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Research on game strategies of participants in highway prevention and noise pollution control

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Abstract: To uncover the decision-making mechanisms and evolutionary dynamics of multiple stakeholders in highway noise pollution control, a three-party evolutionary game model involving the government, operators, and the public is constructed. The operation period is divided into different stages for differentiated analysis. A simulation analysis was performed on the Lituo sinking section of the Beijing-Hong Kong-Macao Highway to assess the impact of variations in critical elements on the system. The results indicate that the Lituo sinking section of the Beijing-Hong Kong-Macao Highway is currently in its early stage of development, with the corresponding strategies being active regulation, excessive emissions, and supervision. When the cost of the government's active regulation decreases from 1×10^5 to 5×10^4 yuan, the system converges more rapidly toward the active regulation strategy. When the cost of the operator's excessive emissions increases from 14.08×10^6 to 20.00×10^6 yuan, the system drives the operator toward the standardized emission strategy. In addition, when the cost of public supervision decreases from 15×10^4 to 5×10^4 yuan and the compensation paid by operators to the public increases from 1.288×10^6 to 2.576×10^6 yuan, the system converges more quickly toward the supervision strategy. The cost of the operator's excessive emissions serves as the core decision variable for achieving the ideal equilibrium in the three-party game involving government active regulation, operator standardized emissions, and public supervision.

Key words: noise prevention and control; operational period; evolutionary game; Beijing-Hong Kong-Macao Highway Lituo sinking section

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The transport sector ranks among the world's largest carbon-emitting industries. Transportation-related noise pollution has drawn increasing attention, with road traffic noise identified as the predominant cause. At the institutional level, governments can use incentives such as subsidies, tax breaks, and fee waivers to encourage operators to develop new technologies aimed at reducing noise pollution. From a practical perspective, highway operators can mitigate noise by rebuilding pavements to reduce noise, regulating vehicle use, implementing real-time monitoring, and conducting regular maintenance. At the demand level, the public's limited awareness of environmental preservation and lack of supervision increase their vulnerability to noise and auditory disturbances, making them vital external catalysts. Consistent with the stakeholder principle[1], these stakeholders collectively influence progress in the prevention and control of noise pollution.

Environmental noise refers to all unwanted sounds in our communities, except those originating in workplaces[2]. The 19th CPC National Congress report explicitly advocates for the "implementation of the most stringent ecological environmental protection system," aiming to build a beautiful China and restore nature to a state of tranquility, harmony, and beauty, where "tranquility" specifically denotes the absence of noise pollution[3]. China began addressing noise pollution in the early 1960s. The People's Republic of China Noise Pollution Prevention and Control Law was revised in December 2021 and came into effect on World Environment Day in June 2022. In the past 60 years, China's noise control efforts have evolved significantly, progressing from basic measures to the development of a comprehensive disciplinary system[4]. Zhang et al. [5] introduced an active control technique for reducing in-car road noise. Wei et al. [6] summarized the work and challenges in preventing and controlling noise pollution on highways and urban roads in China. Ren et al. [7] analyzed and compared the noise characteristics of different pavement types. Zhang et al. [8] introduced an active control technique for reducing impact noise in road noise control sys-

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tems. Mao et al.[9] examined urban inhabitants' response curve to traffic noise in 2022 and identified the noise irritation threshold in residential zones. Vijay et al.[10] measured the traffic volume and noise levels during morning and evening peak hours, while Wen et al.[11] reviewed 282 domestic and international studies to summarize technologies and methods for monitoring urban road traffic noise. Cai et al.[12] monitored noise across multiple urban traffic routes and analyzed the disparities in sound pressure level spectra under different spectrum correction values. Li et al.[13] proposed a computer vision-based method for quick estimation of urban road noise. Forouhid et al.[14] identified vehicle speed, road width, and land use as key factors influencing various sound levels produced by moving cars, resulting in a noise level increase of 0.002 dB. Mirzahossein et al.[15] presented a method for evaluating traffic capacity under environmental constraints based on acceptable levels of air and noise pollutants. Shen et al.[16] suggested an STSHAEKF technique to mitigate the effects of uncertain noise interference and quality parameter discrepancies on vehicle state estimation. Alberto et al.[17] proposed that system noise is regulated by a tuning parameter representing the stochasticity level during the strategy revision stage.

This study develops a sophisticated game model based on evolutionary game theory to analyze various interactions among the government, operators, and the public in decision-making and evolution processes. It utilizes the life cycle to categorize different stages of highway operation, examines strategies of diverse actors, and promotes environmentally friendly growth of highways.

1 Model Construction and Analysis

1.1 Model assumption

Based on evolutionary game theory, a three-party evolutionary game model is constructed[18] with the following assumptions.

Assumption 1 The government (including provincial and local ecological environment bureaus, transportation committees, finance bureaus, and other relevant departments), operators (government-regulated highway operating entities), and the public constitute a complete structure. Each entity is treated as a rational actor endowed with norms and rights guiding its behavior.

Assumption 2 The government implements a system of incentives and sanctions to assist operators in minimizing noise. Excessive emitters that violate noise pollution standards are subject to fines, credit penalties, temporary remedial measures, and operational restrictions.

Assumption 3 Owing to informational asymmetry, operators may engage in illegal emissions due to "moral hazard" and "adverse selection." If the public adopts a supervisory strategy and an operator violates noise regulations, reporting or whistleblowing could jeopardize the operator's interests.

1.2 Model parameterization

In the evolutionary game framework, the three parties iteratively adjust strategies to reach the Nash equilibrium. The government has two strategy options: active and passive regulation. The likelihood of choosing active regulation is denoted by x (where $0<x<1$), while that of choosing passive regulation is expressed as $1-x$, subject to the constraint $a<b<1$. Operators have two strategic options: standardized emissions and excessive emissions, with the probability of selecting legal emission denoted as y ($0<y<1$) and that of selecting illegal emission as $1-y$. Similarly, the public has two strategies: supervision and non-supervision, with the likelihood of selecting supervision denoted as z ($0<z<1$) and non-supervision as $1-z$. Table 1 presents the game payoffs. Here, r represents the government's benefit from successful investi-

