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Evolutionary Game Analysis of Automakers' Green Production Considering Consumer Environmental Preference and Government Subsidies

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Abstract

In the context of escalating global environmental pressure, the green transformation of the automotive industry is of vital importance for sustainable development. Based on the theory of evolutionary game, this paper constructs a dynamic interaction model of automotive manufacturing enterprises and consumers in green production and consumption decision-making. The research shows: Firstly, consumers' green environmental preferences and government green consumption subsidies are the key factors driving the evolution of both parties' strategies. When consumers' preferences are low and subsidies are insufficient, the system tends towards the traditional production and consumption mode; while when preferences and subsidies both exceed the critical value, the system rapidly converges to a stable state of green production and consumption. Secondly, through simulation analysis, the synergy of high green consumption preferences and high subsidies can significantly accelerate the green transformation process of automotive enterprises and strengthen consumers' green consumption intentions. Moreover, the analysis of the evolution trajectory in the phase plane indicates that in the low parameter scenario, the system's evolution path is smooth, while in the high parameter scenario, although there will be short-term supply-demand imbalance and strategy fluctuations, under the joint effect of policies and the market, the system can successfully overcome the transformation pain period and achieve a stable evolution towards a green equilibrium.

Keywords

Evolutionary Game; Green Production; Consumer Environmental Preference; Government Subsidy; Automotive Industry.

1. Introduction

As global environmental issues become increasingly severe, especially with the continuous increase in pressure from climate change and resource depletion, promoting the green transformation of industries has become a key path for achieving sustainable development. The automotive industry, as an important pillar of the national economy and one of the main sources of traditional energy consumption and emissions, the promotion of its green production model is of great significance. Against this backdrop, understanding the interaction mechanism between car manufacturers and consumers in green production and green consumption decisions, as well as how this interaction evolves over time and eventually may reach a stable state, has important theoretical and practical significance for designing effective policy levers and promoting the green upgrade of the automotive industry.

This study focuses on the strategic interaction between automotive manufacturing enterprises and consumers during the process of green transformation. Consumers consider whether to choose new energy vehicles based on their own circumstances. According to consumers' preferences, they can be classified as green consumers and traditional consumers. Green consumers are willing to pay a certain premium for green products. Existing research has shown that heightened consumer environmental awareness increases public demand for green products to some extent, thereby enabling firms to achieve higher profitability and encouraging them to increase investment in green technology innovation [1]. The transition to green production and consumption essentially aims to minimize environmental impact and maximize resource utilization throughout the entire economic system. However, as economic agents, producers and consumers face an inherent contradiction between pursuing their own maximum interests and minimizing social welfare losses [2]. Wen Xingqi et al. (2018) [3] constructed a Stackelberg game model among members of a green supply chain based on three government subsidy strategies. Through theoretical proof and numerical simulation, they compared the effectiveness of different subsidy strategies under the same government subsidy expenditure. Their findings indicate that changes in the green preference coefficient and the input cost coefficient do not affect the ranking of the three subsidy strategies. Shi et al. (2023) [4] developed a tripartite evolutionary game model from a supply chain perspective, including the government, consumers, and new energy vehicle manufacturers, and discussed the evolutionary stable strategies of the game participants. The study found that government subsidies influence the speed and direction of stabilization in the strategy choices of consumers and automobile manufacturers.

Based on the above analysis, consumers' environmental awareness and green consumption ability are the key factors driving green production in manufacturing enterprises. However, most existing literature focuses on government subsidy mechanisms or consumer behavior strategies, or comprehensively explores the impact of consumer behavior under the government subsidy framework on green supply chain decisions. Few literatures apply consumer behavior to the game of enterprises' green production strategies. In view of this, this paper constructs an evolutionary game model between enterprises and consumers based on evolutionary game theory, and further analyzes the impact of consumer behavior on the production decisions of manufacturing enterprises.

2. Construction of Evolutionary Game Model

2.1 Model Basic Assumptions and Payoff Matrix

H1: The evolutionary game involves two populations: automobile manufacturers and consumers. The production strategy of a manufacturer can be either green production or traditional production. The probability that a manufacturer adopts green production is denoted as x, and the probability of adopting traditional production is $1-x$. The consumption strategy of a consumer can be either green consumption or traditional consumption. The probability that a consumer adopts green consumption is denoted as y, and the probability of adopting traditional consumption is $1-y$, where $(x,y)\in[0,1]$.

