International Journal of Global Economics and Management
ISSN: 3005-9690 (Print), ISSN: 3005-8090 (Online) | Volume 7, Number 1, Year 2025
DOI: https://doi.org/10.62051/ijgem.v7n1.01
Journal homepage: https://ijgem.org

Evolutionary Game Analysis on Shared Electric Bike Recycling Decisions between Government and Operators

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ABSTRACT

To address the game-theoretic challenges in shared electric bike recycling between government and operators, this study develops an evolutionary game model to analyze their decision-making interaction mechanisms. By solving replicator dynamic equations and Jacobian matrices, we identify evolutionarily stable strategies. Using Matlab simulation tools, we quantify the threshold effects of environmental taxes and recycling subsidies on equilibrium decisions, revealing the critical synergy between policy incentives-penalties mechanisms and technical standards in enhancing recycling rates. This research provides quantitative decision-making support for resolving the dilemma between shared electric bike recycling and government regulatory oversight.

KEYWORDS

Shared electric bikes; Recycling decisions; Government regulation; Evolutionary game

1. INTRODUCTION

The rapid expansion of the shared electric bike market has brought environmental governance issues into sharp focus. Improper disposal of retired bikes, particularly their batteries and metal components, poses significant environmental contamination risks. Heavy metals in lithium batteries, if leaked into soil or water sources, threaten ecosystems and public health over the long term. Although some cities have implemented recycling policies, enforcement remains inconsistent. In certain regions, recycling rates remain below 50%, with abandoned bikes often stockpiled indiscriminately or dismantled through illegal channels, reflecting a stark disconnect between policy frameworks and market practices [1].

The core conflict arises from misaligned interests between governments and operators regarding recycling responsibilities and cost-sharing. From the governmental perspective, the absence of a unified national policy tailored to shared electric bike recycling—coupled with disparities in existing regulations for shared bicycles, retired batteries, and private e-bikes—creates implementation challenges. Local governments face a dilemma: stringent regulatory measures require substantial investments in technological upgrades, personnel training, and enforcement, which may exceed short-term fiscal capacities, while lax oversight risks escalating environmental degradation, public criticism, and long-term governance costs [2]. For operators, proactive recycling entails high compliance costs and operational pressures, necessitating logistics system improvements or partnerships with specialized teams. In the absence of effective incentives, companies tend to prioritize low-cost, low-effort disposal methods to sustain profitability, despite potential penalties and reputational damage [3]. The interplay between short-term gains and long-term benefits exemplifies a non-cooperative game characterized by asymmetric information and bounded rationality, often trapping stakeholders in a vicious cycle of ineffective regulation-passive recycling.

This study employs a dynamic evolutionary game framework to unravel the interaction mechanisms between government regulatory decisions and operator recycling behaviors. Key research questions include:

(1) How can governments balance regulatory costs and environmental benefits to design policy instruments under bounded rationality?

(2) How do operators adapt recycling strategies amid policy pressures and market competition?

(3) What coordination mechanisms can achieve dual optimization of environmental outcomes and corporate interests?

By clarifying these relationships, this research aims to provide theoretical foundations for optimizing policy design and advancing the green transition of the shared electric bike industry. A schematic diagram of the evolutionary game model between governments and shared electric bike platforms is illustrated in Figure 1.

