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Research on Evolutionary Game of Adopting Blockchain-Based Automotive Traceability

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Abstract: To adopt the blockchain-based automobile traceability system (BCATS) and increase the transparency of the Chinese auto market, this study constructs a tripartite evolutionary game model of manufacturers, regulators, and consumers, discusses the evolutionary stabilization strategy (ESS) under different cases, and analyzes the influencing factors on the tripartite ESS through numerical simulation. The study finds that there exists an ESS of blockchain adoption and tripartite cooperation, and it is influenced by different factors including blockchain construction cost, traceability service price, and government subsidy. Lowering the blockchain construction cost, and increasing the traceability service price and government subsidy can all have a positive impact on accomplishing the ideal ESS, but the latter two can also have a negative impact when they are beyond the scope of effectiveness. The study results provide practical recommendations for adopting blockchain in the auto traceability, which can help to promote blockchain in the Chinese auto market.

Keywords: blockchain; automotive supply chain; traceability system; tripartite evolutionary game model; adoption mechanism; government subsidy; price increase

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1. Introduction

As the economy develops, the production and sales volumes of Chinese automobiles in 2023 reached 30.1 million and 30.0 million, up 11.6% and 12% year-on-year, respectively [1]. The auto industry has emerged as a cornerstone of the Chinese economy. Meanwhile, the number of vehicle recalls in 2023 reached 6.7 million, an increase of 49.9% from 2022 [2], due to increased market awareness regarding lethal vehicle failures. Both have led to greater emphasis on technology that tracks the automotive supply chain. Given the complexity of the chain [3,4], tracking it cannot solely rely on manpower and paper records, but must use the automobile traceability system (ATS). Most ATSs use a centralized database [5] to store the data, such as the ERP (Enterprise Resource Planning) system provided by SAP (System Applications and Products). Nowadays, these systems are exposing information security problems, such as information silos and single point risk [6,7], and the blockchain is becoming a new technical scheme for the ATS.

Blockchain is suitable for the ATS, with decentralization, high transparency, and data security [8,9]. Leveraging these advantages, both the government and various enterprises have introduced corresponding policies and projects pertaining to this area. Regarding government policies, the 'Guiding Opinions on Accelerating the Application and Industrial Development of Blockchain Technology' aims to promote the application of blockchain in the economy, including product traceability, and the 'Guide for Standard System Construction of Blockchain and Distributed Accounting Technology' aims to strengthen the top-level design of blockchain standard work. Regarding enterprise projects, CAAM (China Association of Automobile Manufacturers) released the 'Vehicle Data Blockchain Platform' in order to facilitate data sharing between enterprises, and the BMW (Bavarian Motor

Works) Group utilizes blockchain in the 'Part Chain' project to ensure the traceability of international supply chains.

Despite the technical [10–14] and policy feasibility, the market adoption of the blockchain-based automobile traceability (BCATS) has been slow due to the involvement of numerous stakeholders, such as manufacturers, regulators, and consumers, whose opinions must be carefully considered. As a new technology, blockchain could affect the landscape of traceability services and subsequently the decisions of stakeholders [15–18]. Therefore, the adoption of BCATS among stakeholders is a dynamic and continuous process. The evolutionary game method captures the strategic evolution of multi-party interactions, ultimately establishing a stable equilibrium state [19–24], which is suitable for the situation and offers a robust methodology for examining market willingness. Nevertheless, there is little research on the BCATS adoption process within the auto market.

This paper mainly discusses how the stakeholders accept BCATS, in order to promote the blockchain technology and improve the transparency of the auto market. The primary objective of this study is to describe the interactive process of BCATS adoption by the tripartite stakeholders. Specifically, this study uses the evolutionary game method to build a decision-making model among them, analyze the evolution process and influencing factors of BCATS adoption, and put forward practical suggestions. Given the importance of the automotive industry, research on BCATS is evolving and distinct. This research contributes to the knowledge system within the auto market by using a simulation perspective to analyze the BCATS adoption mechanism at multiple levels; through simulation analysis, this paper provides practical implications for governments and manufacturers on adopting BCATS to promote efficient auto traceability.

This study is organized as follows. Section 2 provides a literature review. Section 3 analyzes conflicts about BCATS adoption among three players, and constructs the tripartite game model. Section 4 analyzes the equilibrium and stability of the model. Section 5 analyzes the influence of different factors. Section 6 discusses the theoretical results and practical contributions. Section 7 summarizes main conclusions.

2. Literature Review

This study examines the process of BCATS adoption within the auto market, and this section provides a literature review on the blockchain-based traceability principle, BCATS research, adoption mechanisms, and the evolutionary game method, and points out major differences from this study.

A blockchain is a decentralized ledger integrating consensus mechanisms, timestamps, and smart contracts and enabling comprehensive product lifecycle tracking within the supply chain [8,9]. A substantial body of research [25–27] has demonstrated the superiority of blockchain in comparison to centralized data management approaches, primarily due to the following factors: (1) Transparency, facilitated by decentralization, eliminates the reliance on third-party trust. (2) Data security, ensured by the chain structure and consensus mechanism, mitigates single points of failure. (3) Automated applications, such as verification, recording, and querying, enabled by smart contracts, enhance the traceability effectiveness. Further, blockchain is classified into the public chain, consortium chain, and private chain based on the access mechanism. Most traceability systems are designed with consortium chains, which combine the openness of public chains with the privacy of private chains, making them suitable for traceability scenarios involving multiple businesses and consumers. Currently, the blockchain technology finds applications in diverse sectors ranging from light [28,29] to heavy industry [30,31], all showcasing its exceptional capability as a data tracing solution across various industries.

The safety requirements for cars are higher than those for most light industrial products, given that automobiles serve as a primary means of transportation. Additionally, being a widely sold civilian tool sets the car apart from most heavy industry products. Consequently, the ATS holds unique research value. There are studies using the blockchain to build systems and trace the automotive manufacturing process. Gupta and Verma [10] proposed a collision liability recognition framework based on blockchain to identify the people in charge in a traffic accident. Ada et al. [11] developed a blockchain system that can track logistics ownership, understand inventory status, and improve traceability. Patro et al. [12] combined Ethereum and the Interplanetary File System to propose an optimized big data scheme to obtain automotive information peer-to-peer. Li et al. [13] combined a two-layer attribute-based auditable model to propose a supply chain system based on Hyperledger Fabric. Dierksmeier and Seele [14] applied blockchain to car transactions for Porsche AG, allowing users to interact directly with the vehicle supply chain. These studies demonstrate the technical feasibility of BCATS from the perspectives of industry analysis, framework design, and system simulation.

However, in addition to considering technical feasibility, the promotion of new technology also involves the expectation and acceptance of various stakeholders. Several studies analyze the acceptance process of innovative technologies in the market from the perspectives of multiple stakeholders and the impact of technologies on industries. Zhou et al. [15] proved that the diffusion path of digital technology is different due to the boundary and heterogeneity of industries. Rao and Kashore [16] illustrated that the adoption of the new energy technology is driven by policies and incentives. Kristensson et al. [17] showed how consumer preferences affect technology adoption and how technology practices influence consumer behavior. Palm [18] illustrated the impact of new energy technology on industry markets, namely that it can drive key factors related to institutions, adopters, and supply. These studies illustrate that new technologies interact with stakeholders and that their adoption is a dynamic process. The automotive market includes various stakeholders, such as manufacturers, consumers, and regulators. Consumers and regulators are concerned about the price and efficiency of traceability services [32], and the adoption of new traceability technologies requires coordination between the government and enterprises [33]. Therefore, the BCATS adoption in the market is also a multi-party dynamic process.

In a multi-party dynamic model, strategies continuously evolve. Other decision-making approaches, which emphasize static equilibrium, struggle to capture the group's activity trajectory. The evolutionary game method requires the limited rationality of the participants and describes the multi-party interactions and equilibrium states. It is advantageous for analyzing the multi-party interaction over time. This method can study the decision-making evolution among multiple players in the automobile market. Song et al. [19] proposed a model among manufacturers, consumers, and the government to find the influence of policies. Schmeiser [20] built a model between consumers and the government to research product supervision. Wen and Cheng [21] found that enterprises can improve product competitiveness according to consumers' quality awareness by the evolutionary game method. This method can also study the adoption of a technology in an industry. Li and Liang [22] applied the method to examine the effectiveness of subsidies for healthcare institutions adopting the blockchain. Zheng et al. [23] built a model among producers, processors, and the government to analyze the blockchain adoption strategy for the agricultural supply chain. Su et al. [24] constructed a model to analyze the impact of blockchain on the evolutionary stability among financial institutions and enterprises. These studies demonstrate that the evolutionary game method provides a reliable way to study the market's willingness to apply the BCATS.

