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RESEARCH ARTICLE

Evolutionary Game and Simulation Analysis of Intelligent Connected Vehicle Industry With Cross-Border Collaborative Innovation

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ABSTRACT The Made in China 2025 national strategy has prioritized intelligent connected vehicles (ICV) to realize the intelligence and connection transformation and upgrading of the automotive industry, ushering in unprecedented development opportunities. There are two technology paths in the ICV industry: single-vehicle intelligence and vehicle-infrastructure collaboration. Both face problem of low technological innovation efficiency, and key to solving it is breaking down barriers between enterprises and realizing cross-border collaborative innovation. This study offers a new cross-border collaborative innovation development paradigm for the ICV industry, centered on automotive enterprises and technology platform providers. This study examines the impact of changes in key parameters on the evolutionary results using the system dynamics method to analyze the efficiency of cross-border collaborative innovation in the ICV industry. The simulation results showed that cross-border collaborative innovation is inevitable for the ICV industry. Furthermore, compared to the single-vehicle intelligence scenario, the vehicle-infrastructure collaboration scenario shows faster convergence between automotive enterprises and technology platform providers. Finally, the choice of system collaborative innovation strategy is influenced by default cost and the collaborative innovation risk coefficient, whereas the cost-sharing coefficient and network connection fee only have an impact on the cross-border collaborative innovation system's rate of evolution in the ICV industry.

INDEX TERMS Intelligent connected vehicle, cross-border collaborative innovation, single-vehicle intelligence, vehicle-infrastructure collaboration, system dynamics.

I. INTRODUCTION

The automobile industry has entered the crucial development stage of electrification, networking, and intelligent transformation as a result of a new round of global technology revolution and substantial changes in the industry. Intelligent connected vehicles (ICVs), which organically blend telematics and smart vehicles, have been elevated to a national strategy under China's Made in China 2025 national strategy, ushering in new development potential. The global market penetration rate of new cars with intelligent network functionalities is currently around 45%, and by 2025, is predicted to reach approximately 60%. In 2025, China's market penetration rate for ICVs is expected to surpass 75%, which is greater than the global market's assembly rate [1]. However, while ICVs become a strategic high point illustrating the path of industrial upgrading as well as the future development trend of automotive technology, the impact of issues such as lack of technical path clarity, enterprise transformation and upgrading lack sufficient vigor on the ICV industry is more prominent [2].

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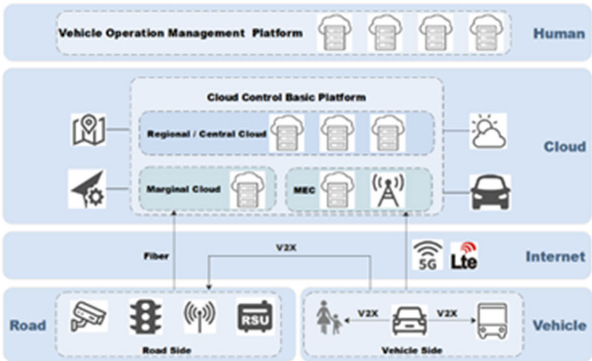

FIGURE 1. **Comparison of ICV technology paths.**

In most nations, the ICV sector follows one of two technology paths: single-vehicle intelligence (SVI) or vehicle-infrastructure collaboration (VIC) [3]. Google took the lead in initiating autonomous driving research and development (R&D) in the United States in 2009, and the technology has been gradually commercialized in recent years [4]. However, the disadvantages of high prices and restricted safety of SVI have increasingly emerged with the advent of autonomous vehicles in the automotive market [5]. According to an MIT assessment released in 2020, the SVI-based technology development route will take at least 10 years to attain large-scale industrialization. The VIC system was created against this backdrop as an advanced development form of SVI. By adding roadside perception to vehicle-side perception, the technical path of vehicle-road coordination improves the coupling relationship between people, vehicles, and roads. It also realizes cooperative perception and decision-making of human-vehicle-road-cloud [6], which ensures the safety of autonomous driving [7]; transfers a portion of the vehicle-side cost to the roadside, which quickens the adoption of intelligent networked vehicles [8]. Additionally, its fitted vehicle external information interaction device (V2X: vehicle to everything) can be used to link the vehicle with the environment, for instance, Mushroom Car Union assists Hengyang City in the development of a smart transportation system from the perspective of both the vehicle and the road, using the technical path of vehicle-infrastructure cooperation and the full package of intelligent transportation AI cloud platform [9], which not only boosts traffic safety in Hengyang City but also increases Hengyang City's effectiveness. [10]. Figure 1 shows a comparison of the technical paths of SVI and VIC.

The intelligent connected market industry's external ecological construction is based on information and communication technology behemoths, like Baidu, Tencent, Ali, and others, which have extensive user ecological coverage, as well as cutting-edge technologies, like artificial intelligence and big data [11]. As technology platform providers, these businesses engage closely with companies in the traditional automotive industry chain on vehicle networking, autonomous driving solutions, high-precision positioning, and other areas to help speed the industrialization of ICVs. For example, SAIC has partnered with Zhangjiang Hi-Tech and Ali to form Jiji Auto; Geely and Baidu have established Pixel-J Auto Co. Ltd.; and FAW and Ali have formed a strategic partnership to develop the Zebra Smart System to develop a future generation of vehicles. According to the China Intellectual Property Office, Baidu, Huawei, Google, and other Internet businesses have filed several patent applications in the disciplines of sophisticated sensors, environmental perception, cloud platform, and other areas, demonstrating their excellent R&D capabilities. According to HIS Markit, during the next 3 years, the number of new automobiles equipped with BAT's intelligent Internet-connected services will expand at a compound annual rate of roughly 15%.