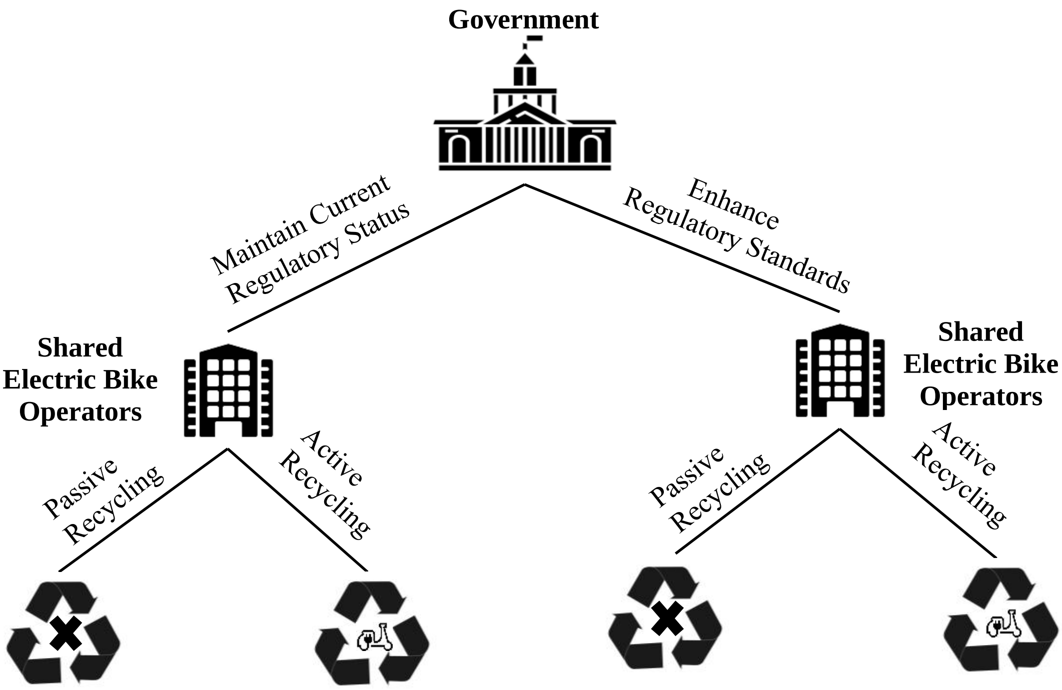

Figure 1. Diagram of the Evolutionary Game Model for Shared E-Bike Recycling Decisions Between Governments and Operators

2. LITERATURE REVIEW

Research on recycling models in shared mobility predominantly focuses on multi-tier decision-making relationships among manufacturers, operators, and recyclers. Some scholars have further integrated government regulations, consumer behavior, or technical parameters into game-theoretic frameworks to elucidate supply chain equilibria in complex market environments.

A common research theme is the game-theoretic interactions between governments and enterprises over recycling policies. Sun analyzed China’s discarded bicycle recycling system by comparing Extended Producer Responsibility (EPR) and green tax mechanisms. Their two-player game model, which considered government supervision and corporate recycling decisions, demonstrated that setting a minimum recycling standard at 0.65 and adopting dynamic supervision with reward-priority incentives significantly increases corporate adoption of EPR [3]. Liu applied evolutionary game theory to compare fixed versus degressive recycling subsidies, revealing that degressive subsidies combined with adaptive thresholds can effectively promote EPR compliance under stringent supervision [5, 6]. Si developed a tripartite evolutionary game model involving governments, enterprises, and consumers, identifying an equilibrium where governments cease supervision, enterprises adopt EPR, and consumers engage in recycling. Their sensitivity analysis highlighted that consumer subsidies, environmental taxes, and recycling conversion efficiency sequentially amplify decision-making impacts [6]. Liu constructed a quadripartite evolutionary game model (government, manufacturer, platform, consumer) for shared bike recycling, finding that recycling efforts correlate with profit margins and that raising supervision costs and consumer subsidies enhances recovery rates [7]. Similarly, Zhang explored a three-party decision mechanism using evolutionary game theory and system dynamics, emphasizing that governmental revenue stability underpins recycling systems, while operator profits under deposit systems exhibit negligible policy sensitivity [8].

However, scant research addresses recycling strategies for shared e-bikes and their lithium batteries. Shi emphasized the heightened complexity of recycling electric micromobility services due to multi-stakeholder coordination, capital intensity, battery disposal, and safety regulations [9]. Liu formulated a Stackelberg game model for e-waste recycling under market-driven deposit systems, demonstrating that manufacturer-led recycling maximizes supply chain profits, whereas third-party models suffer from channel fragmentation. Their numerical simulations revealed a 12%–18% recycling volume increase per 10% deposit increment [10]. Ma proposed a static game model integrating governments, manufacturers, and consumers, advocating for IoT-enabled recycling networks and stricter producer supervision to incentivize lithium battery recycling [11].

Existing studies predominantly focus on conventional bikes and generic battery recycling, neglecting systematic analyses of e-bike battery complexities, such as heavy metal pollution risks, cross-regional regulatory gaps, and technical barriers in disassembly. Additionally, most models treat technological and economic factors exogenously, overlooking endogenous interactions between disassembly efficiency and policy instruments.

