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Research on the Tripartite Evolutionary Game of Government, Automakers, and Consumers under Replacement Subsidies ——An Analysis Considering Automakers' Charging Pile Strategy and Consumer Purchasing Behavior#

Xiancheng Luo[1], Lijing Zhu[1*]

1 School of Economics and Management, China University of Petroleum (Beijing), Beijing, China;
(Corresponding Author: zhulj@cup.edu.cn)

ABSTRACT

By the end of 2022, the Chinese government had completely phased out subsidies for the purchase of electric vehicles and introduced replacement subsidies instead, aiming to promote the electrification of automobiles by incentivizing consumers to replace fuel vehicles with electric ones. This paper employs evolutionary game theory to construct a tripartite evolutionary game model of the government, automakers, and consumers. It analyzes the evolutionary strategies of automaker and consumer decisions under both proactive and passive subsidy attitudes of the government, coupled with system dynamics simulations. The study investigates the evolutionary stable states of the government, automakers, and consumers, as well as the impact of external variables on the strategic choices of the involved parties. Simulation results indicate that the government's strategic choices at the initial stages of new energy vehicle development are crucial for the system to reach a positive stable state; operational revenues from charging stations and the utility derived from new energy vehicles are the primary drivers for automakers and consumers to adopt proactive strategies, respectively. This research provides a quantitative analysis of government subsidies to inform the optimization of new energy vehicle subsidy policies.

Keywords: new energy vehicles, replacement subsidies, evolutionary game, system dynamics

1. INTRODUCTION

Under substantial government subsidies, by the end of 2023, the ownership of new energy vehicles in China reached 20.41 million units, accounting for 6.07% of the total number of vehicles, showing a rapid growth trend. However, more than a decade of purchase subsidies have placed a significant financial burden on the government, leading to the formal termination of the new energy vehicle purchase subsidy policy at the end of 2022. The exit of purchase subsidies does not imply the cessation of government policy support for the development of new energy vehicles. Instead, replacement subsidies were introduced with the 2022 'Beijing Plan to Encourage the Upgrading and Replacement of Vehicles' and 'Shanghai Regulations for Promoting Automobile Consumption Subsidies', which specifically provided subsidies for users who replace their vehicles with new energy ones. On April 12, 2024, China's Ministry of Commerce and 13 other departments jointly issued the 'Action Plan to Promote the Replacement of Consumer Goods', specifying key tasks for vehicle replacement. As of August 2022, the national car ownership reached 312 million units, making it the largest car stock market in the world. The introduction of replacement subsidies aims to focus on this massive stock market to promote the development of new energy vehicles and increase the electrification rate of the automotive industry. Additionally, the government has also introduced several policies to increase the number and operational level of charging infrastructure. Against the backdrop of government policy incentives, combined with the current development status of new energy vehicles and their charging infrastructure in China, addressing the complex relationships among stakeholders such as the government, automakers, and consumers, strengthening the promotional effects of government subsidies and regulatory policies, and encouraging automakers to actively build and operate charging stations are pressing challenges that need to be addressed in the development of China's new energy vehicle industry.

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Scholars both domestically and internationally have conducted extensive research on the impact of government policies on the new energy vehicle market and its participants. Early studies primarily focused on the impact of purchase subsidies, as explored by Yi Hu et al. [3] and Xiao Zhou et al. [4]. With the phase-out of purchase subsidies, some scholars have investigated government policies in the post-subsidy era [5], gradually shifting attention to subsidies for charging infrastructure [6]. However, there is scant literature on the policy effects of newer subsidies such as vehicle replacement subsidies and operating subsidies for charging stations. Some scholars have studied the interactions and decision-making behaviors among stakeholders in the charging pile market, with most constructing game models to optimize decisions for governments, businesses, and consumers. Zhu et al. [7] developed a three-level Stackelberg game model among electricity suppliers, charging facility operators, and investors to study the tripartite decision-making mechanism during the construction of charging piles, while Wang Wei et al. [8] built an evolutionary game model to explore the interactions and decision-making processes among governments, operators, and consumers during the operation of charging piles. Yet, few studies have examined the decision-making mechanisms of stakeholders in the electric vehicle and charging pile markets in the context of replacement subsidies.

