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Using Evolutionary Game Theory to Study Behavioral Strategies of the Government and Carriers Under Different Transshipment Modes

LIJUAN YANG[1,2], YU ZHANG[1], RAYMOND CHIONG[3], (Senior Member, IEEE), SANDEEP DHAKAL[3], AND QIANGQIANG QI[1]
[1]School of Logistics Engineering, Wuhan University of Technology, Wuhan 430063, China
[2]School of Management, Guilin University of Aerospace Technology, Guilin 541004, China
[3]School of Electrical Engineering and Computing, The University of Newcastle, Callaghan, NSW 2308, Australia

Corresponding author: Yu Zhang (sanli@whut.edu.cn)

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ABSTRACT Due to severe congestion before the Three Gorges Dam, roll-on/roll-off and container carriers are encouraged to adopt water-land transshipment mode. Owing to high transit and road costs, however, carriers are reluctant to adopt this mode. In this paper, we study the spatial-temporal relationship between the transshipment mode and the transshipment cost. Furthermore, we analyze the feasibility of subsidy strategies with regards to water-land transshipment from the standpoint of the government. An evolutionary game theory model is used to identify the equilibrium points of transshipment and non-transshipment, as well as subsidy and non-subsidy strategies available to carriers and the government, respectively, under different scenarios. With a transshipment job for a major carrier as an example, freight prices offered by carriers and subsidies provided by the government under water-road and water-road-water modes are analyzed, with the aim of providing strategic input for both the government and the carriers.

INDEX TERMS Three Gorges Dam, transshipment, evolutionary game theory.

I. INTRODUCTION

Inland waterway transport, which is characterized by its ability to handle large capacity, low transportation cost, and environment-friendliness, has attracted much attention owing to globalization and growing foreign trade volumes. In China, the Yangtze river plays a leading role with a total cargo volume of 2.69 billion tons in 2018, and is an irreplaceable transport corridor. It has been the busiest navigable inland waterway in the world since 2006.

The Three Gorges Dam (TGD), at the upper stream of the Yangtze River, has been an infrastructure bottleneck due to the insufficient navigation capacity of locks [1]–[4] (see Figure 1). According to Three Gorges' Navigation Authority, there are 300 ships, on average, waiting for passing locks daily, with a delay of at least 3 days. Occasionally, the TGD has to implement reverse-directional single lock operations for emergencies such as extreme weather conditions,

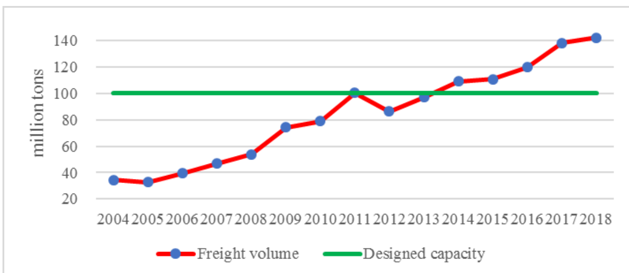

FIGURE 1. Development of the TGD.

accidents, and equipment malfunctions [3], [4], which further aggravates congestion. Thus, the TGD is a major impediment to the future development of the Yangtse river as an inland transport corridor [4], [5].

In the United States, similar lock congestion is common on the Upper Mississippi River (UMR) [6]–[12]. Various alternative strategies and improvements have been considered for relieving traffic congestion, and several simulation tools

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have also been developed to validate such strategies with the help of queuing theories [8], [13]. A fixed effects regression model with regards to lock usage and lock characteristics for alleviating congestion on individual locks along the UMR system was proposed by Reynaerts [14]. A non-parametric model to relieve congestion, taking into account the arrival, waiting and lockage time of vessels at the UMR's locks, was presented by Zhang *et al.* [15].

Congestion problems on the Three Gorges-Gezhouba Dam (TGGD) have also attracted the attention of researchers and practitioners, with the goal of reducing the waiting time and alleviating navigation pressure. Due to the limited capacity and insufficient throughput constraints of the dam, high traffic density has led to increased congestion and delays. Studies were conducted on an optimal co-scheduling strategy for the two dams at the Three Gorges with regards to operational and dispatch scheduling to minimize the total weighted tardiness or the waiting time of ships [16]. Wang and Ruan [17] and Wang *et al.* [18] provided mathematical models to minimize the total navigation ship-lock waiting time under multiple constraints for the TGGD co-scheduling problem.

Other solutions for relieving lock congestion problems, such as building new locks [10] or adding more parallel channels [16], can be found in the relevant literature too, but they are generally very expensive and face restrictions owing to spatial and geographical conditions. Lock capacity expansion on the Mississippi River system and China waterway system have also been discussed [6], [19], [20]. Besides being prohibitively expensive, such solutions have a significant environmental impact and will, therefore, encounter major implementation issues.