Building on prior literature, this study addresses these gaps. While shared mobility research has advanced multi-agent game models and EPR-dynamic regulation synergies, its emphasis on traditional bikes leaves e-bike battery complexities underexplored. Herein, we employ evolutionary game theory to investigate dynamic interactions among governments, enterprises, and consumers, elucidating how policy tools modulate recycling behaviors. Under bounded rationality assumptions, we analyze trial-and-error behaviors in early policy implementation, including informal recyclers' responses to supervision intensity and nonlinear impacts of subsidy tapering on technology adoption. This framework aims to inform adaptive policy design for sustainable e-bike recycling.

3. MODEL DEVELOPMENT

3.1. Model Assumptions

This study focuses on the dynamic game relationship between governments and operators in the recycling regulation of shared e-bikes. The following assumptions guide the decision-making process:

3.1.1. Bounded Rationality

Under bounded rationality theory, participants cannot fully predict each other's decisions or environmental changes. Decisions rely on historical experience and partial information, with cognitive and informational constraints driving participants to pursue satisficing solutions rather than optimal ones [12]. Governments may misjudge operator behavior trends due to data latency, while operators struggle to predict policy adjustments accurately amid market volatility.

3.1.2. Dynamic Evolutionary Mechanism

Participants' strategies evolve over time through fitness-driven adaptation, following a "trial-error-imitation-improvement" process. The replicator dynamic equations describe changes in strategy proportions, enabling analysis of long-term equilibria via evolutionary stable strategies.

3.1.3. Information Asymmetry

Governments and operators face asymmetries in monitoring recycling behaviors and policy implementation costs. Governments lack real-time data on operators' actual recycling efficiency or covert non-compliance, while operators lack complete information on policy adjustment timeliness or government investments in regulatory technology.

3.1.4. Strategic Interdependence

Decisions exhibit mutual feedback: one party's strategic adjustment triggers adaptive responses from the other. Government policies directly affect operators' recycling cost structures, while operators' recycling volumes influence manufacturers' production costs.

3.2. Parameter Definitions

Key parameters are defined in Table 1:

Table 1. Parameter Definitions for Government-Operator Evolutionary Game

Symbol	Parameter Name	Parameter Explanation
E_c	Environmental tax	Penalty tax imposed on operators with passive recycling strategies.
S_r	Unit recycling subsidy	Incentive subsidy granted to operators adopting active recycling.
C_g	Fixed supervision cost	Fixed cost for governments to maintain current regulatory practices.
ΔCg	Marginal supervision cost	Additional cost for governments to enhance supervision intensity.
R	Reputation loss	Environmental damage-induced reputational loss for governments under passive recycling.
P	Net profit from passive recycling	Operators' net profit from passive recycling.
ΔC_m	Active recycling cost premium	Additional compliance cost for operators adopting active recycling.
P_m	Active recycling profit	Long-term profit from standardized recycling processes.
η	Environmental benefit	Quantified environmental value per unit of recycled e-bikes.

3.3. Strategy Space

3.3.1. Government (Public Environmental Interest Representative)

Maintain current supervision (S_1): Continue existing policies for shared bikes, private e-bikes, and battery recycling. No dedicated regulations for shared e-bikes, minimizing costs but risking environmental harm and reputational damage from operator non-compliance.

Enhance supervision intensity (S_2): Establish dedicated regulations to strengthen oversight. Higher costs but penalizes passive recycling via environmental taxes.

3.3.2. Operator (Market Entity)

Passive recycling (A_1): Minimal compliance via low-cost dismantling, informal channels, or component reuse. Higher short-term profits but subject to penalties.

Active recycling (A_2): Full compliance with standardized recycling processes. Higher upfront costs but ensures long-term profitability and subsidy eligibility.

The payoff matrix for the government-operator evolutionary game is summarized in Table 2.

Table 2. Payoff Matrix for Government-Operator Evolutionary Game

Decision Combinations	Government Payoff	Operator Payoff
(S_1, A_1)	$-C_g - R$	P
(S_1, A_2)	$-C_g$	$-\Delta C_m + P_m$
(S_2, A_1)	$-C_g - \Delta C_m + E_c - R$	$P - E_c$
(S_2, A_2)	$-C_g - \Delta C_g + \eta - S_r$	$-\Delta C_m + P_m + S_r + \eta$

3.4. Evolutionary Game Model

As the regulator of public interests, the government dynamically adjusts its decisions based on operators' recycling behavior. Let $x \in [0, 1]$ represent the proportion of governments adopting the enhanced regulatory level S_2. The expected payoffs for the government under different strategies are as follows:

Expected payoff for S_1:

$$E_g(S_1) = y(-C_g) + (1 - y)(-C_g - R) \tag{1}$$

Expected payoff for S_2:

$$E_g(S_2) = y(-C_g - \Delta C_g + \eta - S_r) + (1 - y)(-C_g - \Delta C_g + E_c - R) \tag{2}$$

Average expected payoff for the government:

$$\overline{E_g} = xE_g(S_2) + (1 - x)E_g(S_1) \tag{3}$$

Replicator dynamics for government strategy x:

$$\frac{dx}{dt} = x\left[E_g(S_2) - \overline{E_g}\right] = x(1 - x)[E_g(S_2) - E_g(S_1)] \tag{4}$$

Expanding this equation yields:

$$\frac{dx}{dt} = x(1 - x)[(\eta - E_c - S_r)y + E_c - \Delta C_g] \tag{5}$$

When$(\eta - E_c - S_r)y > -E_c + C$, the government tends to increase its regulatory level.

Operators, as market participants, balance policy pressure and economic interests. Let $y \in [0, 1]$ denote the proportion of operators adopting active recycling A_2. The replicator dynamics are constructed as follows:

Expected payoff for A_1:

$$E_m(A_1)x(P - E_c) + (1 - x)P \tag{6}$$

Expected payoff for A_2:

$$E_m(A_2)=x(-\Delta C_m + P_m + S_r) + (1 - x)(-\Delta C_m + P_m) \tag{7}$$

Average expected payoff for the operator:

$$\overline{E_m} = yE_m(A_2) + (1-y)E_m(A_1) \tag{8}$$

Replicator dynamics for operator strategy y:

$$\frac{dy}{dt} = y[E_m(A_2) - \overline{E_m}] = y(1-y)[E_m(A_2) + E_m(A_1)] \tag{9}$$

Expanding this equation yields:

$$\frac{dy}{dt} = y(1-y)[(S_r + E_c)x - \Delta C_m + P_m P] \tag{10}$$

When $(S_r + E_c)x > \Delta C_m + P - P_m$, operators tend to adopt active recycling.

Coupled asymmetric evolutionary game system:

$$\begin{cases} \frac{dx}{dt} = x(1-x)[(\eta - E_c - S_r)y + E_c - \Delta C_g] \\ \frac{dy}{dt} = y(1-y)[(S_r + E_c)x - \Delta C_m + P_m P] \end{cases} \tag{11}$$

Equilibrium Analysis in the Evolutionary Game Model

In evolutionary game theory, equilibrium points represent stable states where the decision proportions of the government and operators cease to change (i.e., dx/dt=0 and dy/dt=0). These equilibria can be categorized into two types:

(1) Pure-strategy equilibria: Either x∈{0, 1} or y∈{0, 1}, indicating one or both parties adopt a single strategy exclusively.

(2) Mixed-strategy equilibria: x, y∈[0, 1], where both parties adopt strategies probabilistically.

Not all equilibria are stable. Stability is determined by analyzing the eigenvalues of the Jacobian matrix, which evaluates the local slopes of the dynamic equations near equilibrium points. The Jacobian matrix is constructed as:

$$J = \begin{bmatrix} \frac{\partial(dx/dt)}{\partial x} & \frac{\partial(dx/dt)}{\partial y} \\ \frac{\partial(dy/dt)}{\partial x} & \frac{\partial(dy/dt)}{\partial y} \end{bmatrix} \tag{12}$$

Stability criteria based on eigenvalues are:

Evolutionarily Stable Strategy (ESS): Both eigenvalues are negative.

Saddle Point: One positive and one negative eigenvalue; instability depends on initial conditions.

Unstable Point: Both eigenvalues are positive; the system cannot converge.

By solving the coupled Eq.11 under dx/dt=0and dy/dt=0, the pure-strategy equilibria are derived as shown in Table 3.