Table 1 Payoff matrix for three-population games

Government	Operator	Public	
		Supervision	No supervised
Active supervision	Standardized emission	$\begin{bmatrix} B_1 - C_1 - T_1 + M_1 R_{\mathrm{EL}} \\ R_{\mathrm{EL}} - C_3 - C_{\mathrm{E}} + T_1 \\ L_{10} + B_3 + nx - C_{\mathrm{p}} \end{bmatrix}$	$\begin{bmatrix} -C_1 - T_1 + M_1 R_{\mathrm{EL}} \\ R_{\mathrm{EL}} - C_3 - C_{\mathrm{E}} + T_1 \\ L_{10} \end{bmatrix}$
	Excessive emission	$\begin{bmatrix} a(r + T_3) + (1 - a)T_2 - C_1 + B_1 \\ a(M_2 R_{\mathrm{EI}} - C_4 - T_3) + (1 - a)(M_2 R_{\mathrm{EI}} - C_4 - T_2) - D \\ L_{10} + B_3 + nx - C_{\mathrm{p}} \end{bmatrix}$	$\begin{bmatrix} a(r + T_3) + (1 - a)T_2 - C_1 \\ a(M_2 R_{\mathrm{EI}} - C_4 - T_3) + (1 - a)(M_2 R_{\mathrm{EI}} - C_4 - T_2) \\ L_{10} - F \end{bmatrix}$
Passive supervision	Standardized emission	$\begin{bmatrix} B_1 - C_2 - T_1 + M_1 R_{\mathrm{EL}} \\ R_{\mathrm{EL}} - C_3 - C_{\mathrm{E}} + T_1 \\ L_{10} + B_3 - C_{\mathrm{p}} \end{bmatrix}$	$\begin{bmatrix} -C_2 - T_1 + M_1 R_{\mathrm{EL}} \\ R_{\mathrm{EL}} - C_3 - C_{\mathrm{E}} + T_1 \\ L_{10} \end{bmatrix}$
	Excessive emission	$\begin{bmatrix} b(r + T_3) + (1 - b)T_2 - C_2 + B_1 \\ b(M_2 R_{\mathrm{EI}} - C_4 - T_3) + (1 - b)(M_2 R_{\mathrm{EI}} - C_4 - T_2) - D \\ L_{10} + B_3 - C_{\mathrm{p}} \end{bmatrix}$	$\begin{bmatrix} b(r + T_3) + (1 - b)T_2 - C_2 \\ b(M_2 R_{\mathrm{EI}} - C_4 - T_3) + (1 - b)(M_2 R_{\mathrm{EI}} - C_4 - T_2) \\ L_{10} - F \end{bmatrix}$

gations; C_1 and C_2 represent the costs of active and passive regulation, respectively; a and b represent the success rates of active and passive supervision, respectively; M_1 and M_2 represent the conversion coefficients of revenue of the government and the operator, respectively; n represents the effect of regulation on the public; B_1 denotes the government's rewards for mass supervision; R_{EL} and R_{EI} represent the benefits of standardized and excessive emissions from operators, respectively; C_3 and C_4 are the costs associated with standardized and excessive emissions generated by operators, respectively; L_{10} indicates the basic expected benefits of public supervision; D represents losses to operators due to public protests; B_3 represents the compensation paid by operators to the public; F captures the negative externalities caused by operators; T_1 and T_2 represent government subsidies to operators and pollution fines imposed on operators, respectively; C_{p} is the cost of the public supervision; T_3 is the environmental tax levied by operators; C_{E} denotes the operators covering government compliance fees.

1.3 Model analysis

1.3.1 Stability analysis of government strategies

The government's expected return under active regulation is denoted as U_1, while its expected return under passive regulation and the average expected return are denoted as U_2 and U_3, respectively.

$$\begin{aligned} U_1 = {} & x[y(zB_1 - C_1 - T_1 + M_1R_{\mathrm{EL}}) + \\ & (1-y)(zB_1 + a(r+T_3) + (1-a)T_2 - C_1)] + \\ & (1-x)[y(zB_1 - C_2 - T_1 + M_1R_{\mathrm{EL}}) + \\ & (1-y)(zB_1 + b(r+T_3) + (1-b)T_2 - C_2)] = \\ & y(zB_1 - C_1 - T_1 + M_1R_{\mathrm{EL}}) + \\ & (1-y)[zB_1 + a(r+T_3) + (1-a)T_2 - C_1] \end{aligned} \tag{1}$$

$$\begin{aligned} U_2 = {} & y(zB_1 - C_2 - T_1 + M_1R_{\mathrm{EL}}) + \\ & (1-y)[zB_1 + b(r+T_3) + (1-b)T_2 - C_2] \end{aligned} \tag{2}$$

$$\begin{aligned} U_3 = {} & xU_1 + (1-x)U_2 = \\ & x[y(zB_1 - C_1 - T_1 + M_1R_{\mathrm{EL}}) + \\ & (1-y)(zB_1 + a(r+T_3) + (1-a)T_2 - C_1)] + \\ & (1-x)[y(zB_1 - C_2 - T_1 + M_1R_{\mathrm{EL}}) + \\ & (1-y)(zB_1 + b(r+T) + (1-b)T_2 - C_2)] \end{aligned} \tag{3}$$

The government's replication dynamic equation is denoted as $F(x)$ and expressed as

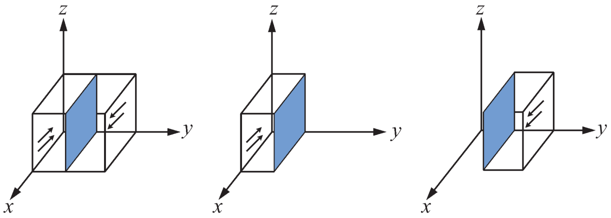
$$\begin{aligned} F(x) = {} & \frac{\mathrm{d}x}{\mathrm{d}t} = x(1-x)(U_1 - U_2) = \\ & x(1-x)\Big\{y(C_2 - C_1) + (1-y)[(a-b)(r+ \\ & T_3 - T_2) - (C_1 - C_2)]\Big\} \end{aligned} \tag{4}$$

The first derivative of $F(x)$ and the definitions of $G(y)$ are as follows:

$$\begin{aligned} \frac{\mathrm{d}(F(x))}{\mathrm{d}x} = {} & (1-2x)\Big\{y(C_2 - C_1) + \\ & (1-y)[(a-b)(r+T_3-T_2) - (C_1 - C_2)]\Big\} \end{aligned} \tag{5}$$

$$\begin{aligned} G(y) = {} & y(C_2 - C_1) + \\ & (1-y)[(a-b)(r+T_3-T_2) - (C_1 - C_2)] \end{aligned} \tag{6}$$

The government adopts "active regulation" in a stable state, where $F(x)=0, \frac{\mathrm{d}(F(x))}{\mathrm{d}x} < 0$. $G(y)$ is a monotonically increasing function of y, reflecting the government's preference for active control due to higher costs associated with passive regulation. $y = (1 - C_2 - C_1)/[(b-a)(r+T_3-T_2)] = y^*$, $G(y)=0$, the government is currently unable to establish a stable strategy. When $y < y^*$, $\left.\frac{\mathrm{d}(F(x))}{\mathrm{d}x}\right|_{x=0} < 0$, $x=0$ represents the government's stable strategy, and when $y > y^*$, $x=1$ represents the stable strategy for the government. The dynamic evolution of government decision-making is shown in Fig. 1.



(a) (b) (c)

Fig. 1 Government evolutionary stage diagram. (a) $y=y^*$; (b) $y<y^*$; (c) $y>y^*$

1.3.2 Stability analysis of operators' strategies

The operator's expected return under standardized emissions is denoted as U_4, while the expected return under excessive emissions and the average expected return are denoted as U_5 and U_6, respectively.

$$U_4 = R_{\mathrm{EL}} - C_3 - C_{\mathrm{E}} + T_1 \tag{7}$$

$$\begin{aligned} U_5 = {} & x[a(M_2R_{\mathrm{EI}} - C_4 - T_3) + \\ & (1-a)(M_2R_{\mathrm{EI}} - C_4 - T_2) - zD] + \\ & (1-x)[b(M_2R_{\mathrm{EI}} - C_4 - T_3) + \\ & (1-b)(M_2R_{\mathrm{EI}} - C_4 - T_2) - zD] = \\ & [xa + (1-x)b](M_2R_{\mathrm{EI}} - C_4 - T_3) + \\ & [1 - xa - (1-x)b](M_2R_{\mathrm{EI}} - C_4 - T_2) - zD \end{aligned} \tag{8}$$

$$\begin{aligned} U_6 = {} & yU_4 + (1-y)U_5 = \\ & y(R_{\mathrm{EL}} - C_3 - C_{\mathrm{E}} + T_1) + \\ & (1-y)\Big\{M_2R_{\mathrm{EL}} - C_4 - [xa + (1-x)b] \\ & (f_2 + T_3 - T_2) - T_2 - zD\Big\} \end{aligned} \tag{9}$$