This study's main focus is how to encourage collaborative change between automakers and technology platform providers and how to identify the optimum technology path. The following questions are addressed in this study. (1) What is the dynamic evolution process of collaborative transformation and upgrading of intelligent networking by automakers and technology platform providers progressing along diverse technology paths? (2) What elements will influence both parties' collaborative innovation? The answers to these questions are crucial for improving the scale and industrialization of ICVs.

To investigate these issues, this study builds an evolutionary game model with traditional automobile enterprises and technology platform providers represented by technology companies as the main players; constructs a cause-and-effect loop diagram to investigate the dynamic evolution law of the collaborative transformation process of the intelligent connected transformation of the automobile industry; and establishes two SVI and VIC system dynamics models by adjusting parameter values for simulation. We aim to analyze and explore which technology path can effectively promote cooperation between the two parties, as well as what factors will affect cooperation between automobile enterprises and technology platform providers.

The rest of the paper is organized as follows. Section II gives an overview of the relevant research. The evolutionary game theoretical model and the evolutionary stability strategy analysis are described in Section III. In Section IV, we establish a system dynamics model to simulate the ICV cross-border collaborative innovation game system, and then perform sensitivity analysis on key affecting parameters. The conclusions, policy recommendations, and future work are discussed in Section V.

II. LITERATURE REVIEW

Because ICV has only been popular for a short time, the majority of current research focuses on the new industry insights and technology path analysis. In terms of insight into the new ICV industry, Feng [12] stated that ICV cross-border collaborative development has greater development advantages and practical significance than traditional independent

R&D, based on the industry background of China's massive automobile and Internet sectors. Some scholars have further proposed a cross-border collaborative innovation model between automotive enterprises and technology platform providers, which could improve the beneficial interaction between industries, optimize resource allocation, generate significant information system benefits, and speed up the ICV industry's high-end transformation and upgrading [13]. As a result, Li et al. [14] recommended that the government work to improve the external ecological environment to foster the collaborative development of ICVs. A national joint innovation centre for ICVs and a national ICV basic data platform, in addition to policy and financial support, are required to capture the market and consumer demand preferences on time through information technology means, such as big data analysis, cloud computing, and artificial intelligence, and to better promote the industrialization and scale development of ICVs [15]. According to previous studies, cross-border integration and collaborative innovation are critical to the scale development of China's ICV industry, but the majority of these studies have been conducted from macro and static perspectives, which cannot accurately reflect the micro-dynamic development process of ICV cross-border collaborative innovation.

In terms of ICV development technology path identification, the debate over SVI and VIC has not reached consensus: some scholars consider that VIC with roadside sensing devices can sense more information than SVI [16]; for example, Liang [17] considered that the driving safety of vehicles in SVI is limited by the sensors and computing unit devices they are equipped with and that there are still many 'long-tail effects' that are difficult to deal with. By simulating the influence of the VIC's main roadside device RSU in three scenarios: turning, post-accident, and emergency vehicle circumstances, Golestan et al. [18] discovered that the VIC considerably increases the safety and stability of autonomous driving. Ni et al. [19] proposed a multi-vehicle cooperative operating system in a vehicular network environment based on wireless communication technologies of connected vehicles, such as V2X and 5G carried by the VIC, arguing that adopting a new form of ICV would help improve traffic efficiency, save resources, reduce pollution, and lower accident rates. Another group of researchers questioned the VIC network's security and stability, with Gerla et al. [20] claiming that in the event of a malicious attack during cloud sensing, ICVs were likely to disable steering or braking systems and that such an attack could be fatal in the case of autonomous driving due to the lack of backup controls. According to Guerrero-Ibanez et al. [21], the performance of the Vehicular Cloud is likely to be impacted by vehicle movement, which can diminish a vehicle's ability to act as a cloud server and cause traffic congestion [22]. However, these discussions have focused solely on technical issues, ignoring the disparities in the impact of cross-border collaborative innovation behavior on ICV path optimization.

Most existing studies on the problem of cross-border collaborative innovation use the evolutionary game and system dynamics models, which can describe the various states of the system bodies' decisions and the dynamic process of state changes and examine the model simulation process through parameter adjustment. When studying the collaboration between upstream and downstream governments and shipping enterprises to control inland navigation pollution, Xu et al. [23] used evolutionary game theory and a system dynamics model to depict the dynamic evolutionary process of the three parties' choice of cooperative strategies. Fan et al. [24] constructed an evolutionary game model to investigate the evolutionary path and key influencing factors in the cooperative interaction between local governments and polluting businesses in environmental control. However, evolutionary game and system dynamics models are rarely applied in the field of ICVs, since the multiplicity of variables increases the model's complexity. Internal driving factors and external ecological construction factors are influencing factors in ICV industry collaborative innovation from the standpoint of influencing variables. The primary external ecological construction components to encourage cross-border collaborative innovation are policy environment support and financial environment support [25], while internal drivers include the strength of the industry–university–research relationship and innovation investment [26].

