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Understanding the Impact of Invalid Parking Areas on Shared Bicycle Parking Governance Systems

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ABSTRACT
The existence of invalid parking areas significantly contributes to the disorderly parking of shared bicycles. A thorough investigation into the effectiveness of various management mechanisms in addressing this issue is crucial for promoting the sustainable development of the shared bicycle market. This study establishes an evolutionary game model among three stakeholders: the government, enterprises and users. The model integrates the rate of invalid parking areas and governmental supervision methodologies, which have been largely overlooked in existing literature. The strategy stability of each stakeholder is analysed using the Lyapunov discriminant method. Furthermore, the impact of various parameters on the evolutionary process is examined through numerical simulations. The findings indicate the following. (1) Differing initial levels of willingness among stakeholders significantly affect both the speed and trajectory of system evolution. (2) The primary objective of effectively managing shared bicycle parking is to enhance the efficiency of enterprise-constructed parking areas. (3) Increasing government fines while improving enterprise reward and punishment mechanisms proves to be an effective strategy for fostering a healthier shared bicycle parking governance system. These results provide actionable recommendations for regulating uncontrolled shared bicycle parking and optimising urban transportation resource utilisation within a more realistic modelling framework.

KEYWORDS
invalid parking area; shared bicycle parking; sharing economy; tripartite evolutionary game; simulation analysis.

1. INTRODUCTION

In recent years, with the flourishing development of the sharing economy and the internet, shared bicycles have emerged as a novel transportation modality exemplifying the sharing economy and operating on rental models facilitated by internet-based platforms [1, 2]. Shared bicycle programs have gained increasing prominence in various countries, primarily due to their convenience, low-carbon environmental benefits, economic flexibility and government support [3–5]. However, the proliferation of shared bicycles has increased dramatically, propelled by substantial market adoption [6]. This has severely strained urban spatial resources and pushed city traffic management systems towards operational limits, largely due to the problem of unregulated parking. Consequently, the governance of shared bicycle parking has emerged as a significant area of research interest.

A review of extant literature reveals that scholars have explored issues of shared bicycle parking areas from a variety of perspectives, such as parking area demand planning [7, 8], parking area layout modelling [9, 10], parking area preference design [11–13], parking area on-site repairs [14] and case study [15]. The introduction of designated parking areas has fairly alleviated parking disorder. Nevertheless, due to their limited capacity, parking shortages persist, seriously affecting the sustainable development of the shared bicycle market. Addressing this issue, Styre et al. and Caggiani et al. have flexibly planned parking demand in residential areas and optimised the redistribution of shared bicycles [16, 17].

Beyond logistical concerns, scholars have increasingly applied game theory to analyse the decision-making and the evolution process among stakeholders in shared bicycle systems. Cui and Xiao examined the factors influencing the efficacy of quota policies during periods of peak demand and off-peak demand using a tripartite dynamic game. Their findings suggest that such policies are effective during periods of high demand, but their effectiveness diminishes during off-peak seasons [18]. Yang and Ma established an evolutionary game model to explore opportunistic user behaviour and stakeholders' roles [19]. Tan et al., employing the Bertrand game model, analysed pricing and placement strategies, exploring optimal pricing approaches for markets of varying scales [20]. Scholars have used game theory to study the integration of shared bicycles with public transportation, which has the potential to enhance overall social welfare. Integration costs between systems are a key factor in determining the feasibility of such coexistence [21, 22]. Jia et al. investigated the issue of the gradual phasing out of subsidy policies by evolutionary game theory and concluded that the removal of subsidies promotes system equilibrium [23].

In summary, existing research has predominantly focused on parking site selection, parking area design, parking service management and optimisation, consumer preference analysis, the integration of shared bicycles with public transportation and the management of invalid parking areas. However, few studies have used evolutionary game theory to explore stakeholder behaviours when parking areas are invalid. Prior work has mainly addressed whether supervision should be applied, but little attention has been paid to discussing the implementation effect of different supervision methods. The novelty of this study lies in integrating invalid parking areas into an evolutionary game framework to investigate how varying the rate of invalid parking areas influences user behaviour. The optimal supervision of the government varies in different situations, and is verified through numerical simulations by changing the initial willingness of the stakeholders.

The contributions of this study are summarised as follows. First, a tripartite evolutionary game model is established, which among government departments, shared bicycle enterprises and shared bicycle users (henceforth referred to as the government, enterprises and users) is used to analyse the stability and interrelationships of stakeholders' strategic choices under varying conditions. Second, the Lyapunov discriminant method is employed to determine the stability conditions for various equilibrium points within the shared bicycle parking governance system. Finally, MATLAB is utilised for numerical simulation of the stable points, preliminary strategy alterations and primary factors influencing strategy selection for each game stakeholder across five distinct scenarios. This methodological approach was instrumental in verifying the validity of the theoretical analysis and proposing efficacious recommendations to enhance the governance system of shared bicycle parking and promote the sustainable development of urban transportation, as evident in the game results.

The remainder of this paper is organised as follows. Section 2 formulates the evolutionary game model that serves as the foundation for our analysis. Section 3 analyses the stability of stakeholder strategy, examining the stability of various equilibria and the conditions required for such stability. Section 4 presents the numerical simulations that empirically validate the theoretical findings discussed earlier. Finally, Section 5 provides a comprehensive summary of the key insights and contributions of this study.

2. PROBLEM DESCRIPTION AND MODELLING

In the urban transportation system, shared bicycles play an important role in meeting the short-distance travel needs of residents. However, with the continuous expansion of shared bicycle parking, it is beset with a multitude of complex and serious challenges, as evidenced by illegal parking issues in various cities, the need for improved maintenance management, and the safety hazards that have arisen.

2.1 Problem description

One challenge is the emergence of invalid parking areas, which increases cycling costs for users and necessitates the implementation of supervisory measures to resolve the issue. The term "invalid parking area" refers to a designated parking location in which, upon vehicle return, no parking spaces are accessible. This concept underscores significant challenges within parking facility operations. In these instances, users typically opt to return the vehicle in proximity to their location to mitigate the inconvenience associated with finding suitable parking. However, this short-sighted approach to parking may lead to the formation of invalid parking areas, exacerbating unregulated parking. The phenomenon of invalid probability is intricately linked to urban infrastructure development, particularly when governmental entities and private enterprises inadequately provision parking facilities.

Simultaneously, governments and enterprises are tasked with the challenge of effectively managing construction costs, optimising bicycle scheduling and maintenance, and ensuring the system's economic viability, all while upholding standardised parking practices for bicycles [24]. Currently, the varied parking behaviours of users exert differential impacts on the system. For example, standardised parking by users will enhance the image of the city, improve road safety and save resources to bring social benefits to the government. At the same time, it enhances the visibility of active management companies and brings additional benefits to them. Conversely, this approach is predicted to have adverse effects on the city's image and increase safety risks when users park in an irregular and unmanaged manner, resulting in increased governance costs for the government.

In addition, the unreasonable reward and punishment system of the government and enterprises will aggravate the phenomenon of unregulated parking. The above problems will directly affect the overall operational efficiency and evolutionary trajectory of the shared bicycle parking governance system. To solve these problems, this study aims to deeply explore effective ways to save the social resources of urban transportation while regulating users' parking behaviours through the study of the evolutionary game of shared bicycle parking governance. Based on this foundation, the paper establishes a logical relationship diagram for a tripartite evolutionary game involving the government, enterprises and users, which is illustrated in *Figure 1*.