The operator's replication dynamic equation is denoted as $F(y)$, expressed as follows:

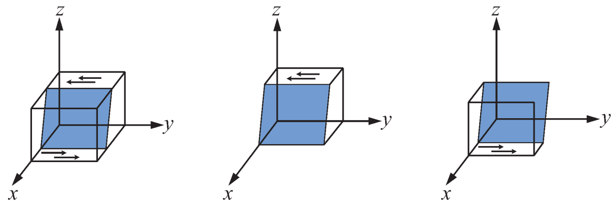
$$F(y)=\frac{\mathrm{d}y}{\mathrm{d}t}=y(1-y)(U_4-U_5)=y(1-y)\Big\{R_{\mathrm{EL}}-C_3-C_{\mathrm{E}}+T_1-[xa+(1-x)b](M_2R_{\mathrm{EI}}-C_4-T_3)-[1-xa-(1-x)b](M_2R_{\mathrm{EI}}-C_4-T_2)+zD\Big\} \tag{10}$$

The first derivative of $F(y)$ and the definitions of $G(x)$ are as follows:

$$\frac{\mathrm{d}(F(y))}{\mathrm{d}y}=(1-2y)\Big\{R_{\mathrm{EL}}-C_3-C_{\mathrm{E}}+T_1-[xa+(1-x)b](M_2R_{\mathrm{EI}}-C_4-T_3)-[1-xa-(1-x)b](M_2R_{\mathrm{EI}}-C_4-T_2)+zD\Big\} \tag{11}$$

$$G(x)=R_{\mathrm{EL}}-C_3-C_{\mathrm{E}}+T_1-[xa+(1-x)b](M_2R_{\mathrm{EI}}-C_4-T_3)-[1-xa-(1-x)b](M_2R_{\mathrm{EI}}-C_4-T_2)+zD \tag{12}$$

The operator adopts "standardized emissions" in a stable state, where $F(y)=0$, $\frac{\mathrm{d}(F(y))}{\mathrm{d}y}<0$. $G(x)$ is a monotonically increasing function of x; when $G(x)=0$, $\frac{\mathrm{d}(F(y))}{\mathrm{d}y}=0$, and $x=[R_{\mathrm{EL}}-C_3-C_{\mathrm{E}}+T_1+zD+C_4+bT_3+(1-b)T_2-M_2R_{\mathrm{EI}}]/[(a-b)(T_2-T_3)]=x^*$, the operator cannot establish a stable strategy. When $x<x^*$, $y=0$ represents the operator's stable strategy. When $x<x^*$, $y=1$ represents the operator's stable strategy. In practice, $T_2>T_3$, and operators are more likely to discharge legally to avoid steeper penalties. The dynamic evolution of operator decision-making is shown in Fig. 2.



(a) (b) (c)

Fig. 2 Operators' evolutionary stage diagram. (a) $x=x^*$; (b) $x<x^*$; (c) $x>x^*$

1.3.3 Stability analysis of public strategies

The public's expected return under supervision is denoted as U_7. Its expected return under non-supervision and the average expected return are denoted as U_8 and U_9, respectively.

$$U_7=L_{10}+B_3-C_{\mathrm{p}}+nx \tag{13}$$

$$U_8=L_{10}-(1-y)F \tag{14}$$

$$U_9=zU_7+(1-z)U_8=z(L_{10}+B_3-C_{\mathrm{p}}+nx)+(1-z)[L_{10}-(1-y)F] \tag{15}$$

The public's replication dynamic equation is denoted as $F(z)$ and expressed as

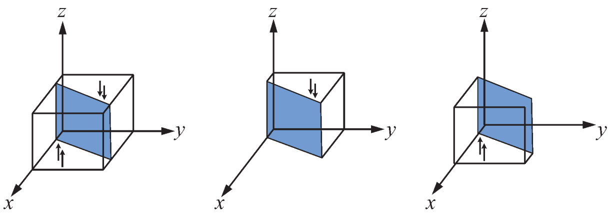
$$F(z)=\frac{\mathrm{d}z}{\mathrm{d}t}=z(1-z)(U_7-U_8)=z(1-z)[B_3-C_{\mathrm{p}}+nx+(1-y)F] \tag{16}$$

The first derivative of $F(z)$ and the definitions of $H(x)$ are as follows:

$$\frac{\mathrm{d}(F(z))}{\mathrm{d}z}=[B_3-C_{\mathrm{p}}+nx+(1-y)F](1-2z) \tag{17}$$

$$H(x)=B_3-C_{\mathrm{p}}+nx+(1-y)F \tag{18}$$

The public adopts "supervision" in a stable condition, where $F(z)=0$, $\frac{\mathrm{d}(F(z))}{\mathrm{d}z}<0$. $H(x)$ is a monotonically increasing function of x, $H(x)=0$, $\mathrm{d}(F(z))/\mathrm{d}z=0$, $x=[C_{\mathrm{p}}-B_3-(1-y)F]/n=x^*$, the public cannot determine a stable strategy. When $x<x^*$, $z=0$ represents the public stable strategy. When $x<x^*$, $z=1$ represents the public stable strategy. The dynamic evolution of public decision-making is shown in Fig. 3.



(a) (b) (c)

Fig. 3 Public evolutionary stage diagram. (a) $x=x^*$; (b) $x<x^*$; (c) $x>x^*$

1.3.4 Systematic analysis of the subject of the three-party game

A three-dimensional dynamic system can be derived from the replicated dynamic equations of the government, operators, and the public.

$$F(x)=x(1-x)\Big\{y(C_2-C_1)+(1-y)[(a-b)(r+T_3-T_2)-(C_1-C_2)]\Big\} \tag{19a}$$

$$F(y)=y(1-y)\Big\{R_{\mathrm{EL}}-C_3-C_{\mathrm{E}}+T_1-x[xa+(1-x)b](M_2R_{\mathrm{EI}}-C_4-T_3)-[1-xa-(1-x)b](M_2R_{\mathrm{EI}}-C_4-T_2)+zD]\Big\} \tag{19b}$$

$$F(z)=z(1-z)[B_3-C_{\mathrm{p}}+nx+(1-y)F] \tag{19c}$$

By setting $F(x)=0$, $F(y)=0$, and $F(z)=0$, the system's equilibrium points $E_1(0,0,0)$, $E_2(1,0,0)$, $E_3(0,1,0)$, $E_4(0,0,1)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, $E_8(1,1,1)$, and $E_9(x^*,y^*,z^*)$ can be identified. The strategic solution (x^*,y^*,z^*) includes both pure and hybrid strategy options. Friedman's evolutionary game theory suggests that the stable points of the replicator dynamic equations match pure-strategy Nash equilibria. As E_9 represents a mixed-strategy Nash equilibrium, it cannot serve as a stable point. Therefore, the stability of the equilibrium points E_1 to E_8 must be further analyzed.

