Research on Digital Transformation Coordination Mechanism of Vehicle Enterprises Based on Tripartite Evolutionary Game Model

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Abstract. Industry-University-Research (IUR) collaboration network is an important driving force for digital transformation. At the same time, under the background of manufacturing service transformation, policy support and consumer demand are crucial to the digital transformation of vehicle enterprises. Therefore, this paper constructs a tripartite evolutionary game model for the digital transformation of government—industry—university—research—consumer which guided by the government, led by the pan-automotive industry bodies, and collaborated with consumers. Combined with numerical simulation analysis, this article examines the factors that influence the choice of digital transformation strategies. The results show that the degree of government guidance is related to the initial willingness of vehicle enterprises and consumers; vehicle enterprises and consumers have asymmetrical influence on each other; the establishment of a digital coordination mechanism needs to play a moderating role of blocking factors. Finally, based on the status quo of digital transformation of our country's vehicle enterprises, relevant suggestions are given in terms of improving consumers' willingness and net incomes.

Keywords: digital transformation · tripartite evolutionary game model · government—industry—university—research—consumer

1 Introduction

The new round of scientific and technological revolution and industrial changes are surging, leading the world to enter a period of economic development dominated by the information industry, and digital transformation is the general trend. The digital transformation of vehicle enterprises requires that the personalized needs of consumers be penetrated into the entire life cycle of the vehicles. In recent years, vehicle enterprises have established digital transformation platforms of IUR covering the main bodies of the pan-automotive industry, in order to better understand consumers and iterate agilely. However, it is still in the stage of digital exploration. Enterprises are facing difficulties and concerns such as insufficient transformation capabilities, high transformation costs, and external consumers are faced with concerns such as high participation costs and personal information leakage risks, which restrict the input of demand-side data. Therefore, the

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results of the digital transformation of vehicle enterprises are not satisfactory. In order to gain an advantage in the new round of international competition, our country has followed the footsteps of developed countries to upgrade digital transformation to a national strategy, at the same time, government departments are actively building a governance system related to digital transformation. This article regards the main bodies of the pan-automotive industry in the platform of IUR as a unified whole, and puts the government and consumer as the main bodies into the game. By constructing a tripartite evolutionary game model, it analyzes the digital transformation mechanism guided by the government, led by the pan-automotive industry bodies, and collaborated with consumers. Finally, it provides theoretical support for digital transformation.

2 Establish the Payment Matrix

2.1 Model Hypothesis

Each subject in the tripartite evolutionary game is bounded rationally, so the whole process is not a one-time game, but a process in which subjects continue to learn and imitate from high-yield groups through multiple games over time and finally find the optimal strategies.

2.1.1 Participants

This article assumes that there are three types of participants in the system, namely the government (G) [1], the pan-automotive industry bodies centered on vehicle enterprises (E, hereinafter referred to as vehicle enterprises), and end consumers (U) [2]. The government mainly provides policy guidance, capacity support and compliance supervision; vehicle enterprises are mainly responsible for digital demand expression, collaborative information acquisition, digital technology transformation, business value creation, etc.; end consumers provide heterogeneous demand data and behavioral data as basic resources for digital transformation.

2.1.2 Cooperation Strategy

In the process of digital transformation, the government strategy set is (participation, non-participation); the vehicle enterprise strategy set is (participation, non-participation); consumers determine the degree of data authorization based on the degree of trust in the enterprises, and the strategy set is (strong dependence, weak dependence).

2.1.3 Cooperation Cost

C_1, C_2 represent the initial costs of government and vehicle enterprises participating in digital transformation. When consumers choose strong dependence, they will invest a certain cost C_3. When consumers choose weak dependence, the investment cost and the additional cost of enterprises participating in collaborative innovation are related to the degree of collaborative openness a, respectively $a * C_3$, $a * C_{co}$. Government participation will reduce the collaborative costs of enterprises and consumers. Assuming that m, n are the co-innovation cost reduction coefficients of vehicle enterprises and consumers, the costs of the two under government participation are respectively $m * (C_2 + a * C_{CO})$, $n * a * C_3$.

