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A Three-way Evolutionary Game Analysis of Collaborative Innovation Development of Traditional Automobile Enterprises under the Dual-carbon Background

Yichang Liu

Faculty of Transportation Engineering, Kunming University of Science and Technology, Kunming, China

202210606230@stu.kust.edu.cn

Abstract. Driven by the dual-carbon target, the collaborative innovation between traditional automobile enterprises and knowledge production institutions has become a key path to promote the green transformation of the industry. This paper builds a three-party evolutionary game model of the government, traditional automobile enterprises, and knowledge production institutions based on evolutionary game theory. By examining the strategic interactions and dynamic evolution laws of the three stakeholders, it reveals the evolutionary mechanism of collaborative innovation at various stages of development. The study shows that: in the initial stage of the industry, the government dominates the market through subsidies and penalties, but traditional automobile enterprises have high cooperation costs and insufficient short-term benefits, and knowledge production institutions have low participation due to the difficulty of technological transformation; with the continuous optimization of the policy and the maturity of the market, the three parties gradually form positive synergies, and the marginal effect of government subsidies and penalties is diminishing; and finally, in the maturity stage, the three parties and the knowledge production institutions have a positive synergy through the interaction and dynamic evolution law. Ultimately, in the mature stage, traditional automobile enterprises and knowledge production institutions realize autonomous cooperation through technology sharing and market mechanism, and the government can gradually withdraw from intervention. Sensitivity analysis shows that high penalties and moderate subsidies are the core levers to promote collaborative innovation, while high regulatory costs will weaken the government's ability to regulate.

Keywords: Dual-carbon, automotive companies, co-innovation, evolutionary games, industry life cycle

1. Introduction

The global carbon neutral process is accelerating the reconstruction of the automotive industry landscape. According to data from the International Energy Agency (IEA), in 2022, transportation-related carbon emissions will make up 24% of world emissions, with traditional fuel vehicles contributing more than 60%. China, as the world's largest auto producer and seller, will produce more than 30 million vehicles in 2023, but under the goal of “40% penetration rate of new energy vehicles” proposed in the “Peak Carbon Action Program by 2030”, traditional automobile enterprises are facing multiple challenges. On the one hand, the high cost of pure electric platform research and development, such as Volkswagen MEB platform investment of 7 billion euros, far beyond the affordability of small and medium-sized enterprises; on the other hand, the technology conversion rate of colleges and universities and scientific research institutions for a long time is less than 15%, and there is a significant fault in the cooperation between industry, academia and research. At the same time, after the 2020-2023 new energy subsidy slopes back, about 25% of the car companies appeared technology route swing, for example, the Great Wall Motor stopped selling the Black Cat model, exposing the contradiction between policy dependence and technological autonomy. In this context, exploring the collaborative innovation mechanism among the government, automobile enterprises and knowledge production institutions has become a key path to solving the dual objectives of “low-carbon transformation” and “cost reduction and efficiency enhancement”.

The low-carbon transformation of traditional automobile enterprises needs to rely on multi-party collaboration to break through the technological lock. Wu Junmin et al. through the new energy vehicle government, industry and academia tripartite game model found that the speed of enterprise participation in collaborative innovation is significantly faster than that of colleges and universities (the difference in the stabilization rate of 30%-40%), but the willingness of government participation declines with the increase in the input of enterprises and universities [1]. This finding maps to the traditional automotive scenario, suggesting that short-term gains need to be balanced with long-term technology substitution goals through policy design. Chunjian Yang further pointed out that the sensitivity difference of the revenue sharing coefficient (δ) in supply chain collaboration is significant, and the tolerance of battery manufacturers to δ reduction is 50% lower than that of vehicle companies, which is a warning for the cooperation between traditional automobile enterprises and hydrogen fuel technology providers [2].