As evidenced by the above studies, many scholars have demonstrated the feasibility of the BCATS and its relation to the quality of automobiles in the market, but few researchers have paid attention to the attitudes of manufacturers, regulators, and consumers in the automotive market towards the BCATS. Although there are studies on the adoption and decision-making evolution of new digital technology, providing references for the factors and methods of stakeholders, the field of automotive traceability is seldom explored.

Addressing the aforementioned insufficiency, this paper aims at the process of the BCATS adoption by the stakeholders in the auto market with the evolutionary game method, expanding research on the BCATS and technology adoption. This paper makes the following main contributions. Firstly, it identifies three stakeholders involved in the automotive traceability and analyzes their contradiction with BCATS. Secondly, it uses an evolutionary game model to describe the decision-making processes of the tripartite, and identifies the evolutionary stabilization strategy (ESS), in which all stakeholders accept the BCATS. Thirdly, it uses stability theory and data simulations to analyze the factors that affect the evolutionary process and stable state. Lastly, the theoretical results lead to practical recommendations for the adoption of blockchain in the auto traceability.

3. Model Building

Building on the theoretical basis discussed above, this section first explains the advantage of the evolutionary game method for this research. Then, it describes the problem of BCATS adoption among stakeholders. Finally, the experimental conditions and corresponding parameters are established for the evolutionary game analysis.

3.1. Method Description

The evolutionary game method is suitable for analyzing multi-party time-evolving game mechanisms compared with other decision theories. The core theoretical foundation of the method is equilibrium points, stable points, and Lyapunov system stability theory. The equilibrium point is a point where the system remains invariant with respect to time. The stable point is an equilibrium point where the system will return to its original state after being slightly disturbed. The Lyapunov system stability theory defines the Lyapunov function $V(t)$ as satisfying the following:

$$\forall t \geq 0,\ V(t) > 0,\ V(0) = 0 \text{ and } \dot{V}(t) < 0, \quad (1)$$

and indicates that if there is a Lyapunov function $V(t)$ near an equilibrium point in the system, then this point is judged to be a stable point [34]. The theory provides a direct method for measuring the deviation degree of the system from the equilibrium point.

The goal of the method is to find the evolutionary stabilization strategy (ESS), which emphasizes the stability within a population over the long-term dynamic evolution, making the method suitable for describing multi-party dynamic games [35]. Based on the Nash equilibrium concept, a strategy is an ESS if and only if the following applies:

$$\begin{gathered} \pi(p',\ p') > \pi(p,p'),\ \forall p_i, p'_i \in [0,1] \ and\ p \neq p', \\ \pi(p',p') = \pi(p,p') \Rightarrow \pi(p',p) > \pi(p,p),\ \forall p \neq p', \end{gathered} \quad (2)$$

where π is the fitness of the entire participants, $p = (p_1, p_2, \ldots)$ is any mix strategy ratio combination in a participant population, and $p' = (p'_1, p'_2, \ldots)$ is an equilibrium point. The method includes the following steps.

Firstly, by determining assumptions and defining the behavior options and revenue models of participants, a theoretical framework is established. Evolutionary game theory assumes that participants make decisions with limited information and cognitive abilities, bringing the model closer to the game process in the real world.

The second step involves calculating the payoff of all strategies. Based on each participant's behavior and revenue, the total return for different strategy combinations is calculated. This helps to understand the adaptability of different strategies in a population and how they are affected by other strategies. The overall strategy combination $s = (s_1, s_2, \ldots, s_n)$, the mix strategy ratio $p = (p_1, p_2, \ldots, p_n)$, and payoff combination $\pi = (\pi_1, \pi_2, \ldots, \pi_n)$ could be put into the payoff matrix for easy observation and analysis, where $i(i \in \{1, 2, \ldots, n\})$ indicates the participant of the group [22].

Thirdly, the method uses the replication dynamic equations to describe the propagation and evolution of different strategies. The change in the strategy set s is determined by the behavior ratio p_i of different individuals, and the ratio p_i is related to the individual payoff π_i and the overall average payoff $\overline{\pi}$, which is determined by the overall strategy s.

By comparing returns, participants' strategies influence each other and change over time. The replication dynamic equation F_i is described as follows,

$$F_i(p_i, t) = p_i * (\pi_i - \overline{\pi}), \quad \overline{\pi} = \sum_{i=1}^{n} p_i * \pi_i, \tag{3}$$

which simulates the evolution strategy of the group. By calculating the partial derivatives of the equation with respect to the different players $\partial F_i / \partial p_j \big|_{i,j \in \{1,2,\ldots,n\}}$, it is possible to observe how players influence the others [23].

The fourth step is stability analysis. Based on the Lyapunov system stability theory, the stability is determined by analyzing the equilibrium points of replication dynamic equations. The goal is to evaluate whether the system can return to a stable state after being disturbed. The first is to determine the equilibrium points. When the group rates are all zero, $F_i(p_i) = 0 \; \forall i \in \{1, 2, \ldots, n\}$, the group ratio $p = (p_1, p_2, \ldots, p_n)$ represents the equilibrium point. The next step is to build the Jacobi matrix J, which consists of the partial derivative of the replication dynamic F_i with p_i, as follows:

$$J = \left[\frac{\partial F_i}{\partial p_j} \right]_{n \times n}, \tag{4}$$

which is used to analyze the stability near equilibrium points and find the stable point. Then, by substituting the equilibrium points, the eigenvalues $\lambda_i (i \in \{1, 2, \ldots, n\}$ of the matrix are obtained. The point where all the eigenvalues are negative $(\lambda_i < 0, \forall i \in \{1, 2, \ldots, n\})$ is the asymptotically stable equilibrium point according to the Lyapunov system stability theory, satisfying the condition of the ESS in Equation (2) [34].

Fifthly, the results of theoretical analysis can be verified by numerical simulation, and the evolution process under different conditions is observed to analyze the sensitivity to parameters. This step visually demonstrates the dynamic evolution process, verifies the accuracy of the theoretical analysis, and identifies key system factors. Finally, the theoretical results are linked to game phenomena in the real world and translated into the solution of practical problems, which gives theoretical results practical value.

The above steps constitute a complete process of the evolutionary game method, which enables researchers to analyze and predict the stability and evolutionary outcomes of multi-party dynamic games from various perspectives. It shows that the evolutionary game method is a reliable method to study the acceptance process of BCATS.

3.2. Problem Description

To describe the problem of BCATS adoption in the automobile market, the players involved in the game and their target regarding the ATS are identified first. This study divides the stakeholders into three players, manufacturers, regulators, and consumers, as follows: (1) Manufacturers include supply chain enterprises such as parts suppliers, logistics service providers, and repair shops. They build the ATS to provide traceability information to regulators and consumers, comply with quality regulations, and establish brand image [36,37]. (2) Regulators include the Ministry of Industry and Information Technology, Market Administration, and other government departments in China. They formulate quality regulations and promote innovation subsidies [38] in order to improve the information transparency of the auto market and discover quality issues quickly [33]. (3) Consumers are the source of market value, because serving them drives manufacturers to build the ATS, and protecting their rights is an administrative goal of regulators [32]. Consumers use the ATS to trace the origin and quality indicators of the car. Identifying counterfeit and shoddy products can reduce the risk of driving a faulty car [39]. In general, the three players are involved and influencing each other in the interest relationship involving the ATS, as shown in Figure 1, in which the numbers refer to the behaviors of manufacturers, regulators, and consumers.

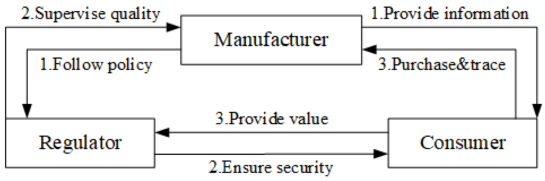

Figure 1. Tripartite interest relationship in automotive traceability system.

The traditional ATS faces issues with easily concealed information and low traceability efficiency, while the BCATS can efficiently update and trace information, and it is typically based on a consortium chain [10–14]. The consortium chain is built by the organizations that make up the alliance, which combines the advantages of both private and public chains. Compared with the private chain, its decisions require consensus among organizations, and it has a higher degree of decentralization, while maintaining control over control internal nodes [29], and compared with the public chain, it has a limited number of nodes, is more efficient, and retains the ability for public access [30]. Therefore, the consortium chain is suitable for the BCATS, which is jointly managed by multiple manufacturers and regulators, and opens information to consumers. On the other hand, because the consortium chain requires the alliance members to maintain the system, the construction costs also need to be paid by them [15].