In conclusion, the existing research on ICV cross-border collaborative innovation under the SVI and VIC gives some background for this study, but there are certain limitations. First, while academics have thoroughly investigated the macroscopic driving mechanisms of ICV cross-border collaborative innovation, they have not elucidated the microscopic driving channels of inter-firm collaborative innovation behavior. Second, the optimal path selection of ICVs has been studied in the literature, but few studies have considered the optimal path from the perspective of cross-border collaborative innovation. Third, existing studies on collaborative innovation in the ICV industry have largely been conducted from a static perspective, with little regard for the dynamic evolution of the collaborative innovation process in the ICV industry and quantitative analysis of the factors influencing the selection of collaborative innovation strategies.

As a result, this study builds an evolutionary game model of ICV cross-industry collaborative innovation with traditional automobile enterprises and technology platform providers as the main bodies; considers the dynamic evolution process of game subjects' behavior under the two technology paths of SVI and VIC' establishes a system dynamics model; and analyses the influence of key variables on cross-industry collaborative innovation. This research serves as a reference for the ICV industry's collaborative innovation and operation mechanisms and provides a theoretical foundation for scientific policy-making related to the industry's growth and industrialization.

III. PROPOSED MODEL AND METHOD

There are two participants in ICV cross-border collaborative innovation in this model, traditional automobile enterprises and technology platform providers. When automotive enterprises and technology platform providers collaborate on ICV R&D and innovation services, they increase the total level of ICV innovation R&D across both technology paths, resulting in significant economic and societal benefits.

A. ASSUMPTIONS

Assumption 1: Collaboration or non-collaboration are the options for both automobile enterprises and technology platform providers. Assume that the probability of collaboration for automotive enterprises is x ($0 \leq x \leq 1$) and that the probability of non-collaboration is 1-x; that the probability of collaboration for technology platform providers is y ($0 \leq y \leq 1$) and that the probability of non-collaboration is 1-y.

Assumption 2: If both the automotive enterprises and the technology platform providers choose not to collaborate, their revenues do not change and remain constant under independent decision making; in other words, the automotive enterprises' profit level is π_1 and the technology platform providers' profit level is π_2.

Assumption 3: Collaborative innovation would be more advantageous than solo invention if both sides choose to collaborate. The sharing of R&D costs and risks, as well as the increase in predicted rewards, are two advantages of collaborative innovation. Assume that the increase in revenue of automotive enterprises and technology platform providers is γ_i and φ_i $(i = 1, 2)$, respectively, and that the collaboration cost paid by automotive enterprises to technology platform providers is T. Automotive enterprises must pay an additional cost fe for the network connection if they choose the VIC. Additionally, both parties must bear the expense of technical input when collaborating on SVI or VIC R&D is C_i $(i = S, V)$. Because the SVI system necessitates expensive sensors and computing platforms, $C_S > C_V$. α is the cost-sharing coefficient($0 < \alpha < 1$), that is, the technology platform providers' input cost is αC_i and the automobile enterprises' input cost is $(1-\alpha) C_i$, satisfying $\gamma_i\pi_1 - (1-\alpha) C_i - T - fe > 0$, $\varphi_i\pi_2 - \alpha C_i + T > 0$; that is, the profit after the two parties' collaboration is greater than the profit before the collaboration.

Assumption 4: If one party defaults during the collaboration, the defaulting party would be responsible for the default cost P to compensate the collaborating party for its losses.

Assumption 5: If the value of traditional automobile enterprises and technology platform providers in the process of collaborative innovation due to knowledge premium is V_i $(i = 1, 2)$, which is obtained by the subject of the other side of the game; at the same time, both enterprises would exchange or share some core technologies in the process of collaborative innovation, it would be possible for the other side to imitate or copy important technical achievements, and this risk would restrict the possibility of collaborative innovation. Assume that both companies' technology reserves are β_i $(i = 1, 2)$, their technology sharing degree is μ_i $(i = 1, 2)$, and their collaborative innovation risk coefficient is χ_i $(i = 1, 2)$.

TABLE 1. Payoff matrix in the SVI Scenario.

Automotive enterprises	Technology platform providers: Collaboration	Technology platform providers: Non-collaboration
Collaboration	$(1+\gamma_1)\pi_1-(1\text{-}\alpha)C_S-T+V_2-\beta_1\theta_1\chi_1$	π_1+P+V_2
	$(1+\varphi_1)\pi_2-\alpha C_S+T+V_1-\beta_2\theta_2\chi_2$	π_2-P
Non-collaboration	π_1-P	π_1
	π_2+P+V_1	π_2

B. MODEL

1) EVOLUTIONARY GAME MODEL UNDER SVI SCENARIO

The game payoff matrix between automotive enterprises and technology platform providers in the SVI scenario can be created by combining the preceding assumptions, as shown in Table 1.