H2: If a firm chooses green production, it can obtain additional benefits γ derived from its green image, while also incurring a higher production cost C_g. The production cost of traditional products is denoted as C_t. If a firm chooses traditional production, it incurs an additional expense β due to reputation loss. The prices of green products and traditional products are denoted as p_1 and p_2, respectively, with $p_1>p_2$. The parameter α $(0<\alpha<1)$ represents the greenness level of the product; the greenness level α of traditional products is zero.

H3： Assume that consumers can obtain a value v from the automobile product they purchase, with $v>p_0>p_1>0$. Let θ represent the degree of consumers' environmental preference for green products; accordingly, the degree of preference for traditional products is $1-\theta$. The perceived loss of traditional consumers when purchasing a green product is denoted as L_1, and the perceived loss of green consumers when purchasing a traditional product is denoted as L_2.

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H4: The government provides consumers who purchase green products with a green consumption subsidy of αS, where S denotes the government subsidy to consumers, based on the greenness level of the enterprise's product.

Based on the above basic assumptions, the symbols are explained in Table 1, and the game payoff matrix between manufacturing firms and consumers is established as shown in Table 2.

Table 1. Nomenclature

Symbol	Description
c_g	Production cost of green products
c_t	Production cost of traditional products
p_1	Price of green products
p_2	Price of traditional products
θ	Consumer environmental preference
β	Additional expense for traditional products
S	Government subsidy
α	Greenness level
γ	Additional benefits of green products
v	Value consumers obtain from the purchased product
L_1	Perceived loss of traditional consumers when purchasing green products
L_2	Perceived loss of green consumers when purchasing conventional products

Table 2. Payoff Matrix for Both Automobile Manufacturers and Consumers

Automakers	Consumer	
	Green consumption (y)	Traditional consumption (1-y)
Green production (x)	$\gamma+p_1-c_g$, $v+\alpha S-p_1$	$\theta(\gamma+p_1-c_g)$, $\theta(v+\alpha S-p_1-L_1)$
Traditional production (1-x)	$(1-\theta)(p_2-c_t-\beta)$, $(1-\theta)(v-p_2-L_2)$	$p_2-c_t-\beta$, $v-p_2$

2.2 Solution of the Evolutionary Game Model

Let E_x be the expected payoff of a manufacturing firm choosing green production, E_{1-x} be the expected payoff of a manufacturing firm choosing traditional production, and E_1 be the average expected payoff of the manufacturing firm.Then

$$
\begin{gathered}
E_X=\theta（\gamma+p_1-c_g） +(1-\theta)y(\gamma+p_1-c_g) \\
E_1-x=p_2-c_t-\beta-y\theta(p_2-c_t-\beta) \\
E_1=xE_X+(1-x)E_1-x
\end{gathered} \tag{1}
$$

According to the evolutionary game model, the replication dynamic equation for manufacturing firms adopting green production is as follows:

$$
F(x)=\frac{dx}{dt}=x(1-x)(E_X-E_1-x)=[(\theta+y-y\theta)(\gamma+p_1-c_g)-(1-y\theta)(p_2-c_t-\beta)] \tag{2}
$$

Similarly, the replication dynamic equation for consumers is as follows:

$$
E_y=x(v+\alpha S-p_1)+1-x[(1-\theta)(v-p_2-L_2)] \tag{3}
$$

$$
E_1-y=x[\theta(v+\alpha S-p_1-L_1]+[(1-x)(v-p_2)] \tag{4}
$$

$$
E_2=xEy+(1-x)E_1-y \tag{5}
$$

$$
\begin{aligned}
F(y)=\frac{dy}{dt}&=y(1-y)(Ey-E_1-y) \\
&=y(1-y)\{x[(v+\alpha S-p_1)-\theta(v+\alpha S-p_1-L_1)] \\
&\quad+(1-x)[(1-\theta)(v-p_2-L_2)-(v-p_2)]\}
\end{aligned} \tag{6}
$$

The strategy by which participating agents adjust their behavior based on their own payoffs and ultimately enable the system to achieve dynamic equilibrium is called the Evolutionarily Stable Strategy (ESS). In determining the Evolutionarily Stable Strategy, it is first necessary to solve for the equilibrium points of the evolutionary game[5].