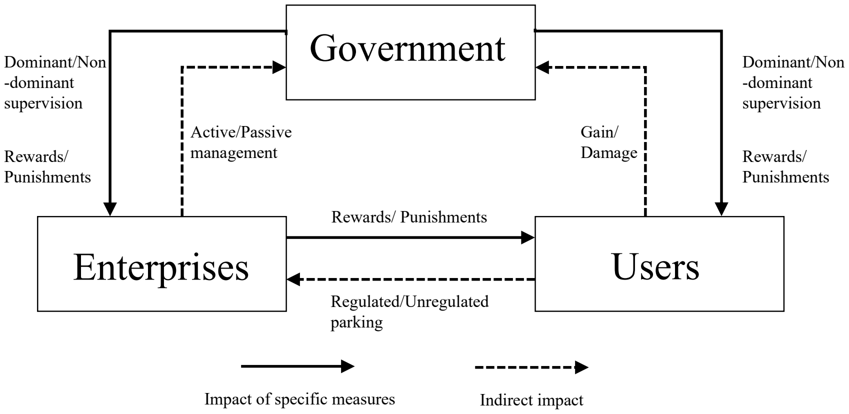


Figure 1 – Logical relationship diagram of a tripartite evolutionary game

2.2 Hypotheses of the model

To develop the game model and evaluate the stability of strategy and equilibrium points for each stakeholder, as well as the impact of various parameters on strategy selection, we make the following assumptions.

Assumption 1: The stakeholders involved in urban bicycle sharing include government, enterprises and users, all of whom are considered bounded rational stakeholders in this ecosystem.

Assumption 2: The government's strategy set consists of two strategies: dominant supervision and non-dominant supervision. In contrast, the enterprise's strategy set encompasses two distinct management styles: active management and passive management. Additionally, the user's strategy set includes two parking regulations: regulated parking and unregulated parking.

Assumption 3: It is hypothesised that when the government adopts the dominant supervision strategy, and the enterprises opt for passive management, the rate of invalid parking area is represented by α. The rate of invalid parking area is defined by β when the enterprise employs the active management strategy and the government adopts the non-dominant supervision strategy. Assuming independence between the effectiveness of government construction and management of the parking area and the effectiveness of enterprise management of the same parking area, the rate of invalid parking area when the government chooses the dominant supervision strategy and the enterprises choose active management is $\alpha \cdot \beta$. When the government chooses the non-dominant supervision strategy and the enterprise adopts passive management, the rate of invalid parking areas is indicated by γ ($\alpha, \beta, \gamma \in (0,1)$, $\gamma > \alpha$ and $\gamma > \beta$).

Assumption 4: It is posited that the adoption of a dominant supervision strategy by the government incurs a cost designated as C_1. Rewards are R_1 (or fines F_1) for users who choose a regulated parking strategy (or unregulated parking strategy); fines are F_2 (or rewards R_2) for enterprises that choose a passive management strategy (or active management strategy). The government incurs a cost when it adopts a non-dominant supervision strategy, denoted by C_2 ($C_1 > C_2$), and imposes penalties on enterprises when there is unregulated parking behaviour, represented by F_3. The social advantages derived from the regulation of parking by users can be denoted as R_3. In contexts where users choose unregulated parking, enterprises implement a passive management strategy, and the government adopts a non-dominant supervisory strategy, the social governance costs I are attributed to the government.

Assumption 5: The financial costs of active management strategy selection by the enterprise are denoted by C_3. Concurrently, users who choose regulated parking receive a reward R_4, contributing revenue R_5 to the enterprise ($R_5 > R_4$). The implementation of a passive management strategy by the enterprise is associated with negligible cost implications.

Assumption 6: Users employing an unregulated parking strategy can derive a level of convenience J from this approach. Concurrently, they are subjected to cleanup scheduling fees and penalties F_4 imposed by enterprises that implement an active management strategy. Conversely, users choosing a regulated parking strategy will face additional costs C_4 associated with their cycling. All of the aforementioned parameters exhibit positive values.

2.3 Basic model

In alignment with the previously stated assumptions, *Table 1* illustrates the payoff matrix for government, enterprises and users. The replicated dynamic equations associated with each stakeholder are derived to formulate an evolutionary game model, as informed by the payoff matrix.

Table 1 – Payoff matrix for government, enterprises and users

Government	Enterprises	Users	
		Regulated parking	Unregulated parking
Dominant supervision	Active management	$-R_1 - R_2 - C_1 + R_3$	$F_1 - R_2 - C_1$
		$R_2 - R_4 + R_5 - C_3$	$R_2 - C_3$
		$R_1 + R_4 - \alpha\beta C_4$	$J - F_1 - F_4$
	Passive management	$-R_1 + F_2 - C_1 + R_3$	$F_1 + F_2 - C_1$
		$-F_2$	$-F_2$
		$R_1 - \alpha C_4$	$J - F_1$
Non-dominant supervision	Active management	$-C_2 + R_3$	$-C_2$
		$-R_4 + R_5 - C_3$	$-F_3 - C_3$
		$R_4 - \beta C_4$	$J - F_4$
	Passive management	$-C_2 + R_3$	$-C_2 - I$
		0	$-F_3$
		$-\gamma C_4$	J

3. MODEL ANALYSIS

It is postulated that the probability of the government selecting a dominant supervision strategy is denoted as x ($0 \le x \le 1$), whereas the probability of the government opting for a non-dominant supervision strategy is represented by $1 - x$. The probabilities associated with the employment of active management and passive management by enterprises are denoted by y ($0 \le y \le 1$) and $1 - y$, respectively. The probability of a user opting for the regulated parking strategy is denoted as z ($0 \le z \le 1$), while the probability of selecting the unregulated parking strategy is represented by $1 - z$. The replicated dynamic equations of the government, enterprises and users in the shared bicycle parking governance system are obtained. The evolution paths and stable strategy of the government, enterprises and users are analysed based on the replicated dynamic equations.

3.1 The replicated dynamic equations of the government, enterprises and users

Let the expected profit for the government when it chooses the dominant (or non-dominant) supervision strategy be s_1 (or s_2) and the average expected profit be $\bar{s}_x$, then there is:

$$\begin{aligned} s_1 = {} & yz(-R_1 - R_2 - C_1 + R_3) + y(1-z)(F_1 - R_2 - C_1) + (1-y)z(-R_1 + F_2 - C_1 + R_3) \\ & + (1-y)(1-z)(F_1 + F_2 - C_1) \end{aligned} \tag{1}$$

$$s_2 = yz(-C_2 + R_3) + y(1-z)(-C_2) + (1-y)z(-C_2 + R_3) + (1-y)(1-z)(-C_2 - I) \tag{2}$$

$$\bar{s}_x = xs_1 + (1-x)s_2 \tag{3}$$

The replicated dynamic equation for the dominant supervision strategy by the government is:

$$\begin{aligned} F(x) &= \frac{\mathrm{d}x}{\mathrm{d}t} = x(s_1 - \bar{s}_x) = x(1-x)(s_1 - s_2) \\ &= x(1-x)[F_1 + F_2 - C_1 + C_2 + I - (R_2 + F_2 + I)y - (R_1 + F_1 + I)z + Iyz] \end{aligned} \tag{4}$$