To address congestion issues and increased freight volumes, the Three Gorges Transshipment System has been developed as an alternative transportation mode, which facilitates Roll-on/Roll-off (RO-RO) and allows container ships to transfer cargoes by water-land or water-land-water transshipment mode. In transshipment mode, cargoes are unloaded on the docks or terminals in front of locks, and then transported by land transport such as road and railway. The South Transshipment Highway has already opened to traffic, and carriers are encouraged to engage in transshipment to alleviate congestion (see Figure 2). Despite convenient transshipment conditions, the transshipment ratio is quite low because of the carriers' reluctance to take this mode owing to high transit and road transportation costs. Models of locks and different kinds of water–land transshipment of mixed transportation systems for the TGD were established in [3] and [21]. However, none of them discussed research focusing on issues of subsidy policy of the government, behavioral strategies of the government and carriers, and carrier pricing.

Subsidization, which is a price-based instrument of governments, can potentially enable carriers to offer a more competitive freight price and thus improve the transshipment ratio. Evolutionary game theory has proven to be an effective analytical tool for studying the relationship between

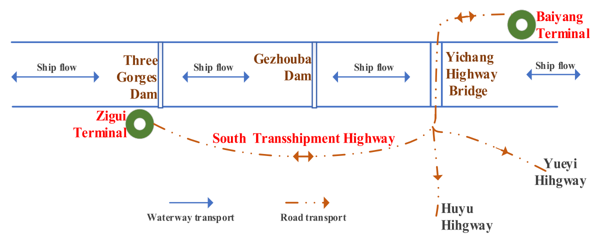


FIGURE 2. **Water-land transshipment at the TGD.**

policy makers like governments and receptors like ship carriers. However, there is no previous work regarding the behavioral strategy of carriers and the government for the Three Gorges Transshipment System. Similarly, the impact of different government subsidy policies for the carriers has been considered by only a few prior studies. Effective policy guidance is, therefore, required to regulate, guide and adjust ship flows for reducing congestion pressure and improving the utilization of road infrastructure.

Considering the issues discussed above, we propose an evolutionary game theory model to address the following questions:

(1) How can we understand the behavioral strategies of RO-RO and container carriers toward the adoption of transshipment in case of congestion? Or should they wait for lockage mode regardless of the time and delay costs?

(2) Should the government provide subsidies to the carriers for encouraging transshipment mode to reduce the congestion pressure before the TGD? Will government subsidies be effective in promoting transshipment mode?

(3) Given various subsidy mechanisms, which mechanism is the best for encouraging carriers to adopt transshipment mode for congestion alleviation? Or what is the suitable freight price for carriers to adopt transshipment mode under different transshipment modes?

(4) Should subsidies be the same for water-road or water-road-water transshipment modes? More importantly, can subsidies really achieve the desired result of congestion alleviation?

Based on the above questions, we explore different transshipment mechanisms to elaborate the spatial-temporal relationship between different transshipment modes and the transshipment cost, with the aim of explaining the effect of government policies on the behavior of carriers, and determining whether carriers would adopt transshipment in response to government subsidies. Given the above, this paper contributes to the literature by exploring this research avenue, and major contributions of our study can be summarized as follows:

- This work takes the lead in studying behavioral strategies of the government and carriers in the transshipment system of the TGD, and provides suggestions to the government and shipping enterprises for the development of long-term strategic decisions by incorporating transshipment;

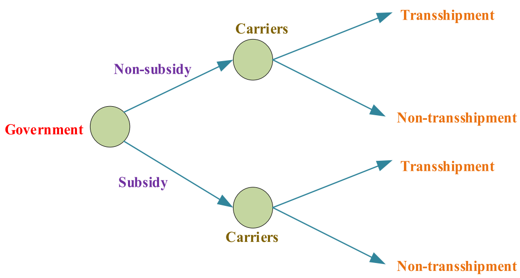


FIGURE 3. A tree structure of the government and carriers for the evolutionary game model.

- It is found that subsidy schemes can contribute toward alleviating the congestion before the TGD. This can also provide policy guidelines for other transshipment modes, such as water-railway-water or water-railway transshipment modes;

The rest of this paper is organized as follows. Our model construction and analysis are presented in Section II. In Section III, we present a case study for understanding the relationship between the government and carriers, and discuss the results of simulation experiments conducted to verify the evolutionary stable strategy (ESS). Finally, our conclusion is drawn in Section IV.

II. MODEL ESTABLISHMENT

A. BASIC ASSUMPTIONS

Hypothesis 1. Main participants in the game model are the local government and carriers, who are faced with uncertain situations and have bounded rationality. Initially, their behavioral strategies are not optimal because of the lack of complete information. Through constant exploration and the availability of more information, they can gradually find suitable behavioral strategies.

Hypothesis 2. Carriers act to maximize their profits and can opt for either transshipment and non-transshipment. The local government acts as the policymaker, and there are two policies available: subsidy and non-subsidy with maximum profits. In the case of government subsidy to carriers, it cannot exceed their cost.

