environmental awareness contributes to early EV purchases, as environmental awareness and the green consumer base grow, the carbon footprint will soon become public knowledge, and negative opinion regarding the life-cycle assessment of EV performance at this stage will spread rapidly. If the country's energy mix and EV manufacturers' battery technologies do not improve significantly in a short time, environmental awareness is likely to detriment the EV adoption behavior, which contradicts the country's goal of promoting EV development to support future transportation transitions.

Second, the key parameters of the PCT scheme, such as emission constraints and transaction costs, will directly determine the direction of their influence on the EV adoption behavior. This study indicates that neither a loose carbon emission constraint nor a negligible transaction cost will significantly impact the environmental awareness of residents, and will, therefore, have a weak effect on the promotion of EVs. However, overly stringent constraints limit residents' demand for traveling by private cars, and encourage them to change their travel patterns, resulting in a decline in EV adoption behavior. Therefore, after considering residents' environmental awareness, this study concludes that the impact of PCT on the EV adoption is not monotonic, and the results provide a theoretical basis for setting reasonable core indicators, such as total emissions and transaction costs.

Third, based on these findings, government subsidies to EV firms and behavioral guidance to consumers (e. g., PCT schemes) may not always be mutually reinforcing, and may even counteract one other in promoting the EV adoption. Governments have already implemented three types of traditional incentives: make fiscal incentives to lower the cost of EVs compared with traditional fuel vehicles, change its infrastructure to ensure that EVs are as convenient to use as traditional fuel vehicles, and organize activities to increase consumers' awareness and acceptance of EVs. Our results indicate that governments must balance these incentives with PCT to optimize EV sales or total emissions of the automobile industry. For instance, given the government's fiscal constraints, our results can inspire governments to rationally allocate the proportion of investment between PCT and other incentives, thereby significantly improving policy implementation effectiveness or reducing government expenditures.

In summary, the structural description of the EV adoption conducted in this study provides a normative guidance for the study of the complex and abstract behavioral evolution. Additionally, the proposed evolutionary system, stochastic Petri Net model, and its isomorphic Markov chain have objectively reflected the influence of PCT on the evolutionary equilibrium state of the adoption behavior, which is conducive to the evaluation of the probability of policy failure. That is, pertinent government incentives may not promote residents' EV adoption behavior, and may even hamper it. Our simulation results will further provide a theoretical basis for the formulation of the PCT scheme's core parameters.

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Conflict of interest

The authors declare no conflict of interest.

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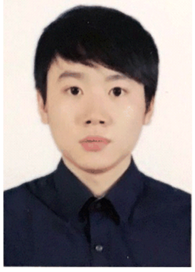

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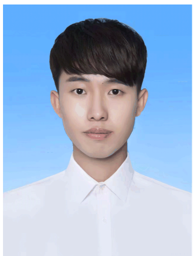

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基于随机 Petri 网的个人碳交易机制下电动汽车采纳行为演化研究

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摘要：环境问题的日益紧迫与企业碳交易试点的快速推进预示着个人碳交易机制(Personal Carbon Trading, PCT)有望在未来落地,这将极大地影响消费者的绿色意识与行为决策. 本研究构建随机 Petri 网(SPN)模型,以分析 PCT 机制下居民电动汽车采纳行为的演化过程,并定量地探讨环境意识和 PCT 机制对电动车采纳行为的影响作用. PCT 的“总量控制”与“自由交易”的特色能显著提高消费者的环保意识,但本文结果表明,这对现阶段的电动汽车采纳行为是一把“双刃剑”,导致政府引入 PCT 机制并不一定对居民电动汽车的采纳产生正向影响. 具体来说,环境意识在提高消费者为低碳产品支付溢价的意愿的同时,也引发了人们对电动车实际低碳性能和低碳出行方式的质疑. 因此,政府应协调 PCT 政策和传统激励政策的力度,以最大限度地实现促进电动汽车产销量的目标. 本研究有助于更好地理解 PCT 机制下居民电动汽车采纳行为的演化路径,为政府决策和电动汽车企业的产品设计和定价提供理论支持.

关键词：电动汽车;环境意识;个人碳交易;Petri 网