Let the expected profit for the enterprise when it chooses the active (or passive) management strategy be s_3 (or s_4) and the average expected profit be $\bar{s}_y$, then there is:

$$\begin{aligned} s_3 = {} & xz(R_2 - R_4 + R_5 - C_3) + x(1-z)(R_2 - C_3) + (1-x)z(-R_4 + R_5 - C_3) \\ & +(1-x)(1-z)(-F_3 - C_3) \end{aligned} \tag{5}$$

$$s_4 = xz(-F_2) + x(1-z)(-F_2) + (1-x)z \cdot 0 + (1-x)(1-z)(-F_3) \tag{6}$$

$$\bar{s}_y = ys_3 + (1-y)s_4 \tag{7}$$

The replicated dynamic equation for the active management strategy by the enterprise is:

$$F(y) = \frac{\mathrm{d}y}{\mathrm{d}t} = y(s_3 - \bar{s}_y) = y(1-y)(s_3 - s_4) = y(1-y)[-C_3 + (R_2 + F_2)x + (R_5 - R_4)z] \tag{8}$$

Let the expected profit for users when it chooses the regulated parking (or unregulated parking) strategy be s_5 (or s_6) and the average expected profit be $\bar{s}_z$, then there is:

$$s_5 = xy(R_1 + R_4 - \alpha\beta C_4) + x(1-y)(R_1 - \alpha C_4) + (1-x)y(R_4 - \beta C_4) + (1-x)(1-y)(-\gamma C_4) \tag{9}$$

$$s_6 = xy(J - F_1 - F_4) + x(1-y)(J - F_1) + (1-x)y(J - F_4) + (1-x)(1-y)J \tag{10}$$

$$\bar{s}_z = zs_5 + (1-z)s_6 \tag{11}$$

Then, the replicated dynamic equation for the regulated parking strategy by the user is:

$$\begin{aligned} F(z) &= \frac{\mathrm{d}z}{\mathrm{d}t} = z(s_5 - \bar{s}_z) = z(1-z)(s_5 - s_6) \\ &= z(1-z)\begin{bmatrix} -\gamma C_4 - J + (R_1 + F_1 - \alpha C_4 + \gamma C_4)x + \\ (R_4 + F_4 - \beta C_4 + \gamma C_4)y + (\alpha + \beta - \gamma - \alpha\beta)C_4xy \end{bmatrix} \end{aligned} \tag{12}$$

3.2 Strategy stability analysis of the government

The stability theorem of the differential equation indicates that the probability of the government selecting the dominant supervision strategy is in a stable state when $F(x) = 0$ and $\frac{\mathrm{d}F(x)}{\mathrm{d}x} < 0$. Considering *Equation 4*, let condition $y_0 = \frac{[F_1 + F_2 - C_1 + C_2 + I - (R_1 + F_1 + I)z]}{R_2 + F_2 + I(1-z)}$ be established. When condition $y = y_0$ is satisfied, it consequently follows that $\frac{\mathrm{d}F(x)}{\mathrm{d}x} \equiv 0$ and $F(x) \equiv 0$ hold. Thus, at this point, allowing x to take any arbitrary value indicates that the government's strategy attains a stable equilibrium.

When $y \neq y_0$, so that $G(y) = F_1 + F_2 - C_1 + C_2 + I - (R_2 + F_2 + I)y - (R_1 + F_1 + I)z + Iyz$, $\frac{\partial G(y)}{\partial y} = -R_2 - F_2 - I(1 - z)$, by the previous assumptions $\frac{\partial G(y)}{\partial y} < 0$, $G(y)$ is a decreasing function about y. In conclusion, when $y < y_0$ occurs, it leads to $G(y) > 0$, $\left.\frac{\mathrm{d}F(x)}{\mathrm{d}x}\right|_{x=0} > 0$, and $\left.\frac{\mathrm{d}F(x)}{\mathrm{d}x}\right|_{x=1} < 0$. The evolutionary stable state of the government is denoted as $x = 1$. Conversely, when $y > y_0$ takes place, it results in $G(y) < 0$, $\left.\frac{\mathrm{d}F(x)}{\mathrm{d}x}\right|_{x=0} < 0$, and $\left.\frac{\mathrm{d}F(x)}{\mathrm{d}x}\right|_{x=1} > 0$. The evolutionary stable state of the government is represented by $x = 0$. The evolution of governmental strategy is depicted in *Figure 2*.

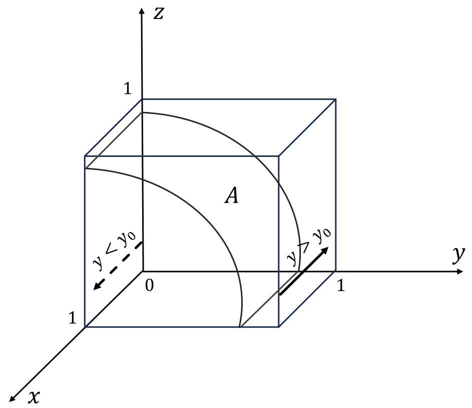


Figure 2 – Evolutionary process of the government strategy

3.3 Strategy stability analysis of the enterprises

According to *Equation 8*, let $z_1 = \frac{C_3 - (R_2 + F_2)x}{(R_5 - R_4)}$ be established. It can similarly be deduced that when $z = z_1$ holds true, consequently $\frac{\mathrm{d}F(y)}{\mathrm{d}y} \equiv 0$ and $F(y) \equiv 0$ follow. At this juncture, y can assume any value, indicating that the enterprise strategy is in a stable state.

When $z \neq z_1$ occurs, let $H(z) = -C_3 + (R_2 + F_2)x + (R_5 - R_4)z$ be established. By the given assumption $R_5 - R_4 > 0$, it follows that $\frac{\partial H(z)}{\partial z} = R_5 - R_4 > 0$. Consequently, $H(z)$ is an increasing function for z. Therefore, when $z < z_1$ is satisfied, it leads to $H(z) < 0$, $\left.\frac{\mathrm{d}F(y)}{\mathrm{d}y}\right|_{y=0} < 0$, and $\left.\frac{\mathrm{d}F(y)}{\mathrm{d}y}\right|_{y=1} > 0$. The state represented by $y = 0$ signifies the evolutionary stable state within the enterprise. Conversely, when $z > z_1$ holds true, it results in $H(z) > 0$, $\left.\frac{\mathrm{d}F(y)}{\mathrm{d}y}\right|_{y=0} > 0$, and $\left.\frac{\mathrm{d}F(y)}{\mathrm{d}y}\right|_{y=1} < 0$, establishing $y = 1$ as another evolutionary stable state in the enterprise framework. The evolutionary trajectory of enterprise strategy is illustrated in *Figure 3*.

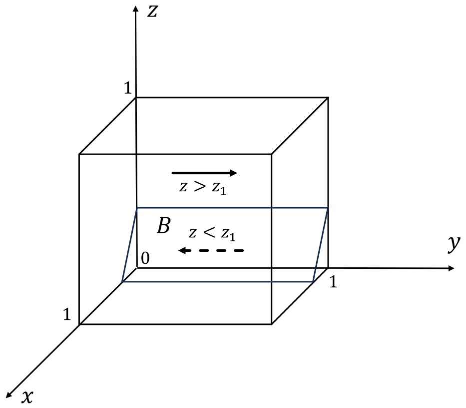


Figure 3 – Evolutionary process of the enterprise strategy

3.4 Strategy stability analysis of the users

Considering *Equation 12*, let condition $x_1 = \frac{\gamma C_4 + J - (R_4 + F_4 - \beta C_4 + \gamma C_4)y}{R_1 + F_1 + C_4[(1-y)(\gamma - \alpha) + \beta y(1-\alpha)]}$ be established. When condition $x = x_1$ is met, it consequently follows that $\frac{\mathrm{d}F(z)}{\mathrm{d}z} \equiv 0$ and $F(z) \equiv 0$ hold true. Thus, at this point, allowing z to take any arbitrary value indicates that the users' game strategy attains a stable equilibrium.