Hypothesis 3. Given the assumption that carriers adopt the transshipment strategy with probability x ($0 < x < 1$), the opposing non-transshipment strategy has a probability of $1 - x$. The selection probability of the subsidy strategy by the government is y ($0 < y < 1$), whereas the selection probability of non-subsidy is $1 - y$. In selecting their strategies, each party hopes to maximize its own utility. The tree structure of the game model under different strategies is shown in Figure 3.

B. EVOLUTIONARY GAME MODELING

Based on the above assumptions, parameters and variable symbols with their descriptions are shown in Table 1. Similarly, the income matrix of game participants under different strategies is shown in Table 2.

TABLE 1. Parameter and variable symbol descriptions.

Parameters	Descriptions
k	RO-RO and container ships
Q	Ship freight volume
π_k^1	Profit of carriers via transshipment mode
π_k^2	Profit of carriers via lockage mode
C_k^1	Cost of carriers via transshipment mode
C_k^2	Cost of carriers via lockage mode
F_1	Government profit with carriers' transshipment mode
F_2	Government profit with carriers' lockage mode
S	Subsidies for carriers by the government
C_g^1	Management cost paid by the government
C_g^2	Supervision cost for the government with carriers' lockage mode

TABLE 2. The payoff matrix.

		Carriers	
		Transshipment (x)	Non-transshipment ($1-x$)
Government	Subsidy (y)	$F_1 - C_g^1 - S$ $\pi_k^1 - C_k^1 + S$	$F_2 - C_g^1 - C_g^2 - S$ $\pi_k^2 - C_k^2 + S$
	Non-subsidy ($1-y$)	$F_1 - C_g^1$ $\pi_k^1 - C_k^1$	$F_2 - C_g^1 - C_g^2$ $\pi_k^2 - C_k^2$

According to Table 2, we can get the profit functions for both the government and carriers under different strategies as follows:

The profit when carriers choose to carry out transshipment activities is:

$$U_{11} = y(\pi_k^1 - C_k^1 + S) + (1 - y)(\pi_k^1 - C_k^1) \quad (1)$$

The profit when carriers choose to carry out non-transshipment activities is:

$$U_{12} = y(\pi_k^2 - C_k^2 + S) + (1 - y)(\pi_k^2 - C_k^2) \quad (2)$$

The average expected payoff is represented as follows:

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

The profit when the government chooses to offer subsidies is:

$$U_{21} = x(F_1 - C_g^1 - S) + (1 - x)(F_2 - C_g^1 - C_g^2 - S) \quad (4)$$

The profit when the government chooses not to offer subsidies is:

$$U_{22} = x(F_1 - C_g^1) + (1 - x)(F_2 - C_g^1 - C_g^2) \quad (5)$$

TABLE 3. Determinants and traces of the Jacobian matrix for different equilibrium points.

	$Det(J)$	$Tr(J)$
(0,0)	-AS	A-S
(0,1)	AS	A+S
(1,0)	AS	-(A+S)
(1,1)	-AS	-(A-S)

The average expected payoff is represented as follows:

$$U_2 = yU_{21} + (1-y)U_{22} \tag{6}$$

The evolutionary replicator dynamics equation when carriers choose the transshipment strategy is:

$$F_x = dx/dt = x(U_{11} - U_1) = x(1-x)(\pi_k^1 - C_k^1 - \pi_k^2 + C_k^2) \tag{7}$$

The replicator dynamics equation when the government chooses to offer subsidies is:

$$F_y = dy/dt = y(U_{21} - U_2) = y(1-y)(-S) \tag{8}$$

According to Friedman [22], the stability of equilibrium points can be analyzed using the Jacobian matrix. The Jacobian matrix of the above replicator dynamics system (I) is as follows:

$$J = \begin{bmatrix} \frac{\partial F_x}{\partial x} & \frac{\partial F_x}{\partial y} \\ \frac{\partial F_y}{\partial x} & \frac{\partial F_y}{\partial y} \end{bmatrix} = \begin{bmatrix} J_{11} J_{12} \\ J_{21} J_{22} \end{bmatrix} \tag{9}$$

$$J_{11} = (1-2x)(\pi_k^1 - C_k^1 - \pi_k^2 + C_k^2) \tag{10}$$

$$J_{22} = (1-2y)(-S) \tag{11}$$

$$J_{12} = 0 \tag{12}$$

$$J_{21} = 0 \tag{13}$$

$$\begin{aligned} Det\,(J) &= (J_{11}J_{22} - J_{12}J_{21}) = [(1-2x) \\ &\quad \times (\pi_k^1 - C_k^1 - \pi_k^2 + C_k^2) \times (1-2y)(-S)] - 0 \\ &= (1-2x)(1-2y)(\pi_k^1 - C_k^1 - \pi_k^2 + C_k^2)(-S) \end{aligned} \tag{14}$$

$$\begin{aligned} Tr\,(J) &= J_{11} + J_{22} = (1-2x)(\pi_k^1 - C_k^1 - \pi_k^2 \\ &\quad + C_k^2) + (1-2y)(-S) \\ &= (1-2x)(\pi_k^1 - C_k^1 - \pi_k^2 + C_k^2) - S(1-2y) \end{aligned} \tag{15}$$

Let $A = \pi_k^1 - C_k^1 - \pi_k^2 + C_k^2$, then, different equilibrium points of the Jacobian matrix are shown in Table 3.