The traceability work based on the BCATS is as follows. First, the production information of each vehicle at every link of the supply chain is recorded in the BCATS and shared with all users. Each vehicle has a unique identification code, which corresponds directly to the information on the chain. Vehicles from the same supply chain are linked through the information chain on the BCATS [10,11]. Then, when a sold vehicle is found to have quality problems by the consumer and reported to manufacturers and regulators, the BCATS can trace the supply chain of the vehicle based on the identification code, locate the problematic link and other cars sold from the same chain, update the history of them on the BCATS, and issue warnings to other consumers [12,13].

The production information and reported problems are transparent with the BCATS, that affects the interests of all three stakeholders. While fully disclosing information helps to enhance brand image, enterprises also face information security risks [37]. Market transparency benefits regulators, but regulators remain wary of subsidy policies [33]. For consumers, the BCATS helps them track products and spot quality problems. The change in interests leads to new contradictions, as shown in Figure 2, where the solid lines indicate conflicts between players, and the dashed lines indicate their strategy to adopt the BCATS. (1) The cost of developing new technologies and building a new system could be huge. Manufacturers may pass on the cost to consumers by raising prices, such as the ever-increasing price of smartphones in the market [40]. (2) Regulators encourage new technologies to promote the market transparency. However, this conflicts with the interests of manufacturers who prefer to hide information, as disclosing the truth would expose them to commercial and security liability risks [41]. (3) The service price is an extra expenditure and quality problems could remain hidden for a long time. Some people have no intention of traceability, which contradicts the goal of regulators to ensure social security [20]. It can be seen that BCATS adoption is in a state of contradictory obstacles. The tripartite affect each other, which makes this a dynamic process, necessitating the study of stable strategies and influencing factors in the game.

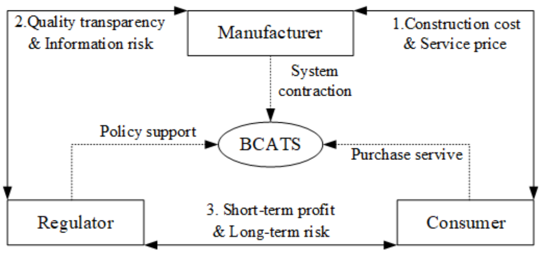

Figure 2. Tripartite conflicts around blockchain application.

3.3. Assumptions and Parameters

Based on the problem description, this study makes parameters and assumptions as follows for providing a theoretical framework for building the model. All the parameters are listed in Table 1 and positive.

Table 1. Model parameters.

Parameters	Parameter Description
Q	The original price of automobiles
α	The price increase for BCATS service
R	The utility of brand image enhancement
A	The subsidy for supporting BCATS
P	The penalty for false quality information
U	The utility of qualified automobiles
S_0	The feedback with supporting BCATS
S_1	The feedback with supervising market
S_2	The impact with passive regulation
L	The loss from disqualified automobiles
C_0	The basic cost of manufacturing automobiles
C_1	The risk cost of disclosing truth
C_2	The technical cost of building BCATS
C_3	The administrative cost of active governance
C_4	The efficiency cost gap of BCATS
x	Probability of manufacturers choosing "blockchain"
y	Probability of regulators choosing "active"
z	Probability of consumers choosing "accept"

Assumption 1. *The three players are the manufacturer, the regulator, and the consumer. It is assumed that all the players are finite rational agents, and the game strategy of each player evolves over time and eventually stabilizes at the optimal strategy. The goal of all participants is to maximize their own benefits.*

Assumption 2. *The strategy choice for the manufacturer is ("blockchain", "non-blockchain"), where the former refers to building the BCATS on the supply chain and the latter uses the traditional centralized system. The strategy choice for the regulator is ("active", "passive"); the former refers to the proactive governance of the automotive market, including innovative subsidy policies and regular inspections, and the latter means relying on industry self-regulation and stepping in only when problems arise. The strategy choice for the consumer is ("accept", "reject"), where the former purchases automobiles and a relevant traceability service and the latter involves rejecting them.*

Assumption 3. *The original price of the automobile is Q, and its basic manufacturing cost is C_0. From the copyright litigation of Apple and Samsung, which exposed their sensitive information such as profit margins, led to them being exploited by other competitors, and affected their corporate strategies [42], there is a risk of information security when enterprises publicly disclose data. According to the literature [13], blockchain has higher transparency than centralized systems, and it can increase the amount of information disclosed by enterprises [41] and enhance consumer goodwill [37]. Let the additional information risk cost be C_1, and the enhanced brand image benefit be R. According to the literature [43], information opacity can reduce information risk, but the probability of safety accidents caused by insufficient quality information will increase. According to the literature [15], since the BCATS is a technological innovation, additional development and maintenance costs are required, which are set as C_2. In order to transfer these costs, enterprises can increase the service price based on the product price [19,40], and the percentage increase is α. When manufacturers choose "blockchain", they pay the information risk cost C_1 and the BCATS cost C_2, and increase the production price by α percentage. When manufacturers choose "non-blockchain", they can avoid the risk cost by concealing information.*

Assumption 4. *According to the literature [33], regulators proactively issue policies to manage the market and increase management costs, which are set as C_3. According to subsidy policies in other industries [38], regulators support technology innovation manufacturers through tax reductions and other means, with a subsidy amount of A. In accordance with information disclosure regulations such as the Product Quality Law, for manufacturers that hide information and cause quality accidents, a fine of P is imposed and used to compensate victims. From the literature [43], it can be known that quality accidents have an impact on multiple aspects including the victims and social stability, which is quantified as S_0, S_1, and S_2 according to the results. When regulators choose "active", if manufacturers choose "blockchain", regulators support them with subsides of A, and receive positive feedback S_0 if consumers accept it; if manufacturers choose "non-blockchain", because of the possibility of concealing, regulators punish them by P, recover the victim, and thus obtain positive feedback S_1. When regulators choose "passive" and consumers buy cars of uncertain quality, regulators bear the negative impact S_2.*

Assumption 5. *The benefit that consumers obtain from purchasing quality-normal products is U. According to the literature [43], there is a probability of purchasing quality problem vehicles due to information asymmetry, causing losses set as L. From the literature [26], the BCATS is more efficient than traditional traceability methods, reducing traceability costs set as C_4. From the literature [37], information transparency is beneficial to consumers, whose purchasing of new services benefits the enterprise's brand image set as R. When consumers choose "accept", if manufacturers choose "blockchain", consumers can obtain transparent information and qualified cars, and the manufacturer's brand image can enhance; if manufacturers choose "non-blockchain", consumers suffer losses L, and then they trace the information inefficiently for claim.*

The above assumptions list three players, each with two strategies. With the players using different strategies, a total of eight strategy combinations can be obtained, corresponding to eight payoff combinations. It can be seen that participants' choices of different strategies not only change their own returns, but also affect the others. After summarizing and analyzing the above assumptions, the corresponding relationship among eight strategy combinations and respective payoffs in the tripartite evolutionary game regarding the BCATS is expressed in a payoff matrix form, as shown in Table 2, where from left to right is the strategy mix, the benefits for manufacturers, the benefits for regulators, and the benefits for consumers under the mix, and the probability symbols $\{x, y, z, 1-x, 1-y, 1-z\}$, respectively, represent the corresponding strategies {"blockchain", "active", "accept", "non-blockchain", "passive", "reject"}.

Table 2. Payoff matrix.

Strategy Set	Manufacturer	Regulator	Consumer
(x, y, z)	$(1+\alpha)Q + A + R - C_0 - C_1 - C_2$	$S_0 - A - C_3$	$U - (1+\alpha)Q$
$(x, y, 1-z)$	$A - C_2$	$-A - C_3$	0
$(x, 1-y, z)$	$(1+\alpha)Q + R - C_0 - C_1 - C_2$	0	$U - (1+\alpha)Q$
$(x, 1-y, 1-z)$	$-C_2$	0	0
$(1-x, y, z)$	$Q - C_0 - P - L$	$S_1 + P - C_3$	$U - Q - C_4$
$(1-x, y, 1-z)$	0	$-C_3$	0
$(1-x, 1-y, z)$	$Q - C_0$	$-S_2$	$U - Q - C_4 - L$
$(1-x, 1-y, 1-z)$	0	0	0

4. Evolutionary Game Model Analysis

Following the establishment of a hypothetical model for tripartite evolutionary game interactions, this section analyzes the system stability. Firstly, the tripartite replication dynamic equations are established and the equilibrium point is identified. Then, the ESS of the model is analyzed by cases according to Lyapunov's stability theory.

4.1. Equilibrium Analysis

Based on the payoff matrix in Table 2, the replicated dynamic differential equations of the players in Proposition 1 are calculated.

