*Journal of Sustainable Development Indicators*
*http://www.sdewes.org/jsdi*

Year 2026, Volume 2, Issue 2, 2030716

***Original Research Article***

# Competitiveness Analysis of Inland Waterway Transport through Game Theory: a Decision-Making Model for Sustainable Logistics

***Yuri Alexandre Meyer*[*], Luiz de Freitas Ayres , Luiz Vicente Figueira De Mello Filho**
School of Technology, University of Campinas, Rua Paschoal Marmo, 1888 – Jardim Nova Itália,
Limeira - SP, CEP: 13484-332. Brazil
e-mail: yameyer@unicamp.br

Cite as: Meyer, Y. A., de Freitas Ayres, L., De Mello Filho, L. V. F., Competitiveness Analysis of Inland Waterway Transport through Game Theory: a Decision-Making Model for Sustainable Logistics, J. sustain. dev. indic., 2(2), 2030716, 2026, DOI: https://doi.org/10.13044/j.sdi.d3.0716

## ABSTRACT

This study introduces a novel tripartite non-cooperative game-theoretic model to analyze the competitiveness of inland waterway transport in emerging economies. The model captures strategic interactions among logistics operators, government agencies, and freight-generating companies, incorporating policy instruments such as subsidies and carbon taxation into the payoff structure. The methodological framework defines utility functions based on operational costs, incentives, environmental factors, and demand responses, and derives Nash equilibria under alternative policy scenarios. Results indicate that, under a combined policy of subsidies (60 units) and carbon taxation (15 units), the system converges to an equilibrium in which inland waterway transport becomes the dominant strategy. In this configuration, the logistics operator achieves a payoff of 135, while road-based alternatives generate negative returns for private companies (-80), reflecting a strong modal shift. The findings demonstrate that the underutilization of inland waterways is primarily driven by misalignment of incentives rather than technical constraints. Furthermore, the model reveals nonlinear policy effects, including diminishing returns to subsidies and asymmetric impacts of carbon taxation, highlighting the importance of coordinated and balanced policy design. By linking strategic outcomes to measurable sustainability indicators, such as emission intensity ($gCO_2$/ton-km), modal share, and logistics efficiency, the proposed framework provides a policy-relevant tool for supporting decarbonization strategies and sustainable logistics planning in alignment with Sustainable Development Goals.

## KEYWORDS

*Inland waterway transport, Game theory, Modal choice, Public policy, Sustainable logistics, Strategic nteractions.*

## INTRODUCTION

Freight demand continues to grow in many regions, while transport systems face increasing pressure to decarbonise, reduce local impacts, and remain cost-competitive. A recent systematic review shows that inland waterway transport is often associated with social, environmental, and economic advantages, but its expansion is commonly constrained by governance, infrastructure, operational limitations, and human-resource barriers [1]. From a logistics-system perspective, inland waterway transport is frequently discussed as a lower-energy

---

[*] Corresponding author

option for suitable cargo profiles, with potential reductions in emissions and operating costs when compared with road-based logistics [2].

In Brazil, however, inland navigation still represents a small share of freight movements, despite the existence of extensive river corridors. A recent Brazil-focused study identifies weak or discontinuous public policies, bureaucratic hurdles, precarious waterway and port infrastructure, and limited integration with other modes as the main constraints on inland waterway development [3]. Stakeholder analyses in the Brazilian Amazon indicate that governance arrangements, licensing disputes, and perceived socio-environmental risks can become decisive elements for whether projects gain legitimacy and continuity [4]. In addition, agribusiness logistics in inland regions reinforces the relevance of reliable multimodal solutions, yet persistent infrastructure bottlenecks and institutional fragmentation continue to limit performance [5].

Because inland waterway development depends on choices made by multiple actors, the problem is inherently strategic. Transport economics highlights that policy instruments, pricing, and coordination mechanisms can shift modal choices and reallocate freight flows across competing alternatives [6]. Game theory offers a formal framework to represent strategic interaction when private operators, public agencies, and freight-generating companies react to each other's decisions. Fudenberg & Tirole [7] provide the foundational treatment of non-cooperative games and equilibrium concepts. Osborne & Rubinstein [8] present a rigorous formulation of strategic and extensive-form games that is widely used in applied modelling.