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} \tag{20}$$

where

$$\frac{\partial F(x)}{\partial x} = \Big\{y(C_2 - C_1) + (1 - y)(a - b)(r + T_3 - T_2) - (C_1 - C_2)]\Big\}(1 - 2x) \tag{21}$$

$$\frac{\partial F(x)}{\partial y} = x(1 - x)[2(C_2 - C_1) - (a - b)(r + T_3 - T_2)] \tag{22}$$

$$\frac{\partial F(x)}{\partial z} = 0 \tag{23}$$

$$\frac{\partial F(y)}{\partial x} = y(1 - y)(a - b)(T_3 - T_2) \tag{24}$$

$$\frac{\partial F(y)}{\partial y} = (1 - 2y)\Big\{R_{\mathrm{EL}} - C_3 - C_{\mathrm{E}} + T_1 - [xa + (1 - x)b](M_2 R_{\mathrm{EI}} - C_4 - T_3) - [1 - xa -(1 - x)b](M_2 R_{\mathrm{EI}} - C_4 - T_2) + zD\Big\} \tag{25}$$

$$\frac{\partial F(y)}{\partial z} = y(1 - y)D \tag{26}$$

$$\frac{\partial F(z)}{\partial x} = z(1 - z)n \tag{27}$$

$$\frac{\partial F(z)}{\partial y} = (1 - 2y)\Big\{R_{\mathrm{EL}} - C_3 - C_{\mathrm{E}} + T_1 - [xa + (1 - x)b](M_2 R_{\mathrm{EI}} - C_4 - T_3) - [1 - xa - (1 - x)b](M_2 R_{\mathrm{EI}} - C_4 - T_2) + zD\Big\} \tag{28}$$

$$\frac{\partial F(z)}{\partial z} = (1 - 2z)[B_3 - C_{\mathrm{p}} + nx + (1 - y)F] \tag{29}$$

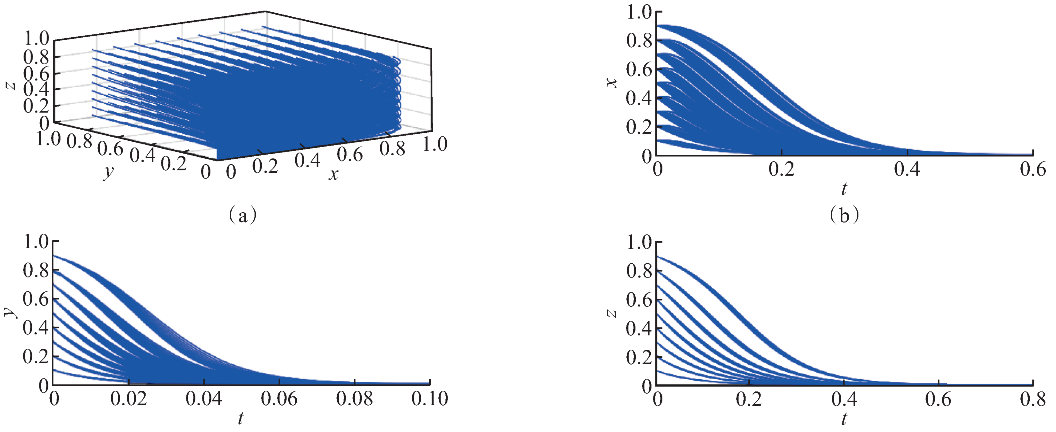
By substituting E_1 to E_8 into the Jacobian matrix, eight corresponding matrices (J_1 to J_8) are obtained. $E_1(0,0,0)$ is equivalent to J_1, while J_2 to J_8 are computed similarly.

$$J_1 = \begin{bmatrix} \frac{\partial F(x)}{\partial x}\Big|(0,0,0) & \frac{\partial F(x)}{\partial y}\Big|(0,0,0) & \frac{\partial F(x)}{\partial z}\Big|(0,0,0) \\ \frac{\partial F(y)}{\partial x}\Big|(0,0,0) & \frac{\partial F(y)}{\partial y}\Big|(0,0,0) & \frac{\partial F(y)}{\partial z}\Big|(0,0,0) \\ \frac{\partial F(z)}{\partial x}\Big|(0,0,0) & \frac{\partial F(z)}{\partial y}\Big|(0,0,0) & \frac{\partial F(z)}{\partial z}\Big|(0,0,0) \end{bmatrix} \tag{30}$$

2 Division of Various Stages of Highway Operation

2.1 Initial stage

In the initial stage of highway operation, government regulatory spending significantly exceeds the benefits, prompting a “passive regulation” approach. The highway operations, relying only on government subsidies, fail to meet basic operational requirements. Operators’ revenues from standardized emissions significantly exceed their expenses, prompting them to adopt the “excessive emission” strategy. The public exhibits a low propensity for preventing noise pollution and control, and generally opts for “non-supervision.” The equilibrium point of the three-party evolutionary game is $E_1(0,0,0)$. The parameters for the three-party game are defined as follows: r=5.0×10^5 yuan, C_1=R_{EI}=1.5×10^5 yuan, C_2=C_4=D=2.0×10^5 yuan, C_{p}=2.5×10^5 yuan, F=2.0×10^4 yuan, B_3=1.0×10^5 yuan, C_3=1.0×10^6 yuan, R_{EL}=5.0×10^4 yuan, T_1=T_2=T_3=1.0×10^5 yuan, C_{E}=4.0×10^5 yuan, a=0.3, b=0.7, n=0.8, M_2=0.5. Fig. 4 shows the strategy selection of the three-party game entities after simulation. The gaming system converges toward passive regulation, excessive emissions, and no supervision.



(a) (b) (c) (d)

Fig. 4 Evolution of tripartite strategic behaviors in the initial stage. (a) Overall strategy selection of the three parties; (b) Government; (c) Operators; (d) Public

2.2 Development stage

In the early development stage of highway operations, technological advancements reduced detection costs, prompting the government to adopt an "active regulation" strategy. Operators continue to pursue the "excessive emissions" strategy due to their low costs and high revenues. The stable equilibrium point of the three-party evolutionary game is $E_6(1, 0, 1)$. The three-way game parameters are set as follows: $r=4.0\times10^5$ yuan, $C_1=7.0\times10^4$ yuan, $C_2=T_2=1.5\times10^5$ yuan, $C_p=B_3=D=R_{EL}=2.0\times10^5$ yuan, $C_3=F=1.0\times10^6$ yuan, $C_4=8.0\times10^5$ yuan, $R_{EI}=7.0\times10^5$ yuan, $T_1=1.0\times10^5$ yuan, $T_3=2.0\times10^5$ yuan, $C_E=4.0\times10^5$ yuan, $a=0.6$, $b=0.75$, $n=1.0$, $M_2=0.7$. Fig. 5 shows the participants' strategic selections in the three-party game based on numerical simulation. Figs. 5(b) and (d) show that the public reaches a stable state of "supervision" more rapidly, while the government converges more slowly toward "active supervision." The gaming system tends toward "active regulation," "excessive emissions," and a "supervision" strategy.