The government subsidy and penalty mechanism is the core lever to drive the transformation of traditional automobile enterprises. Based on contract theory, Li Na demonstrated that when the government's penalty cost for firms (e.g., carbon tax) is higher than 1.5 times the cost of subsidies, the probability of vehicle firms choosing technological innovation increases to 80% [3]. However, their studies also point out that too high regulatory costs (e.g., more than 20% of fiscal expenditure) can lead to policy failure. In addition, some scholars confirmed the key role of government policy on collaborative innovation from the game perspective. According to Li Xinjun and Chen Meina, the government will be more effective at reducing emissions and conserving energy if it implements a recycling reward and punishment system than if it does not, while Xue emphasized that the increase of government regulation and subsidy at the early stage of the game is the core driving force for enterprises to shift to the low-carbon model [4, 5].

Therefore, this paper constructs a tripartite game model in which the government guides, traditional automobile enterprises and academic and research institutions participate to study the strategic interaction and dynamic evolution law of the government, traditional automobile enterprises and academic and research institutions in the process of collaborative innovation, and to reveal the evolution mechanism of collaborative innovation in different stages of development, so as to realize the win-win result for all three parties.

2. Model construction

2.1. Model hypothesis

According to the characteristics of collaborative innovation in the automobile industry, this paper puts forward the following hypotheses:

Hypothesis 1: The evolutionary game model incorporates three stakeholders: the government, traditional automobile enterprises, and knowledge production institutions. All agents exhibit bounded rationality, autonomously determine strategies to maximize individual payoffs, and dynamically adapt tactics through learning during evolutionary processes [6].

Hypothesis 2: Suppose the government has two pure strategies: “government incentives” and “government disincentives”. “Incentive” denotes active intervention where, within the dual-carbon context, authorities implement concrete facilitation measures to foster synergistic innovation between traditional automobile enterprises and knowledge production institutions. “No incentives” means that the government does not take substantive incentives due to financial constraints and cost pressures but only advocates and encourages [7].

Hypothesis 3: Assume that traditional automobile enterprises have two pure strategies: they are free to choose whether to “cooperate with knowledge production institutions” or “not to cooperate with knowledge production institutions”.

Hypothesis 4: The model assumes two pure strategies of knowledge production institutions are “cooperation with automobile enterprises” or “no cooperation with automobile enterprises”.

Hypothesis 5: It is now assumed that the probability of each stakeholder choosing their respective pure strategies is as follows, and each of the three main parties does not know each other's choices: the probability of the government choosing incentives is $x\,(0 \leq x \leq 1)$; the probability of automobile production enterprises choosing cooperation is $y(0 \leq y \leq 1)$; and the probability of knowledge production institutions choosing cooperation is $z(0 \leq z \leq 1)$.

2.2. Parameter setting

During the collaborative innovation development process of vehicle enterprises, the government, traditional automobile enterprises, and knowledge production institutions each exhibit distinct behavioral strategy choices and possess specific interest needs. The behavioral strategy choices adopted by any one of these subjects influence and are simultaneously influenced by the other two. Moreover, variations in these strategic selections lead to differing impacts on enterprise reproduction development[8]. To investigate the benefits and costs associated with the diverse behavioral strategies of these three subjects, this study establishes specific parameters. These parameters are detailed in Table 1.

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Table 1. Definition and description of parameters

Parameter	Description
G	Government interest in pursuing synergistic development
S1	Government subsidies given to automobile producers (e.g., financial subsidies, special financial support, and tax breaks)
S2	Subsidies provided by the government to knowledge production institutions.
P	Penalties for car companies with low co-innovation effectiveness when the government implements incentives (e.g., carbon and energy taxes.)
U	The regulatory costs incurred by the government when selecting incentive strategies.
N	The regulatory costs borne by the government when collaborating on innovative projects with traditional automobile enterprises.
B	Additional benefits to the government (e.g., social and environmental benefits) when traditional automobile enterprises tend to collaborate with knowledge production institutions
C1	Base cost of traditional automobile enterprises not participating in collaborative innovation
C2	Additional costs for traditional automobile enterprises to participate in co-innovation (e.g., technology development costs, increased management costs due to cooperation between the two parties.)
R1	Benefits of traditional automobile enterprises not participating in collaborative innovation
R2	R2 Additional benefits when traditional vehicle enterprises participate in co-innovation (e.g., helping to improve brand effect and corporate image)
C3	Costs of knowledge production institutions when they participate in co-innovation
R3	Benefits when knowledge production institutions do not participate in co-innovation
C4	Additional costs for knowledge production institutions when participating in co-innovation
R4	Additional benefits when knowledge production institutions participate in co-innovation (e.g., better marketing reputation and higher quality of knowledge and human resources.)