When $x \neq x_1$ occurs, let $N(x) = -\gamma C_4 - J + (R_1 + F_1 - \alpha C_4 + \gamma C_4)x + (R_4 + F_4 - \beta C_4 + \gamma C_4)y + (\alpha + \beta - \gamma - \alpha\beta)C_4 xy$ be established. By the given assumption $\gamma > \alpha$, it follows that $\frac{\partial N(x)}{\partial x} = \{R_1 + F_1 + C_4[(1-y)(\gamma - \alpha) + \beta y(1-\alpha)]\} > 0$. Consequently, $N(x)$ is an increasing function for x. Therefore, when $x < x_1$ is satisfied, it leads to $N(x) < 0$, $\left.\frac{\mathrm{d}F(z)}{\mathrm{d}z}\right|_{z=0} < 0$, and $\left.\frac{\mathrm{d}F(z)}{\mathrm{d}z}\right|_{z=1} > 0$. The state represented by $z = 0$ signifies the evolutionary stable state within the user. Conversely, when $x > x_1$ holds true, it results in $N(x) > 0$, $\left.\frac{\mathrm{d}F(z)}{\mathrm{d}z}\right|_{z=0} > 0$, and $\left.\frac{\mathrm{d}F(z)}{\mathrm{d}z}\right|_{z=1} < 0$, establishing $z = 1$ as another evolutionary stable state in the user framework. The evolutionary trajectory of user strategy is illustrated in *Figure 4*.

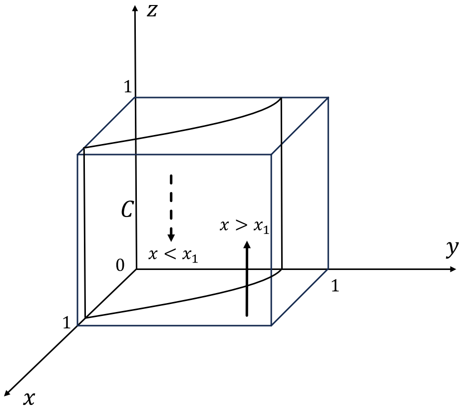


Figure 4 – Evolutionary process of the users' strategy

3.5 Stability analysis of the tripartite evolutionary game

According to *Equations 4, 8 and 12*, the shared bicycle parking management system can be expressed by the following system of equations:

$$\begin{cases} F(x) = \dfrac{\mathrm{d}x}{\mathrm{d}t} = x(1-x)[F_1 + F_2 - C_1 + C_2 + I - (R_2 + F_2 + I)y - (R_1 + F_1 + I)z + Iyz] \\ F(y) = \dfrac{\mathrm{d}y}{\mathrm{d}t} = y(1-y)[-C_3 + (R_2 + F_2)x + (R_5 - R_4)z] \\ F(z) = \dfrac{\mathrm{d}z}{\mathrm{d}t} = z(1-z)\begin{bmatrix} -\gamma C_4 - J + (R_1 + F_1 - \alpha C_4 + \gamma C_4)x + \\ (R_4 + F_4 - \beta C_4 + \gamma C_4)y + (\alpha + \beta - \gamma - \alpha\beta)C_4 xy \end{bmatrix} \end{cases} \tag{13}$$

According to the theorems of game theory, the evolutionary stable strategy of an asymmetric game system is the pure strategy Nash equilibrium of the system [25, 26]. As demonstrated in *Equation 13*, the eight pure strategy Nash equilibria of the system are as follows: $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$ and $E_8(1,1,1)$. It is important to note that the equilibrium point is not necessarily the evolutionary stable point of the system. Therefore, the positive and negative cases of the eigenvalues of the system Jacobian matrix are used below to determine the stability of the system equilibrium point [27, 28]. The Jacobian matrix of the system is denoted by J_F.

$$J_F = \begin{pmatrix} \dfrac{\partial F(x)}{\partial x} & \dfrac{\partial F(x)}{\partial y} & \dfrac{\partial F(x)}{\partial z} \\ \dfrac{\partial F(y)}{\partial x} & \dfrac{\partial F(y)}{\partial y} & \dfrac{\partial F(y)}{\partial z} \\ \dfrac{\partial F(z)}{\partial x} & \dfrac{\partial F(z)}{\partial y} & \dfrac{\partial F(z)}{\partial z} \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \tag{14}$$

where

$$a_{11} = (1-2x)[F_1 + F_2 - C_1 + C_2 + I - (R_2 + F_2 + I)y - (R_1 + F_1 + I)z + Iyz] \tag{15}$$

$$a_{12} = x(1-x)[-R_2 - F_2 - I(1-z)] \tag{16}$$

$$a_{13} = x(1-x)[-R_1 - F_1 - I(1-y)] \tag{17}$$

$$a_{21} = y(1-y)(R_2 + F_2) \tag{18}$$

$$a_{22} = (1-2y)[-C_3 + (R_2 + F_2)x + (R_5 - R_4)z] \tag{19}$$

$$a_{23} = y(1-y)(R_5 - R_4) \tag{20}$$

$$a_{31} = z(1-z)\{R_1 + F_1 + C_4[(1-y)(\gamma - \alpha) + \beta y(1-\alpha)]\} \tag{21}$$

$$a_{32} = z(1-z)\{R_4 + F_4 + C_4[(1-x)(\gamma - \beta) + \beta x(1-\alpha)]\} \tag{22}$$

$$a_{33} = (1-2z)\begin{bmatrix} -\gamma C_4 - J + (R_1 + F_1 - \alpha C_4 + \gamma C_4)x + \\ (R_4 + F_4 - \beta C_4 + \gamma C_4)y + (\alpha + \beta - \gamma - \alpha\beta)C_4 xy \end{bmatrix} \tag{23}$$

Accordingly, as posited by Lyapunov, an equilibrium point is considered to be an evolutionary stable point of a system, given that all the eigenvalues of the Jacobian matrix have negative real parts [29]. Conversely, an equilibrium is deemed unstable when at least one positive real part of the eigenvalues is present. The stability of Jacobian matrices for the aforementioned eight pure-strategy Nash equilibria, along with the positive and negative eigenvalue scenarios, is elucidated in *Table 2*.

According to the data presented in *Table 2*, which correspond to the Jacobian matrix eigenvalues for each equilibrium point, it can be determined that at least one of the eigenvalues corresponding to equilibrium points $E_3(0,1,0)$, $E_4(0,0,1)$ and $E_8(1,1,1)$ is positive. Therefore, points $E_3(0,1,0)$, $E_4(0,0,1)$ and $E_8(1,1,1)$ cannot be stable. The stability of the remaining five equilibrium points is discussed as follows.