Proposition 1. The equilibrium points of the replicator dynamics system (I) are (0,0), (0,1), (1,0), (1,1).

Proof 1. To seek the system's stable strategy, let the replicator dynamic equation of the government and carriers be zero, i.e., $F_x = 0$, $F_y = 0$; then, we get the equilibrium points as (0,0), (0,1), (1,0), (1,1).

Proposition 2.

(1) Case 1: When A<0, S>0, A-S<0, A+S>0, there exists an ESS (0,0) in the replicator dynamics system (I). The behavior strategy is (Non-transshipment, Non-subsidy). The evolutionary path is displayed in Figure 4(a).

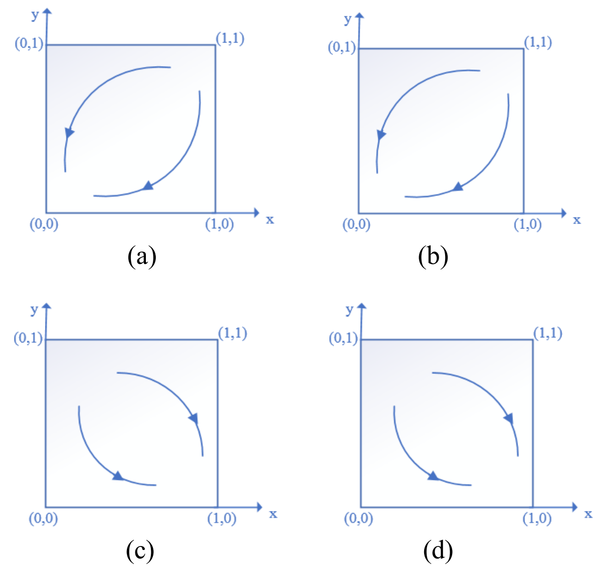


FIGURE 4. Local stability of the evolutionary game between the government and carriers.

(2) Case 2: When A<0, S>0, A-S<0, A+S<0, then (0,0) is an ESS in the replicator dynamics system (I). The behavior strategy is (Non-transshipment, Non-subsidy). The evolutionary path is displayed in Figure 4(b).

(3) Case 3: When A>0, S>0, A+S>0, A-S>0, the replicator dynamic system (I) has an ESS of (1,0). The behavior strategy is (Transshipment, Non-subsidy). The evolutionary path is displayed in Figure 4(c).

(4) Case 4: When A>0, S>0, A+S>0, A-S<0, then (1,0) is an ESS in the replicator dynamic system (I). The behavior strategy is (Transshipment, Non-subsidy). The evolutionary path is displayed in Figure 4(d).

Proof 2.

We analyze the local stability of the four equilibrium points obtained from Proposition 1 under different constraints. From Figures 4(a)-(b) and Table 4, (0,0) has the local stability under Cases 1 and 2, as it represents a stable equilibrium in the system evolution and the ESS of (Non-transshipment, Non-subsidy). With carriers and the government choosing non-transshipment and non-subsidy strategies, respectively, the system's evolutionary equilibrium reaches a stable state with the maximum payoff for both players. (1,1) indicates an unstable system evolutionary equilibrium, and (0,1) and (1,0) are saddle points.

Similarly, from Figures 4(c)-(d) and Table 5, the system converges to (1,0), which has local stability under Cases 3 and 4. Therefore, the only ESS for the system is when carriers choose to adopt transshipment mode, and the government would not offer subsidies. (0,0) and (1,1) are saddle points, and (0,1) is the unstable system evolutionary equilibrium.

III. NUMERICAL SIMULATION ANALYSIS

China Changjiang National Shipping Group Company Ltd (CCNSC) is the largest shipping company in China for inland

TABLE 4. Local stability analysis of the evolutionary game between the government and carriers.

Cases 1, 2						
Equilibrium points	A<0					
	S>0					
	A-S<0					
	A+S>0 (a)			A+S<0 (b)		
	$Det(J)$	$Tr(J)$	State	$Det(J)$	$Tr(J)$	State
(0,0)	+	-	ESS	+	-	ESS
(0,1)	-	+	Saddle point	-	-	Saddle point
(1,0)	-	-	Saddle point	-	+	Saddle point
(1,1)	+	+	Instability point	+	+	Instability point

TABLE 5. Local stability analysis of the evolutionary game between the government and carriers.