With these parameters set and defined, this study proposes the expected benefits of each stakeholder for each stakeholder under their respective strategic combinations, thus constructing an extended formulation of this three-way evolutionary game as shown below:

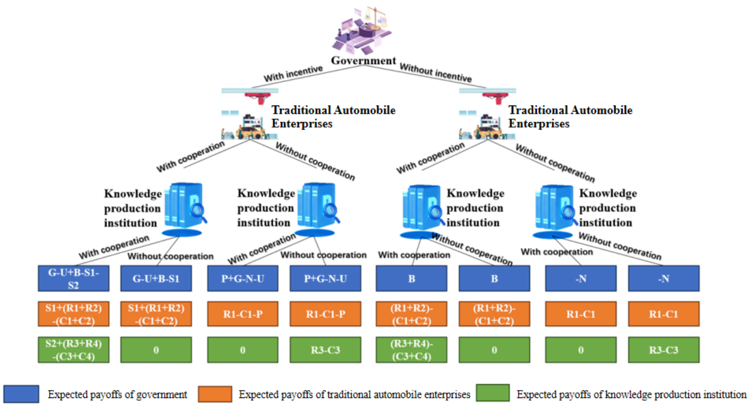

Figure 1. Expanded representation of the tripartite evolutionary game between the government, traditional automobile enterprises, and knowledge production institutions

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The parameters and expected return expressions in Figure 1 above are simplified expressions, in practice there may be some relevant coefficients or the rest of the possible uninvolved parameters exist, this paper is only to consider the above parameters as the verification object.

2.3. Modeling and solving

The government's expected return, which is calculated in this study from the two scenarios of implementing incentives and not implementing incentives, denoted by E_x and E_{1-x} , respectively, and the government's average expected return, denoted by $\overline{E_x}$, is given:

$$Ex = yz(G + B - S_1 - S_2 - U) + y(1 - z)(G + B - U - S_1) +$$

$$(1 - y)z(G + P - U - N) + (1 - y)(1 - z)(G + P - U - N)$$

$$E_{1-x} = yzB + y(1 - z)B + (1 - y)z(-N) + (1 - y)(1 - z)(-N)$$

$$\overline{E_x} = xE_x + \left(1 - x\right)E_{1-x}$$

Similar to the government, for traditional automobile enterprises, this study calculates from two scenarios of cooperation and non-cooperation, which are denoted by E_y and E_{1-y} , respectively, and the average return of the car companies is denoted by $\overline{E_y}$, then there are:

$$E_y = xz[S_1 + (F_1 + F_2) - (C_1 + C_2)] + x(1 - z)[S_1 + (F_1 + F_2) - (C_1 + C_2)]$$

$$+(1 - x)z[(F_1 + F_2) - (C_1 + C_2)] + (1 - x)(1 - z)[(F_1 + F_2) - (C_1 + C_2)]$$

$$E_{1-y} = xz(F_1 - P - C_1) + x(1 - z)(F_1 - P - C_1) + (1 - x)z(F_1 - C_1) + (1 - x)(1 - z)(F_1 - C_1)$$

$$\overline{E_y} = yE_y + \left(1 - y\right)E_{1-y}$$

Similarly, in this study, the expected returns of knowledge production institutions are set as cooperation E_z and non-cooperation E_{1-z} , and the average expected return of knowledge production institutions is $\overline{E_z}$, then there are:

$$E_z = xy[S_2 + (F_3 + F_4) - (C_3 + C_4)] + 0 + (1 - x)y[(F_3 + F_4) - (C_3 + C_4)] + 0$$

$$E_{1-z} = 0 + x(1 - y)(F_3 - C_3) + 0 + (1 - x)(1 - y)(F_3 - C_3)$$

$$\overline{E_z} = zE_z + \left(1 - z\right)E_{1-z}$$

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2.3.1. Revenue expectation function