Table 3. Strategy Equilibrium Analysis

Equilibrium Point	Jacobian Eigenvalues	Existence Conditions
$E_1(0, 0)$	$\lambda_1 = -\Delta C_g + E_c$ $\lambda_2 = -\Delta C_m + P_m - P$	1. $\Delta C_g > E_c$ 2. $\Delta C_m + P > P_m$
$E_2(0, 1)$	$\lambda_1 = -\Delta C_g - S_r + \eta$ $\lambda_2 = \Delta C_m - P_m + P$	1. $\Delta C_g + S_r > \eta$ 2. $P_m > \Delta C_m + P$
$E_3(1, 0)$	$\lambda_1 = \Delta C_g - E_c$ $\lambda_2 = E_c + S_r - \Delta C_m + P_m - P$	1. $E_c > \Delta C_g$ 2. $\Delta C_m + P > S_r + \Delta C_g + P_m$
$E_4(1, 1)$	$\lambda_1 = \Delta C_g + S_r + E_c - \eta$ $\lambda_2 = \Delta C_m - P_m + P - S_r - E_c$	1. $\eta > \Delta C_g + S_r + E_c$ 2. $S_r + E_c + P_m > \Delta C_m + P$

Mixed-Strategy Equilibria represent dynamic balances where both parties probabilistically choose strategies. These points are typically saddle points or unstable nodes. Solving dx/dt=0and dy/dt=0:

$$x^* = \frac{\Delta C_m - P_m + P}{S_r + E_c} \tag{13}$$

$$y^* = \frac{\Delta C_g - E_c}{\eta - S_r - E_c} \tag{14}$$

Existence conditions for E* (x*, y*):

1) $x^* \epsilon [0, 1]$

If $S_r+E_c>0$, then $\Delta C_m-P_m+P\geq 0$ and $\Delta C_m-P_m+P\leq S_r+E_c$.

If $S_r+E_c<0$, then $\Delta C_m-P_m+P\leq 0$ and $\Delta C_m-P_m+P\geq S_r+E_c$.

2) $y^* \epsilon [0, 1]$

If $\eta-E_c-S_r>0$, then $\Delta C_g-E_c\geq 0$ and $\Delta C_g-E_c\leq \eta-E_c-S_r$.

If $\eta-E_c-S_r<0$, then $\Delta C_g-E_c\leq 0$ and $\Delta C_g-E_c\geq \eta-E_c-S_r$.

4. CASE STUDY

4.1. Case Overview

This study selects Nanning(Guangxi) as the case study. As one of China's first pilot cities for standardized shared e-bike management, Nanning has implemented a policy framework covering the entire lifecycle of shared e-bikes, including production, recycling, and registration. By 2024, shared e-bikes accounted for over 30% of green travel in the city, with 5 million registered users and 135,000 deployed units [13]. Daily ridership exceeded 200,000 trips, averaging 2.3 kilometers per ride. The Internet Rental Bicycle Service Quality Assessment Report published by the Nanning Transportation Bureau provides publicly accessible data on deployment volumes, retirement volumes, environmental taxes, and fiscal subsidies, which align with the model's requirements [14].

4.2. Parameter Settings

The case parameters are defined in Table 4:

Table 4. Case Parameter Settings

Symbol	Value CNY/unit	Explanation
E_c	20	Calculated based on Guangxi's environmental tax rates: 1.8 CNY/ton for air pollutants and 2.8 CNY/ton for water pollutants, adjust for battery pollution costs [15]
S_r	10	Estimated from shared-bike recycling subsidies and waste battery recycling policies [16]
C_g	12	Derived from Nanning's 2024 regulatory budget allocated across 135,000 deployed e-bikes [17]
ΔC_g	15	Estimated from GEM Co.'s 2024 technical whitepaper on battery recycling [18]
R	10	Estimated based on accident rate, single-incident handling cost, and superimposed public opinion cost [19]
P	500	Includes lithium battery disassembly (350 CNY) and scrap motor recycling (150 CNY) [20]
ΔC_m	125	Based on lead-acid battery recycling costs specified in Technical Specifications for Waste Battery Recycling [21]
P_m	725	Sum of P (500 CNY), secondary battery utilization (200 CNY), and carbon credits (25 CNY). Carbon credits: 75%×558kg CO_2/unit×58CNY/ton÷1000≈25CNY [22]
η	50	Combines carbon reduction (25%×558kg CO_2×58CNY/ton) and pollution control savings (30 CNY/unit) [23]

4.3. Case Results

Using the evolutionary game model with Nanning's parameters, the equilibrium points and stability analyses are summarized in Table 5:

Table 5. Case Equilibrium Analysis

Equilibrium Point	Jacobian Eigenvalues	Stability	Analysis
$E_1(0, 0)$	$\lambda_1=5$ $\lambda_2=100$	Unstable	Both eigenvalues positive; system cannot stabilize.
$E_2(0, 1)$	$\lambda_1=25$ $\lambda_2=-100$	Saddle Point	Mixed eigenvalues; trajectories diverge toward $E_4(1, 1)$.
$E_3(1, 0)$	$\lambda_1=-5$ $\lambda_2=115$	Saddle Point	Mixed eigenvalues; trajectories diverge toward $E_4(1, 1)$.
$E_4(1, 1)$	$\lambda_1=-5$ $\lambda_2=-130$	ESS	Both eigenvalues negative; stability conditions satisfied: $\eta>\Delta C_g+S_r+E_c$ and $S_r+E_c+P_m>\Delta C_m+P$. System converges to E_4.
$E^*(x^*, y^*)$	$x^*=-3.33$ $y^*=-0.25$	Infeasible	x, $y^*\in[0, 1]$, so no valid mixed equilibrium.

4.3.1. Equilibrium Point $E_1(0, 0)$

When the government maintains the current regulatory intensity while operators adopt passive recycling, the system's stability requires two conditions, the government's marginal cost of maintaining regulation must exceed the environmental tax revenue, and the total benefits of passive recycling for operators must outweigh those of active recycling. However, in the actual case study, the environmental tax exceeds the government's marginal cost, and the net revenue from active recycling significantly surpasses the total costs of passive recycling, rendering both conditions invalid.

Eigenvalue analysis of the Jacobian matrix reveals two positive eigenvalues, indicating that the system will rapidly deviate from this state due to the government's inability to cover regulatory costs with environmental tax revenues and operators' preference for higher profits through active recycling. Consequently, this equilibrium is unsustainable and evolves toward enhanced regulation and active recycling.

4.3.2. Equilibrium Point $E_2(1, 0)$

Under this scenario, the system's existence depends on the government's cost-benefit trade-off between regulatory costs and environmental benefits. Specifically, the total cost of maintaining regulation should exceed environmental benefits, while operators' active recycling profits must dominate compliance costs. However, in practice, environmental benefits far outweigh regulatory costs, and active recycling yields substantially higher net revenues than passive strategies. The Jacobian matrix eigenvalues show a positive value for the government and a negative value for operators This contradiction leads the system to converge toward the stable equilibrium of enhanced regulation and active recycling $E_4(1, 1)$.

4.3.3. Equilibrium Point $E_3(0, 1)$

This equilibrium requires the environmental tax to exceed the government's marginal regulatory cost and operators' passive recycling profits to overcome policy penalties. However, the case study demonstrates that passive recycling revenues fall below policy-induced financial pressures. The Jacobian matrix eigenvalues reveal a negative value for the government and a positive value for operators. Thus, this state serves only as a transient phase, ultimately evolving toward stable compliance.

4.3.4. Equilibrium Point $E_4(1, 1)$

Stability here necessitates two conditions, environmental benefits must offset the government's total regulatory costs, and policy incentives must exceed operators' compliance costs. The case study confirms that environmental benefits marginally exceed regulatory expenditures, while policy incentives dominate operational costs. Both eigenvalues of the Jacobian matrix are negative, confirming evolutionary stability. This equilibrium establishes a self-reinforcing "high regulation–high recycling" mechanism, where governments balance taxes and subsidies, and operators maximize profits under policy support.

4.3.5. Mixed Strategy Equilibrium $E^*(x^*, y^*)$

The calculated probabilities for mixed strategies exceed the feasible range [0, 1], indicating the absence of a valid probabilistic equilibrium. This implies that corner equilibria dominate under current policy parameters, necessitating unambiguous incentives rather than probabilistic mechanisms to guide stakeholder decisions.

The evolutionary process of the case study is illustrated in Figure 2.