Table 2 – Stability analysis of equilibrium point

Equilibrium point	Eigenvalue	Stability	Requirements for establishment
$E_1(0,0,0)$	$\lambda_1 = F_1 + F_2 - C_1 + C_2 + I, \lambda_2 = -C_3 < 0,$ $\lambda_3 = -\gamma C_4 - J < 0$	Stable	①
$E_2(1,0,0)$	$\lambda_1 = -(F_1 + F_2 - C_1 + C_2 + I), \lambda_2 = F_2 - C_3 + R_2,$ $\lambda_3 = F_1 - J + R_1 - \alpha C_4$	Stable	②
$E_3(0,1,0)$	$\lambda_1 = F_1 + C_2 - C_1 - R_2, \lambda_2 = C_3 > 0,$ $\lambda_3 = F_4 - J + R_4 - \beta C_4$	Unstable	/
$E_4(0,0,1)$	$\lambda_1 = F_2 + C_2 - C_1 - R_1, \lambda_2 = R_5 - R_4 - C_3,$ $\lambda_3 = \gamma C_4 + J > 0$	Unstable	/
$E_5(1,1,0)$	$\lambda_1 = -(F_1 + C_2 - C_1 - R_2), \lambda_2 = C_3 - R_2 - F_2,$ $\lambda_3 = F_1 + F_4 + R_1 + R_4 - \alpha\beta C_4 - J$	Stable	③
$E_6(1,0,1)$	$\lambda_1 = -(F_2 + C_2 - C_1 - R_1),$ $\lambda_2 = F_2 - C_3 + R_2 + R_5 - R_4, \lambda_3 = J - F_1 - R_1 + \alpha C_4$	Stable	④
$E_7(0,1,1)$	$\lambda_1 = C_2 - C_1 - R_1 - R_2 < 0, \lambda_2 = C_3 + R_4 - R_5,$ $\lambda_3 = J + \beta C_4 - R_4 - F_4$	Stable	⑤
$E_8(1,1,1)$	$\lambda_1 = -(C_2 - C_1 - R_1 - R_2) > 0, \lambda_2 = C_3 - R_2 -$ $F_2 - R_5 + R_4, \lambda_3 = J + \alpha\beta C_4 - F_1 - F_4 - R_1 - R_4$	Unstable	/

Note(s): / indicates no constraints. ①$F_1 + F_2 - C_1 + C_2 + I < 0$; ②$-(F_1 + F_2 - C_1 + C_2 + I) < 0$, $F_2 - C_3 + R_2 < 0$, $F_1 - J + R_1 - \alpha C_4 < 0$; ③$-(F_1 + C_2 - C_1 - R_2) < 0$, $C_3 - R_2 - F_2 < 0$, $F_1 + F_4 + R_1 + R_4 - \alpha\beta C_4 - J < 0$; ④$-(F_2 + C_2 - C_1 - R_1) < 0$, $F_2 - C_3 + R_2 + R_5 - R_4 < 0$, $J - F_1 - R_1 + \alpha C_4 < 0$; ⑤$C_3 + R_4 - R_5 < 0$, $J + \beta C_4 - R_4 - F_4 < 0$.

Scenario 1: When $F_1 + F_2 - C_1 + C_2 + I < 0$, the evolutionary game system reaches a stable state and the evolutionary stable point is $E_1(0,0,0)$. The corresponding evolutionary stable strategy (ESS) is (non-dominant supervision, passive management, unregulated parking) as illustrated in *Figure 5b*.

Scenario 1 states that the difference between the costs to the government of choosing a dominant and a non-dominant supervision strategy is greater than the sum of the fines it imposes on unregulated parking users, passive management enterprises and the government's increased social governance costs due to unregulated parking.

At this juncture, the government will elect to abstain from the imposition of a dominant supervision strategy, as the associated financial burden is deemed excessive. Consequently, enterprises and users influenced by the government's strategic choices will be more inclined to choose passive management and an unregulated parking strategy. This will engender a vicious cycle within the parking management system, thereby imperilling the urban transportation system. This situation corresponds to the low initial willingness of the stakeholders. The government can reduce expenditures related to the supervision of shared bicycle parking governance by adopting measures such as digital regulatory platforms, data-sharing mechanisms, public oversight and joint punishment systems, and augmenting the penalty, thus safeguarding the vital supervision function of the government. These measures are crucial to break the vicious circle and avoid the collapse of the shared bicycle parking governance system.

Scenario 2: When $-(F_1 + F_2 - C_1 + C_2 + I) < 0$, $F_2 - C_3 + R_2 < 0$ and $F_1 - J + R_1 - \alpha C_4 < 0$, the evolutionary game system reaches a stable state and the evolutionary stable point is $E_2(1,0,0)$. The corresponding ESS is (dominant supervision, passive management, unregulated parking) as shown in *Figure 5c*.

Scenario 3: When $-(F_1 + C_2 - C_1 - R_2) < 0$, $C_3 - R_2 - F_2 < 0$ and $F_1 + F_4 + R_1 + R_4 - \alpha\beta C_4 - J < 0$, the evolutionary game system reaches a stable state and the evolutionary stable point is $E_5(1,1,0)$. The corresponding ESS is (dominant supervision, active management, unregulated parking) as shown in *Figure 5d*.

Scenario 4: When $-(F_2 + C_2 - C_1 - R_1) < 0$, $F_2 - C_3 + R_2 + R_5 - R_4 < 0$ and $J - F_1 - R_1 + \alpha C_4 < 0$, the evolutionary game system reaches a stable state and the evolutionary stable point is $E_6(1,0,1)$. The corresponding ESS is (dominant supervision, passive management, regulated parking) as shown in *Figure 5e*.

Scenario 5: When $C_3 + R_4 - R_5 < 0$ and $J + \beta C_4 - R_4 - F_4 < 0$, the evolutionary game system reaches a stable state and the evolutionary stable point is $E_7(0,1,1)$. The corresponding ESS is (non-dominant supervision, active management, regulated parking) as shown in *Figure 5a*.

Consequently, the additional benefit that an enterprise receives when it chooses an active management strategy is greater than the sum of its management costs at that point and the rewards it gives to regulated parking users. The sum of the convenience gained by users when they choose unregulated parking and the additional cost of riding when the enterprise actively manages it is less than the sum of the rewards that active management enterprises give to users who park in regulated parking and the penalties that they impose on users who park in unregulated parking.

In the evolutionary process under this condition, enterprises and users have a propensity to adopt active management and the regulated parking strategy. Consequently, the shared bicycle parking governance system can be improved. To save social resources and be influenced by the decision-making of the remaining two stakeholders, the government will gradually shift to a non-dominant supervision strategy. The enterprises can establish a membership system to cultivate a positive and dynamic brand image, thereby enhancing the benefits of active management. Concurrently, enterprises are leveraging existing parking facilities to facilitate expansion, thereby reducing users' parking costs and the convenience associated with unregulated parking. The proposed initiative aims to achieve stable conditions, thereby facilitating the transition of the shared bicycle parking governance system into a virtuous cycle.