The expected payoff of the collaborative strategy chosen by automotive enterprises is marked as U_{11}.

$$U_{11} = y\left((1+\gamma_1)\pi_1 - (1-\alpha) C_S - T + V_2 - \beta_1\theta_1\chi_1\right) + (1-y)(\pi_1 + P + V_2) \quad (1)$$

The expected payoff of the non-collaborative strategy chosen by automotive enterprises is marked as U_{12}.

$$U_{12} = y(\pi_1 - P) + (1-y)\pi_1 \quad (2)$$

The average payoff of automotive enterprises' strategy is marked as U_1.

$$U_1 = xU_{11} + (1-x) U_{12} \quad (3)$$

The replication dynamics equation for automotive enterprises, according to the Malthusian equation, is correspondingly as follow:

$$\begin{aligned} F(x) &= \frac{d_x}{d_t} = x(U_{11} - U_1) \\ &= x(1-x)\left(P + V_2 + y\left(\gamma_1\pi_1 - (1-\alpha) C_S - T - \beta_1\theta_1\chi_1\right)\right) \end{aligned} \quad (4)$$

Similarly, for technology platform providers, the replication dynamics equation is as follow:

$$\begin{aligned} F(y) &= \frac{d_y}{d_t} = y(U_{21} - U_2) \\ &= y(1-y)\left(P + V_1 + x\left(\varphi_1\pi_2 - \alpha C_S + T - \beta_2\theta_2\chi_2\right)\right) \end{aligned} \quad (5)$$

According to Friedman, the differential equation system's evolutionary stability strategy may be determined from the Jacobi matrix's local stability analysis, and the Jacobi matrix can be calculated from the abovementioned replicated dynamic equations (6), as shown at the bottom of the next page.

The Jacobi matrix's determinant det(J) and trace tr(J) are calculated using the above equations (7) and (8), as shown at the bottom of the next page.

TABLE 2. Analysis of equilibrium stability in the SVI scenario.

Equilibrium point	det(J)	tr(J)	Result	Asymptotically stable condition
(0,0)	+	+	Instability point	-
(0,1)	-	N	Saddle point	-
(1,0)	-	N	Saddle point	-
(1,1)	+	-	ESS	$p+V_2+\gamma_1\pi_1-(1-\alpha)C_S-T-\beta_1\theta_1\chi_1$ $p+V_1+\varphi_1\pi_2-\alpha C_S+T-\beta_2\theta_2\chi_2>0$
(P*,q*)	-		Saddle point	-

Note:"+ indicates greater than 0, - indicates less than 0, and N indicates not sure.

All the equilibrium points' asymptotically stable conditions and stability are shown in Table 2.

Table 2 shows that this system has four evolutionary equilibriums, and the only evolutionary stability strategy is (1, 1), which corresponds to the evolutionary stability strategy combination (collaboration, collaboration), indicating that the final equilibrium state is (collaboration, collaboration). This is congruent with the current situation: when automotive enterprises and technology platform providers join in SVI's R&D collaboration at the same time, both parties profit the most, and both parties pick collaboration as the best stable strategic combination.

2) EVOLUTIONARY GAME MODEL UNDER VIC SCENARIO

The game payoff matrix between automotive enterprises and technology platform providers in the VIC scenario can be created by combining the preceding assumptions, as shown in Table 3.

Similarly, the replication dynamics equations for automotive enterprises and technology platform providers are as follows:

$$\begin{aligned} F(x) &= \frac{d_x}{d_t} = x(U_{11}-U_1) \\ &= x(1-x)(P+V_2+y(\gamma_2\pi_1-(1-\alpha)C_V \\ &\qquad -T-\beta_1\theta_1\chi_1-fe)) \end{aligned} \tag{9}$$

TABLE 3. Payoff matrix in the VIC scenario.

Automotive enterprises	Technology platform providers: Collaboration	Non-collaboration
Collaboration	$(1+\gamma_2)\pi_1-(1\text{-}\alpha)C_V-T+V_2-\beta_1\theta_1\chi_1-fe$	π_1+P+V_2
	$(1+\varphi_2)\pi_2-\alpha C_V+T+V_1-\beta_2\theta_2\chi_2$	π_2-P
Non-collaboration	π_1-P	π_1
	π_2+P+V_1	π_2

TABLE 4. Analysis of equilibrium stability in the VIC scenario.

Equilibrium point	det(J)	tr(J)	Result	Asymptotically stable condition
(0,0)	+	+	Instability point	-
(0,1)	-	N	Saddle point	-
(1,0)	-	N	Saddle point	-
(1,1)	+	-	ESS	$p+V_2+\gamma_2\pi_1-(1-\alpha)C_V-T-\beta_1\theta_1\chi_1-$ $p+V_1+\varphi_2\pi_2-\alpha C_V+T-\beta_2\theta_2\chi_2>0$
(P*,q*)	-		Saddle point	-

Note: + indicates greater than 0, - indicates less than 0, and N indicates not sure.

$$\begin{aligned} F(y) &= \frac{d_y}{d_t} = y(U_{21}-U_2) \\ &= y(1-y)(P+V_1+x(\varphi_2\pi_2-\alpha C_V \\ &\qquad +T-\beta_2\theta_2\chi_2)) \end{aligned} \tag{10}$$

According to Friedman, the differential equation system's evolutionary stability strategy may be determined from the Jacobi matrix's local stability analysis; the Jacobi matrix can be calculated from the above replicated dynamic equations (11), as shown at the bottom of the next page.