Cases 3,4						
Equilibrium points	A>0					
	S>0					
	A+S>0					
	A-S>0 (a)			A-S<0 (b)		
	$Det(J)$	$Tr(J)$	State	$Det(J)$	$Tr(J)$	State
(0,0)	-	+	Saddle point	-	-	Saddle point
(0,1)	+	+	Instability point	+	+	Instability point
(1,0)	+	-	ESS	+	-	ESS
(1,1)	-	-	Saddle point	-	+	Saddle point

waterway transportation. They primarily work in RO-RO ships' transportation in the Yangtze River from Chongqing to Wuhan or to Shanghai, and vice-versa. Sometimes they must use transshipment to meet customers' requirements because of serious congestion at the TGD. For example, on the 18th of October 2018, they transferred the cargo to road transportation at Zigui Terminal using 320 vehicles for a journey from Chongqing to Wuhan. With water-land transshipment, they transported the cargo three days earlier than normal. It is known that the waterway unit cost is 0.15 RMB/(t· km), the road unit cost is 1 RMB/(t· km), the time waiting cost before the TGD is 1 RMB/(h· t), and the contract freight price is 700 RMB per vehicle. Each vehicle can be converted to 1.5 ton. The waterway distance from Chongqing to Wuhan is 1286 km, Chongqing to the TGD is 606 km, and the road distance from the TGD to Wuhan is 350 km. Meanwhile, Wuhan's Shipping Management Committee provides a subsidy of 1 RMB per vehicle for inbound RO-RO ships with inland waterway transportation. Initial parameters for the simulation analysis are presented in Table 6.

TABLE 6. Initial values of the parameters via water-road transshipment mode.

Parameters	Values
π_k^1	224000
π_k^2	224000
C_k^1	211632
C_k^2	127152
Q	320
F_1	22800
F_2	0
S	320
C_g^1	27000
C_g^2	100

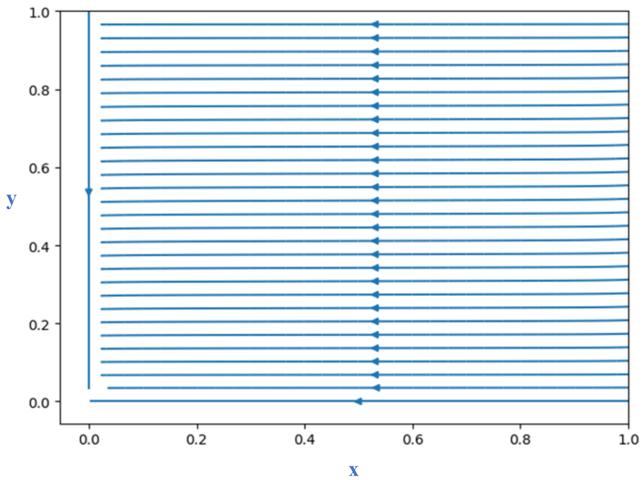


FIGURE 5. The evolution phase diagram for Case 2.

We used Python 3.7 to simulate the system's evolution process, with the main parameters in different initial states. Based on the current water-road transshipment mode, when A<0, A-S<0, and A+S<0, we can see in Figures 5, 6 and 7 that all the evolutionary curves converge to ESS (0,0). This shows that, in the current state, carriers should not adopt transshipment mode and the government should not provide subsidies to carriers. Figure 6 and Figure 7 show the changing trend of different x and different y with time of t. When t is between 0.1 and 0.2, some smooth curves go downward sharply, which means the effect of t is quite significant. On the whole, the curves of x and y all converge to 0. From Figure 8, with the initial values (x,y) set to (0.5,0.53), we can see that both x and y converge to (0,0) with time t to reach a steady state. Thus, Case 2 is verified.

In the quantity-based subsidy scheme for water-road transshipment mode, the government will provide subsidies to carriers to encourage transshipment adoption. Under the same contract freight price, Figure 9 shows evolutionary paths of

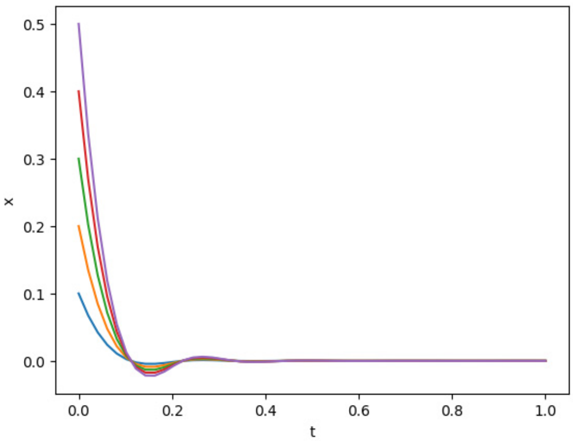


FIGURE 6. Trajectories of *dx / dt* for Case 2.

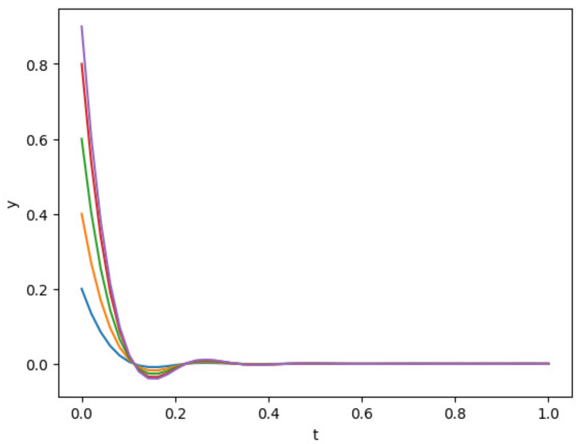


FIGURE 7. Trajectories of *dy / dt* for Case 2.