Proposition 1. *The replicator dynamic equations of manufacturers, regulators, and consumers are* $F_1(x)$, $F_2(y)$, *and* $F_3(z)$, *respectively, as follows,*

$$\begin{cases} F_1(x) = x(1-x)f_1(x) \\ F_2(y) = y(1-y)f_2(y) \\ F_3(z) = z(1-z)f_3(z) \end{cases} \tag{5}$$

where $f_1(x) = ((P+L)y + \alpha Q + R - C_1)z + Ay - C_2$, $f_2(y) = (S_0 x + (S_1 + S_2 + P)(1-x))z - Ax - C_3$, $f_3(z) = U - L(1-x)(1-y) - C_4(1-x) - Q(1+\alpha x)$. *(The proof process is shown in Appendix A).*

For the manufacturer, according to the replicator dynamic equation $F_1(x)$ in Equation (5), $F_1(x) \equiv 0$ and the equilibrium state always exist when $y = y_0 = \frac{(C_1 - R - \alpha Q)z + C_2}{(P+L)z + A}$ and x is arbitrary in $[0,1]$. When $y \neq y_0$, both $F_1(x) = 0$ and $F_1'(x) < 0$ must hold simultaneously to satisfy the stability condition of the differential equation. The equilibrium points $x = 0$ and $x = 1$ are obtained from $F_1(x) = 0$. If $0 < y < y_0$, $F_1'(x)\big|_{x=0} < 0$ and $F_1'(x)\big|_{x=1} > 0$ are satisfied, and thus $x = 0$ is the stable strategy; if $1 > y > y_0$, $F_1'(x)\big|_{x=0} > 0$ and $F_1'(x)\big|_{x=1} < 0$ are satisfied, and $x = 1$ is stable. Because the probability of the manufacturer choosing "blockchain" increases from $x = 0$ to $x = 1$ as y increases, Finding 1 can be obtained.

Finding 1. *As the regulator enforces regulatory policies and innovation support more actively, the probability of manufacturers choosing "blockchain" increases.*

For the regulator, according to the replicator dynamic equation $F_2(y)$ in Equation (5), $F_2(y) \equiv 0$ and the equilibrium state always exist when $z = z_0 = \frac{Ax + C_3}{S_0 x + (S_1 + S_2 + P)(1-x)}$, and y is arbitrary in $[0,1]$. When $z \neq z_0$, both $F_2(y) = 0$ and $F_2'(y) < 0$ must hold to satisfy the stability condition. From $F_2(y) = 0$, we obtain the equilibrium points $y = 0$ and $y = 1$. If $0 < z < z_0$, $F_2'(y)\big|_{y=0} < 0$ and $F_2'(y)\big|_{y=1} > 0$ are satisfied, and thus $y = 0$ is the stable strategy; if $1 > z > z_0$, $F_2'(y)\big|_{y=0} > 0$ and $F_2'(y)\big|_{y=1} < 0$ are satisfied, and $y = 1$ is stable. As z increases, the probability that the regulator chooses "active" increases from $y = 0$ to $y = 1$, which leads to Finding 2.

Finding 2. *Regulators choosing "active" are supported by the increasing consumption from consumers in the automobile market.*

For consumers, according to the equation $F_3(z)$ in Equation (5), $F_3(z) = 0$ and the equilibrium state always exist when $x = x_0 = \frac{L(1-y) + Q + C_4 - U}{L(1-y) + C_4 - \alpha Q}$, and z is arbitrary in $[0,1]$. When $x \neq x_0$, $F_3(z) = 0$ and $F_3'(z) < 0$ must hold simultaneously to satisfy the stability condition. $z = 0$ and $z = 1$ are obtained from $F_3(z) = 0$. If $0 < x < x_0$, as $F_3'(z)\big|_{z=0} < 0$ and $F_3'(z)\big|_{z=1} > 0$ are satisfied, $z = 0$ is stable; if $1 > x > x_0$, $F_3'(z)\big|_{z=0} > 0$ and $F_3'(z)\big|_{z=1} < 0$, and thus $z = 1$ is the stable strategy. The probability of the consumer choosing "accept" increases from $z = 0$ to $z = 1$ as x increases, which leads to Finding 3.

Finding 3. *Consumers are more willing to choose "accept" with the traceability service based on blockchain technology applied by the manufacturer.*

Based on the game matrix in Table 2 and the way how the decisions of three parties affect others from Finding 1 to 3, the equilibrium points for the three players in the evolutionary game model in Proposition 2 is calculated.

Proposition 2. *The candidate equilibrium points of the tripartite evolutionary game include* $E_1 = (0,0,0)$, $E_2 = (1,0,0)$, $E_3 = (0,1,0)$, $E_4 = (0,0,1)$, $E_5 = (1,1,0)$, $E_6 = (1,0,1)$, $E_7 =$

$(0,1,1)$, $E_8 = (1,1,1)$, $E_9 = \left(0, \frac{C_4+L+Q-U}{L}, \frac{C_3}{S_1+S_2+P}\right)$, $E_{10} = \left(1, y^*, \frac{A+C_3}{S_0}\right)$ ($y^* \in [0,1]$ *is an arbitrary value*), $E_{11} = \left(\frac{C_4+L+Q-U}{C_4+L-\alpha Q}, 0, \frac{C_2}{\alpha Q+R-C_1}\right)$, $E_{12} = \left(\frac{C_4+Q-U}{C_4-\alpha Q}, 1, \frac{C_2-A}{\alpha Q+R+P+L-C_1}\right)$, *and* $E_{13} = \left(\frac{S_1+S_2+P-C_3}{S_1+S_2+P+A-S_0}, \frac{C_1+C_2-R-\alpha Q}{A+L+P}, 1\right)$, *where the points* E_1 *to* E_8 *can satisfy the stability condition in any case, and the points* E_9 *to* E_{13} *need parameters to satisfy specific requirements, respectively.*

(The proof process is shown in Appendix B.)

4.2. Stability Analysis

The equilibrium point is a strict Nash equilibrium if the asymmetric model reaches the stable state [34]. Since such a point is purely a strategic Nash equilibrium, only the equilibrium points E_1 to E_8 have to be discussed in relation to the asymptotic stability for this game model. The Jacobi matrix J of the model is calculated from Equation (5), as follows.

$$J(x,y,z) = \begin{bmatrix} \frac{\partial F_1}{\partial x} & \frac{\partial F_1}{\partial y} & \frac{\partial F_1}{\partial z} \\ \frac{\partial F_2}{\partial x} & \frac{\partial F_2}{\partial y} & \frac{\partial F_3}{\partial z} \\ \frac{\partial F_3}{\partial x} & \frac{\partial F_3}{\partial y} & \frac{\partial F_3}{\partial z} \end{bmatrix} \tag{6}$$

According to Lyapunov's stability theory, the equilibrium is an ESS if and only if all the eigenvalues are negative; on the contrary, the system is unstable. Using $|\lambda I_3 - J| = 0$ based on Equation (6), the eigenvalues $\lambda_i (i = 1,2,3)$ of E_1 to E_8 are calculated and shown in Table 3, where I_3 is a third-order unit matrix and λ represents the eigenvalue.

Table 3. Eigenvalues of equilibrium points.

Point	Eigenvalue λ_1	Eigenvalue λ_2	Eigenvalue λ_3
$E_1(0,0,0)$	$-C_2$	$-C_3$	$U-Q-L-C_4$
$E_2(1,0,0)$	C_2	$-A-C_3$	$U-(1+\alpha)Q$
$E_3(0,1,0)$	$A-C_2$	C_3	$U-Q-C_4$
$E_4(0,0,1)$	$\alpha Q+R-C_1-C_2$	$S_1+S_2+P-C_3$	$-U+Q+L+C_4$
$E_5(1,1,0)$	$-A+C_2$	$A+C_3$	$U-(1+\alpha)Q$
$E_6(1,0,1)$	$-\alpha Q-R+C_1+C_2$	S_0-A-C_3	$-U+(1+\alpha)Q$
$E_7(0,1,1)$	$\alpha Q+R+A+P+L-C_1-C_2$	$-S_1-S_2-P+C_3$	$-U+Q+C_4$
$E_8(1,1,1)$	$-\alpha Q-R-A-P-L+C_1+C_2$	$-S_0+A+C_3$	$-U+(1+\alpha)Q$

The plus and minus of some eigenvalues can be determined as all parameters are positive, but the others cannot. This study adjusts the parameter conditions to obtain the ESS and the three cases shown in Table 4, where "Y" indicates the ESS, and "N" does the opposite. To make the analysis simple and general, we pre-set the condition $Q+L+C_4 > U$, which indicates that consumers suffer losses definitively when they purchase a disqualified vehicle and fail to recover damage. The following is an analysis of three cases.

Table 4. Stability analysis of equilibrium points.