Therefore, this paper constructs a tripartite evolutionary game model involving the government, automakers, and consumers based on the context of replacement subsidies. It analyzes the decision-making behaviors of automakers and consumers under different subsidy attitudes of the government and uses system dynamics simulation to study the impact of variations in parameters on the strategy choices of the participants in the tripartite evolutionary game. Finally, based on the simulation results, the paper offers policy recommendations for the development of new energy vehicles and their market, providing a theoretical basis for the Chinese government to formulate reasonable policies.

2. MODEL CONSTRUCTION

2.1 *Problem Description*

The evolutionary game model constructed in this paper involves three participating entities: the government, automakers, and consumers. The government, as the subsidizer for consumers' replacement of new energy vehicles and automakers' construction of charging stations, has a strategy set consisting of {proactive subsidies, passive subsidies}. Automakers, as producers and sellers of vehicles and builders of charging stations, have a strategy set consisting of {proactive construction, passive construction}. Consumers (currently owning gasoline vehicles) as the demanders of vehicles, have a strategy set consisting of {replacing with new energy vehicles, replacing with gasoline vehicles}.

2.2 *Basic Assumptions*

Assumption 1: In the evolutionary game model, the government, automakers, and consumers are all groups with bounded rationality, each pursuing the maximization of their own benefits during the game process.

Assumption 2: In the evolutionary game process, the probability that the government adopts a proactive subsidy strategy is x, the probability that automakers adopt a construction strategy is y, and the probability that consumers choose to replace with new energy vehicles is z, with x, y, and z all lying within the interval [0,1].

Assumption 3: If the government opts for a passive subsidy strategy, it will not provide any subsidies to consumers or automakers. When the government adopts a proactive subsidy policy, it will provide subsidies to consumers who replace their vehicles with new energy vehicles, with the subsidy amount set at S_1, and will also subsidize automakers that decide to build charging stations, with the subsidy amount set at S_2 (a percentage of the construction costs). Along with the proactive subsidy strategy, the government will regulate the construction of charging stations by automakers, with the regulation cost denoted as C_7. If an automaker adopts a passive approach to building charging stations, the government will impose a fine F_1 on them. The government's proactive subsidy strategy generates positive social reputation, potentially promoting the development of electric vehicles, denoted as E_1.

Assumption 4: If automakers adopt a proactive strategy in building charging stations and construct high-quality charging stations, they can obtain significant profits from their operation, denoted as R_1. Conversely, if automakers adopt a passive construction strategy and build low-quality charging stations, although this will save them a construction cost amounting to C_8, the poor quality of the charging stations will result in lower operational earnings, denoted as R_2. Moreover, low-quality charging stations will have a negative impact on the charging services for new energy vehicle consumers, causing negative utility denoted as U_4. Assume that the costs for automakers to produce gasoline vehicles and new energy vehicles are C_1 and C_2 respectively, and the revenues from selling gasoline vehicles and new energy vehicles are G_1 and G_2 respectively. The costs of building and operating charging stations for automakers are C_3 and C_4 respectively. If automakers adopt a construction strategy, this will also generate positive social reputation and have a proactive effect on promoting the development of electric vehicles, denoted as E_2.