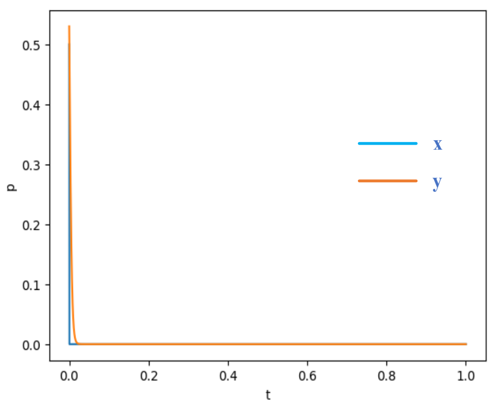


FIGURE 8. Evolutionary paths of carriers and the government.

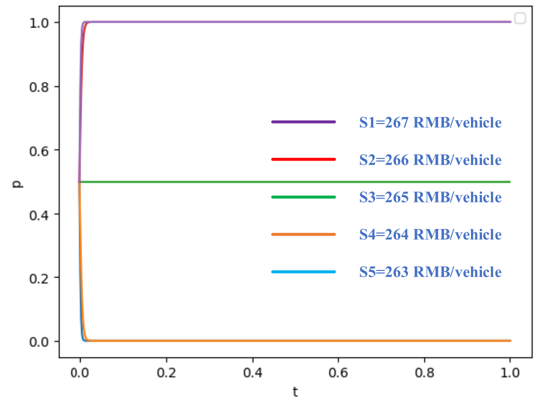


FIGURE 9. Evolutionary paths of subsidies provided by the government.

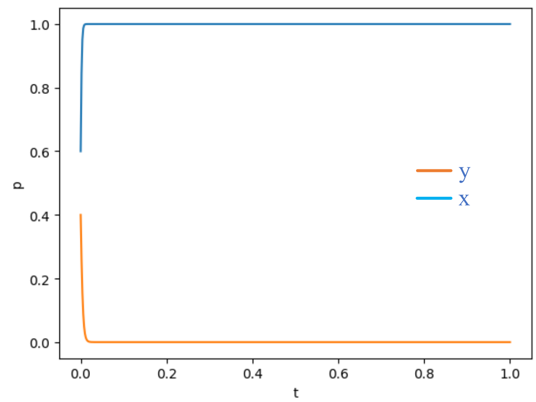


FIGURE 10. Evolutionary paths of water-road-water mode with toll discounts in Case 4.

different subsidies provided to the carriers by the government. It illustrates that when the subsidy is more than 265 RMB per vehicle, RO-RO carriers can adopt water-land transshipment mode to save both delay and time costs.

If carriers adopt water-road-water transshipment mode, trucks should be available to transport containers from Zigui Terminal to Baiyang Terminal through the South Transshipment Highway. Furthermore, the local highway management department has reduced the highway toll for the South Transshipment Highway by 50% from the 1^{st} of January 2019, to encourage water-land transshipment and to lower congestion. With the initial value of (x,y) set to (0.6,0.4), Figure 10 shows the evolutionary paths of the government and the carriers when A>0, A+S>0, A-S<0, which means the government would not provide subsides and the carriers would transfer to water-road-water transshipment mode with profit maximization. Thus, Case 4 is verified.

However, without highway toll discounts and with subsidies from Wuhan's Shipping Management Committee, if carriers are to adopt water-road-water mode, trucks should undertake transportation back and forth many times. If trucks are fully loaded for both legs of the round trip, Figure 11 shows that RO-RO carriers can adopt water-road-water transshipment mode to save time cost and maximize profits when the subsidy provided per vehicle is more than 112 RMB. Thus, congestion pressure can be relieved before the TGD.

Similarly, Figure 12 shows the evolutionary paths of subsidies without highway toll discounts and when the trucks are fully loaded only on one leg of the trip and empty on the other. It can be seen that RO-RO carriers can transfer to

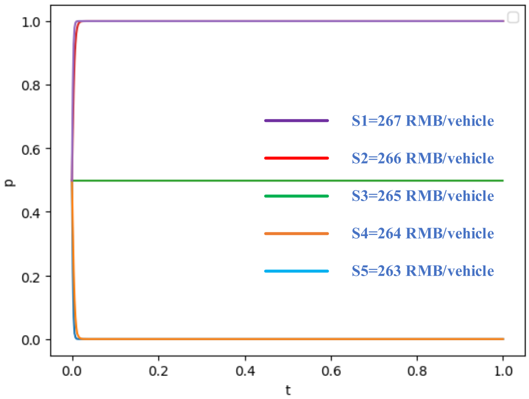


FIGURE 11. Evolutionary paths of subsidies with fully loaded trucks for both legs of the trip.