Point	Case 1				Case 2				Case 3			
	λ_1	λ_2	λ_3	ESS	λ_1	λ_2	λ_3	ESS	λ_1	λ_2	λ_3	ESS
$E_1(0,0,0)$	−	−	−	Y	−	−	−	Y	−	−	−	Y
$E_2(1,0,0)$	+	−	+	N	+	−	+	N	+	−	±	N
$E_3(0,1,0)$	±	+	±	N	±	+	±	N	±	+	+	N
$E_4(0,0,1)$	±	±	+	N	+	±	+	N	±	+	+	N
$E_5(1,1,0)$	∓	+	+	N	∓	+	+	N	∓	+	±	N
$E_6(1,0,1)$	∓	+	−	N	−	−	−	Y	∓	±	∓	N
$E_7(0,1,1)$	+	∓	∓	N	±	∓	∓	N	−	−	−	Y
$E_8(1,1,1)$	−	−	−	Y	∓	+	−	N	+	∓	∓	N

Case 1. *When* $\alpha Q + R + A + P + L > C_1 + C_2$, $S_0 > A + C_3$, *and* $U > (1 + \alpha)Q$, E_8 *has stability and ("blockchain", "active", "accept") becomes an ESS, which is the ideal state of the blockchain system. In this case, for the manufacturer, the benefit including increased price, brand image effect, and subsidy is more than the cost of building the BCATS and the risk of disclosing truthful information; for the regulator, the positive feedback from a more transparent market is higher than the cost of subsidy and active governance; for the consumer, it is effective to purchase cars and a traceability service based on the BCATS.*

Case 2. *When* $\alpha Q + R > C_1 + C_2$, $A + C_3 > S_0$, *and* $U > (1 + \alpha)Q$, E_6 *is stable and three players tend to choose ("blockchain", "passive", "accept") as the ESS. In this case, both the manufacturer and the consumer benefit from the BCATS and become willing to maintain it, even without the support from the regulator; on the other hand, it is not worthwhile for the regulator to carry out active governance anymore.*

Case 3. *When* $C_1 + C_2 > \alpha Q + R + A + P + L$, $S_1 + S_2 + P > C_3$, *and* $U > Q + C_4$, E_7 *has stability and ("non-blockchain", "active", "accept") tends to be the ESS for three players. This case is how do they coordinate and benefit synergistically to ensure the information is transparent without blockchain. Manufacturers use a centralized system and would be punished if quality problems due to information asymmetry are revealed; regulators supervise manufacturers actively to maintain market order; and consumers purchase cars with a little quality risk.*

In the above cases, E_1 remains a stable point and ("non-blockchain", "passive", "reject") is the ESS, in which the three players have to give up cooperation to ensure the minimized loss, as they cannot reasonably distribute the costs and benefits.

5. Numerical Analysis

To verify the validity of the equilibrium and stability analysis, and analyze the influence of different factors on the ESS, this section numerically simulates tripartite evolutionary game processes in fifty units of time. According to references [19], the parameters are initially set to be $(x, y, z) = (0.5, 0.5, 0.5)$, $A = 0.5$, $C_1 = 0.3$, $C_2 = 0.5$, $C_3 = 0.2$, $\alpha = 0.5$, $S_0 = 1.2$, $S_1 = 1$, $S_2 = 1.5$, $Q = 0.5$, $P = 0.5$, $U = 1$, $L = 1$, $R = 0.1$, and $C_4 = 0.5$, and transform separately the initial probability set (x, y, z), BCATS construction cost C_2, price increase α, and subsidy A in the following experiment.

5.1. Influence of the Initial Probability

Figure 3 shows the game process simulation in three cases where the initial probability of the strategy set ("blockchain", "active", "accept"), respectively, is (0.8, 0.8, 0.2), (0.5, 0.5, 0.5), and (0.8, 0.2, 0.2). It illustrates that the initial probability affects the game process and ESS. In Figure 3a, when only the initial probability of consumers choosing "accept" is low, the active governance of regulators is reduced temporarily. However, a large number of manufacturers launching the BCATS service attract consumers in the long term, which promotes regulators to adhere to the original strategy. Finally, the three players are stabilized in the ideal ESS ("blockchain", "active", "accept"). In Figure 3b, when the probabilities of the tripartite strategies are equal and moderate, regulators firstly promote active governance and support more manufacturers to build the BCATS, which attracts consumers. The three players enter smoothly the stable state ("blockchain", "active", "accept"). In Figure 3c, when only the manufacturer choosing "blockchain" has a high probability, although it has great faith, too few consumers and subsidies are not enough to get it through the initial stage.

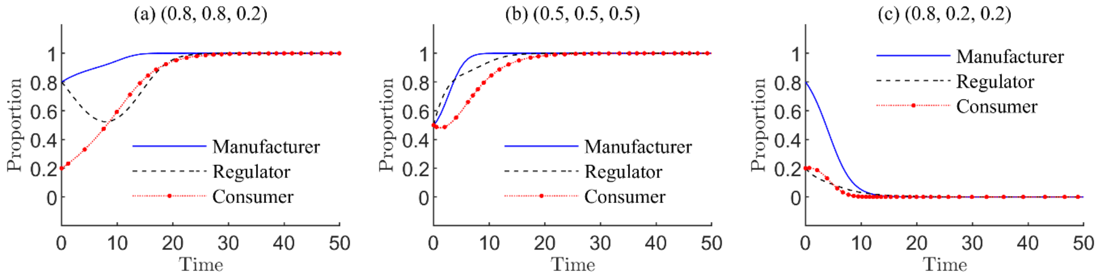

Figure 3. Influence of the initial probability.

5.2. Influence of BCATS Construction Cost

Figure 4 demonstrates game process simulations in which three players enter the ideal ESS (“blockchain”, “active”, “accept”), facing different cost indexes of building the BCATS, illustrating the impact of the cost. As it increases, the manufacturer decelerates into the stable state in Figure 4a, the regulator accelerates in Figure 4b, and the consumer is sync with the manufacturer in Figure 4c. It illustrates that the higher cost would reduce the manufacturer’s revenue and make them hesitate to maintain the blockchain, the regulator is willing to support the manufacturer burdened by this cost difficulty, and the consumer tends to purchase with transparent information, when the initial strategy ratio is moderate.

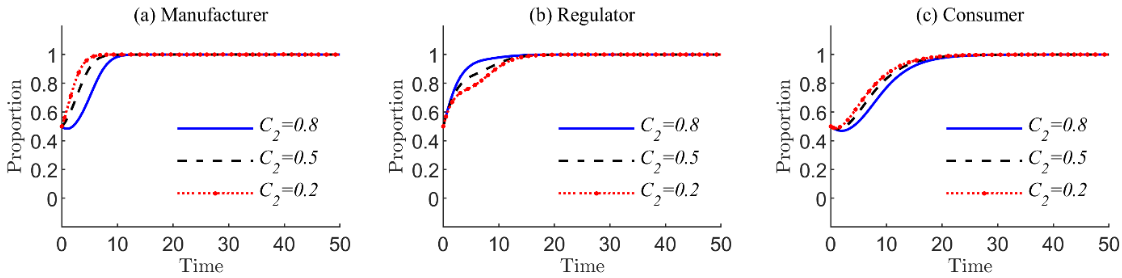

Figure 4. Influence of BCATS construction cost.

5.3. Influence of Price Increase

Figure 5 shows the simulated process entering the ideal ESS, with the automobile’s price increased by the manufacturer. With the increase in price, although the manufacturer accelerates at the beginning, all three players slow down entering the stable state. As can be seen by comparing Figure 5a–c, three players are affected in descending order of the manufacturer, regulator, and consumer. High prices of the BCATS service, while encouraging the manufacturer to stay the system in the short term, could further discourage the consumer from shopping and make the regulator hesitant to take active governance. These long-term effects then would feed back into the manufacturer and result in price adjustment.

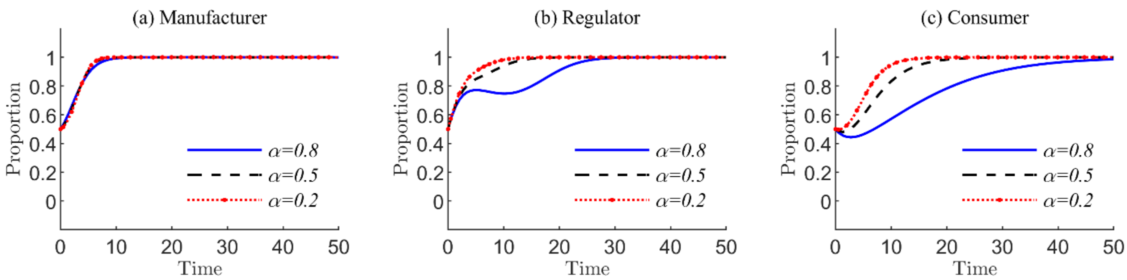

Figure 5. Influence of price increase.