Setting $F(x)=F(y)=0$, four local equilibrium points can be obtained:$B_1(0,0)$, $B_2(1,0)$, $B_3(0,1)$, and $B_4(1,1)$.

2.3 Stability Analysis of the Equilibrium Point

The equilibrium points obtained from the system of replication dynamic equations are not necessarily stable. According to Friedman's method, the evolutionarily stable strategy of the system can be derived by performing a local stability analysis on the Jacobian matrix of the replication dynamic system [6]. Based on Lyapunov's first method: if all eigenvalues of the Jacobian matrix have negative real parts, then the equilibrium point is asymptotically stable [7]. The Jacobian matrix at $B_1(0,0)$ is:

$$
\begin{gathered}
J(0,0)=\begin{bmatrix}\frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y}\end{bmatrix}= \\
\begin{bmatrix}\theta(\gamma+p_1-c_g)-(p_2-c_t-\beta) & 0 \\ 0 & -\theta(v-p_2)-(1-\theta)L_2\end{bmatrix}
\end{gathered} \tag{7}
$$

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The corresponding eigenvalues are: $\lambda_1 = \theta(\gamma + p_1 - c_g) - (p_2 - c_t - \beta)$, $\lambda_2 = -\theta(v - p_2) - (1 - \theta)L_2$, Similarly, the eigenvalues corresponding to each equilibrium point are calculated, as shown in Table 3.

Table 3 . Equilibrium points and their corresponding eigenvalues of the system

Equilibrium point	Eigenvalue	Stability
(0,0)	$\lambda_1 = \theta(\gamma + p_1 - c_g) - (p_2 - c_t - \beta)$ $\lambda_2 = -\theta(v - p_2) - (1 - \theta)L_2$	Stability
(1,0)	$\lambda_1 = -[\theta(\gamma + p_1 - c_g) - (p_2 - c_t - \beta)]$ $\lambda_2 = (1 - \theta)(v + \alpha S - p_1) + \theta L_1$	Unstable
(0,1)	$\lambda_1 = [(\gamma + p_1 - c_g) - (p_2 - c_t - \beta)(1 - \theta)]$ $\lambda_2 = \theta(v - p_2) + (1 - \theta)L_2$	Unstable
(1,1)	$\lambda_1 = -[(\gamma + p_1 - c_g) - (p_2 - c_t - \beta)(1 - \theta)]$ $\lambda_2 = -[(1 - \theta)(v + \alpha S - p_1) + \theta L_1]$	Stability

3. Simulation Analysis

Based on existing research findings and under the condition that the model constraints are satisfied, this paper assigns reasonable values to the relevant parameters of the model. The initial evolutionary values of the automaker's green production probability x and the consumer's green consumption probability y are both set to 0.5. The consumer environmental preference coefficient θ is selected as 0.3, 0.5, and 0.7, respectively [8], and corresponding government green consumption subsidies αS are matched to form three simulation scenarios. In this way, the dynamic evolutionary patterns of the strategic behaviors of automakers and consumers under the joint influence of consumer green preference and government subsidies are investigated. The simulation results are shown in Figure 1.

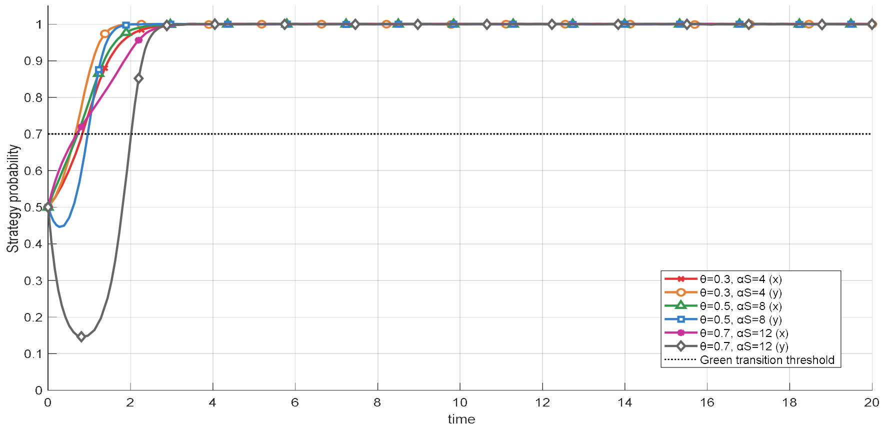

Figure 1. Evolutionary paths of firms and consumers under combinations of consumer green preference and government subsidies

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As shown in Figure 1, within the parameter interval set in this study, an increase in both consumer green preference θ and government green consumption subsidy αS significantly promotes firms' choice of green production and consumers' choice of green consumption. Moreover, the synergistic effect of these two factors effectively accelerates the convergence of the system toward a green equilibrium.