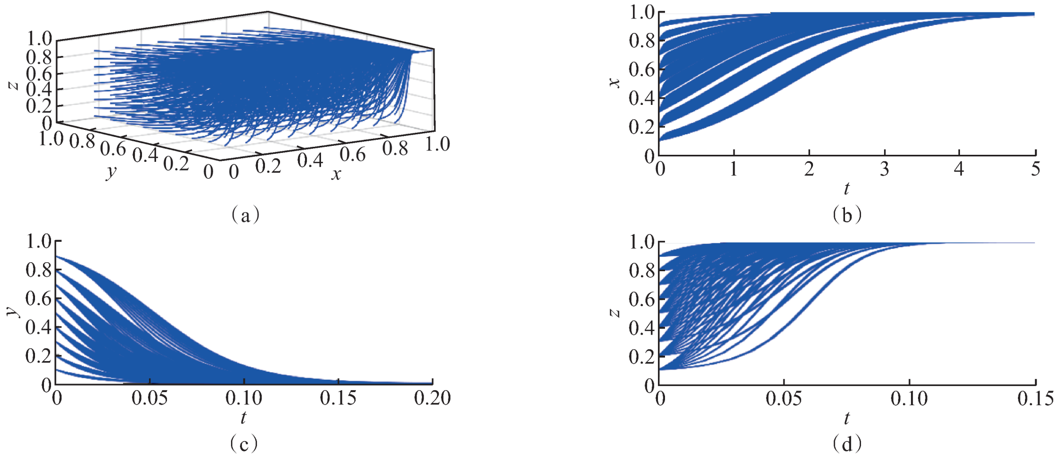


Fig. 5 Evolution of tripartite strategic behaviors in the early development stage. (a) Overall strategy selection of the three parties; (b) Government; (c) Operators; (d) Public

In the later stages of highway operations, noise prevention and control measures are primarily punitive, with incentives playing a secondary role. As regulatory costs steadily decline, the government adopts an "active regulation" policy. Penalties and financial losses, including compensation to the public for unlawful emissions, compel operators to passively adopt a "standardized emissions" approach. As the noise issue remains unresolved, the public continues to adopt the "supervision" technique at this stage. The stable equilibrium point of the three-party evolutionary game is $E_8(1, 1, 1)$. The three-party game parameters are established as follows: $r=C_4=R_{EI}=2.0\times10^6$ yuan, $C_1=5.0\times10^4$ yuan, $C_2=T_2=1.5\times10^5$ yuan, $T_1=C_p=1.0\times10^5$ yuan, $D=5.0\times10^5$ yuan, $C_3=F=R_{EL}=1.0\times10^6$ yuan, $B_3=7.0\times10^5$ yuan, $T_3=2.0\times10^5$ yuan, $C_E=4.0\times10^5$ yuan, $a=0.6$, $b=0.75$, $n=1.5$, $M_2=0.8$. Figs. 6(b) to (d) show that operators quickly reach "standardized emission" status, and the losses from excessive emissions compel compliance. Compared with Fig. 5(b), the government's tendency toward "active regulation" is stronger, and the convergence rate is faster.

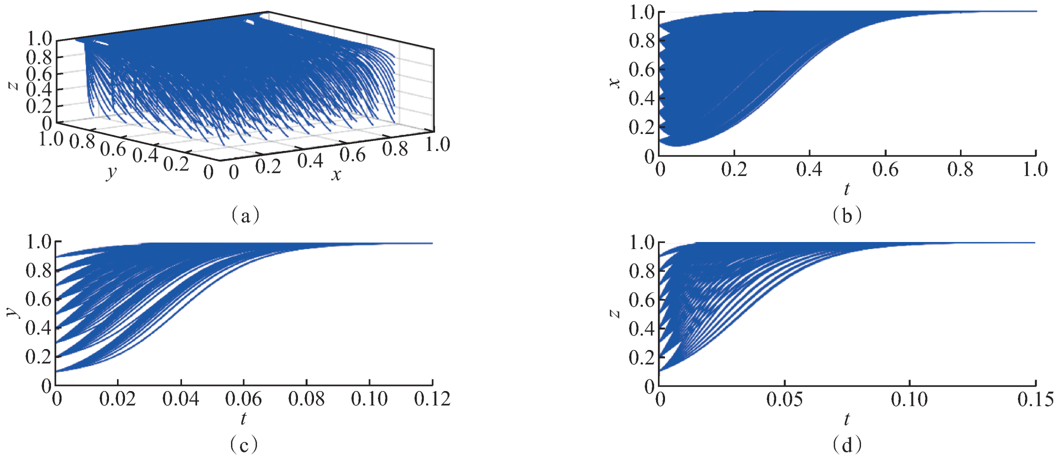


Fig. 6 Evolution of tripartite strategic behaviors in the late development stage. (a) Overall strategy selection of the three parties; (b) Government; (c) Operators; (d) Public

2.3 Mature stage

In the early mature stage of highway operations, sustainable development has emerged as a consensus. The economic benefits of unlawful emissions fall short of those of standardized emissions, while the public actively engages in monitoring and enforcing noise regulations. Both the government and operators improve their social image and reputation by adopting "active regulation" and "standardized emissions" strategies. The stable equilibrium point of the three-party evolutionary game is $E_8(1, 1, 1)$. The three-party game parameters are established as follows: $r=2.5\times10^6$ yuan, $C_1=5.0\times10^4$ yuan, $C_2=T_2=1.5\times10^5$ yuan, $C_p=1.0\times10^5$ yuan, $D=B_3=C_3=1.0\times10^6$ yuan, $F=1.5\times10^6$ yuan, $C_4=5.0\times10^6$ yuan, $R_{EL}=3.0\times10^6$ yuan, $R_{EI}=2.0\times10^6$ yuan, $T_1=T_3=5.0\times10^5$ yuan, $C_E=4.0\times10^5$ yuan, $a=0.6$, $b=0.75$, $n=1.5$, $M_2=0.8$. Fig. 7 shows the strategic selections of the three parties. The gaming system advances active regulation, standardized emissions, and a supervision strategy.

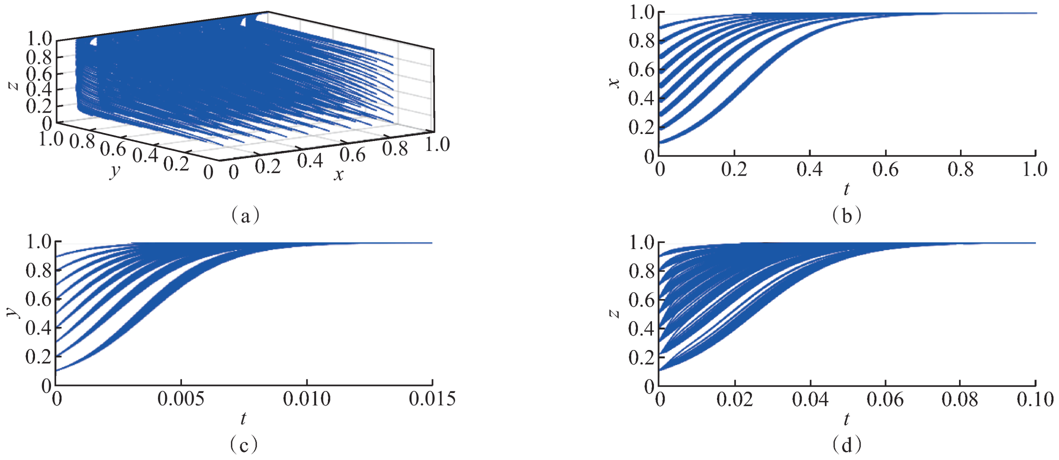


Fig. 7 Evolution of tripartite strategic behaviors in the early mature stage. (a) Overall strategy selection of the three parties; (b) Government; (c) Operators; (d) Public