Similarly, all the equilibrium points' asymptotically stable conditions and stability are shown in Table 4.

Tables 2 and 4 show that the VIC system's evolutionary stability strategy is the same as that of the SVI system; both

$$J = \begin{bmatrix} (1-2x)(P+V_2+y(\gamma_1\pi_1-(1-\alpha)C_S-T-\beta_1\theta_1\chi_1)) & x(1-x)(\gamma_1\pi_1-(1-\alpha)C_S-T-\beta_1\theta_1\chi_1) \\ y(1-y)(\varphi_1\pi_2-\alpha C_S+T-\beta_2\theta_2\chi_2) & (1-2y)(P+V_1+x(\varphi_1\pi_2-\alpha C_S+T-\beta_2\theta_2\chi_2)) \end{bmatrix} \tag{6}$$

$$\begin{aligned} \det(J) &= \begin{vmatrix} (1-2x)(P+V_2+y(\gamma_1\pi_1-(1-\alpha)C_S-T-\beta_1\theta_1\chi_1)) & x(1-x)(\gamma_1\pi_1-(1-\alpha)C_S-T-\beta_1\theta_1\chi_1) \\ y(1-y)(\varphi_1\pi_2-\alpha C_S+T-\beta_2\theta_2\chi_2) & (1-2y)(P+V_1+x(\varphi_1\pi_2-\alpha C_S+T-\beta_2\theta_2\chi_2)) \end{vmatrix} \\ &= (1-2x)(P+V_2+y(\gamma_1\pi_1-(1-\alpha)C_S-T-\beta_1\theta_1\chi_1)) \\ &\quad \cdot(1-2y)(P+V_1+x(\varphi_1\pi_2-\alpha C_S+T-\beta_2\theta_2\chi_2))-x(1-x)(\gamma_1\pi_1-(1-\alpha)C_S-T-\beta_1\theta_1\chi_1) \\ &\quad \cdot y(1-y)(\varphi_1\pi_2-\alpha C_S+T-\beta_2\theta_2\chi_2) \end{aligned} \tag{7}$$

$$\begin{aligned} tr(J) &= \frac{F(x)}{\partial x}+\frac{F(y)}{\partial y} = (1-2x)(P+V_2+y(\gamma_1\pi_1-(1-\alpha)C_S-T-\beta_1\theta_1\chi_1)) \\ &\qquad +(1-2y)(P+V_1+x(\varphi_1\pi_2-\alpha C_S+T-\beta_2\theta_2\chi_2)) \end{aligned} \tag{8}$$

are (1, 1), corresponding to the evolutionary stability strategy combination (collaboration, collaboration), indicating that the technical route has a little influence on both parties' final strategy choices.

IV. SIMULATION AND DISCUSSION

The evolutionary game model is an explanatory elaboration of the process and equilibrium findings, but it cannot capture the evolutionary route of automobile enterprises and technology platform providers' decision-making. This study uses the system dynamics simulation software Vensim PLE based on evolutionary game analysis to model and simulate the game behavior of automotive enterprises and technology platform providers to achieve transformation collaboration, and simulates the dynamic process of decision adjustment of both parties to deeply explore the structure of the model and the behavioral changes of the subject.

A. SD MODELLING OF THE EVOLUTIONARY GAME

1) THE CAUSAL LOOP DIAGRAM OF THE SD MODEL

The collaborative behavior system of automotive intelligent networked transformation empowerment is made up of the willingness to collaborate, R&D investment, accessible revenue, and other elements of both automotive enterprises and technology platform providers. The causal loop diagram of the SD model, as shown in Figure 2, is derived from an examination of the interrelationships among these elements, and its key causal feedback loops are as follows:

1. Automobile enterprises' cooperation investment → automobile enterprises' financial pressure → willingness of automobile enterprises to collaborate.
2. ICV transformation performance → automobile enterprises' available revenue → willingness of automobile enterprises to collaborate.
3. Technology platform providers' collaboration investment → automobile enterprises' financial pressure → willingness of automobile enterprises to collaborate.
4. Technology platform providers' collaboration investment → technology platform providers' financial pressure → willingness of technology platform providers to collaborate.
5. ICV transformation performance → technology platform providers' available revenue → willingness of technology platform providers to collaborate.
6. Automobile enterprises' collaboration investment → technology platform providers' financial pressure → willingness of technology platform providers to collaborate.

2) THE SYSTEM FLOW DIAGRAM OF THE SD MODEL

The system flow diagram model of collaboration decisions between automotive enterprises and technology platform providers may be developed using the aforementioned causality model and its feedback loop analysis by integrating each variable in the system, as illustrated in Figure 3.

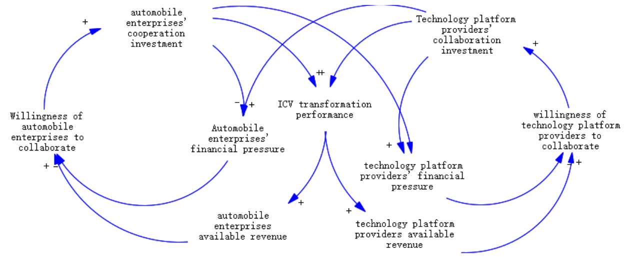

FIGURE 2. The causal loop diagram of the SD model.