This study formulates a non-cooperative game with three agent classes: logistics operators, government agencies responsible for fiscal incentives, and freight-generating companies. The main challenges addressed are the misalignment of incentives that limits modal integration and the difficulty of designing public policies that simultaneously improve competitiveness and reduce environmental impacts. The specific objectives are to (i) define payoff functions that reflect operational costs and policy parameters, (ii) identify Nash equilibria under different fiscal-incentive scenarios, and (iii) discuss policy implications for increasing inland waterway competitiveness while supporting climate-oriented targets. These outcomes are intended to contribute to Sustainable Development Goal 9 (Industry, innovation and infrastructure) and Sustainable Development Goal 13 (Climate action) by supporting evidence-based transport policy design [9], [10].

## THEORETICAL FRAMEWORK

Game Theory offers a formal framework for representing strategic interactions among decision-makers whose outcomes depend on each other's choices [6]. Within this framework, equilibrium concepts such as the Nash equilibrium provide a way to predict stable outcomes in non-cooperative settings [8]. In freight transport and logistics, strategic interactions arise because mode choice, pricing, and capacity decisions depend on the joint behavior of carriers, shippers, and regulators [11]. Recent applications have explicitly incorporated policy intervention into freight-transport games, showing how taxes, subsidies, and regulation can alter incentives toward more sustainable outcomes [12].

For inland waterway transport in Brazil, underutilization has been associated with limited infrastructure, weak modal integration, and institutional constraints, which suggests that a multi-actor strategic model is appropriate [5]. Project governance and budget execution also condition the feasibility of public investments in waterways and, therefore, shape the strategic environment faced by private actors [4]. Consistent with the scope of the Journal of Sustainable Development Indicators, this study links strategic outcomes to sustainability objectives and community well-being, including the United Nations Sustainable Development Goals [1].

### Logistics Operators

Logistics operators provide freight services using different transport modes and, in many corridors, can choose between road, rail, and inland waterways. Mode choice and investment decisions are typically driven by cost, reliability, frequency, transit time, and infrastructure accessibility [11]. In the Brazilian context, river-based operations face additional uncertainty linked to hydrological variability, uneven port performance, and limited intermodal integration [3]. Given these constraints, operators may avoid committing capacity to inland waterways unless infrastructure and demand conditions reduce perceived risks and improve the expected payoff relative to alternative modes.

## Government Agencies

Public agencies influence freight systems through investment planning and regulatory instruments, including infrastructure spending, taxation, subsidies, concessions, and environmental standards [11]. In Brazil, the development of inland waterways has been affected by governance arrangements and the ability to execute budgets for navigation, dredging, and port-related projects [4]. Game-theoretic modeling provides a structured way to test how alternative policy packages change private incentives and can reduce market failures that keep freight in higher-emission modes. Recent work on emission regulation illustrates how strategic behavior responds to fee-based mechanisms and dynamic enforcement, reinforcing the need to represent regulation explicitly in payoff structures [13].

## Freight-Generating Companies

Freight-generating companies determine effective demand for transport services and influence modal split through contracting practices, service-level requirements, and willingness to bear switching costs [11]. In emerging economies, shippers often perceive inland waterways as less flexible and less reliable because of service discontinuities, seasonal navigability, and limited terminal availability [3]. At the same time, sustainability targets and stakeholder pressure can increase the attractiveness of lower-emission modes when reliable service is available, which can be represented through environmental terms in the utility function [1]. The strategic interactions described above are summarized in **Figure 1**, which illustrates the relationships among the main agents and the role of policy instruments in shaping equilibrium outcomes.