In the late mature stage of highway operations, the government expands incentive programs and consistently reduces regulatory costs, thereby promoting "active regulation." Considering the long-term benefits, operators adopt the "standardized emissions." Government regulation has mitigated the social impact of negative externalities; however, society has "tacitly accepted" the remaining negative externalities. Efforts to further reduce these residual negative externalities through individual activities are irrational and inefficient, as the cost of individual action far exceeds the benefits. The public tends to choose "non-supervision" due to noise and other negative externalities. The stable equilibrium point of the three-party evolutionary game is $E_5(1, 1, 0)$. The three-party game parameters are set as follows: $r=R_{EL}=5.0\times10^6$ yuan, $C_1=2.0\times10^4$ yuan, $C_2=5.0\times10^4$ yuan, $C_p=T_2=2.0\times10^5$ yuan, $C_4=D=2.0\times10^6$ yuan, $F=C_E=3.0\times10^5$ yuan, $B_3=1.0\times10^5$ yuan, $C_3=T_3=5.0\times10^5$ yuan, $R_{EI}=T_1=1.0\times10^6$ yuan, $a=0.8$, $b=0.90$, $n=1.0$, $M_2=0.8$. Fig. 8 shows the strategic selections of the three parties. The gaming system advances "active regulation," "standardized emissions," and a "no supervision" strategy.

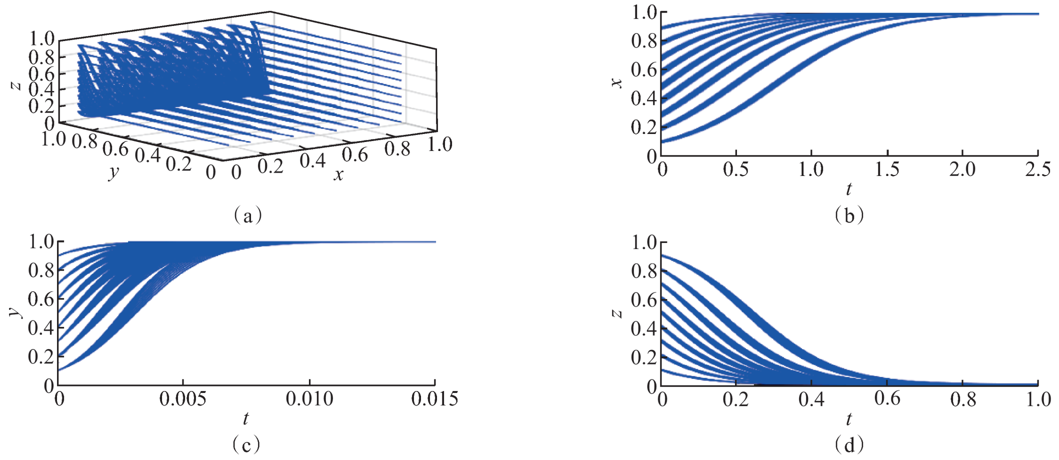


Fig. 8 Evolution of tripartite strategic behaviors in the late mature stage. (a) Overall strategy selection of the three parties; (b) Government; (c) Operators; (d) Public

3 Simulation Analysis

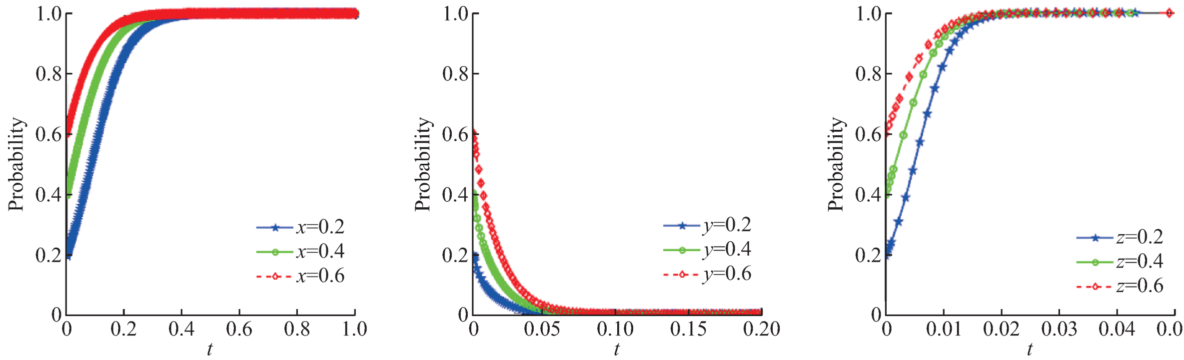
3.1 Initial parameter setting

The Changsha Rail Transit Company Limited manages the Lito sinking section of the Beijing-Hong Kong-Macao Highway, situated between the Yuhua and the Lijiatang Interchanges in Changsha, Hunan Province. This section spans 3.709 km and opened to traffic at the end of January 2016. The Changsha Wanli Times Community in Yuhua District, located approximately 200 to 300 m from the sunken area, is home to around 1 288 households. In 2017, the Yuhua District Environmental Protection Bureau commissioned a third-party organization to conduct a noise assessment study, which confirmed that community noise levels significantly exceeded national guidelines. Constructing a 3.71-km sound barrier along the entire line will require a total investment of 40 million yuan. The principal parameters are set as follows: $r=4.0\times10^6$ yuan, $C_1=1.0\times10^5$ yuan, $C_2=3.0\times10^5$ yuan, $C_3=1.0\times10^6$ yuan, $C_4=14.08\times10^6$ yuan, $C_p=1.5\times10^5$ yuan, $D=12.88\times10^5$ yuan, $F=25.76\times10^5$ yuan, $B_3=12.88\times10^5$ yuan, $T_1=0$ yuan, $T_2=1.0\times10^5$ yuan, $T_3=13.44\times10^4$ yuan, $R_{EL}=7.89\times10^6$ yuan, $R_{EI}=286.244\times10^5$ yuan, $C_E=2.0\times10^5$ yuan, $a=0.5$, $b=0.51$, $n=0.8$, $M_2=0.8$.

In 2017, shortly after the road opened, efforts shifted from establishing basic traffic functionality to addressing specific operational issues and optimizations. This pattern does not fit the early operational stage, including basic operations, and the setup of a simple management system. Thus, it is not part of the highway's initial operational phase. Facility construction during this period remains incomplete and is actively progressing while optimizing the process. Therefore, it corresponds to the early development stage, known as system construction, rather than the later stage of stable operation.

3.2 Initial simulation analysis

Fig. 9 shows the simulation results of the probability fluctuations in the behavioral selection techniques of the government, operator, and public. Regardless of the initial triadic game goals, the system consistently tends toward active supervision, excessive emissions, and supervision techniques. Fig. 9(a) shows how the three groups evolve in response to the fluctuations in the government's selection strategy probabilities at $x=0.2$, 0.4, 0.6. If y and z are held constant, increasing x accelerates the government's convergence rate toward a stable state of active supervision. Fig. 9(b) shows how the three groups evolve in response to changes in the government's selection strategy probabilities at $y=0.2$, 0.4, 0.6. If x and z are held constant, increasing y slows the operators' convergence rate, ultimately leading to a stable state characterized by excessive emissions. Fig. 9(c) shows how the three groups evolve in response to the changes in the government's selection strategy probabilities at $z=0.2$, 0.4, 0.6. If x and y are held constant, increasing z accelerates public convergence, leading to faster stabilization characterized by supervision. Despite varying initial intentions, both the government and the public reach faster stability with minimal difference in their progress, suggesting that early preferences have limited influence on both parties. The operator's decisions slow down, and the time needed to reach stability strategy increases as the initial intent intensifies. As a result, encouraging the operator to impose penalties can slow down excessive emissions and expedite the game system's evolution.