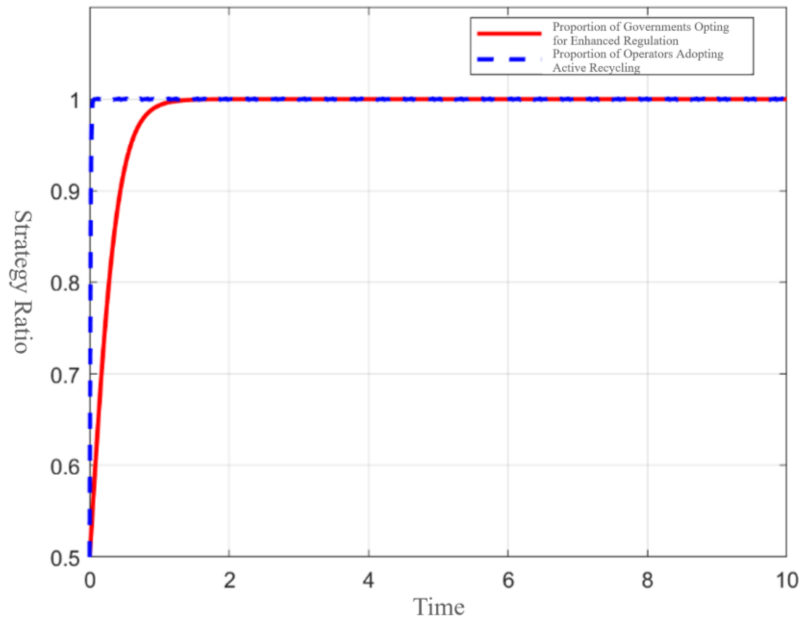

Figure 2. Evolutionary Game Process of Nanning Shared E-Bike Recycling Case (Time)

Simulation analysis of the current case reveals that the system ultimately stabilizes at the equilibrium where governments adopt strengthened regulation and operators implement active recycling.

From the governmental decision-making perspective, the preset environmental benefits must offset the total costs incurred during regulation. Specifically, only when environmental benefits surpass the sum of the marginal costs of strengthened regulation, recycling subsidies, and potential environmental tax losses can the strengthened regulation strategy yield long-term positive returns, thereby motivating governments to sustain high-intensity oversight. This design embodies the policy logic that regulatory actions form sustainable incentives only when the long-term ecological value significantly outweighs administrative investments.

For operators, decision-making hinges on comparing the economic benefits of different recycling strategies. When the comprehensive benefits of active recycling exceed the net income from traditional disposal methods, enterprises spontaneously transition to compliant recycling. Simulation parameters demonstrate that the sum of active recycling's technological benefits and policy subsidies substantially surpasses the combination of passive recycling's short-term gains and potential environmental tax burdens. This benefit structure effectively reverses the traditional dilemma in environmental governance where non-compliance costs fall below compliance costs, guiding market behaviors through economic leverage.

The model constructs a multi-stakeholder win-win incentive compatibility mechanism: governments alleviate enterprises' transitional pains through moderate subsidies while offsetting regulatory costs via endogenous accumulation of environmental benefits; enterprises, supported by policies, transform environmental investments into new profit growth points through technological upgrades. This institutional design avoids the high execution costs of traditional command-and-control approaches and mitigates market failure risks inherent in pure market regulation, showcasing the unique advantages of innovative environmental governance tools.

4.4. Results Analysis

Dynamic simulations of the evolutionary game model for shared e-bikes in Nanning City reveal the strategic interaction patterns between governmental regulation and operator recycling behaviors. By altering initial probabilities, the dynamic relationship between the probability of governments strengthening regulation (x) and operators adopting active recycling (y) is illustrated in Figure 3.

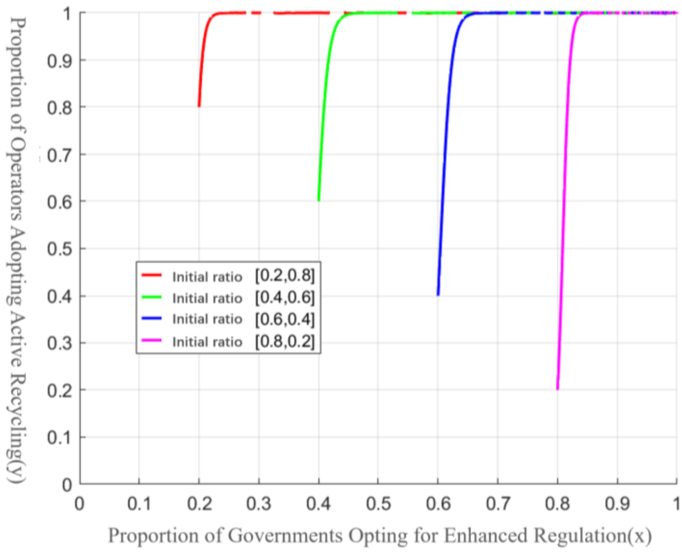

Figure 3. Evolutionary Game Process of the Case Study Under Modified Probabilities

Four sets of initial values demonstrate both universal patterns and differentiated evolutionary trajectories:

(1) Low Initial Regulation & High Recycling Willingness (x=0.2, y=0.8)

The system exhibits rapid response characteristics, with the proportion of actively recycling operators approaching saturation via near-exponential growth. This steep ascent indicates that modest regulatory strengthening can trigger positive feedback mechanisms among environmentally conscious enterprises. The critical point (x=0.4) identifies the interval of maximal marginal policy effectiveness, where each unit increase in regulatory intensity generates approximately 30% growth in recycling rates.