Based on $F(x)=\frac{dx}{dt}=x\left(v_{11}-\overline{v_1}\right)=x\left[v_{11}-xv_{11}-(1-x)v_{12}\right]=x(1-x)\left(v_{11}-v_{12}\right)$, and the above expectation equation, the replication dynamics equation for each participant that can be obtained is:

$$F(x)=\frac{dx}{dt}=x(1-x)\left(G+P-U-yS_1-yP-zyS_2\right)$$

$$F\left(y\right)=\frac{dy}{dt}=y\left(1-y\right)\left(xS_1+xP-C_2+R_2\right)$$

$$F(z)=\frac{dz}{dt}=z(1-z)\left(xyS_2+2yR_3-2yC_3+yR_4-yC_4-R_3+C_3\right)$$

According to the stability principle of differential equations of Weinstein (1986), eight local pure strategy equilibrium points, i.e., (0, 0, 0), (0, 0, 1), (0, 1, 0), (1, 0, 0), (0, 1, 1), (1, 1, 0), (1, 0, 1), and (1, 1, 1), are found by making the dynamic equations F=0. Then, according to the evolutionary game theory and Lyapunov stability theory, when all the eigenvalues of the Jacobi matrix are non-positive, the corresponding equilibrium point is defined as the evolutionary stability point (ESS). Substituting the above eight equilibrium points into the Jacobi matrix and analyzing its stability, the results obtained are shown in Table 2.

Table 2. Eigenvalues and stabilization conditions for each equilibrium point

Equilibrium Point	Eigenvalue			Conditions for Evolutionary Stability
	λ_1	λ_2	λ_3	
(0,0,0)	G+P-U	F2-C2	C3-F3	$\lambda_1<0$; $\lambda_2<0$; $\lambda_3<0$
(1,0,0)	U-P-G	F2-C2+P+S1	C3-F3	
(0,1,0)	G-S1-U	C2-F2	F3-C4-C3+F4	
(0,0,1)	G+P-U	F2-C2	F3-C3	
(1,1,0)	S1-G+U	C2-F2-P-S1	F3-C4-C3+F4+S2	
(1,0,1)	U-P-G	F2-C2+P+S1	F3-C3	
(0,1,1)	G-S1-S2-U	C2-F2	C3+C4-F3-F4	
(1,1,1)	S1-G+S2+U	C2-F2-P-S1	C3+C4-F3-F4-S2	

2.3.2. Life cycle evolution of collaborative innovation in traditional automobile enterprises

According to the industry life cycle theory, the evolution of co-innovation between traditional automobile enterprises and knowledge production institutions can be analyzed through three-stage equilibrium conditions (as shown in the Table 3), in the initial stage, the government intervenes in the market through subsidies (S1, S2) and penalties (P) cost to promote the co-innovation co-development; in the developmental stage, driven by the favorable policies, the traditional automobile enterprises and knowledge production institutions deepen the co-innovation development; then in the maturity stage, the market can realize self-operation, and the government will gradually withdraw from the intervention, and the automobile industry's co-innovation development has entered a sustainable state.

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Table 3. Eigenvalues and stabilization conditions for each equilibrium point

Stage	Equilibrium Point	Core Condition	Evolutionary Logic
Initial Stage	(1,0,0)	1. U>U+P+G (Government incentive benefits > Regulatory costs)2. S1+S2+U>U+G (Costs of innovation for traditional automobile enterprises > Benefits of co - innovation for traditional automobile enterprises)3. C3+C3>F3 (Net benefits of knowledge production institutions > Costs)	The government intervenes in the market through subsidies (S1, S2) and penalties (P) to promote the collaborative innovative development of traditional automobile enterprises and knowledge production institutions.
Development stage	(1,1,1)	1. S1+S2+U>U+G (Net benefits of government incentive costs > Benefits)2. C2+F2>P+S1 (Benefits > Costs of co - innovation for traditional automobile enterprises)3. C3+CA+F3+4+S2 (Combined benefits > Costs for knowledge production institutions)	Driven by policies, traditional automobile enterprises and knowledge production institutions gradually deepen collaborative innovation and development, forming a positive cycle.
Maturity stage	(0,1,1)	1. C2+F2>S2+U (Cost of government regulation > Benefit)2. G<S1+S2 (Autonomous benefits of traditional automobile enterprises > Costs)3. C3+CA+F3>F3+4 (Net benefits of autonomy for knowledge production institutions > Costs)	The market becomes self - functioning, the government withdraws from intervention. Traditional enterprises and knowledge production institutions enter a state of sustainable development.