4. NUMERICAL SIMULATION ANALYSIS

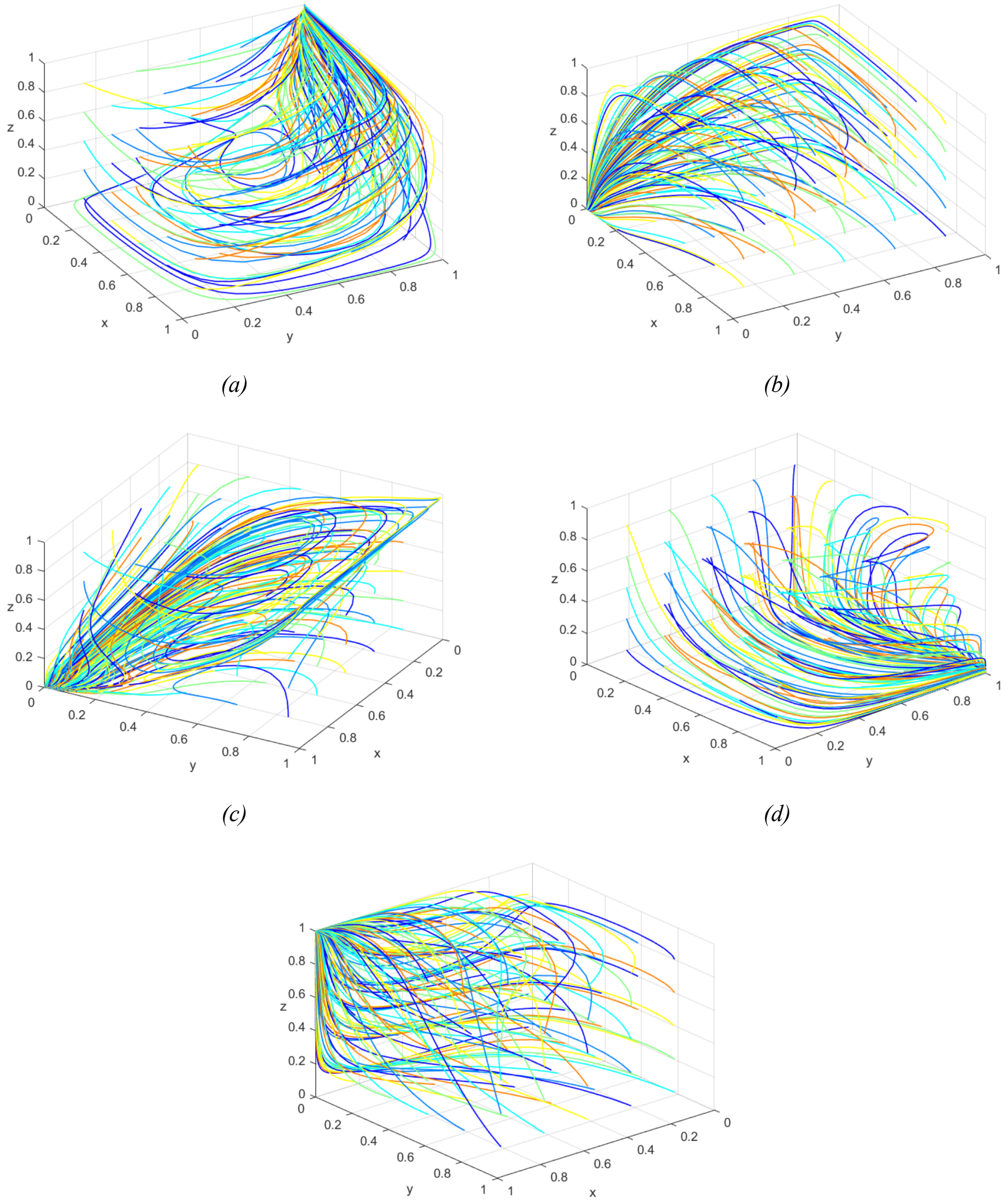
To verify the validity of the evolutionary stability analysis, the evolutionary process and the evolutionary stable strategy are visualised, and the influence of relevant factors on the strategy choice of each stakeholder is explored [30–32]. In this paper, we utilise the numerical simulation technique in MATLAB (R2021b) to analyse the tripartite evolutionary game process [33, 34]. In the realm of simulation model selection, it has been observed that these models prioritise structural validity, consistency and adaptability over strict realism [35]. When estimating model parameters, the scarcity of first-hand, precise data is often a significant challenge. Consequently, the focus shifts to capturing the behavioural trends of the entire system and understanding the effects of parameter modifications, rather than achieving highly accurate outcomes. Particular parameters must conform to the model's assumptions and underlying conceptual frameworks to ensure the integrity and applicability of the simulation.

Initially, the parameter is set as follows: $F_1 = 20$, $F_2 = 50$, $F_3 = 40$, $F_4 = 20$, $R_1 = 10$, $R_2 = 20$, $R_3 = 50$, $R_4 = 10$, $R_5 = 60$, $C_1 = 40$, $C_2 = 10$, $C_3 = 20$, $C_4 = 40$, $I = 60$, $J = 10$, $\alpha = 0.4$, $\beta = 0.3$, $\gamma = 0.8$ to verify scenario 5, as illustrated in *Figure 5a*, and the other four scenarios by changing the assignment of the initially given partial parameters. In turn, we analyse the effects of the initial strategy, the probability of the invalid parking area, and the rewards and penalties on the evolutionary process of the system.

4.1 Simulation validation of the evolutionary stable strategy for five scenarios

This section provides a comprehensive verification of the simulation outcomes across various scenarios by systematically manipulating specific parameter values while maintaining others at their initial settings. In the context of scenario 1, we analyse the results obtained with parameters $C_1 = 150$ and $C_3 = 60$, as illustrated in *Figure 5b*. For scenario 2, we turn our attention to parameters $C_3 = 80$ and $J = 30$, with the corresponding simulation results depicted in *Figure 5c*. Likewise, scenario 3 focuses on parameters $F_1 = 60$ and $J = 100$, as demonstrated in *Figure 5d*, while scenario 4 examines the outcomes associated with parameters $F_1 = 60$ and $C_3 = 130$, represented in *Figure 5e*. Each scenario aims to elucidate the impact of the selected parameters on the overall simulation results.

It can be shown that the evolutionary stable points of the system vary for different values of the parameters, which are $E_7(0,1,1)$, $E_1(0,0,0)$, $E_2(1,0,0)$, $E_5(1,1,0)$ and $E_6(1,0,1)$. The numerical simulation results are consistent with the conclusions of the stability analysis. Therefore, the results of the numerical simulation are of guiding significance for ensuring the standardised parking of shared bicycles.