2.1.4 Cooperation Income

R_1,R_4 represent the inherent incomes of government participation and non-participation in digital transformation, R_2,R_3 represent the inherent incomes of vehicle enterprises and consumers. The joint income of vehicle enterprises and consumers is R_{CO}, the distribution coefficient [3] of the enterprises is β, so the joint income of enterprises is $\beta * R_{CO}$, and the joint income of consumers is $(1 - \beta) * R_{CO}$. Suppose the degree of collaboration and openness between consumers and enterprises is a, when consumers choose weak dependence, the joint incomes of enterprises and consumers are respectively $\beta * a * R_{CO}$,$(1 - \beta) * a * R_{CO}$. Suppose the government's coordinated income conversion coefficient is r_g, the government's joint income increases $r_g * a * R_{CO}$.

2.2 Income Payment Matrix

In the game model, it is assumed that the probability of government, vehicle enterprises and consumers participating in digital transformation is x, y, z. Combining model assumptions, the following digital transformation game payment matrixes are obtained (Table 1).

Table 1. Payment Matrix

Strategies	Government	Enterprises	Consumers
(p, non-p, strong dependence)	$R_1 + r_g * R_{CO} - C_1$	$R_2 + \beta * R_{CO} - m * (C_2 + C_{CO})$	$R_3 + (1 - \beta) * R_{CO} - n * C_3$
(p, p, weak dependence)	$R_1 + r_g * a * R_{CO} - C_1$	$R_2 + \beta * a * R_{CO} - m(C_2 + a * C_{CO})$	$R_3 + (1 - \beta) * a * R_{CO} - n * a * C_3$
(p, non-p, strong dependence)	$R_1 - C_1$	R_2	$R_3 - n * C_3$
(p, non-p, weak dependence)	$R_1 - C_1$	R_2	R_3
(non-p, p, strong dependence)	$R_4 + r_g * R_{CO}$	$R_2 + \beta * R_{CO} - (C_2 + C_{CO})$	$R_3 + (1 - \beta) * R_{CO} - C_3$
(non-p, p, weak dependence)	$R_4 + r_g * a * R_{CO}$	$R_2 + \beta * a * R_{CO} - (C_2 + a * C_{CO})$	$R_3 + (1 - \beta) * a * R_{CO} - a * C_3$
(non-p, non-p, strong dependence)	R_4	R_2	$R_3 - C_3$
(n, non-p, weak dependence)	R_4	R_2	R_3

3 Solve Evolutionary Stability Strategy

3.1 Build Income Functions

According to the payment matrixs, the expected net income of the government choosing the "participation" strategy, "non-participation" strategy, and the average expected net income are as follows.

$$E(x) = yz[R_1 + r_g * R_{co} - C_1] + y(1-z)[R_1 + r_g * a * R_{co} - C_1]+ \\ (1-y)z[R_1 - C_1] + (1-y)(1-z)[R_1 - C_1] \tag{1}$$

$$E(1-x) = yz[R_4 + r_g * R_{co}] + y(1-z)[R_4 + r_g * a * R_{co}]+ \\ (1-y)z * R_4 + (1-y)(1-z) * R_4 \tag{2}$$

$$\overline{E}_g = xE(x) + (1-x)E(1-x) \tag{3}$$

The expected net income of vehicle enterprises choosing the "participation" strategy, "non-participation" strategy, and the average expected net income are as follows.

$$E(y) = xz[R_2 + \beta * R_{co} - m * (C_2 + C_{co})] + x(1-z)[R_2+ \\ \beta * a * R_{co} - m * (C_2 + a * C_{co})] + (1-x)z[R_{2_2} + \beta * R_{co}- \\ (C_2 + C_{co})] + (1-x)(1-z)[R_2 + \beta * a * R_{co} - (C_2 + a * C_{co})] \tag{4}$$

$$E(1-y) = xzR_2 + x(1-z)R_2 + (1-x)z * R_2 + (1-x)(1-z)R_2 \tag{5}$$

$$\overline{E}_e = yE(y) + (1-y)E(1-y) \tag{6}$$

The expected net income of consumers choosing the "strong dependence" strategy, "weak dependence" strategy, and the average expected net income are as follows.