Assumption 5: Assume that consumers currently owning gasoline vehicles all have a need to replace their cars, and they can choose to replace them with new energy vehicles or continue to replace them with gasoline vehicles. If consumers opt to replace with new energy vehicles, they will receive a government replacement subsidy, and since new energy vehicles are environmentally friendly, the positive environmental benefit is denoted as E_3. If consumers choose to continue replacing with gasoline vehicles, they will not receive any subsidies, and since gasoline vehicles are environmentally unfriendly, the negative environmental impact is denoted as E_4. Assume the costs for consumers to purchase gasoline vehicles and new energy vehicles are C_5 and C_6 respectively, the tangible assets obtained after replacing the vehicle are denoted as *V*, and the residual value of the scrapped gasoline car is denoted as *r*. The utilities derived from gasoline vehicles and new energy vehicles are U_1 and U_2 respectively, and the construction of charging stations by automakers will bring additional utility to consumers who replace with new energy vehicles, denoted as U_3 .*Model Establishment*

Based on the assumptions above, an evolutionary game payoff matrix involving the three parties—government, automakers, and consumers—is constructed as shown in Table 1.

Table 1

The evolutionary game payment matrix of the government, automaker and consumer

consumer	government	Automaker	
		positive attitude(y)	negative attitudes(1-y)
replacement of fuel vehicles (1-z)	positive attitude (x)	$E_1+E_2-E_3-C_3S_2-C_7$ $C_3S_2+G_1-C_1-C_3-C_4$ $\mathrm{V}+U_1-C_5+\mathrm{r}$	$E_1+E_2-E_3-C_7-C_3S_2+F_1$ $C_3S_2+G_1-C_1-C_3-C_4+C_8-F_1$ $\mathrm{V}+U_1-C_5+\mathrm{r}$
	negative attitudes (1-x)	E_2-E_3 $G_1-C_1-C_3-C_4$ $\mathrm{V}+U_1-C_5+\mathrm{r}$	E_2-E_3 $G_1-C_1-C_3-C_4+C_8$ $\mathrm{V}+U_1-C_5+\mathrm{r}$
replacement of new energy vehicles (z)	positive attitude (x)	$E_1+E_2+E_4-C_3S_2-S_1-C_7$ $C_3S_2+G_2-C_2-C_3-C_4+R_1$ $\mathrm{V}+U_2-C_6+\mathrm{r}+S_1+U_3$	$E_1+E_2+E_4-C_3S_2-S_1-C_7+F_1$ $C_3S_2+G_2-C_2-C_3-C_4+R_2-F_1+C_8$ $\mathrm{V}+U_2-C_6+\mathrm{r}+S_1-U_4$
	negative attitudes (1-x)	E_2+E_4 $G_2-C_2-C_3-C_4+R_1$ $\mathrm{V}+U_2-C_6+\mathrm{r}+U_3$	E_2+E_4 $G_2-C_2-C_3-C_4+R_2+C_8$ $\mathrm{V}+U_2-C_6+\mathrm{r}-U_4$

3. EVOLUTIONARY GAME EQUILIBRIUM ANALYSIS

3.1 Expected Profits and Average Profits

Assume E_{11} is the expected revenue for the government under a proactive subsidy and regulatory strategy, E_{12} is the expected revenue for the government under a passive subsidy and regulatory strategy, and E_1 is the average expected revenue for the government, then

$$E_{11} = -yF_1 + zE_3 + zE_4 - zS_1 - C_3S_2 + E_1 + E_2 - E_3 + F_1 - C_7$$

$$E_{12} = zE_3 + zE_4 + E_2 - E_3$$

$$E_1 = xE_{11} + (1-x)E_{12}$$

Based on the principles of replicator dynamics and the government's expected revenue function, the government's replicator dynamics equation is constructed as follows:

$$F(x) = \frac{dx}{dt} = x(E_{11} - E_1) = x(1-x)(E_{11} - E_{12})$$

Similarly, the expected revenues and replicator dynamics equations for automakers and consumers can be derived as follows:

$$E_{21} = xC_3S_2 + zC_1 + zG_2 + zR_1 - zC_2 - zG_1 + G_1 - C_1 - C_3 - C_4$$

$$E_{22} = xC_3S_2 - xF_1 + zC_1 + zG_2 + zR_2 - zC_2 - zG_1 + G_1 - C_1 - C_3 - C_4 + C_8$$