(2) Moderate Initial Regulation & Recycling (x =0.4, y =0.6)

The evolution displays two-phase dynamics. When$x \in [0.4, 0.6]$, active recycling adoption increases linearly, followed by accelerated growth after x=0.6. This bifurcation reflects the impact of enterprise technological upgrade cycles: initial regulatory pressure addresses existing equipment retrofitting costs, while post-threshold effects manifest scale economies. Notably, the growth rate at x=0.6 surpasses other initial conditions, suggesting optimal policy leverage in intermediate initial states.

(3) High Initial Regulation & Low Recycling (x=0.6, y=0.4)

Significant policy resistance emerges, with only 25% of operators transitioning to active recycling as regulation intensifies from 0.6 to 0.8—markedly lower than other scenarios. This phenomenon likely stems from compliance fatigue under prolonged high-intensity regulation, causing diminishing marginal policy utility. The inflection at x=0.85 indicates that surpassing specific regulatory thresholds transforms passive compliance into proactive technological upgrades.

(4) Extreme Initial Regulation (x=0.8, y=0.2)

The trajectory exhibits threshold-driven abrupt transitions. Despite low initial operator willingness, intensified regulation forces operators to rapidly adopt active recycling, with adoption rates leaping from 0.4 to 1 within a narrow interval. This nonlinear shift corresponds to a fundamental restructuring of operator decision-making when regulatory pressure exceeds cost-bearing thresholds.

All trajectories converge to theoretical optima once regulatory and recycling rates surpass critical thresholds, yet initial conditions profoundly influence threshold positions and evolutionary speeds. Low-regulation/high-recycling scenarios exhibit highest policy sensitivity (x=0.4), while high-regulation/low-recycling conditions require stronger interventions (x=0.8) to trigger phase transitions.

These findings provide quantitative foundations for graded and categorized regulation, recommending dynamic policy adjustments based on regional enterprise characteristics to minimize environmental governance costs.

5. CONCLUSION

This study constructs an evolutionary game model to analyze strategic interactions between governments and operators in shared e-bike recycling decisions, revealing equilibrium mechanisms and dynamic evolution patterns. First, an asymmetric evolutionary game framework is established under assumptions of bounded rationality, information asymmetry, and dynamic evolution. Replicator dynamic equations and Jacobian matrix analyses identify evolutionarily stable strategies, validated through empirical simulations in Nanning [23].

Results demonstrate that long-term system equilibria depend on the synergistic effects of policy instruments and technical standards. Stable convergence toward strengthened regulation and active recycling occurs when environmental benefits significantly exceed governmental regulatory costs and policy incentives cover operators' compliance investments. The Nanning case confirms that dynamic reward-penalty mechanisms and carbon trading revenue designs effectively balance regulatory costs and environmental benefits, incentivizing operator compliance. Other potential equilibria are excluded due to mismatched cost-benefit principles, underscoring policy synergy's critical role in resolving regulatory dilemmas [24].

By integrating evolutionary game theory with empirical analysis, this research provides theoretical and practical insights for green governance in the sharing economy, offering quantitative decision support for governmental regulatory optimization and corporate environmental performance enhancement. However, the model's focus on bilateral government-operator interactions limits exploration of manufacturers' technological upgrade impacts on recycling systems. Furthermore, synergistic threshold effects between policy tools and techno-economic parameters require quantification through hierarchical decision frameworks. Complex issues—such as nonlinear relationships between technological upgrade costs and subsidy elasticity, and carbon trading mechanisms' regulatory effects on long-term equilibria—warrant deeper investigation in extended game-theoretic models.

ACKNOWLEDGEMENTS

The authors would like to express gratitude to the anonymous reviewers for their constructive feedback, which significantly improved the quality of this manuscript. Special thanks to the Relevant institution for providing valuable case data.

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