$$E(z) = xy[R_3 + (1-\beta) * R_{co} - n * C_3] + x(1-y)[R_3 - n * C_3]+ \\ (1-x)y[R_3 + (1-\beta) * R_{co} - C_3] + (1-x)(1-y)(R_3 - C_3) \tag{7}$$

$$E(1-z) = xy[R_3 + (1-\beta) * R_{CO} - n * a * C_3] + x(1-y)R_3+ \\ (1-x)y[R_3 + (1-\beta) * a * R_{CO} - a * C_3] + (1-x)(1-y)R_3 \tag{8}$$

$$\overline{E}_u = zE(z) + (1-z)E(1-z) \tag{9}$$

3.2 Strategy Analysis Based on Replicated Dynamic Equation

From the income functions, the replicated dynamic equations of the government, vehicle enterprises and consumers can be obtained as follows.

$$F(x) = \frac{dx}{dt} = x[E(x) - \overline{E}_g] = x(1-x)(R_1 - C_1 - R_4) \tag{10}$$

$$F(y) = \frac{dy}{dt} = y[E(y) - \overline{E}_e] = y(1-y)[xz(1-m)(1-a)C_{co} + x(1-m)(C_2 + aC_{co}) + z(1-a)(\beta * R_{co} - C_{co}) + (\beta aR_{co} - C_2 - aC_{co})] \tag{11}$$

$$F(z) = \frac{dz}{dt} = z[E(z) - \overline{E}_u] = z(1-z)\{xya(n-1)C_3 + x(1-n)C_3 + y[(1-\beta)(1-a)R_{co} + aC_3] - C_3\} \tag{12}$$

Let $F(x) = F(y) = F(z) = 0$, obtain the local stable equilibrium points: $E_1(0, 0, 0)$, $E_2(1, 0, 0)$, $E_3(0, 1, 0)$, $E_4(0, 0, 1)$, $E_5(0, 1, 1)$, $E_6(1, 0, 1)$, $E_7(1, 1, 0)$, $E_8(1, 1, 1)$.

3.3 Stability Analysis of Equilibrium Points

According to the method proposed by Friedman, the evolutionary stability strategy (ESS) can be obtained from the local stability analysis of the Jacobian matrix of the system, that is, the evolutionary stability points of the system are such that all eigenvalues of the Jacobian are non-positive. According to the replicated dynamic equations, the Jacobian matrix of the system is as follows. Substitute 8 equilibrium points into the Jacobian matrix to obtain the eigenvalues. The results are shown in the Table 3 below.

$$\begin{bmatrix} (1-2x)(R_1 - C_1 - R_4) & 0 & 0 \\ y(1-y)[z(1-m)(1-a)C_{co} + (1-m)(C_2 + aC_{co})] & (1-2y)[xz(1-m)(1-a)C_{co} + x(1-m)(C_2 + aC_{co}) + z(1-a)(\beta R_{co} - C_{co}) + (\beta aR_{co} - C_2 - aC_{co})] & y(1-y)(1-a)(\beta R_{co} - C_{co}) \\ z(1-z)(1-n)C_3(1-ya) & z(1-z)[xa(n-1)C_3 + (1-\beta)(1-a)R_{co} + aC_3] & (1-2z)\{xya(n-1)C_3 + x(1-n)C_3 + y[(1-\beta)(1-a)R_{co} + aC_3] - C_3\} \end{bmatrix}$$

In order to analyze the positive and negative characteristics of eigenvalues, this article is based on the assumption that the net incomes of digital transformation of the government, vehicle enterprises and consumers are greater than the net incomes of non-participation:$R_1 - C_1 - R_4 > 0$,$\beta R_{co} - C_2 - C_{co} > 0$,$(1-\beta)R_{co} - C_3 > 0$. Due to the uncertainty of the positive and negative characteristics of some eigenvalues, we classify and discuss the stable strategies of evolutionary games.