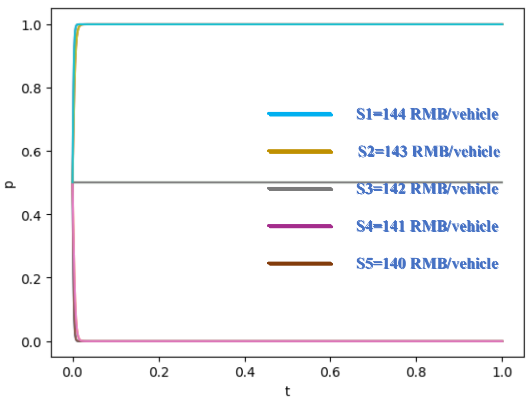


FIGURE 12. Evolutionary paths of subsidies with trucks fully loaded and empty on the outward and return legs, respectively.

water-road-water mode with the aim of profit maximization only when the subsidy provided per vehicle is more than 142 RMB.

IV. CONCLUSION

Due to high transit and road transportation costs, RO-RO and container carriers are reluctant to adopt water-land transshipment mode before the TGD. The government aims to encourage partial ship flows through water-land transshipment mode with the purpose of alleviating lock congestion. Based on this, our paper explored the spatial-temporal relationship between transshipment mode and high costs such as transit and road transportation costs. The feasibility of subsidy policies that the government can adopt was also explored, by considering subsidies under different transshipment modes and freight prices. An evolutionary game theory model was developed to identify equilibrium points of transshipment and non-transshipment, as well as subsidy and non-subsidy strategies adopted by the government and carriers under different scenarios. Taking a transportation job of CCNSC as an example, freight prices provided by the carriers and subsidies offered by the government under water-road and water-road-water modes were analyzed. The results of these analyses can provide strategic support for carriers and the government. It is believed that this work can provide strategic input for the government regarding subsidy policies, and can lay the foundation for subsidy policies for water-railway or water-railway-water transshipment mode.

REFERENCES

[1] Y. Yuan, B. Ji, X. Yuan, and Y. Huang, "Lockage scheduling of three Gorges–Gezhouba dams by hybrid of chaotic particle swarm optimization and heuristic-adjusted strategies," *Appl. Math. Comput.*, vol. 270, pp. 74–89, Nov. 2015.

[2] H. Shi, P. Xu, and Z. Yang, "Optimization of transport network in the Basin of Yangtze River with minimization of environmental emission and transport/investment costs," *Adv. Mech. Eng.*, vol. 8, no. 8, Aug. 2016, Art. no. 168781401666092.

[3] X. Yuan, B. Ji, Y. Yuan, X. Wu, and X. Zhang, "Co-scheduling of lock and water–land transshipment for ships passing the dam," *Appl. Soft Comput.*, vol. 45, pp. 150–162, Aug. 2016.

[4] X. P. Yan, C. P. Wan, D. Zhang, and Z. L. Yang, "Safety management of waterway congestions under dynamic risk conditions—A case study of the Yangtze River," *Appl. Soft Comput.*, vol. 59, pp. 115–128, Oct. 2017.

[5] E. C. Ortega. (2013). *Regional Divergence Regarding Transport Flows Especially Within the Danube Region*. [Online]. Available: https://upcommons.upc.edu/handle/2099.1/25268

[6] D. Ronen and R. Nauss. (2003). Upper Mississippi River and Illinois Waterways: How to Reduce Waiting Times of Vessels While Using the Current Infrastructure. Center for Transportation Studies. [Online]. Available: https://pdfs.semanticscholar.org/c6c8/cc1c034d584e7cce47c8df0bb4ca19dee80c.pdf

[7] R. M. Nauss, "Optimal sequencing in the presence of setup times for tow/barge traffic through a river lock," *Eur. J. Oper. Res.*, vol. 187, no. 3, pp. 1268–1281, Jun. 2008.

[8] L. Douglas Smith, R. M. Nauss, D. C. Mattfeld, J. Li, J. F. Ehmke, and M. Reindl, "Scheduling operations at system choke points with sequence-dependent delays and processing times," *Transp. Res. E, Logistics Transp. Rev.*, vol. 47, no. 5, pp. 669–680, Sep. 2011.

[9] J. F. Campbell, L. D. Smith, C. D. Sweeney, II, R. Mundy, and M. Robert Nauss, "Decision tools for reducing congestion at locks on the upper Mississippi river," in *Proc. 40th Hawaii Int. Con. Syst. Sci.*, Waikoloa, HI, USA, 2007, pp. 1530–1605.

[10] F. James Campbell, L. D. Smith, and C. D. Sweeney, II, "A robust strategy for managing congestion at locks on the Upper Mississippi River," in *Proc. 42nd Hawaii Int. Con. Syst. Sci.*, Big Island, HI, USA, 2009, pp. 1–10.