$$E_2 = yE_{21} + (1-y)E_{22}$$

$$F(y) = \frac{dy}{dt} = y(E_{21} - E_2) = y(1-y)(E_{21} - E_{22})$$

$$E_{31} = xS_1 + yU_3 + yU_4 + \mathrm{V} + U_2 - U_4 - C_6 + \mathrm{r}$$

$$E_{32} = \mathrm{V} + U_1 - C_5 + \mathrm{r}$$

$$E_3 = zE_{31} + (1-z)E_{32}$$

$$F(z) = \frac{dz}{dt} = z(E_{31} - E_3) = z(1-z)(E_{31} - E_{32})$$

3.2 Equilibrium Analysis of the Tri-Party Evolutionary Game System

According to the replicator dynamics equations of the government, automakers, and consumers, the system of replicator dynamics equations for the tripartite evolutionary game is as follows:

$$\begin{cases} F(x) = x(1-x)(-yF_1 - zS_1 - C_3S_2 + E_1 + F_1 - C_7) \\ F(y) = y(1-y)(xF_1 + zR_1 - zR_2 - C_8) \\ F(z) = z(1-z)(xS_1 + yU_3 + yU_4 + C_5 - C_6 + U_2 - U_1 - U_4) \end{cases}$$

Solving the replicator dynamics equations for the government, automakers, and consumers yields eight solutions, which define the boundaries of the evolutionary game. In addition, there exists an equilibrium solution (x^*, y^*, z^*). To analyze the stability points of the tripartite group evolutionary game, the asymptotic stability can be assessed qualitatively using the Jacobian matrix. According to the Lyapunov indirect method, if all three eigenvalues of the Jacobian matrix at the equilibrium point are negative, then the equilibrium point is an evolutionarily stable strategy [9,10]. The Jacobian matrix of this replicator dynamics system is:

$$\begin{bmatrix} (1-2x)(-yF_1 - zS_1 - C_3S_2 + E_1 + F_1 - C_7) & x(1-x)(-F_1) & x(1-x)(-S_1) \\ y(1-y)(F_1) & (1-2y)(xF_1 + zR_1 - zR_2 - C_8) & y(1-y)(R_1 - R_2) \\ z(1-z)S_1 & z(1-z)(U_3 + U_4) & (1-2z)(xS_1 + yU_3 + yU_4 + C_5 - C_6 + U_2 - U_1 - U_4) \end{bmatrix}$$

From the Jacobian matrix, eight pure strategy stable points, E_1 to E_8, of the three-dimensional dynamic system can be determined. The eigenvalues corresponding to each equilibrium point's Jacobian matrix are shown in Table 2:

This paper discusses the stable strategies of the evolutionary game in two scenarios corresponding to different stages in the development of electric vehicles.