The combined effect of green preference and government subsidies on the probability x of enterprises engaging in green production is as follows: When the consumer green preference $\theta = 0.3$and the government subsidy intensity $\alpha S = 4$, the probability x of enterprises choosing green production shows a monotonically increasing trend, but the convergence speed is the slowest, and it takes a long time to stabilize at 1. This indicates that when the consumer green preference is low and the government subsidy intensity is insufficient, the motivation for enterprises to shift to green production is weak, and the transformation progress is slow. When $\theta = 0.5$ and αS = 8, the growth rate of x significantly accelerates, and it approaches 1 more quickly than the low-parameter scenario, indicating that as the consumer green preference and government subsidy levels increase, the incentive for enterprises to undergo green transformation strengthens, and the transformation process significantly speeds up. When $\theta = 0.7$and $\alpha S = 12$, x can rapidly increase and stabilize at 1 within a very short period of time, indicating that under the dual incentives of high consumer green preference and strong government subsidy intensity, enterprises can quickly make green production decisions and complete the green transformation rapidly.

The combined effect of green preference and government subsidies on the probability y of consumers' green consumption is as follows: Under the conditions of $\theta = 0.3$ and $\alpha S = 4$, the variable y shows a monotonically increasing trend in the early stage of evolution, without significant fluctuations, and eventually converges steadily to 1. This indicates that in an environment where both consumers' green preferences and subsidy levels are relatively low, the process of consumers forming a green consumption intention is relatively smooth. When $\theta = 0.5$ and $\alpha S = 8$, y shows a slight decrease in the early stage of evolution, but the decline is limited. Subsequently, it quickly recovers and stabilizes at 1, suggesting that moderate levels of preference and subsidies can effectively alleviate consumers' concerns about short-term costs, reduce their strategic fluctuations, and promote the rapid formation of green consumption intentions. When $\theta = 0.7$ and $\alpha S = 12$, y shows a significant decrease in the early stage of evolution, then quickly rebounds and approaches 1. This indicates that in the case of high consumers' green preferences, although consumers experience significant strategic fluctuations due to short-term cost perception, the strong government subsidies can effectively counteract this effect, prompting consumers to quickly form stable green consumption habits.

Within the parameters examined in this study, the strategies of enterprises and consumers in all three scenarios eventually converged to the evolutionary stable equilibrium of (1,1). However, there were significant differences in their evolutionary paths and convergence characteristics: in the low-preference and low-subsidy scenarios, the system's evolutionary path was the smoothest and the convergence speed was the fastest; while in the medium and high-parameter scenarios, the consumers' green consumption intentions experienced short-term strategic fluctuations in the initial stage, but under the combined effect of subsidies and preferences, the system was able to overcome the transitional pain period and eventually stabilize and converge to the green equilibrium. This indicates that an increase in parameter levels does not simply accelerate the transformation process; instead, it achieves the evolution towards the same green equilibrium by changing the short-term decision-making paths of the subjects.

In conclusion, the synergy between consumers' green preferences θ and the government's green consumption subsidies αS is the key factor driving the system towards green equilibrium. The gray horizontal dotted line in the figure represents the green transition threshold line. When the probability of green strategies adopted by enterprises and consumers exceeds this threshold, the system will enter a stable evolution interval and spontaneously converge towards green equilibrium.

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To further explore the strategic interaction between car manufacturers and consumers, as well as the overall evolution trend of the system, this paper constructs the phase plane evolution trajectory within the strategy space. The results are shown in Figure 2. In the figure, the horizontal axis x represents the probability of green production by the car manufacturers, and the vertical axis y represents the probability of green consumption by consumers. The four corner points correspond to the pure strategy equilibria of the system, and the dotted line $y = x$ serves as the reference line for strategy synchronization.