(a) (b) (c)

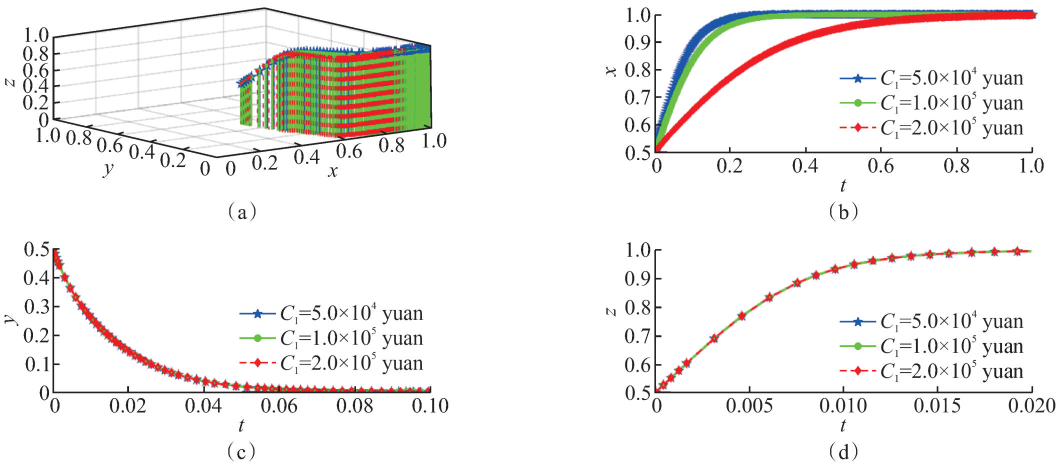
Fig. 9 Influence of initial probabilities of the game agent's behavior selection on evolutionary results. (a) Government; (b) Operators; (c) Public

3.3 Sensitivity analysis

In replicator dynamic systems, changes in key parameters can affect evolutionary games. This study conducts a sensitivity analysis to adjust the impact on the results using the Lito sinking section of the Beijing-Hong Kong-Macao Highway as a reference, setting the initial game variables at 0. 5 and selecting critical early developmental stage factors for sensitivity analysis.

3.3.1 Government regulatory costs

Fig. 10 examines the impact of the government's active regulatory cost (C_1) on system stability. C_1 is set at 5.0×10^4, 1.0×10^5, 2.0×10^5 yuan for the low, medium, and high levels, respectively. Fig. 10(a) shows that the government responds sensitively to the changes in proactive regulation costs. Fig. 10(b) shows that with a decrease in C_1 from 1.0×10^5 to 5.0×10^4 yuan, the system rapidly converges with the active regulation strategy. Increasing C_1 from 1.0×10^5 to 2.0×10^5 yuan, which shows increasing costs of active regulation, prevents the government from reaching an optimal game state. For effective regulation strategies, governments must consider financial resource allocation and balanced spending across multiple fields, such as environmental protection, education, and medical care. When active supervision costs limit funding for other essential public services and infrastructure projects, the government cannot reach a stable state. Figs. 10(c) and (d) show that changes in C_1 do not affect the strategy choices of the operators or the public.

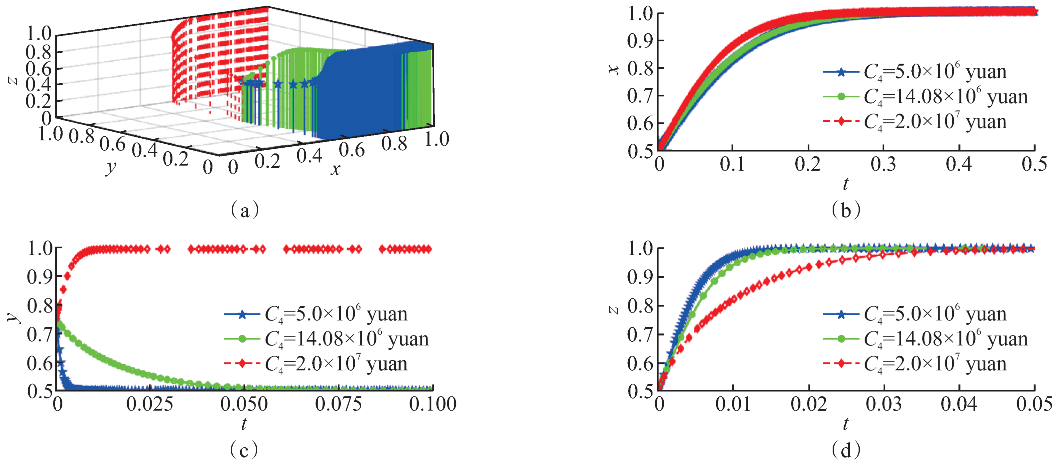


(a) (b) (c) (d)

Fig. 10 Effects of the cost of active supervision by the government on equilibrium stable strategies. (a) Overall strategy selection of the three parties; (b) Government; (c) Operators; (d) Public

3.3.2 Operator emission costs

Fig. 11 examines how the changes in the operator's excessive emission cost (C_4) affect system stability. C_4 is set at 5.0×10^6, 14.08×10^6, 2.0×10^7 yuan, indicating low, medium, and high levels, respectively. Fig. 11(a) shows that changes in C_4 significantly affect the three participants' strategic behaviors in the game, with the operator showing the highest sensitivity to the costs of illegal emissions. Fig. 11(b) shows that higher excessive emission costs lead to the government quickly reaching a stable active regulation state. Fig. 11(c) shows that by decreasing C_4 from 14.08×10^6 to 5.0×10^6 yuan, the operator quickly reaches a state of excessive emissions. Increasing C_4 from 14.08×10^6 to 2.0×10^7 yuan in the system forces the operator to choose the standard emission strategy. Fig. 11(d) shows that increased excessive emission costs reduce the convergence rate of the public's supervision strategy. The public is typically passive about

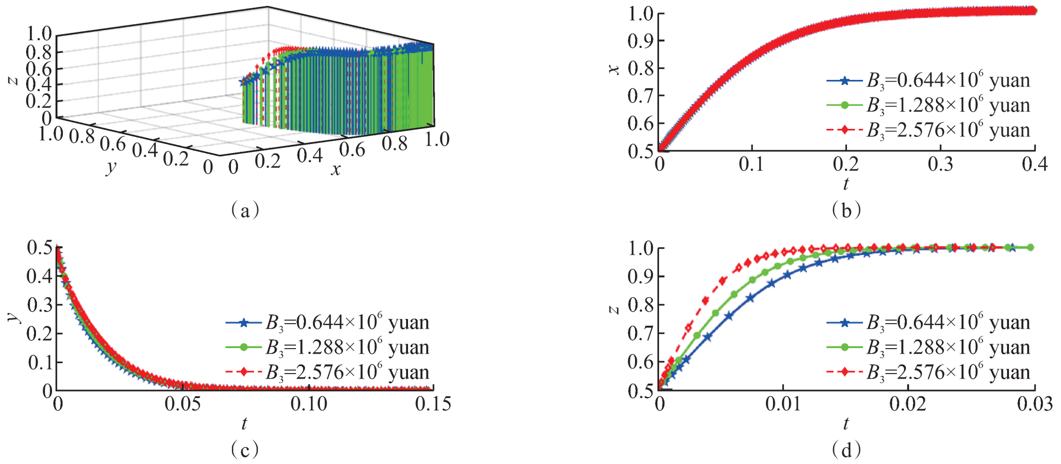


(a) (b) (c) (d)