5.4. Influence of Subsidy

Figure 6 shows the game simulation that the regulator changes the subsidy for technological innovation. As the subsidy increases, the manufacturer accelerates into the stable state in Figure 6a. On the contrary, in Figure 6b, the regulator slows down and even changes the strategy. The consumer is barely affected in Figure 6c. The increased subsidy could not only offset the cost of BCATS construction but also increase the financial burden on the regulator and lead to strategy adjustment. Since the subsidy does not affect directly the price and utility of vehicle products, it has little impact on the consumer.

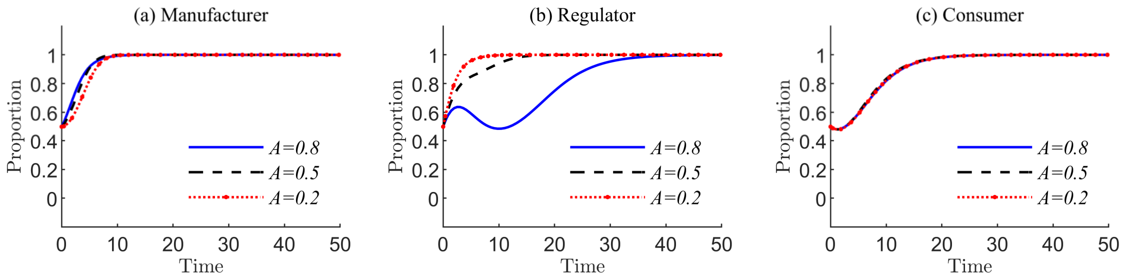

Figure 6. Influence of subsidy.

6. Discussion

Based on the above BCATS adoption mechanism study, this section highlights the novelty of this study, discusses the theoretical analysis results, and puts forward practical guidance suggestions for the automobile market, and points out the limitations.

This study draws on research from multiple fields and introduces new insights. BCATS technology studies demonstrate the technical feasibility, the digital technology adoption mechanism studies identify the factors that influence the tripartite decision, and the evolutionary game studies provide the method of studying the dynamic group behavior. Building on these studies, this paper uses the evolutionary game method to study the process of BCATS adoption in the auto market for the first time. Furthermore, considering the impact of the BCATS on stakeholders, including the information risk and brand image of manufacturers, the subsidy policy of the regulator, and the traceability benefit of consumers, this study initially describes the decision-making evolution of the tripartite in adopting the BCATS. As reviewed in Section 2, this study has not been previously undertaken in these fields, highlighting the novelty of this study.

Based on the above simulation analysis, this study obtains the following theoretical analysis results. Firstly, according to Section 4.1, the strategies of the three players affect each other. The probability of the manufacturer choosing "blockchain" and building a blockchain traceability system increases as the regulator actively enforces quality regulation. The regulator choosing "active" with active policy enforcement is supported by the consumer increasing consumption. The consumer is more willing to choose "accept" and purchase the BCATS service. Secondly, according to Section 4.2, there are several ESSs depending on different conditions. The state ("blockchain", "active", "accept") is the ideal ESS that all three players adopt the BCATS and profit from the BCATS. The state ("blockchain", "passive", "accept") is the ESS when the BCATS is maintained only by manufacturers and consumers. The state ("non-blockchain", "active", "accept") is a coordinated way for the three players to trace cars without blockchain. The three enter the state ("non-blockchain", "passive", "reject") when negotiations break down. Thirdly, according to Section 5, the tripartite ESS is affected by many factors, including the initial probability, BCATS construction cost, price increase, and subsidy. For the initial probability, the ideal ESS requires the general support from three players to cooperate, or the strong support from any two players to change the third strategy. For the system construction cost, if it is too high, it would be difficult for the manufacturer to maintain and provide services to consumers, and regulators would provide subsidies if there is a certain base. For the price increase, the excessive increase of the traceability service price does little to support manufacturers, but much to discourage the regulator and consumer. For the subsidy, it could support manufacturers to build the BCATS, but too much of it would inhibit regulators.

Practical suggestions are put forward based on the theoretical outcomes, in order to facilitate the adoption of BCATS and enhance information transparency in the auto market. Firstly, since both regulators and consumers are inclined to support manufacturers' decision when they opt to construct the BCATS, overly high blockchain costs would make it difficult for them to maintain the new digital system. Thus, manufacturers should stick to their decision to build the BCATS and simultaneously consider approaches to reduce technical costs, such as supply chain integration and collaboration with technological institutions. Secondly, the value-adding of service fees is beneficial for manufacturers but significantly restrains consumers from purchasing services. Therefore, manufacturers should not regard it as the expected revenue of the project but rather focus on brand image to attract more consumers. Thirdly, the subsidy of regulators can steer the strategies of enterprises and consumers towards ("blockchain", "accept"); therefore regulators should adhere to the subsidy policies. Simultaneously, regulators should also establish a scientific reward and punishment mechanism to sustain a long-term project. Fourthly, consumers tend to purchase traceability services. Hence, manufacturers and regulators should enhance consumers' recognition to traceable services, enabling them to be aware, and then they would naturally make decisions for quality assurance by themselves.

Nevertheless, this paper has limitations. For example, the interest network in this study is relatively simplified, the parameters are subjectively set, and several other influencing factors have not been considered. In practice, the automobile manufacturing supply chain is not monolithic, and parts suppliers, manufacturers, sales platforms, and other links also engage in internal competition and external game interactions. Market data vary across different regions and vehicle types. Besides regulators and consumers, third-party institutions such as banks and insurance companies also play a role.

7. Conclusions

Automotive manufacturing is a pillar industry, and blockchain is an emerging digital technology whose impact mechanism is widely concerned by practitioners and researchers. This paper aims to discuss the evolution of stakeholders in the auto market and deepen their understanding of how to accept the BCATS. Through in-depth research, the theoretical and practical contributions of this study are concluded as follows. Firstly, this study for the first time uses the evolutionary game method to describe BCATS adoption in the automobile market, analyzing the stakeholders, their interactions, and the influencing factors in the decision-making process, and providing a theoretical basis for further research on BCATS application. Secondly, this study constructs an evolutionary model and its stable states among manufacturers, regulators, and consumers, provides a simulation perspective for the market to accept the BCATS, and establishes a relevant theoretical framework. Thirdly, this paper uses stability theory and numerical simulation to simulate the adoption process in different states, and based on the theoretical results, offers practical suggestions for manufacturers and regulators to facilitate the market's adoption of the BCATS.

Based on the contributions and limitations of this study, future research directions are suggested. One direction is to expand the network of stakeholders in the market, including insurance and research institutions, as well as intra-supply chain enterprises. Another direction is to introduce data from different regions and enterprises to enhance reliability and differentiation. A third direction is to extend the development route of the technology and study the diffusion mechanisms' post-market adoption of blockchain.

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Appendix A

Proof of Proposition 1. The replication dynamic equations of three parties are calculated successively based on the payoff matrix in Table 2. Since the basic operation flow of the three equations is similar, only the manufacturer's replication dynamic equation is described in detail. The game fitness of each party is defined as the growth rate of the investment funds that adopt a particular strategy after each game.

Firstly, we calculated the replication dynamic equation when manufacturers choose "blockchain". Suppose that the expected returns of the producer when choosing "blockchain" and "non-blockchain" strategies are, respectively, π_{11} and π_{12}, which can be calculated from four strategy and payoff combinations corresponding to the strategies, by summing the product of return and probability, shown as follows,

$$\begin{aligned}\pi_{11} = yz((1+\alpha)Q + A + R - C_0 - C_1 - C_2) + y(1-z)(A - C_2) + z(1-y)((1+\alpha)Q + R - C_0 - C_1 - C_2) \\ -(1-z)(1-y)C_2,\end{aligned} \tag{A1}$$

$$\pi_{12}\& = yz(Q - C_0 - P - L) + z(1-y)(Q - C_0). \tag{A2}$$

Then, the overall expected return of manufacturers can be obtained by the two expected returns and weighted mean formula $\overline{\pi} = x\pi_{11} - (1-x)\pi_{12}$, and the replicator dynamic equation for manufacturers choosing "blockchain" can be obtained by simplifying Equation (3).

$$\begin{aligned}F_1(x) = \tfrac{dx}{dt} = x(\pi_{11} - \overline{\pi}) = x(\pi_{11} - (x\pi_{11} - (1-x)\pi_{12})) = x(1-x)(\pi_{11} - \pi_{12}) \\ = (1-x)((P+L)yz + \alpha Qz + Rz - C_1 zAy - C_2).\end{aligned} \tag{A3}$$