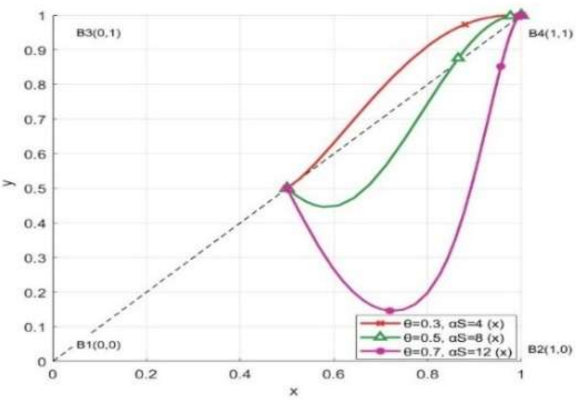

Figure 2. Phase-plane evolutionary trajectories in the strategy space

As shown in Figure 2, under the three different parameter settings, the system eventually converges to the evolutionary stable equilibrium B4(1,1), which represents the collaborative green strategy of "automakers implementing green production and consumers choosing green consumption". However, the evolutionary paths in each scenario show significant differences.

When $\theta = 0.3$ and $\alpha S = 4$, the evolution trajectory is always above the $y = x$ line and shows a monotonically increasing trend. This indicates that under the conditions of low preference and low subsidy, the green consumption willingness of consumers is always slightly higher than that of the car manufacturers, forming a mild positive feedback mechanism of "demand driving supply". The evolution process of the entire system is relatively stable, without any phenomena of supply-demand mismatch or policy fluctuations.

When $\theta = 0.5$ and $\alpha S = 8$, the trajectory briefly crossed the $y = x$ line, and then quickly rebounded. This indicates that, under the influence of moderate levels of preference and subsidy, the green production intentions of car manufacturers once exceeded those of consumers, resulting in a slight imbalance of "supply leading demand". However, under the self-regulating effect of the market mechanism, consumers' green consumption intentions quickly followed suit, and the system returned to the track of coordinated evolution.

When $\theta = 0.7$ and $\alpha S = 12$, the trajectory significantly deviates from the $y = x$ line and sinks towards the x-axis, then rebounds rapidly. This indicates that in the high-preference and high-subsidy scenario, consumers experienced relatively strong strategic fluctuations due to their perception of short-term costs. The willingness to consume green products significantly decreased, which at one point led to the automotive companies lacking sufficient green production motivation. However, the high-intensity government subsidies ultimately effectively offset the short-term impact, causing the consumers' willingness to consume green products to rapidly recover. This, in turn, compelled the enterprises to accelerate their green transformation, promoting the system to smoothly overcome the transition pain period and ultimately achieving convergence towards a green equilibrium.

In conclusion, the phase plane trajectory verifies the conclusion of the time series analysis, that is, the synergy between consumers' green preferences and government subsidies is the key to driving the

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system towards green equilibrium. Under low parameters, the evolution path of the system is smooth. Under high parameters, although there may be short-term supply and demand imbalances, with the joint effect of policies and the market, the system can still successfully overcome the transitional pain period and achieve a stable evolution towards the (1,1) equilibrium.

4. Conclusion and Recommendations

4.1 Main Conclusion

This paper focuses on the issue of the green transformation of the automotive industry and constructs a dual-agent evolutionary game model consisting of automotive enterprises and consumers. Through model solution, equilibrium stability analysis, and numerical simulation, the paper systematically examines the influence patterns of consumers' environmental preferences and government green consumption subsidies on the strategy evolution process of both parties. The main conclusions obtained are as follows:

(1)Through the solution of the evolutionary game model and the analysis of equilibrium stability, it can be known that the system has four local equilibrium points. Among them, only the traditional production-consumption equilibrium point (0,0) and the green production-consumption equilibrium point (1,1) possess evolutionary stability, while the two equilibrium points (1,0) and (0,1) exhibit unstable states. Therefore, the strategies of the two players in the game will eventually evolve towards either the traditional mode or the green mode.