Fig. 11 Effects of the cost of excessive emissions by the operators on equilibrium stable strategies. (a) Overall strategy selection of the three parties; (b) Government; (c) Operators; (d) Public noise pollution supervision. Higher emissions costs can accelerate the entire game system's stabilization and prompt operators to adopt standardized emission strategies, which help the public to achieve effective environmental governance efficiently. Thus, when C_4 reaches a specific value, the tripartite game system achieves the optimal equilibrium strategy, denoted as $E_8(1,1,1)$, characterized by government active regulation, operator-standardized emissions, and public supervision.

3.3.3 Level of public participation

Fig. 12 examines how modifications in B_3 operator remuneration affect system stability for the public. The B_3 payment per household from 1 000 yuan is adjusted to 500 and 2 000 yuan for 1 288 households, resulting in total B_3 amounts of 0.644×10^6, 1.288×10^6, and 2.576×10^6 yuan for the low, medium, and high scenarios, respectively. Fig. 12(a) shows that the public is highly sensitive to variations in B_3 compensation. Figs. 12(b) and (c) indicate that variations in the existing B_3 compensation level have a minimal impact on the government's and operators' decisions. Fig. 12(d) shows that increasing B_3 from 1.288×10^6 to 2.576×10^6 yuan accelerates the system's convergence toward the supervision strategy. Appropriate remuneration can help curb increased unlawful expenses. If the compensation is fair, public motivation to assert their rights through litigation or demonstration will decrease.

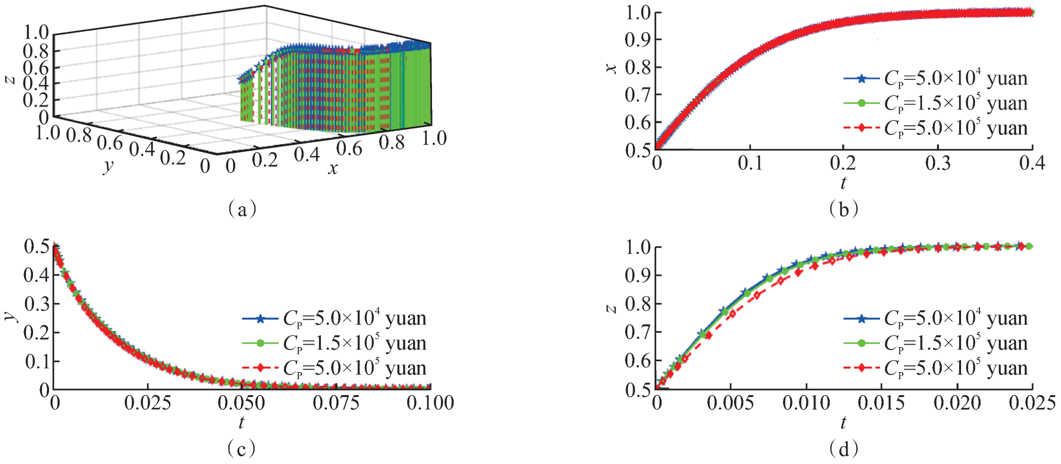


(a) (b)

(c) (d)

Fig. 12 Effects of the Compensation by operators to the public on equilibrium stable strategies. (a) Overall strategy selection of the three parties; (b) Government; (c) Operators; (d) Public

Fig. 13 examines how the changes in the cost of public supervision (C_{p}) affect system stability. C_{p} is set as 5.0×10^4, 1.5×10^5, and 5.0×10^5 yuan for the low, medium, and high scenarios, respectively. Fig. 13(a) shows that changes in C_{p} significantly influence the public's strategy choices. Figs. 13(b) and (c) show that current changes in C_{p} have a limited impact on the government's and operators' strategic choices. Fig. 13(d) shows that reducing C_{p} from 1.5×10^5 to 5.0×10^4 accelerates system convergence toward the supervision strategy. Reducing public supervision costs encourages the public to form a balance, significantly increases the risk of illegal activities by operators, easily exposes illegal behaviors, and prompts operators to choose the standardized emission strategy.



(a) (b)

(c) (d)

Fig. 13 Effects of the cost of the public's choice of supervision on equilibrium stable strategies. (a) Overall strategy selection of the three parties; (b) Government; (c) Operators; (d) Public

4 Conclusions

(1) Highway noise prevention and control show distinct stages, each characterized by distinct strategic equilibrium points among game participants. As the system progresses through operational and developmental stages, constructive engagement between the public and the government encourages the operator to adopt an effective and stable legal emission policy. In the initial stage of mature operation, all three parties established a stable equilibrium within the game system. During the late maturation stage, considering the negative externalities of noise, the public chose a non-supervisory stance and achieved a realistic social strategy.

(2) In 2017, the early developmental stages of the Lito sinking section of the Beijing-Hong Kong-Macao Highway were marked by active supervision, excessive emissions, and supervision. The system had not yet reached equilibrium. Increasing the cost of illegal emissions can accelerate stabilization and foster collaboration.

(3) Appropriate reduction in the cost of proactive regulation incentivizes government behavior. Higher costs can delay the government's convergence toward stability, while lower costs accelerate it. This allows third-party game participants to reach a faster equilibrium.

(4) Excessive emissions costs influence the strategic behavior of all three game participants. Operators are particularly sensitive to higher fees and are choosing standardized emissions to promote long-term development, which strengthens stability and increases cooperation between the government and the public.

(5) Reducing the cost of public supervision and increasing operator compensation for public supervision will allow the public to reach a stable condition of supervision more quickly. Changes in supervision costs affect the feasibility of public engagement, while changes in compensation are essential for mitigating conflicts in the short term.

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高速公路噪声防治参与主体博弈策略研究

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摘要：为揭示高速公路噪声污染治理中多主体决策逻辑与系统演化规律，基于演化博弈理论构建政府、运营商、公众三方博弈模型，并将运营期划分为不同阶段进行差异化分析。以京港澳高速公路黎托段为例，评估关键要素变化对系统的影响。结果表明，京港澳高速公路黎托沉陷段处于发展初期，对应策略包括主动监管、超标排放和监督。当政府主动监管成本从10万元降到5万元时，系统以更快的速度收敛于主动监管策略。当运营商超标排放成本从1 408万元增加到2 000万元时，系统迫使运营商选择达标排放策略。此外，当公众监督成本从15万元降至5万元，且运营商对公众的赔偿从128.8万元增至257.6万元时，系统以更快的速度收敛于监督策略。运营商超标排放成本是实现政府积极监管–运营商规范排放–公众监督三方博弈理想均衡的核心决策变量。

关键词：噪声防治；运营期；演化博弈；京港澳高速黎托下沉段

中图分类号：U491.7