[11] W. W. Wilson, L. B. Dahl, and D. R. Taylor, "Impacts of lock capacity expansion on delay costs for grain shipped on the Mississippi River," *J. Trans. Econ. Policy.*, vol. 45, no. 1, pp. 129–154, Jan. 2011.

[12] K. Sweeney, J. Campbell, and D. S. Sweeney, II, "Impact of shippers' choice on transportation system congestion and performance: Integrating random utility with simulation," *Transp. J.*, vol. 53, no. 2, pp. 143–179, Sep. 2014.

[13] L. Smith, D. S. Sweeney, II, and J. Campbell, "Simulation of alternative approaches to relieving congestion at locks in a river transportation system," *J. Oper. Res. Soc.*, vol. 60, no. 4, pp. 519–533, Jan. 2009.

[14] J. Reynaerts, "Estimating Lock Congestion," *Int. J. Shipping Transp. Logistics*, vol. 6, no. 2, pp. 133–151, Aug. 2014.

[15] Y. Y. Zhang, M. S. Chang, and S. W. Fuller, "Statistical analysis of vessel waiting time and lockage time on the Upper Mississippi River," *Maritime Econ. Logistics.*, vol. 17, no. 4, pp. 416–439, Dec. 2015.

[16] X. Zhang, X. Fu, and X. Yuan, "Co-evolutionary strategy algorithm to the lockage scheduling of the three gorges project," in *Proc. IEEE Pacific-Asia Workshop Comput. Intell. Ind. Appl.*, Wuhan, China, Dec. 2008, pp. 583–587.

[17] X. Wang and Q. Ruan, "Genetic algorithm and tabu search hybrid algorithm to co-scheduling model of three Gorges–Gezhou dam," in *Proc. 6th Int. Symp. Neural Netw.*, Wuhan, China, 2009, pp. 581–590.

[18] X. Wang, H. Qi, H. Xiao, X. Zhang, Y. Hu, and X. Feng, "Series queuing network scheduling approach to co-scheduling model of three Gorges–Gezhou dam," *J. Syst. Sci. Complex.*, vol. 23, no. 4, pp. 715–726, Aug. 2010.

[19] X. Zhang, X. Yuan, and Y. Yuan, "Improved hybrid simulated annealing algorithm for navigation scheduling for the two dams of the Three Gorges Project," *Comput. Math. Appl.*, vol. 56, no. 1, pp. 151–159, Jul. 2008.

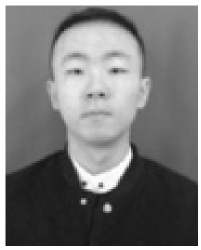
[20] P. Liao, "Improved analytical model for estimating the capacity of a waterway lock," *J. Waterway, Port, Coastal, Ocean Eng.*, vol. 144, no. 6, Nov. 2018, Art. no. 04018021.
[21] B. Ji, X. Yuan, and Y. Yuan, "A binary borg-based heuristic method for solving a multi-objective lock and transshipment co-scheduling problem," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 3, pp. 947–958, Mar. 2019.
[22] D. Friedman, "Evolutionary games in economics," *Econometrica*, vol. 59, no. 3, pp. 637–666, May 1991.

LIJUAN YANG received the M.S. degree from the Transportation College, Jilin University, China. She is currently a Ph.D. student at Wuhan University of Technology, China. She is also a Lecturer with the Guilin University of Aerospace Technology, China. Her research interests include inland waterway transportation, lock scheduling, multimodal transportation, and game models.

YU ZHANG received the Ph.D. degree from the School of Logistics Engineering, Wuhan University of Technology, Wuhan, China, in 2007. He is currently a Professor with the same university. His research interests include supply chain management, optimization, and the development of mathematical models and algorithms.

RAYMOND CHIONG (Senior Member, IEEE) received the M.Sc. degree from the University of Birmingham, Birmingham, U.K., and the Ph.D. degree from The University of Melbourne, Victoria, Australia. He is currently a tenured academic staff member with The University of Newcastle, New South Wales, Australia. He is also a Guest Research Professor with the Center for Modern Information Management, Huazhong University of Science and Technology, Wuhan, China, and a Visiting Scholar with the Department of Automation, Tsinghua University, Beijing, China. His research interests include evolutionary game theory, optimization, data analytics, and modeling of complex adaptive systems with applications in areas such as production and transportation scheduling, energy load forecasting, social behavior modeling, and marketing. He has published over 160 articles in these areas. He is the Editor-in-Chief of the *Journal of Systems and Information Technology*, an Editor of *Engineering Applications of Artificial Intelligence*, and an Associate Editor of the IEEE Computational Intelligence Magazine.

SANDEEP DHAKAL received the M.Sc. degree in artificial intelligence from the University of St Andrews, U.K. He is currently pursuing the Ph.D. degree with The University of Newcastle, Australia. His research interests include evolutionary game theory and agent-based modeling.



QIANGQIANG QI is currently pursuing the M.Sc. degree with Wuhan University of Technology, China. His research interests include intelligent ports and waterway engineering.