(a) *(b)* *(c)* *(d)* *(e)*

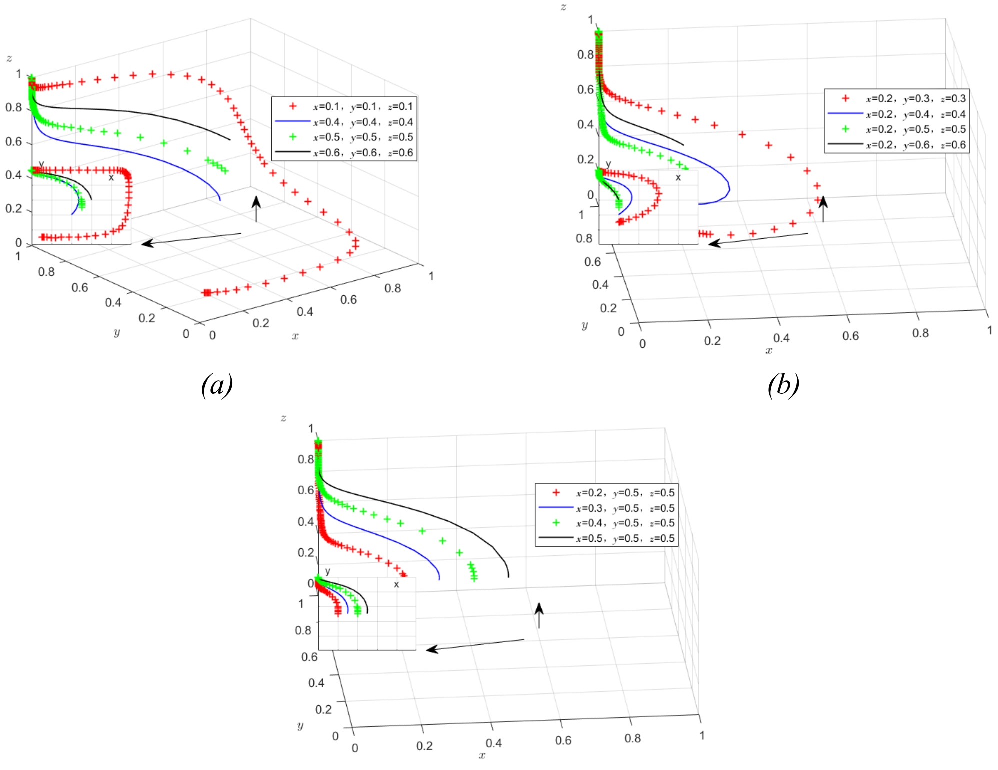
Figure 5 – Evolutionary stable strategy: a) $E_7(0,1,1)$; b) $E_1(0,0,0)$; c) $E_2(1,0,0)$; d) $E_5(1,1,0)$; e) $E_6(1,0,1)$

4.2 The effect of an initial strategy on the evolutionary process of the system

Without changing the initial values of the parameters, *Figure 6* simulates the impact on the stability of the system's evolutionary results when at least one of the three stakeholders – the government, the enterprise and the user – changes its initial willingness. As illustrated in *Figure 6a*, when the three stakeholders simultaneously alter their initial willingness, and under the condition that the probability of enterprises and users opting for the active management strategy and the regulated parking strategy attains a certain threshold, the probability of the government selecting the dominant supervision strategy undergoes a gradual decline, leading to the eventual evolutionary stable point approaching $E_7(0,1,1)$.

Meanwhile, *Figure 6a* offers two conclusions for consideration. First, when the initial willingness intensity of all three stakeholders is low, the government will swiftly adopt the dominant supervision strategy. The government's strategic evolution will subsequently cause the enterprises' and users' strategies to gradually converge on the active management strategy and the regulated parking strategy. Therefore, the government will transition from a dominant supervision strategy to a non-dominant one as the strategy of enterprises and users evolves. Second, empirical evidence suggests that a greater initial willingness from both enterprises and users facilitates a more rapid convergence of the system to a stable state, ultimately promoting a more favourable parking environment.

Furthermore, *Figures 6b and 6c* demonstrate that the probability of selecting the dominant supervision strategy will directly converge to 0 when the initial willingness of both enterprises and users to adopt the active management strategy and the regulated parking strategy is no less than 0.5, irrespective of the value of the government's initial willingness. The initial willingness for enterprises and users must therefore be safeguarded to significantly reduce the government's fiscal burden.



(a) *(b)*

(c)

Figure 6 – Influence of the initial willingness: a) The three stakeholders; b) The two stakeholders; c) The one stakeholder

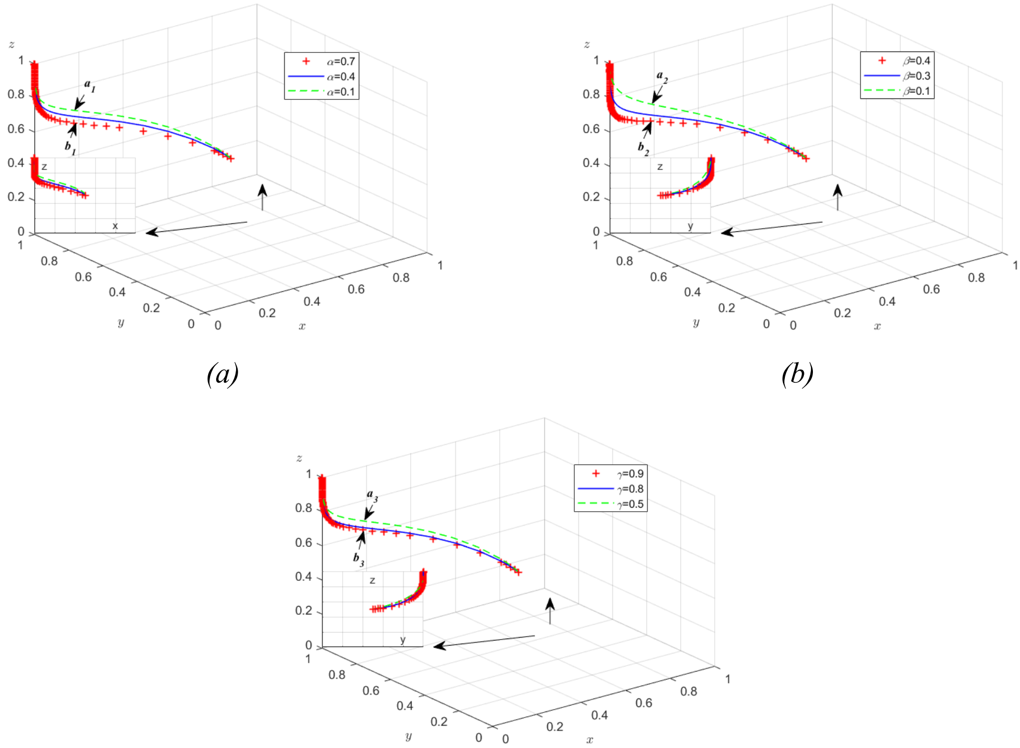
4.3 The influence of the rate of invalid parking area on the evolutionary processes of systems

In order to verify the validity of the analysis, this subsection will examine the effect of the rate of invalid parking areas on the evolutionary process. This analysis is based on the initial values of the parameters and under the assumption that the remaining parameters remain constant, respectively, such that $\alpha = 0.7, 0.4, 0.1$, $\beta = 0.4, 0.3, 0.1$, and $\gamma = 0.9, 0.8, 0.5$. The simulation results are shown in *Figures 7a–7c*.

The analysis presented in *Figure 7* illustrates that the rate of invalid parking areas exerts a negative influence on users' preferences for adopting a regulated parking strategy. Specifically, as the rate of invalid parking α, β, γ decreases, there is a corresponding increase in the likelihood that users will opt for the regulated parking strategy. Moreover, it is noteworthy that the variations in the probabilities of the three different rates of invalid parking area demonstrate distinct degrees of impact on users' strategic selections.

In the analysis presented, the coordinates of the a_i, b_i $(i = 1, 2, 3)$ points in *Figures 7a–7c* are designated as $x = 0.13, y = 0.93$. Notably, as the α value is decreased from 0.7 to 0.1, β from 0.4 to 0.1, and γ from 0.9 to 0.5, there is a significant increase in the probability z that users will select regulated parking, respectively increasing 8%, 10% and 5%. Consequently, the probability of a user opting for regulated parking increases with each unit variation in the three rates of invalid parking area designated as 13.3%, 33.3% and 12.5%. Notably, alterations in probability β exert the most significant influence on the user's strategic choice, followed by probabilities α and γ, respectively.