Table 2
Equilibrium points and their corresponding eigenvalues

Equilibrium point	Eigenvalueλ_1	Eigenvalueλ_2	Eigenvalueλ_3
$E_1(0,0,0)$	$E_1 + F_1 - C_7 - C_3S_2$	$-C_8$	$U_2 - U_1 - U_4 + C_5 - C_6$
$E_2(0,1,0)$	$E_1 - C_3S_2 - C_7$	C_8	$U_3 + U_2 - U_1 + C_5 - C_6$
$E_3(0,0,1)$	$E_1 - S_1 + F_1 - C_7 - C_3S_2$	$R_1 - R_2 - C_8$	$-(U_2 - U_1 - U_4 + C_5 - C_6)$
$E_4(0,1,1)$	$E_1 - S_1 - C_3S_2 - C_7$	$-(R_1 - R_2 - C_8)$	$-(U_3 + U_2 - U_1 + C_5 - C_6)$
$E_5(1,0,0)$	$-(E_1 + F_1 - C_3S_2 - C_7)$	$F_1 - C_8$	$S_1 + U_2 - U_1 - U_4 + C_5 - C_6$
$E_6(1,0,1)$	$-(E_1 - S_1 + F_1 - C_3S_2 - C_7)$	$F_1 + R_1 - R_2 - C_8$	$-(S_1 + U_2 - U_1 - U_4 + C_5 - C_6)$
$E_7(1,1,0)$	$-(E_1 - C_3S_2 - C_7)$	$-(F_1 - C_8)$	$S_1 + U_3 + U_2 - U_1 + C_5 - C_6$
$E_8(1,1,1)$	$-(E_1 - S_1 - C_3S_2 - C_7)$	$-(F_1 + R_1 - R_2 - C_8)$	$-(S_1 + U_3 + U_2 - U_1 + C_5 - C_6)$

Scenario One: In the early stages of new energy vehicle development, consumer acceptance of new energy vehicles is low. To promote the development of new energy sources, the costs incurred by the government far exceed the returns, that is, $E_1 + F_1 - C_7 - C_3S_2 < 0$. Additionally, for consumers, the cost of purchasing new energy vehicles is higher than that of gasoline vehicles, and the utility derived from electric vehicles is less than that from gasoline vehicles, that is, $U_2 - U_1 - U_4 + C_5 - C_6 < 0$. At this time, the equilibrium point of the evolutionary game is $E_1(0,0,0)$, and the eigenvalues of the corresponding Jacobian matrix are all negative.

Scenario Two: As the new energy vehicle industry matures, consumer acceptance of new energy vehicles is higher. For the government, the effects of proactive subsidy policies become more apparent, and the costs of implementation significantly decrease, that is, $E_1 - S_1 - C_3S_2 - C_7 > 0$. For automakers, as new energy vehicles gradually mature, actively building charging stations not only secures government subsidies but also generates substantial profits from the positive operation of the charging stations, thus eliminating the need to take significant risks with passive construction, with $F_1 + R_1 - R_2 - C_8 > 0$. For consumers, a maturing new energy vehicle system not only brings higher travel and charging benefits but also reduces purchase costs and includes government replacement subsidies, making consumers more willing to switch to new energy vehicles, with $S_1 + U_3 + U_2 - U_1 + C_5 - C_6 > 0$. The equilibrium point of the evolutionary game in this scenario is $E_8(1,1,1)$, and the eigenvalues of the corresponding Jacobian matrix are all negative.

4. SYSTEM DYNAMICS MODEL AND SIMULATION ANALYSIS

4.1 *Construction of the System Dynamics Model*

Using Vensim PLE software, based on the previously constructed evolutionary game payoff matrix and expected revenue functions, a system dynamics model of the evolutionary game involving the government, automakers, and consumers is established as shown in Figure 1.

4.2 *Model Simulation Analysis*

Table 3
Initial assignment of external variables

	S_1	S_2	U_1	U_2	U_3	U_4	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	E_1	E_2	E_3	E_4	G_1	G_2	r	v	R_1	R_2	F_1
1	0.5	0.3	5	3	2	2	5	6	10	6	6	7	8	3	2	6	4	4	5.5	6.5	0.5	5.5	5	3	5
2	0.5	0.3	5	7	2	2	5	4	8	5	6	5	4	3	8	2	4	4	5.5	4.5	0.5	5.5	15	10	5