3. Visual analysis and numerical simulation

3.1. Dynamic evolutionary analysis

For a more intuitive observation of the three stakeholders'(government, traditional automobile enterprises, and knowledge production institutions) behavioral dynamic evolution at each stage (initial, development, and maturity) of co-innovation between traditional automobile enterprises and knowledge production institutions in the context of dual-carbon, this paper takes reference from the method of parameter assignment and setting of Zhou Zehui to rationalize the parameters at each of the three stages of the assumptions (as shown in the Table 4)[9].

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Table 4. Values of different parameters for each phase

Parameter/Value	Initiation	Development	Maturity
G	20	25	15
S1	6	12	8
S2	5	10	9
P	4	5	6
U	5	9	8
N	6	7	8
B	20	22	18
C1	12	16	18
C2	15	27	6
R1	15	15	15
R2	7	12	7
C3	8	10	15
R3	12	12	13
C4	10	12	9
R4	8	15	25

3.1.1. Initial stage

According to the values of each parameter corresponding to the initial stage in Table 4 which need to satisfy the stability condition, 100 different sets of (X, Y, Z) initial strategy points are randomly generated using MATLAB R2023b software for verifying whether the equilibrium point (1, 0, 0) is an asymptotically stable equilibrium point in this dynamical system. The different colored lines in Figure 2 indicate the process of the three-way evolutionary game in MATLAB consisting of 100 randomly generated initial strategy sets. After iteration they all converge to the equilibrium point (1, 0, 0), i.e., the evolutionary stable strategies of the government, the traditional automobile enterprises and the knowledge production institutions are government incentive, steam traditional automobile enterprises do not cooperate with the knowledge production institutions, and the knowledge production institutions do not cooperate with the traditional automobile enterprises.

The dynamic evolutionary simulation demonstrates that strategy (1, 0, 0) emerges as the evolutionarily stable strategy (ESS) under standard constraint implementation. This result indicates that during the initial phase: (1) governmental advocacy plays a catalytic role in fostering collaborative innovation between traditional automobile enterprises and knowledge production institutions; (2) High co-innovation costs, the dependence of enterprises' own business paths, and the lack of awareness of the potential value of co-innovation may prevent traditional automobile enterprises from choosing to cooperate with knowledge production institutions; (3) knowledge production institutions still tend not to cooperate with traditional automobile enterprises due to poor expectations of cooperation effects and concerns about cooperation risks.

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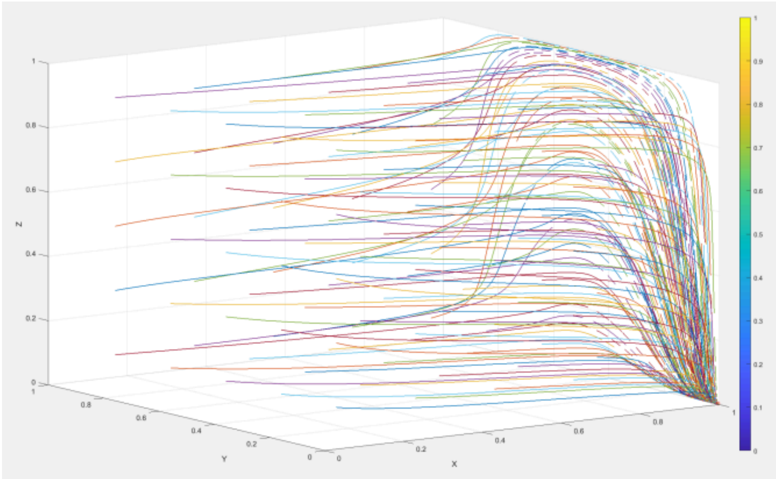

Figure 2. Schematic diagram of the dynamic evolution of the initial stage

3.1.2. Development stage

Figure 3 shows that after iterations they all converge to the equilibrium point (1, 1, 1). During the developmental phase, traditional automobile enterprises progressively shift their strategic orientation from non-cooperation to active collaboration with knowledge production institutions when subjected to balanced government interventions combining financial subsidies and punitive measures. As the number of cooperation projects between traditional automobile enterprises and knowledge production institutions increases and government incentives for co-innovation increase, knowledge production institutions will also participate in cooperation more actively.