The study demonstrated that guaranteeing the efficient construction of parking areas by enterprises is the primary task of the shared bicycle parking governance system. Simultaneously, the government's proactive development of parking areas is crucial in reducing the likelihood. Additionally, urban infrastructure construction is a pivotal component of urban development, playing a vital role in enhancing infrastructure, reducing the rate of invalid parking areas and promoting the effective management of shared bicycle parking systems.



(a) (b)

(c)

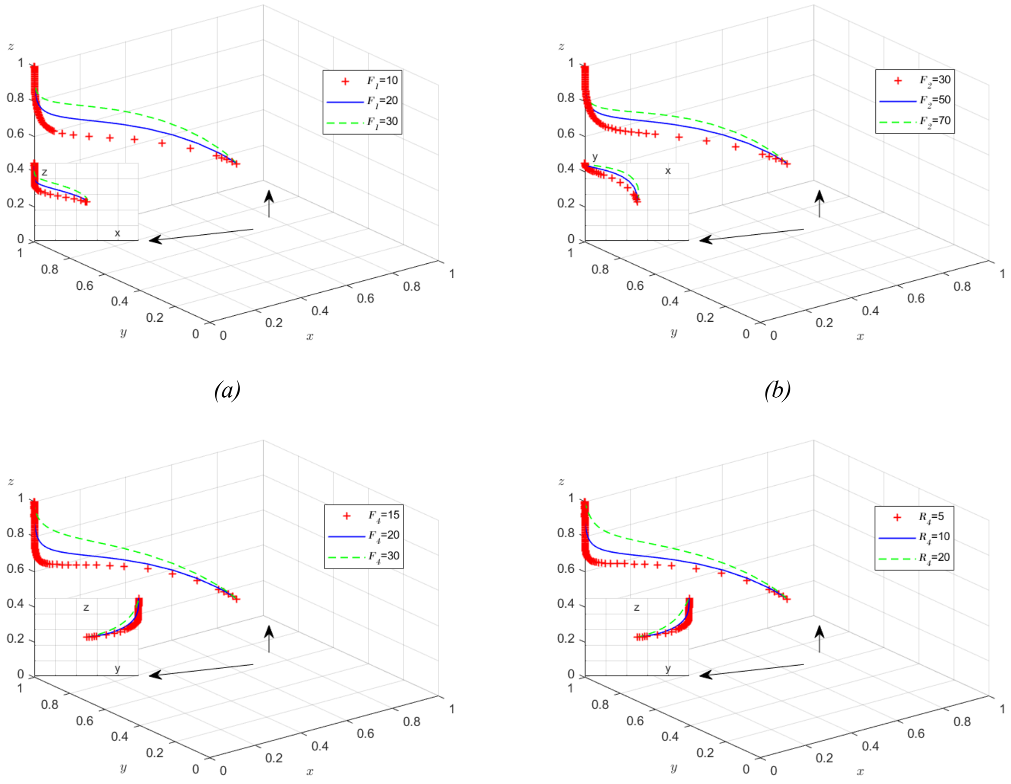
Figure 7 – Influence of the rate of invalid parking area: a) α; b) β; c) γ

4.4 The effect of reward and punishment on the evolutionary process of the system

To analyse the influence of the change of reward and punishment strength on the evolutionary process, based on the initial value of the parameters, respectively $F_1 = 10, 20, 30$, $F_2 = 30, 50, 70$, $F_4 = 15, 20, 30$ and $R_4 = 5, 10, 20$, under the premise that the rest of the parameters remain unchanged, the simulation results are shown in *Figures 8a–8d*.

The illustration in *Figure 8a* indicates that as the government implements a dominant supervision strategy by increasing penalties for non-compliance with parking regulations, users exhibit a heightened tendency to adopt the regulated parking strategy. Specifically, the probability of users selecting the regulated parking option shows a positive correlation with the escalation of fines F_1. Consequently, the implementation of heightened monetary penalties by governmental authorities for individuals who fail to comply with established parking regulations is proposed as a viable strategy to enhance compliance and promote standardised parking practices among users.

As illustrated in *Figure 8b*, the accelerated evolution of enterprises towards an active management strategy is observed to be contingent upon the increase in government fines imposed on enterprises that adopt a passive management strategy. As illustrated in *Figures 8c and 8d*, an increase in the enterprise's sanctioning of unregulated parking users and the provision of incentives to regulated parking users has been observed to result in an accelerated transition of users toward the regulated parking strategy and an elevated probability of selecting it. However, overly high incentives can burden enterprises with active management and dampen their motivation to do so.



(a) *(b)*

(c) *(d)*

Figure 8 – Influence of the reward and punishment: a) F_1*; b)* F_2*; c)* F_4*; d)* R_4

5. CONCLUSIONS

5.1 Main results and recommendations

This study investigated the efficiency of different supervision strategies in addressing the issue of shared bicycle parking in invalid parking areas. First, a tripartite evolutionary game model involving the government, enterprises and users was obtained. Second, the stability of the equilibrium point within the evolutionary game system was analysed; the conditions for its stability were established. Third, numerical simulations were performed by using MATLAB to verify the validity of the theoretical analysis. The following conclusions are as follows.

First, the initial willingness of the government, enterprises and users has a significant effect on the standardised governance of shared bicycle parking. When the initial willingness of each stakeholder increases, the time for users to converge on a regulated parking strategy gradually decreases, which is conducive to the formation of a good parking atmosphere. Concurrently, when the initial willingness of each game stakeholder is minimal, the government should assume primary regulatory responsibilities. The government is able to ensure the continued operation of its regulatory functions through the implementation of measures such as public oversight, joint disciplinary systems and increased penalties. If the initial willingness of users and enterprises exceeds 0.5, the enterprise is assigned the primary regulatory responsibility. It is recommended that the government implement policies such as tax reductions in order to enhance the enterprise's management initiative.

Second, reducing the rate of invalid parking areas can increase the probability of users choosing the regulated parking strategy. The degree of influence, in descending order, is as follows: the rate of invalid parking area when the enterprise takes active management, the rate of invalid parking area when the government takes dominant supervision, and the rate of invalid parking area owing to the imperfection of infrastructure construction. Consequently, the government should provide corresponding policy support to enterprises optimising the construction of parking areas, such as data sharing, financial subsidies and technical assistance.

Third, the government's increase in fines for passive management of enterprises and unregulated parking by users can lead to enterprises choosing an active management strategy and users choosing a regulated parking strategy. Consequently, appropriate increases in government penalties can promote the healthy development of shared bicycle parking governance systems. The enhancement of incentives and penalties for users has been demonstrated to enhance the probability of choosing a regulated parking strategy. However, it is important to note that increasing rewards is not favourable for better management responsibilities. To achieve an ideal stable strategy of non-dominant supervision, active management and regulated parking, it is necessary to satisfy the stability condition. Therefore, the implementation of a reward and punishment system may be considered, with the primary focus being on punishment and rewards serving a supplementary role.

5.2 Future research

This study highlights potential directions for future research. Firstly, interactions among stakeholders exhibit considerable uncertainty, as speculative behaviour, public opinion, emotional fluctuations and other stochastic factors influence their strategic choices. It is suggested that future research should explore the potential impact of stochastic disturbances on evolutionary processes. Secondly, this paper presents a theoretical analysis; however, it lacks adequate empirical validation. It is recommended that future research employ empirical methodologies to substantiate the validity of the proposed theoretical models. Such an approach would enhance the practical relevance and applicability of the research findings.

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