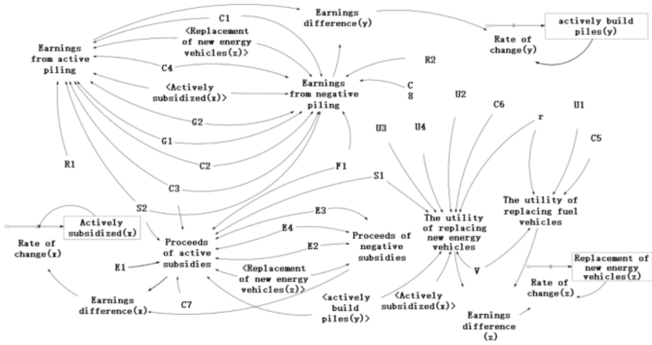

Fig. 1 System Dynamics Modeling of Government, Vehicle Companies and Consumers

In the simulation, the start time (INITIAL TIME) is set at 0, the end time (FINAL TIME) at 5, and the simulation step size (TIME STEP) at 0.01. Referencing related literature [8,11], initial values are assigned to the 25 external variables in the system dynamics model, as shown in Table 3.

Scenario 1: Early Stages of New Energy Vehicle Development

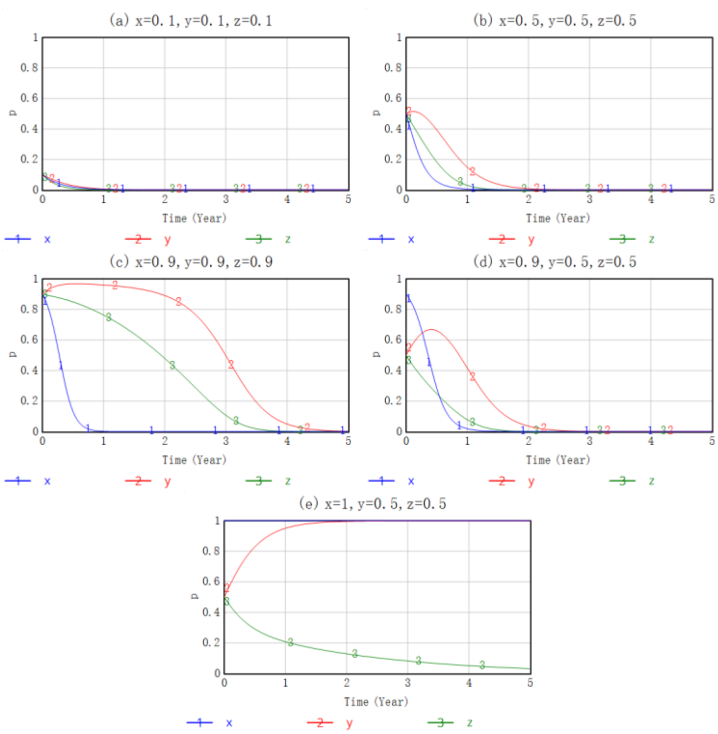

Fig. 2 The effect of initial willingness on evolutionary equilibrium

From the simulation results a, b, and c in Figure 2, it can be observed that when the initial values of external variables meet the conditions for reaching the evolutionary game equilibrium point E_1 (0,0,0) in Scenario 1, i.e., $E_1 + F_1 - C_7 - C_3 S_2 < 0$ and $U_2 - U_1 - U_4 + C_5 - C_6 < 0$, regardless of the initial strategy selection probabilities of the government, automakers, and consumers (excluding the extreme values of 0 and 1), the strategy selection probabilities of all three participating entities in the system will tend towards 0, with the government's probability typically decreasing the fastest. As the promoter of new energy vehicle development, the government tends to move towards a passive subsidy strategy more quickly during the early stages of industry development, when investments are high but the outcomes are very poor. For automakers, the high initial costs of building charging stations and the revenues from operating these stations are insufficient to cover the investment costs, hence they tend to adopt a passive construction strategy. For consumers, factors such as short driving range and inadequate charging infrastructure make them more inclined to continue replacing their vehicles with gasoline cars.