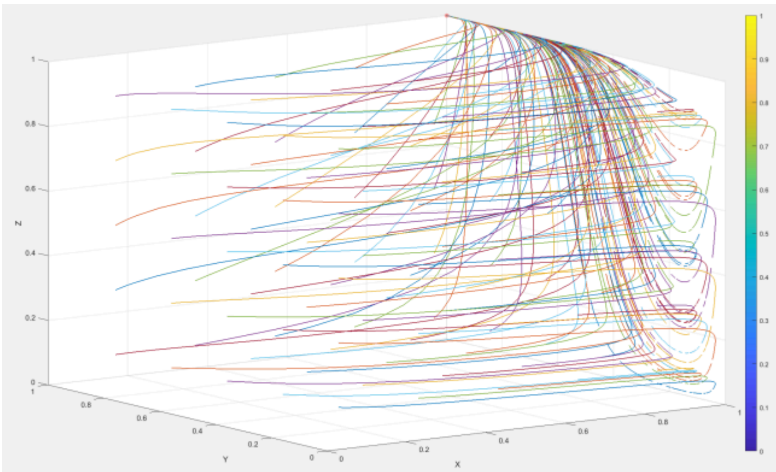

Figure 3. Schematic diagram of the dynamic evolution of the development phases

3.1.3. Maturity stage

Figure 4 shows that after iterations, they all converge to the equilibrium point (0, 1, 1), i.e., the evolutionary stable strategy of the government, automobile producers and knowledge production institutions is government does not incentive, traditional automobile enterprises cooperate with knowledge production institutions, and knowledge production institutions cooperate with traditional automobile enterprises. Further, during the maturity stage, as government policies and regulations become increasingly refined, automotive manufacturers develop more profound recognition of collaborative innovation value, and knowledge production institutions establish stable expectations of cooperative benefits, governmental intervention can be progressively reduced. This evolutionary process culminates in the government's phased market withdrawal, while traditional automobile enterprises and research institutions emerge as the principal actors driving self-sustaining collaborative innovation ecosystems.

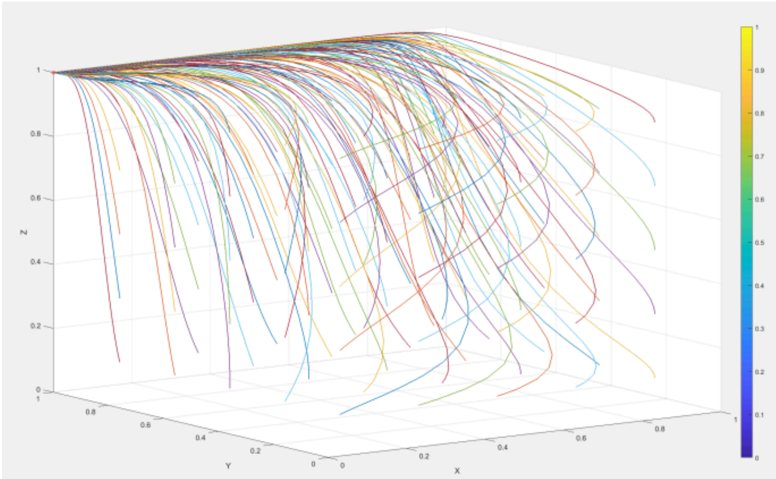

Figure 4. Schematic diagram of the dynamic evolution of the maturity phases

3.2. Sensitivity analysis

Numerical simulations are respectively conducted for the three parameters: the punishment cost (abbreviated as "punishment cost P") imposed by the government on automobile manufacturers that do not participate in collaborative innovation, the regulatory cost (abbreviated as "regulatory cost U") when the government chooses an incentive strategy, and the subsidy cost (abbreviated as "subsidy cost S1") provided by the government to automobile manufacturers that participate in collaborative innovation. The objective is to investigate how relevant government parameters influence the evolutionary game strategies of each stakeholder during the initial stage.