Situation 1: $\beta aR_{co} - m(C_2 + aC_{co}) < 0$. Which means when consumers choose weak dependence, the net incomes of enterprises participating in digital transformation are less than those of not participating. The eigenvalues of the Jacobian matrix corresponding to the equilibrium points $E_2(1, 0, 0)$ and $E_8(1, 1, 1)$ are all negative.

Situation 2: $\beta aR_{co} - m(C_2 + aC_{co}) > 0$. Which means when consumers choose weak dependence, the net incomes of the enterprises' participation in digital transformation are still more than the incomes of non-participation. The eigenvalues of the Jacobian matrix corresponding to the equilibrium point $E_8(1, 1, 1)$ are all negative.

4 Data Analysis

Based on the above analysis, combined with Matlab simulation to explore the influence of each force on the strategies. In the results, the abscissa *t* represents time and the ordinate *P* represents the probability of the subject choosing different strategies over time. In order to ensure the reasonableness, the parameter setting follows the following rules [4]: $C_3 < C_1 < C_2 < C_{co}$, $R_{co} > R_1 > R_2 > R_4 > R_3$, $\beta a R_{co} - m(C_2 + aC_{co}) < 0$, $R_1 - C_1 - R_4 > 0$, $\beta R_{co} - C_2 - C_{co} > 0$, $(1 - \beta)R_{co} - C_3 > 0$, the coefficients including m, n, a, b are between [0, 1], each subject has a neutral attitude towards digital transformation in the initial state which means $x = y = z = 0.5$. Based on the above rules, the parameters are set as follows [2, 5]: $R_1 = 40$, $R_2 = 35$, $R_3 = 10$, $R_4 = 20$, $R_{co} = 100$, $C_1 = 10$, $C_2 = 35$, $C_3 = 8$, $C_{co} = 40$, $m = n = 0.7$, $\beta = 0.9$, $a = 0.1$.

4.1 Simulation Analysis Under the Influence of Government

The government mainly influences the strategies from two aspects: the initial willingness and the cost reduction coefficients. When the subjects' initial willingness is the same and other conditions remain unchanged, the cutoff of the initial willingness is between 0.4 and 0.5, and when it is less than or more than the cutoff, system will eventually tend to stable strategies (participation, non-participation, weak dependence) or (participation, participation, strong dependence); as the initial willingness increases, the speed at which x converges to 1 slows down, and the speed at which y and z converge to 1 speeds up. It shows that when the initial willingness of enterprises and consumers are not very strong, the government will quickly play its leading role to accelerate the strategic choices of enterprises and consumers (Fig. 1).

4.1.1 Simulation Analysis of Initial Willingness

At the same time, simulation analysis results show that when enterprises and consumers have a high initial willingness, even if the government's willingness is low, enterprises