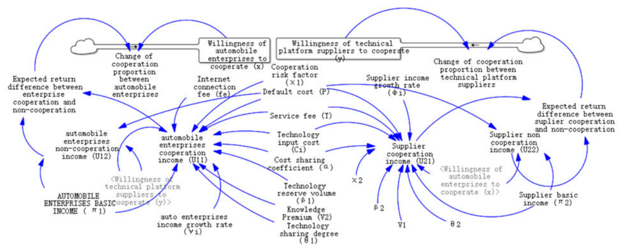

FIGURE 3. The system flow diagram of the SD model.

x and y are horizontal variables, denoting the ratio of automobile enterprises as well as technology platform providers choosing collaboration, respectively. The amount of change in the ratio of automobile enterprises and technology platform providers choosing collaboration denotes the rate of change of the two stocks, respectively, as rate variables. The rest are auxiliary variables. According to the results of the evolutionary game, the relationship between the factors can be clearly seen.

B. NUMERICAL ANALYSIS AND DISCUSSION

The Apollo Moon, created by Polar Fox Motors in collaboration with Baidu, was publicly unveiled as a Baidu Apollo fifth-generation L4-class ICV in June 2021, supporting the VIC while costing only a fraction of the price of an SVI smart car, about 480,000 yuan [27], whereby $C_S = 200$, $C_V = 50$. Pixel-J Auto, which was founded by Geely and Baidu with 55% and 45% of both enterprises' shares, is planned to have a cost-sharing coefficient $\alpha = 0.5$ according to official data. Because the VIC is able to pass some of the vehicle-side costs to the roadside, the profit margin is higher than the reality. As a result, $\gamma_1 = 0.2, \gamma_2 = 0.4, \varphi_1 = 0.6, \varphi_2 = 0.7$. According to Chen and Zhang [28], $P \in [15, 35]$ and $\beta_1 = 0.3, \beta_2 = 0.7, \theta_1 = 0.65, \theta_2 = 0.65, \chi_1 = 0.5, \chi_2 = 0.3, V_1 = 30, V_1 = 20$.

$$J = \begin{bmatrix} (1-2x)\left(P + V_2 + y\left(\gamma_2\pi_1 - (1-\alpha)\,C_V - T - \beta_1\theta_1\chi_1 - fe\right)\right) & x\,(1-x)\left(\gamma_2\pi_1 - (1-\alpha)\,C_V - T - \beta_1\theta_1\chi_1 - fe\right) \\ y\,(1-y)\left(\varphi_2\pi_2 - \alpha C_V + T - \beta_2\theta_2\chi_2\right) & (1-2y)\left(P + V_1 + x\left(\varphi_2\pi_2 - \alpha C_V + T - \beta_2\theta_2\chi_2\right)\right) \end{bmatrix} \tag{11}$$

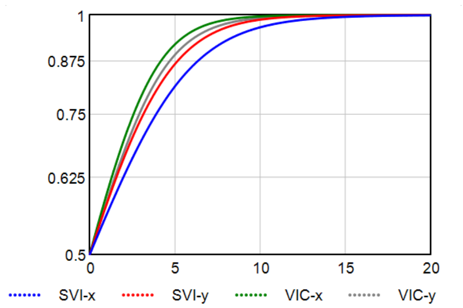

FIGURE 4. Evolutionary results under SVI and VIC.

The game system's initial strategy selection probabilities for both automotive enterprises and technology platform providers are set to 0.5. By modifying the values of parameters, the effects of SVI and VIC on the evolutionary outcome of collaborative innovation, as well as the effects of cost-sharing coefficient, the default cost, network connection fee, and collaborative innovation risk on the evolutionary path, are analyzed.

1) EVOLUTIONARY RESULTS UNDER SVI VERSUS VIC

Figure 4 shows the evolutionary results of the ICV cross-border collaborative innovation game system after simulation. Regardless of the state, collaboration is the final stable equilibrium strategy of automotive enterprises and technology platform providers, and the system's speed of reaching the stable state is accelerated in the VIC state. The road-end construction on which the VIC relies can enhance the human-vehicle-road coupling, make the system controllable and measurable, and reduce randomness, all the while making ICV R&D more meaningful, and implying that optimizing the external environment can lead automotive enterprises and technology platform providers to prefer the collaborative innovation strategy.

Interestingly, the innovative findings of this paper, the automotive enterprises are the first to reach a steady state in the VIC scenario, despite the high network connection fee they have to pay. Technology platform providers are the first to reach the steady state in the case of SVI. This is comparable to the evolution of smartphones, with ICVs progressing from SVI to VIC. With the rapid upgrading of roadside infrastructure and the progressive accumulation of user scale, ICV terminals and carriers will become increasingly important, resulting in a considerable increase in ICV penetration. Automobile enterprises will be the main benefactors as the main body promoting ICVs, increasing the willingness to collaborate on innovation.