3.2.1. Sensitivity analysis of punishment cost (P)

Numerical simulations were conducted by setting the values of punishment cost P as 2, 4, and 10 respectively, and indicated by the results are shown in Figure 5. When P=2 and P=4, both y and z continuously decrease, indicating that lower punishment costs will reduce the enthusiasm of traditional automobile enterprises and knowledge production institutions to participate in collaborative innovation. When P=10, however, both y and z increase progressively, suggesting that a higher punishment intensity will enhance the cooperation willingness of traditional automobile enterprises and the participation willingness of knowledge production institutions. In summary, traditional automobile enterprises and knowledge production institutions show insufficient sensitivity to low punishment costs, while with the strengthening of punishment intensity, the behavioral strategies of the three stakeholders will evolve incrementally toward the optimal equilibrium point.

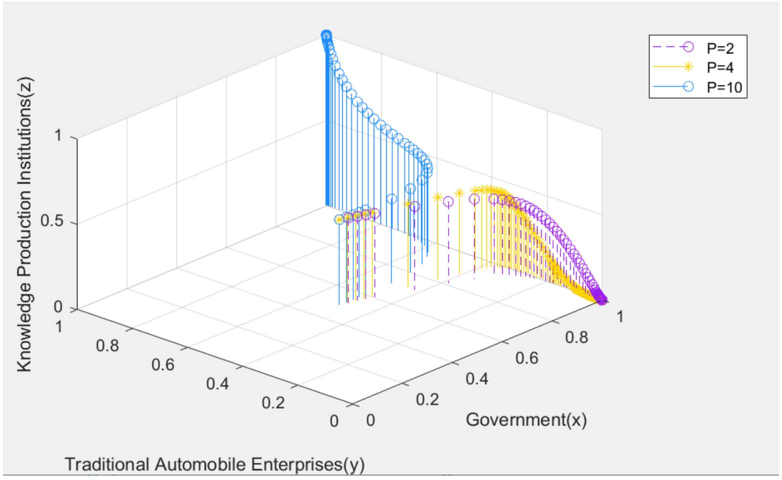

Figure 5. Schematic of penalty cost sensitivity

3.2.2. Sensitivity analysis of regulatory cost (U)

Numerical simulations were conducted by setting the values of regulatory cost U as 5, 15, and 25 respectively, and the results are presented in Figure 6 below. When U=5, U=15, and U=25, both y and z continuously decrease, while x decreases with the increase of regulatory cost. This could imply that excessively high regulatory costs would conversely decrease the government's regulatory willingness, thereby preventing traditional automobile enterprises and knowledge production institutions from opting for collaborative innovation. Thus, the government needs to standardize and guide the development of the collaborative innovation market. Conversely, when government expenditures on regulatory oversight become prohibitively high, creating unsustainable fiscal pressures, this may result in either regulatory collapse or the breakdown of tripartite cooperation.