Secondly, we calculated the replication dynamic equation when regulators choose "active". Suppose that the expected returns of the regulator when choosing "active" and "passive" strategies are, respectively, π_{21} and π_{22}, which can be calculated from four strategy and payoff combinations corresponding to the strategies, shown as follows,

$$\pi_{21}\& = xz(S_0 - A - C_3) - x(1-z)(A + C_3) + z(1-x)(S_1 + P - C_3) - (1-z)(1-x)C_3, \tag{A4}$$

$$\pi_{22} = -z(1-x)S_2. \tag{A5}$$

Then, the replicator dynamic equation for the regulator choosing "active" can be obtained,

$$F_2(y)\& = \frac{dy}{dt} = y(1-y)(\pi_{21} - \pi_{22}) = y(1-y)((S_1 + S_2 + P)(1-x)z + S_0 xz - Ax - C_3). \tag{A6}$$

Thirdly, we calculated the replication dynamic equation when consumers choose "accept". Suppose that the expected returns of the consumer when choosing "accept" and "reject" strategies are, respectively, π_{31} and π_{32}, which can be calculated from four strategy and payoff combinations corresponding to the strategies, shown as follows,

$$\pi_{31}\& = xy(U - (1+\alpha)Q) + y(1-x)(U - Q - C_4) + x(1-y)(U - (1+\alpha)Q) + (1-y)(1-x)(U - Q - C_4 - L), \tag{A7}$$

$$\pi_{32} = 0. \tag{A8}$$

Then, the equation for consumers choosing "accept" can be obtained by simplifying Equation (2),

$$F_3(z)\& = \frac{dz}{dt} = z(1-z)(\pi_{31} - \pi_{32}) = z(1-z)(U - L(1-x)(1-y) - C_4(1-x) - Q(1+\alpha x)). \quad \text{(A9)}$$

The results follow. In summary, Equations (A3), (A6), and (A9) are the replication dynamic equations corresponding to manufacturers choosing "blockchain", regulators choosing "active", and consumers choosing "accept", which describes how the frequency of the strategy set dynamically changes over time. □

Appendix B

Proof of Proposition 2. Because the equilibrium point refers to the system state where the strategy change frequency of participants no longer changes timely and the replication dynamic equation reflects the dynamic change frequency of the strategy, the equilibrium point is the zero solution of the replication dynamic equation system for all participants. That is, equilibrium points satisfy that $F_1(x) = 0$, $F_2(y) = 0$, and $F_3(z) = 0$ simultaneously. As can be seen from Equation (4), replication dynamic equations are represented as the product of three factors, respectively. In order to find the zero point of the system, it should be found points (x, y, z) that satisfy,

$$\{(x,y,z) \in [0,1] | (x = 0 \; or \; x = 1 \; or \; f_1(x) = 0) \; and \; (y = 0 \; or \; y = 1 \; or \; f_2(y) = 0) \; and \; (z = 0 \; or \; z = 1 \; or \; f_3(z) = 0))\}. \quad \text{(A10)}$$

Firstly, it is obvious to find eight points by permutation combining the points whose value is 0 or 1 from condition (B. 1). The points $E_1 = (0,0,0)$, $E_2 = (1,0,0)$, $E_3 = (0,1,0)$, $E_4 = (0,0,1)$, $E_5 = (1,1,0)$, $E_6 = (1,0,1)$, $E_7 = (0,1,1)$, and $E_8 = (1,1,1)$ meet the equilibrium condition and they are all equilibrium points. Because when any two of $\{x, y, z\}$ is 0 or 1, the other must be 0 or 1, so there is no need to discuss this situation.

Then, we find six zero points E_9 to E_{14} in the case, that one of the $\{x, y, z\}$ is fixed to 0 or 1 and the other two take the zero solution of the product factors $\{f_1(x), f_2(y), f_3(z)\}$. These points require parameters limited in the range $[0, 1]$.

Firstly, when we set $x = 0, 1$ in the equations $F_1(x) = 0$, $F_2(y) = 0$, and $F_3(z) = 0$, there are $F_1(x) \equiv 0$, and $E_9 = \left(0, \frac{C_4+L+Q-U}{L}, \frac{C_3}{S_1+S_2+P}\right)$ and $E_{10} = \left(1, y^*, \frac{A+C_3}{S_0}\right)$ satisfying $F_2(y) = 0$ and $F_3(z) = 0$, where $\frac{C_4+L+Q-U}{L}$, $\frac{C_3}{S_1+S_2+P}$, y^* and $\frac{A+C_3}{S_0}$ are arbitrary values in $(0, 1)$. From $0 < \frac{C_4+L+Q-U}{L}, \frac{C_3}{S_1+S_2+P} < 1$, we obtain parameters for equilibrium E_9 satisfying $C_4 + Q < U$ and $C_3 < S_1 + S_2 + P$. From $0 < \frac{A+C_3}{S_0} < 1$, the parameters satisfy $A + C_3 < S_0$ of equilibrium E_{10}.

Secondly, when we set $y = 0, 1$ into equations, we have $F_2(y) \equiv 0$, $E_{11} = \left(\frac{C_4+L+Q-U}{C_4+L-\alpha Q}, 0, \frac{C_2}{\alpha Q+R-C_1}\right)$, and $E_{12} = \left(\frac{C_4+Q-U}{C_4-\alpha Q}, 1, \frac{C_2-A}{\alpha Q+R+P+L-C_1}\right)$ satisfying $F_1(x) = 0$ and $F_3(z) = 0$, where the parameters for equilibrium E_{11} satisfy $0 \leq \frac{C_4+L+Q-U}{C_4+L-\alpha Q}, \frac{C_2}{\alpha Q+R-C_1} \leq 1$ and for equilibrium E_{12} satisfy $0 \leq \frac{C_4+Q-U}{C_4-\alpha Q}, \frac{C_2-A}{\alpha Q+R+P+L-C_1} \leq 1$. Further, the parameter satisfaction is $(1+\alpha)Q < U$ and $C_1 + C_2 < \alpha Q + R$ of E_{11}, and $(1+\alpha)Q < U$ and $C_1 + C_2 < \alpha Q + R + P + L + A$ of E_{12}.

Thirdly, when we set $z = 0, 1$ in the equations $F_1(x) = 0$, $F_2(y) = 0$, and $F_3(z) = 0$, we have $F_3(z) \equiv 0$, $E_{13} = \left(\frac{S_1+S_2+P-C_3}{S_1+S_2+P+A-S_0}, \frac{C_1+C_2-R-\alpha Q}{A+L+P}, 1\right)$, and $E_{14} = \left(-\frac{C_3}{A}, \frac{C_2}{A}, 0\right)$ satisfying $F_1(x) = 0$ and $F_2(y) = 0$. E_{13} is the equilibrium if the parameters satisfy $A + C_3 < S_0$ and $C_1 + C_2 < A + L + P + R + \alpha Q$. E_{14} cannot be the equilibrium, since $-\frac{C_3}{A} < 0$ cannot enter the range $[0, 1]$.

The results follow. Thirteen equilibrium points E_1 to E_{13} are found of the system where E_1 to E_8 is the equilibrium in any case, and E_9 to E_{13} need parameters to satisfy specific requirements. They are necessary to solve the Nash equilibrium of the system and find the ESS of the game model. □