2) EFFECT OF COST-SHARING COEFFICIENT ON EVOLUTIONARY RESULTS

Assume the technology platform providers' cost-sharing coefficients are 0.1, 0.5, and 0.7, and the evolution results of the ICV industry's cross-border collaborative innovation system are illustrated in Figure 5. By adjusting the

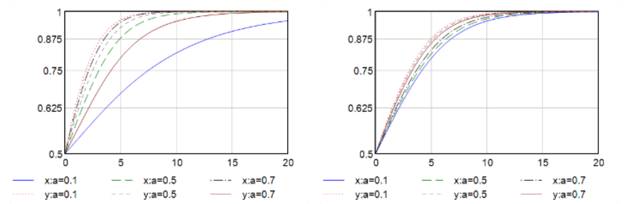

FIGURE 5. Evolutionary results of SVI and VIC with different cost-sharing coefficients.

cost-sharing coefficients of technology platform providers, the paper further finds that when automotive enterprises have a relatively high cost-sharing ratio, despite bearing higher costs, they tend to collaborate with technology platform providers from a long-term perspective of their own development, even if the speed of stabilization for both sides is slower at this time. When technology platform providers have a relatively high cost-sharing ratio, they would suffer significant losses if they are unable to transform their own technology into products and bring them to market. As a result, they tend to collaborate with automotive enterprises in collaborative innovation, and the speed of stabilization between the two sides is accelerated at this time. Because the expense of R&D for an SVI state is substantially higher than that for a VIC state, this phenomenon is even more visible. Governments can grant R&D subsidies to automotive enterprises and technology platform providers that develop ICVs, create a healthy external innovation ecosystem, encourage both sides to collaborate, and improve the efficiency of collaborative innovation implementation.

3) EFFECT OF DEFAULT COST ON EVOLUTIONARY RESULTS

If one of the collaboration partners defaults, the default costs are set to 15, 25, and 35, and the simulation produces the evolution of the cross-border collaborative innovation system of ICVs, as depicted in Figure 6. The default penalty can compel both parties to complete collaborative innovation duties in accordance with the established agreement, and the default amount, regardless of its magnitude, encourages both parties to advance in the collaborative innovation direction. The system tends to reach a steady state at a faster pace as the default cost rises, demonstrating that the greater the default cost, the stronger the constraint on the choice of collaborative innovation strategy. Furthermore, for the same default cost, the SVI scenario has a lower probability of evolving into a collaborative situation than under the VIC scenario, indicating that the VIC environment can successfully foster collaboration between two parties.

4) EFFECT OF NETWORK CONNECTION FEE ON EVOLUTIONARY RESULTS

In the case of VIC, converged ICVs must use 5G technology to interact with real-time information from 'human, vehicle, road, and cloud' to achieve multiple cooperative sensing, and thus, automotive enterprises must pay a network connection fee of 15, 25, or 35, which corresponds to

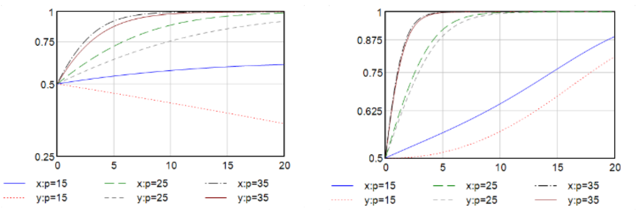

FIGURE 6. Evolutionary results of SVI and VIC with different default costs.

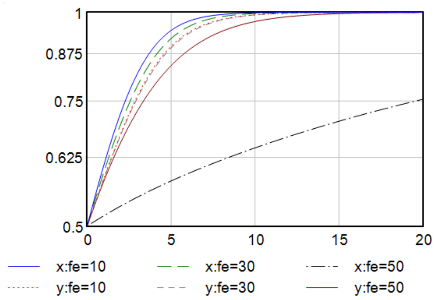

FIGURE 7. Evolutionary results of VIC with different network connection fees.

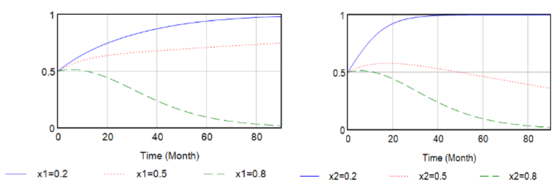

FIGURE 8. Evolutionary results of VIC with different innovation risk coefficients.

three tariff levels of low, medium, and high, respectively. Figure 7 depicts the evolution results of the cross-border collaborative innovation system after simulation. Low and medium network connection fees have little impact on the evolution strategy in this model, especially for technology platform providers; the system's evolution path practically overlaps when the network connection charge is between 10 and 30. When the network connection fee grows greatly ($fe = 50$), the willingness of automotive enterprises to collaborate falls dramatically, and the rate of convergence of technology platform providers to the steady state falls dramatically.

5) EFFECT OF COLLABORATIVE INNOVATION RISK COEFFICIENT ON EVOLUTIONARY RESULTS

Figure 8 depicts the impact of the collaborative innovation risk coefficient on the strategy choice of automotive enterprises and technology platform providers in the SVI scenario, with all other parameters remaining unchanged. The figures shows that when the collaborative innovation risk coefficient χ_i is between 0.5 and 0.8, automotive enterprises' willingness to collaborate shifts to non-collaborative willingness, and when the collaborative innovation risk coefficient χ_i is between 0.2 and 0.5, technology platform providers' willingness to collaborate shifts to non-collaborative willingness. The lower the collaborative innovation risk coefficient, the more quickly the two parties' collaborative innovation evolves. As newcomers to the automotive industry, technology platform providers are more concerned about the negative effects of unknown risk factors on enterprises, and predict and evaluate potential risk factors prior to collaborative innovation to avoid the losses caused by collaboration failure.