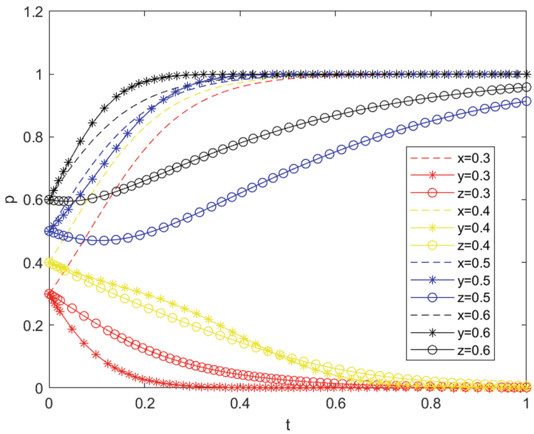

Fig. 1. Result of simultaneous changes of X, Y, Z

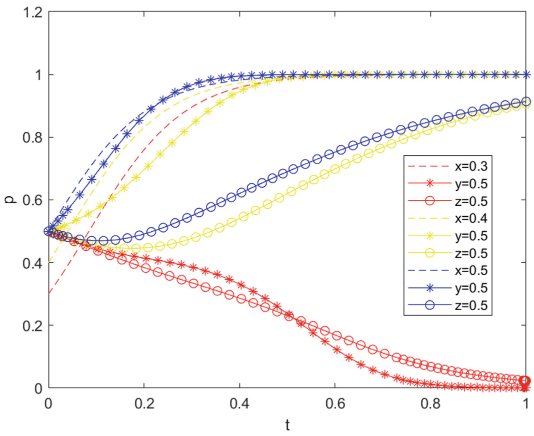

Fig. 2. Results of changes of x

and consumers will choose strategies (participation, strong dependence); when the initial willingness of enterprises and consumers are low, even if the government's willingness is high, enterprises and consumers will eventually choose strategies (non-participation, weak dependence). It shows that market orientation is the key to strategy selection. When the initial willingness of enterprises and consumers are too low or too high, changes in the initial willingness of the government can only change the speed of strategic convergence.

Otherwise, the results show that the cutoff of the government's initial willingness the is between 0.3 and 0.4. When x is less than or more than the cutoff, system eventually tends to stable strategies (participation, non-participation, weak dependence), (participation, participation, strong dependence); with the increase in the government's willingness, the willingness of enterprises and consumers have increased, and the willingness of enterprises is greatly affected by the government. It shows that when the initial willingness of enterprises and consumers are in a medium state, the government's strategic choice will determine the final stable strategies, and enterprises are more sensitive to the government's strategic choice (Fig. 2).

4.1.2 Simulation Analysis of Cost Reduction Coefficients

The results show that the cutoffs of m and n are between 0.7–0.8 and 0.8–0.9. When the coefficients are higher or lower than the cutoffs, system eventually tends to be stable strategies (participation, non-participation, weak dependence), (participation, participation, strong dependence). It shows that when the willingness of each subject is at a moderate level and government participation cannot cause a significant reduction in the participation costs, it is difficult to establish a digital transformation coordination mechanism (Fig. 3).

4.2 Simulation Analysis Under Directly Participating Subjects

The results show that when the government and consumers' willingness are both at a moderate level, the cutoff of y is between 0.3 and 0.4, and when y is less than or

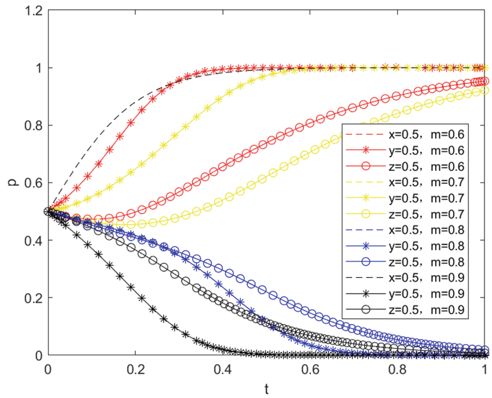

Fig. 3. Results of changes of m(left), n(right)

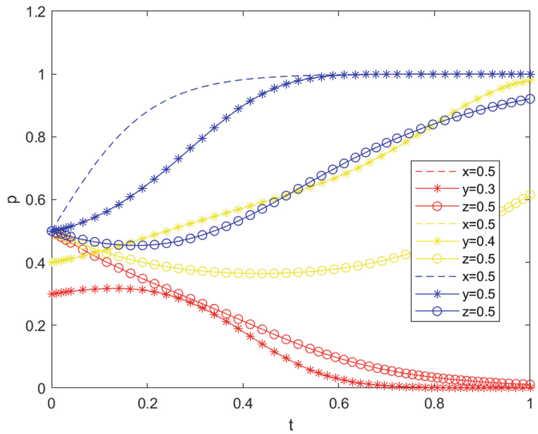

Fig. 4. Results of changes of y(left), z(right)