References

1. Pang, B. In 2023, China's Automobile Production and Sales Exceeded 30 Million for the First Time. Available online: https://www.gov.cn/yaowen/liebiao/202401/content_6925448.htm (accessed on 26 October 2024).
2. Zhu, Y. The State Administration of Market Regulation Announced the National Recall of Automobiles and Consumer Goods in 2023. Available online: https://www.gov.cn/lianbo/bumen/202403/content_6939180.htm (accessed on 26 October 2024).
3. Chen, C.L.; Zhu, Z.P.; Zhou, M.; Tsaur, W.J.; Wu, C.M.; Sun, H. A Secure and Traceable Vehicles and Parts System Based on Blockchain and Smart Contract. *Sensors* **2022**, *22*, 6754. [CrossRef] [PubMed]
4. Lopez-Pimentel, J.C.; Morales-Rosales, L.A.; Algredo-Badillo, I.; Del-Valle-Soto, C. NFT-Vehicle: A Blockchain-Based Tokenization Architecture to Register Transactions over a Vehicle's Life Cycle. *Mathematics* **2023**, *11*, 2801. [CrossRef]
5. Panjavongroj, S.; Phruksaphanrat, B. Selection of ERP System and the Best Practice by Hybrid Method: A Case Study of Thai Automotive Supply Chain Network. *J. Intell. Fuzzy Syst.* **2022**, *43*, 7617–7631. [CrossRef]
6. Sharma, P.K.; Kumar, N.; Park, J.H. Blockchain-Based Distributed Framework for Automotive Industry in a Smart City. *IEEE Trans. Ind. Inform.* **2019**, *15*, 4197–4205. [CrossRef]
7. Xu, X.; Lu, Q.; Liu, Y.; Zhu, L.; Yao, H.; Vasilakos, A.V. Designing Blockchain-Based Applications a Case Study for Imported Product Traceability. *Future Gener. Comput. Syst.—Int. J. Esci.* **2019**, *92*, 399–406. [CrossRef]
8. Yang, L. The Blockchain: State-of-the-Art and Research Challenges. *J. Ind. Inf. Integr.* **2019**, *15*, 80–90. [CrossRef]
9. Zheng, X.R.; Lu, Y. Blockchain Technology—Recent Research and Future Trend. *Enterp. Inf. Syst.* **2022**, *16*, 1939895. [CrossRef]
10. Gupta, S.; Verma, J.K. Reverse Traceability Framework for Identifying Liability of Crashes for Self-Driving Vehicles Using Blockchains. *J. Glob. Inf. Manag.* **2023**, *31*, 1–21. [CrossRef]
11. Ada, N.; Ethirajan, M.; Kumar, A.; Vimal, K.E.K.; Nadeem, S.P.; Kazancoglu, Y.; Kandasamy, J. Blockchain Technology for Enhancing Traceability and Efficiency in Automobile Supply Chain—A Case Study. *Sustainability* **2021**, *13*, 13667. [CrossRef]
12. Patro, P.K.; Ahmad, R.W.; Yaqoob, I.; Salah, K.; Jayaraman, R. Blockchain—Based Solution for Product Recall Management in the Automotive Supply Chain. *IEEE Access* **2021**, *9*, 167756–167775. [CrossRef]
13. Li, S.; Zhou, T.; Yang, H.; Wang, P. Blockchain-Based Secure Storage and Access Control Scheme for Supply Chain Ecological Business Data: A Case Study of the Automotive Industry. *Sensors* **2023**, *23*, 7036. [CrossRef] [PubMed]
14. Dierksmeier, C.; Seele, P. Blockchain and Business Ethics. *Bus. Ethics—Eur. Rev.* **2020**, *29*, 348–359. [CrossRef]
15. Zhou, Y.; Yang, Q.; Lu, S. Research on the Identification and Formation Mechanism of the Main Path of Digital Technology Diffusion: Empirical Evidence from China. *Technol. Soc.* **2023**, *75*, 102398. [CrossRef]
16. Rao, K.U.; Kishore, V.V.N. A Review of Technology Diffusion Models with Special Reference to Renewable Energy Technologies. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1070–1078. [CrossRef]
17. Kristensson, P.; Pedersen, P.E.; Thorbjørnsen, H. New Perspectives on Consumer Adoption and Diffusion of Innovations. *J. Bus. Res.* **2020**, *116*, 522–525. [CrossRef]
18. Palm, A. Innovation Systems for Technology Diffusion: An Analytical Framework and Two Case Studies. *Technol. Forecast. Soc. Chang.* **2022**, *182*, 121821. [CrossRef]
19. Song, R.; Shi, W.; Qin, W.; Xue, X. Exploring the Interplay of New Energy Vehicle Enterprises, Consumers, and Government in the Context of the "Dual Carbon" Target: An Evolutionary Game and Simulation Analysis. *PLoS ONE* **2023**, *18*, e0291175. [CrossRef]
20. Schmeiser, S. Consumer Inference and the Regulation of Consumer Information. *Int. J. Ind. Organ.* **2014**, *37*, 192–200. [CrossRef]
21. Wen, D.; Cheng, L. An Analysis of Discerning Customer Behaviour: An Exploratory Study. *Total Qual. Manag. Bus. Excell.* **2013**, *24*, 1316–1331. [CrossRef]
22. Li, K.; Liang, C. Exploring the Promotion of Blockchain Adoption in the Healthcare Industry through Government Subsidies. *Kybernetes* **2023**, *53*, 5721–5739. [CrossRef]
23. Zheng, Y.; Xu, Y.; Qiu, Z. Blockchain Traceability Adoption in Agricultural Supply Chain Coordination: An Evolutionary Game Analysis. *Agriculture* **2023**, *13*, 184. [CrossRef]
24. Su, L.; Cao, Y.; Li, H.; Tan, J. Blockchain-Driven Optimal Strategies for Supply Chain Finance Based on a Tripartite Game Model. *J. Theor. Appl. Electron. Commer. Res.* **2022**, *17*, 1320–1335. [CrossRef]
25. Azzi, R.; Chamoun, R.K.; Sokhn, M. The Power of a Blockchain-Based Supply Chain. *Comput. Ind. Eng.* **2019**, *135*, 582–592. [CrossRef]
26. Singh, A.; Parizi, R.M.; Zhang, Q.; Choo, K.-K.R.; Dehghantanha, A. Blockchain Smart Contracts Formalization: Approaches and Challenges to Address Vulnerabilities. *Comput. Secur.* **2020**, *88*, 101654. [CrossRef]
27. Ghosh, A.; Gupta, S.; Dua, A.; Kumar, N. Security of Cryptocurrencies in Blockchain Technology: State-of-Art, Challenges and Future Prospects. *J. Netw. Comput. Appl.* **2020**, *163*, 102635. [CrossRef]
28. Bosona, T.; Gebresenbet, G. The Role of Blockchain Technology in Promoting Traceability Systems in Agri-Food Production and Supply Chains. *Sensors* **2023**, *23*, 5342. [CrossRef]
29. Agrawal, T.K.; Kumar, V.; Pal, R.; Wang, L.; Chen, Y. Blockchain-Based Framework for Supply Chain Traceability: A Case Example of Textile and Clothing Industry. *Comput. Ind. Eng.* **2021**, *154*, 107130. [CrossRef]

30. Ho, G.T.S.; Tang, Y.M.; Tsang, K.Y.; Tang, V.; Chau, K.Y. A Blockchain-Based System to Enhance Aircraft Parts Traceability and Trackability for Inventory Management. *Expert Syst. Appl.* **2021**, *179*, 115101. [CrossRef]
31. Zuo, Y. Making Smart Manufacturing Smarter—A Survey on Blockchain Technology in Industry 4.0. *Enterp. Inf. Syst.* **2021**, *15*, 1323–1353. [CrossRef]
32. Golara, S.; Dooley, K.J.; Mousavi, N. Are Dealers Still Relevant? How Dealer Service Quality Impacts Manufacturer Success. *Prod. Oper. Manag.* **2021**, *30*, 3560–3578. [CrossRef]
33. Lin, J.Y. Industrial Policies for Avoiding the Middle-Income Trap: A New Structural Economics Perspective. *J. Chin. Econ. Bus. Stud.* **2017**, *15*, 5–18. [CrossRef]
34. Cressman, R.; Apaloo, J. Evolutionary Game Theory. In *Handbook of Dynamic Game Theory*; Başar, T., Zaccour, G., Eds.; Springer International Publishing: Cham, Switzerland, 2018; pp. 461–510. [CrossRef]
35. Selten, R. A Note on Evolutionarily Stable Strategies in Asymmetric Animal Conflicts. *J. Theor. Biol.* **1980**, *84*, 93–101. [CrossRef] [PubMed]
36. Eggert, A.; Thiesbrummel, C.; Deutscher, C. Heading for New Shores: Do Service and Hybrid Innovations Outperform Product Innovations in Industrial Companies? *Ind. Mark. Manag.* **2015**, *45*, 173–183. [CrossRef]
37. Plumeyer, A.; Kottemann, P.; Böger, D.; Decker, R. Measuring Brand Image: A Systematic Review, Practical Guidance, and Future Research Directions. *Rev. Manag. Sci.* **2019**, *13*, 227–265. [CrossRef]
38. Aghion, P.; Cai, J.; Dewatripont, M.; Du, L.; Harrison, A.; Legros, P. Industrial Policy and Competition. *Am. Econ. J.—Macroecon.* **2015**, *7*, 1–32. [CrossRef]
39. Huang, K.; Wang, J.; Zhang, J. Automotive Supply Chain Disruption Risk Management: A Visualization Analysis Based on Bibliometric. *Processes* **2023**, *11*, 710. [CrossRef]
40. Fan, Y.; Yang, C. Competition, Product Proliferation, and Welfare: A Study of the US Smartphone Market. *Am. Econ. J. Microecon.* **2020**, *12*, 99–134. [CrossRef]
41. Barlybayev, A.; Sharipbay, A.; Shakhmetova, G.; Zhumadillayeva, A. Development of a Flexible Information Security Risk Model Using Machine Learning Methods and Ontologies. *Appl. Sci.* **2024**, *14*, 9858. [CrossRef]
42. Albasoos, H.; Musallami, N. The Conflict between Apple and Samsung over Patents and Copyrights. *Bussecon Rev. Soc. Sci. (2687-2285)* **2020**, *3*, 1–17. [CrossRef]
43. Szász, L.; Csíki, O.; Rácz, B.-G. Sustainability Management in the Global Automotive Industry: A Theoretical Model and Survey Study. *Int. J. Prod. Econ.* **2021**, *235*, 108085. [CrossRef]