V. CONCLUSION AND POLICY RECOMMENDATIONS

Our study presents an evolutionary game model to rethink the dynamics of collaborating between traditional automobile enterprises and technology platform providers to drive cross-border collaborative innovation in the ICV industry. Unlike most previous research on ICV cross-border collaborative innovation [13], SVI and VIC as two different technology paths for the ICV industry, this research constructs SVI and VIC evolutionary game model to explore the microscopic dynamic evolution process respectively. Furthermore, we analyze the influence of some important variables on cross-border collaborative innovation using the system dynamics theory. A successful model should reproduce the fundamental features of target systems while also uncovering novel patterns that have not been recorded in earlier research [26]. Our work not only shows conclusions that are consistent with existing literature, such as the equilibriums coming from evolutionary games, but it also captures the influence of optimal technology path choice on ICV cross-border collaborative innovation. Numerical simulations based on theoretical analysis are also performed and the factors affecting the evolutionary path are analyzed.

A. CONCLUSIONS

(1) Under the context of the complex evolutionary game, the final stable equilibrium strategy between automotive enterprises and technology platform providers is collaboration, whether they choose the SVI or VIC technology path. Therefore, the collaboration is a choice based on the complementarity of resources and capabilities of both parties.

(2) Compared with the SVI technology path, the VIC can make ICV cross-border collaborative innovation system evolve into collaboration state at a faster rate. The time for the system to reach the collaboration state is 20 under the SVI scenario, and the time for the system to reach the collaboration state is 15 under the VIC scenario.

(3) The effect of the default cost and input cost on the speed at the system to reach collaboration state is remarkable. The time for the VIC system to reach the collaboration state is 8 when the default cost is 35, and the time for the VIC system to reach the collaboration state is 14 when the technology platform providers' cost-sharing coefficient is 0.7. This result indicates that an effective penalty mechanism forces both parties to carry out innovation collaboration, which ensures the stability of their collaborative innovation strategies. A reasonable cost allocation mechanism can guarantee both parties to obtain satisfactory benefits and achieve a win-win situation of collaborative innovation.

B. POLICY RECOMMENDATIONS

The "Strategy of Development and Innovation of Intelligence Vehicle" proposes that by 2025, to achieve the condition of autonomous driving of intelligent vehicles to reach scale production, and to build a cross-border integrated intelligent vehicle industry ecosystem. According to this development goal and combined with other ICV industrial policies, we propose the following specific ICV development suggestions from the policy side and the supply side respectively. Among them, the policy side starts from the government's policy making, so it is summarized as top-level design; since this paper focuses on ICV cross-border collaborative innovation, the supply side is summarized as technology innovation.

In terms of top-level design of the government of China, policy support should be strengthened and multiple resources from "government, industry, academia, research" should be integrated. The "Intelligent Networked Vehicle Technology Roadmap 2.0" proposes the collaborative development of automotive and information and communication industries, the formation of a new industrial ecosystem, and the continuous improvement of the policy and regulatory system in 2025. Specifically, faced with significant request for ICV innovation, government should encourage and guide the collaboration of automotive enterprises and technology platform providers such as Internet, software, and hardware. Thus creating a cross-border collaborative innovation ecosystem, which is beneficial to accelerate the growth of the ICV industry and achieve "curve overtaking".

Furthermore, formulating reasonable subsidies and penalties is a critical point to promote ICV cross-border collaborative innovation. Yang's study results show that subsidy and penalty mechanism are important driving factors to boost the initiative and excitement for ICV cross-border collaborative innovation [7]. On the one hand, government could reduce the high cost of technology conversion for enterprises by increasing subsidies for intelligent connected technology to meet the goal of encouraging businesses to convert. On the other hand, as a guarantee for the benefit distribution mechanism, government should gradually establish a perfect system of information disclosure and supervising.

In terms of technology innovation, environmental support should be strengthened and the construction of road-end infrastructure accelerated. According to the existing policies, using VIC as a leveraging centre point for creating smart cars and intelligent transportation could encourage cross-industry R&D collaboration and reduce traffic congestion. The improvement of infrastructure should be hastened, including roadside sensing equipment, 5G communication networks, and big data cloud control platforms, while a full fundamental ecosystem of ICVs should be built, so that "smart cars" can drive on "smart roads", according to the VIC technology path.

C. LIMITATIONS OF THIS RESEARCH

This study provides a theoretical basis for future ICV cross-border collaborative innovation research. However, there are some limitations. For example, only partial genuine data from China have been collected for simulation analysis at this time. Future studies could collect more extensive and detailed data from other nations to arrive at more systematic findings. Furthermore, the major themes of ICV cross-border collaborative innovation are solely traditional automobile enterprises and technological platform providers akin to Internet enterprises. Future studies could focus on a variety of topics, such as the integration of government, industry, academia, and research to conduct collaborative ICV R&D.

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