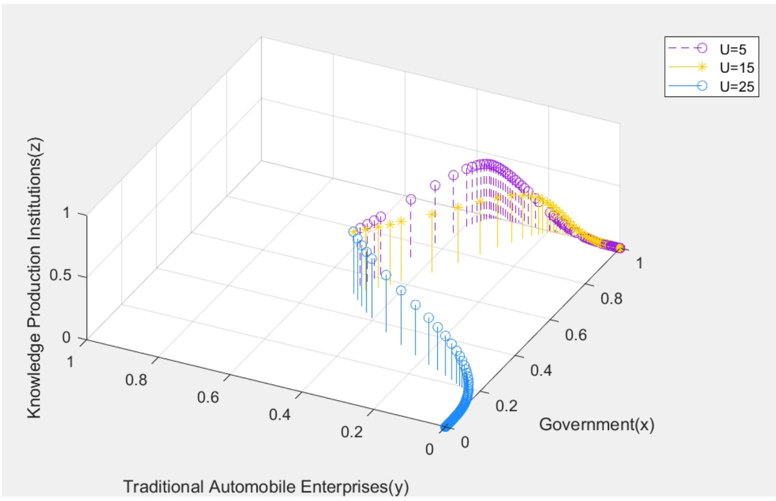

Figure 6. Schematic of regulatory cost sensitivity

3.2.3. Sensitivity analysis of subsidy cost (S1)

Numerical simulations were conducted by setting the subsidy cost S1 as 1, 6, and 12 respectively. As shown in Figure 7, the government ultimately chooses the "incentive" strategy in all three cases (x remains stable), indicating that subsidy adjustments have limited influence on the government's regulatory propensity. When S1=1, the cooperation probabilities between traditional automobile enterprises and knowledge production institutions continue to decline, as low subsidies fail to stimulate the motivation for collaborative innovation. When S1 increases to 6 and 12, y and z significantly grow and approach stable cooperation strategies, suggesting that appropriately increasing subsidies can effectively reduce the collaborative innovation costs of enterprises and enhance the technical transformation willingness of knowledge production institutions. Therefore, insufficient subsidies will lead to the deviation of the tripartite strategies from the optimal equilibrium, while a reasonable increase in subsidies can promote the behavioral strategies to evolve toward better.

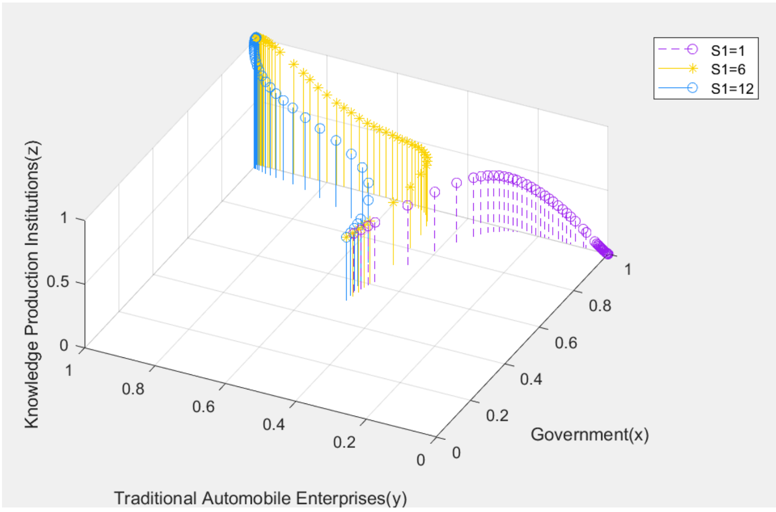

Figure 7. Schematic of subsidy cost sensitivity

4. Conclusion

Based on the above research findings, this paper puts forward the following phased policy suggestions: In the initial stage of collaborative innovation, traditional automotive enterprises are confronted with relatively high transformation costs, and knowledge production institutions are not efficient in technological transformation. The government needs to reduce the cost of participating in collaborative innovation through economic incentives such as tax reduction and exemption, special funds for research and development, and at the same time impose carbon taxes and energy taxes to force enterprises to shift to the path of green development. The government should set up special subsidies to encourage knowledge production institutions to cooperate with traditional automotive enterprises, establish cooperation and exchange platforms, and reduce information asymmetry. In the stage of collaborative innovation development, the government needs to increase investment in joint technology research and development, improve the intellectual property protection system, protect the innovation interests of both sides, encourage financial institutions to develop financial products for collaborative innovation projects, and broaden the financing channels for enterprises. Traditional automotive enterprises need to enhance their innovation capabilities, and knowledge production institutions need to strengthen the market connection of research and development achievements. In the mature stage of joint innovation, the government should shift to establishing an efficient regulatory system, formulating strict industry standards and norms, strengthening environmental protection requirements and quality certifications, while maintaining the order of market competition and gradually withdrawing from direct intervention.

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Future research can further incorporate the uncertainty of technological innovation, the dynamic changes in market demand and the international competitive environment, expand the boundaries of the model, provide more precise decision support for the collaborative innovation of traditional automakers, and contribute to sustainable development under the dual carbon goals.

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