(2) Consumer environmental preferences and government green consumption subsidies are the key variables driving the evolution of automotive companies' and consumers' strategies. Both of them have distinct critical threshold ranges. When the level of consumer environmental preferences is low and the government subsidy is insufficient, the market's green transformation incentives are relatively weak, and the system is long-term locked in the traditional production and consumption mode. Once these two variables exceed their respective critical values, they can effectively drive both parties to adjust their behavioral strategies, enabling the system to rapidly converge to the ideal stable equilibrium state.

(3) There is a clear synergistic promoting effect between consumers' environmental preferences and government subsidies. Consumers' environmental preferences can directly motivate car manufacturers to increase investment in green production from the demand side. Meanwhile, government green consumption subsidies help reduce the cost for consumers to purchase green products, alleviating their concerns about short-term expenses. Under the combined effect of these two factors, not only does it accelerate the green production transformation process of car manufacturers, but also effectively stabilizes consumers' green consumption intentions, reducing the fluctuation in strategies.

(4) The results of numerical simulation and phase plane trajectory analysis show that, under different parameter combinations, although the system can eventually converge to the green equilibrium, there are significant differences in their evolution paths. In the low-preference and low-subsidy scenario, the strategy evolution paths of car manufacturers and consumers are relatively smooth, presenting a stable evolution feature driven by demand and supply; while in the medium-high parameter scenarios, consumers are prone to strategy regression and short-term imbalance between supply and demand in the initial stage. However, relying on the synergy of consumers' endogenous preferences and the exogenous subsidies from the government, the system can effectively overcome the transitional pain period and ultimately achieve a stable evolution towards the green equilibrium.

4.2 Policy Recommendations

Based on the above research conclusions, taking into account the actual development needs of the automotive industry during its green transformation process, this article proposes the following countermeasures and suggestions from three aspects: cultivating consumers' green preferences, optimizing government subsidy policies, and guiding car manufacturers to engage in green production.

(1) Strengthen environmental publicity and education to continuously enhance consumers' green preferences

Governments and society should promote public awareness of green mobility and low-carbon consumption through multiple channels, actively disseminate the environmental value of new energy vehicles, and improve the public's green literacy and sense of environmental responsibility. This will endogenously increase consumers' green preferences. Through regular environmental education, consumers can gradually develop stable green consumption concepts, overcome the critical bottleneck associated with low-preference states, and provide long-term market support for automakers' green production from the demand side.

(2) Implement differentiated subsidy policies and precisely control critical subsidy intensity

Governments should adopt tiered and differentiated subsidy strategies based on variations in consumer preferences. In regions with low environmental preferences, green vehicle purchase subsidies and usage-related benefits should be appropriately increased to compensate for insufficient policy incentives, thereby pushing relevant parameters beyond critical thresholds during the evolutionary process. In regions with medium to high preferences, subsidy structures should be moderately optimized by gradually shifting from universal purchase subsidies to usage- and infrastructure-oriented support, so as to reduce fiscal burdens while avoiding excessive policy intervention. Subsidy intensity should be reasonably calibrated to prevent both insufficient subsidies that lock the system into a traditional equilibrium, and excessively high subsidies that induce significant short-term strategic fluctuations among consumers.

(3) Improve incentive and constraint mechanisms to guide automakers toward sustained green production

Improve the green production incentive and reputation restraint mechanisms for automotive enterprises. For enterprises that adhere to green production and actively develop high-green-degree models, provide preferential policies such as tax cuts and research support; at the same time, strengthen the reputation loss restraint and environmental regulation restraint for traditional production enterprises, increase the implicit costs borne by traditional production methods, thereby forcing automotive enterprises to actively transform towards green production. Relying on the stable expectation of green consumption demand, further consolidate the sustainability of the green equilibrium state.

(4) Establish a synergistic mechanism linking preferences and subsidies to smooth the transitional pains of industrial transformation

It is necessary to ensure that the cultivation of consumer preferences is coordinated with government subsidy policies, forming a dual driving force combining endogenous demand-driven and exogenous policy-supported factors. For the short-term supply-demand imbalance and consumption strategy fluctuations that are likely to occur under the medium-high parameter scenarios, it is recommended to establish a dynamic regulation mechanism. During the transitional period of pain, the subsidy intensity should be adjusted appropriately in a timely manner to smooth the decision-making fluctuations of consumers, ensure the coordinated evolution between automotive enterprises and consumers' strategies, and promote the smooth green upgrade and sustainable development of the automotive industry.

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