Comparing figures b, d, and e in Figure 2, it can be seen that when the government decides to adopt a proactive strategy first, its determination gives automakers greater confidence in the future of new energy vehicles, believing that proactive construction of charging stations will bring considerable revenue from their operation in the future. Therefore, automakers tend to adopt a proactive construction strategy. For consumers, the utility brought by new vehicles is key to their decision to replace with new energy vehicles. In the early stages of new energy vehicle development, shorter driving ranges and incomplete charging infrastructure

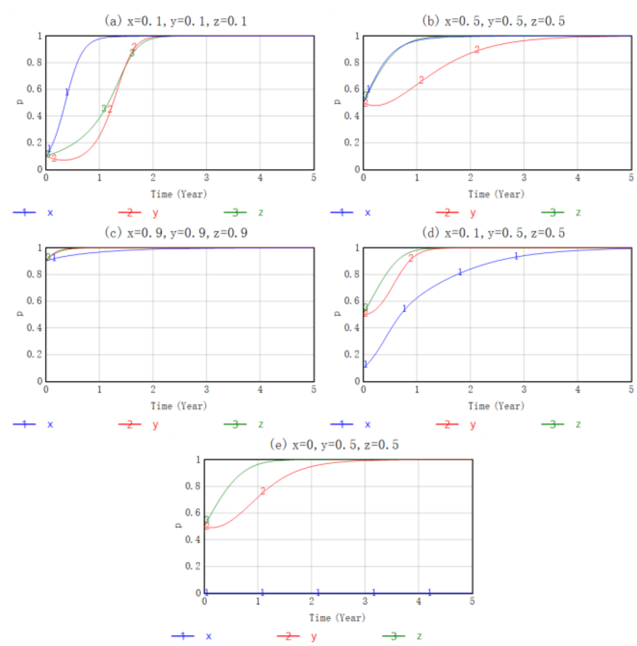

Fig. 3 The effect of initial willingness on evolutionary equilibrium

make consumers less willing to replace with new energy vehicles, and government subsidies are insufficient to change their preference for continuing to replace with gasoline vehicles.

Scenario 2: The Development of New Energy Vehicles Becomes Mature

From the simulation results a, b, and c in Figure 3, it can be observed that when the initial parameter values meet the conditions for reaching the evolutionary game equilibrium point $E_8(1,1,1)$ in Scenario 2, that is, $E_1 - S_1 - C_3 S_2 - C_7 > 0$, $F_1 + R_1 - R_2 - C_8 > 0$ and $S_1 + U_3 + U_2 - U_1 + C_5 - C_6 > 0$, regardless of the initial strategy selection probabilities of the government, automakers, and consumers (not at the extreme values of 0 and 1), the strategy selection probabilities of all three participating entities in the system will tend towards 1. For the government, as new energy vehicles progressively reach maturity, adopting a proactive subsidy strategy significantly stimulates both automakers and consumers to also choose proactive strategies. For automakers, when the industry approaches maturity, the substantial profits from operating charging stations become more attractive. For consumers, as new energy vehicles mature, issues such as short driving ranges and incomplete charging infrastructure have been largely resolved. To satisfy their own low-carbon preferences, they tend to choose to replace with new energy vehicles.

Comparing figures b, d, and e in Figure 3, it is evident that when the government decides to exit the market as the industry matures, automakers and consumers will still maintain their strategies of actively building charging stations and replacing with new energy vehicles. For automakers, a mature new energy vehicle market enables them to earn substantial profits under a proactive construction strategy, making government subsidies for station construction no longer a critical factor in their decision-making. For consumers, in a mature market, they are more concerned with the inherent advantages of new energy vehicles and the convenience of charging, hence they will continue to adopt the strategy of replacing with new energy vehicles.

5. CONCLUSIONS

The research findings of this paper indicate that in the entire system, the decision-making of the three participating entities is influenced by each other. The government, as the main guide, plays a crucial role with its initial decisions in directing the evolutionary path of the entire system; the operational profits from charging stations and the utility provided by new energy vehicles are the main drivers for automakers and consumers to adopt proactive strategies, respectively.

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