more than the cutoff, the final strategy tends to be stable strategies(participation, non-participation, weak dependence), (participation, participation, strong dependence). It shows that the initial willingness of enterprises will affect consumers' strategic choices within a certain range, and the increase of their willingness has a pulling effect on consumers' willingness. And when the government and the enterprises' willingness are both in a medium level, the cutoff of z is between 0.4 and 0.5. When z is less than or more than the cutoff, the system tends to be stable strategies (participation, non-participation, weak dependence) and (participation, participation, strong dependence). It shows that consumers' initial willingness will affect the strategic choices of enterprises within a certain range, and the increase of their initial willingness has a pulling effect on enterprises' willingness (Fig. 4).

According to Fig. 5, when consumers' initial willingness is high, even if the enterprises' initial willingness is low, system will eventually tend to a stable strategies (participation, participation, strong dependence); Similarly, when the initial willingness of

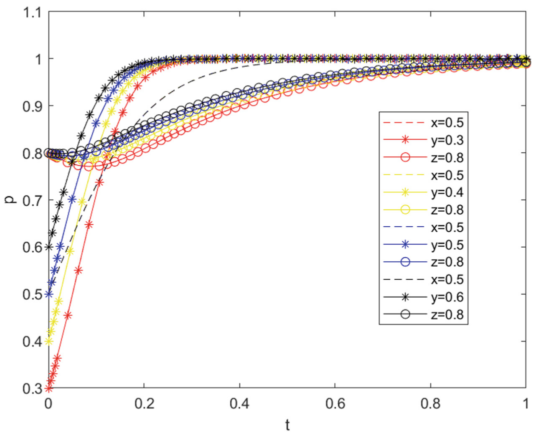

Fig. 5. Results of changes of y(left), z(right)

consumers is very low, even if the initial willingness of the enterprises is high, system will eventually tend to a stable strategies (participation, non-participation, weak dependence). It shows that under the circumstance that the government's willingness remain unchanged, the influence of consumers' willingness on enterprises is greater than the influence of enterprises' willingness on consumers.

5 Conclusion

Based on the premise of the limited rationality of the participants, this paper uses the evolutionary game theory to establish a game model for the digital transformation guided by the government, led by the pan-automotive industry bodies, and collaborated with consumers. It classify and analyze the strategy choices of the government, enterprises and consumers under different conditions, and then combined with numerical analysis, examined the digital transformation strategies and behaviors of the participants and their influencing factors. The following conclusions are reached.

Firstly, the effect of government regulation is related to the initial willingness. ① When the initial willingness of enterprises and consumers are both at a medium level, the increase of government willingness will have a pulling effect on their willingness; ② When the willingness of enterprises and consumers are relatively clear, the government will not affect the strategy choices; ③ If government participation cannot reduce the costs significantly, it is difficult to establish a transformation mechanism.

Secondly, there is an asymmetry in the influence of enterprises and consumers on each other, and consumers have a greater influence on the enterprises, which is the key to establish a digital collaboration mechanism.

Thirdly, the establishment of a digital coordination mechanism needs to play the role of blocking factors, system need coordinate the perception of fairness between enterprises and consumers, and at the same time increase the degree of openness of consumer basic coordination.

In summary, consumers are at the core of the establishment of digital transformation mechanism. The government should conduct selective data disclosure, improve data privacy-related laws and regulations, strengthen data privacy supervision, and encourage the research and promotion of data security related technologies; vehicle enterprises should improve their data governance systems, use private domain traffic to benefit target consumers, establish mutual trust with end consumers, and achieve a win-win business closed loop of "investment-mutual trust-profit-investment" through refined operation management. All in all, the government and enterprises need work together to increase consumer willingness, reduce consumer participation costs, and increase consumer participation benefits.

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