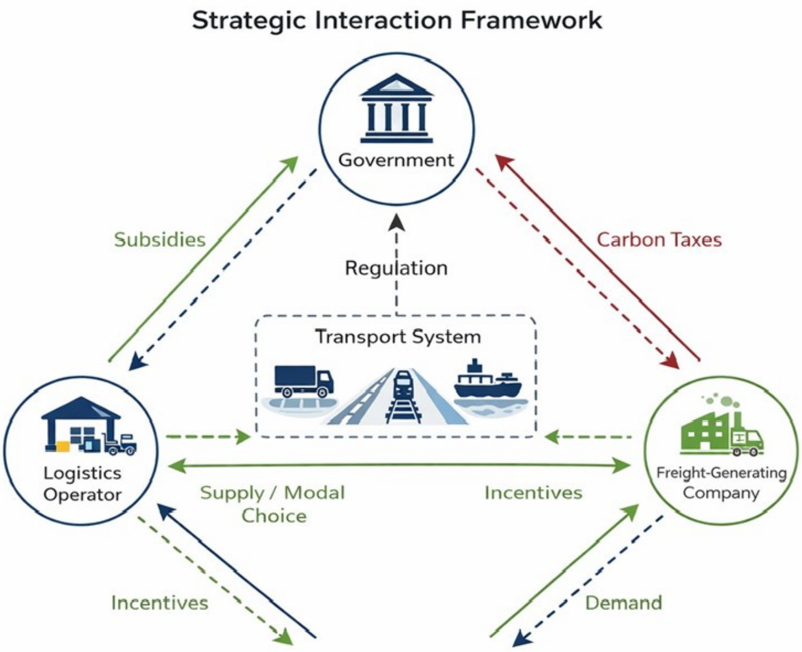

Figure 1. Conceptual framework of the strategic interaction among logistics operators, government agencies, and freight-generating companies. Government policies, including subsidies and carbon taxation, influence incentives and shape modal choice and equilibrium outcomes.

## METHODS

This section describes the methodological framework developed to operationalize the strategic model, detailing the agents involved, their objectives, available strategies, and the formulation of payoff functions. [7] provide the standard foundations of non-cooperative game theory and equilibrium concepts that guide how players, strategies, and payoffs are defined in this study. [8] systematize strategic-form and extensive-form representations and support the notation and equilibrium reasoning adopted in our formulation**.** Although the Brazilian case is used as an illustrative application, the proposed framework is general and can be applied to any freight transport system involving competing modes and regulatory intervention. The model is designed to test a broader methodological hypothesis: that modal shifts depend on the strategic alignment of incentives among heterogeneous agents. To improve reproducibility and clarity, the methodological structure is summarized in a flowchart (**Figure 2**), illustrating how strategies, payoff functions, and equilibrium conditions are integrated.

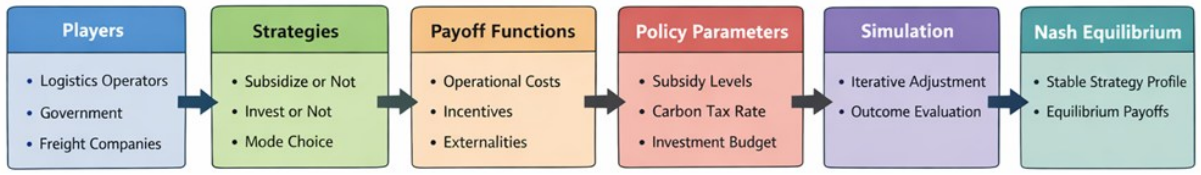

Figure 2. Methodological framework of the tripartite game-theoretic model, illustrating the interaction between players, strategies, payoff functions, policy parameters, and equilibrium outcomes.

**Table 1** presents the actors and their possible strategies, capturing the main decision dimensions in transport logistics systems:

Table 1. Actors and Strategies in Transport Logistics (Corrected)

| Actors | Objectives | Possible Strategies |
|---|---|---|
| Logistics Operators | Maximize profit and/or minimize operational costs. | **Choice of transport mode:**<br>• Inland Waterway Transport (IWT)<br>• Road transport<br>• Rail transport<br>**Infrastructure investment:**<br>• Invest in more efficient equipment (e.g., modern barges, loading systems)<br>• Maintain current infrastructure without additional investment |
| Government Agencies | Improve logistics efficiency, promote environmental sustainability, and encourage IWT. | **Financial incentive policies:**<br>• Direct subsidies for IWT adoption/usage<br>• Tax incentives or fee reductions for IWT<br>**Environmental regulation:**<br>• Carbon tax / emissions regulation on more carbon-intensive modes (e.g., road)<br>• Limited or no implementation of environmental taxes<br>**Infrastructure investment:**<br>• Improve and expand the waterway network (e.g., dredging, ports, terminals)<br>• Maintain current infrastructure without additional investment |

| Actors | Objectives | Possible Strategies |
|---|---|---|
| Private Companies Using Transport | Select transport based on cost, delivery time, and perceived environmental impact. | **Mode selection criteria:**<br>• Lowest total logistics cost<br>• Faster delivery times (often favoring road)<br>• Lower environmental impact (often favoring IWT/rail)<br>**Contracting strategy:**<br>• Long-term contracts with a preferred operator to secure stable rates<br>• Short-term/one-off contracts with different operators |

The next step consists of constructing the payoff matrix, where each combination of strategies represents a distinct interaction scenario among agents. This allows the assessment of outcomes from both economic and environmental perspectives [13]. For clarity, an illustrative example with two agents (logistics operators and government authorities) is summarized in **Table 2**.

Table 2. Simplified Payoff Matrix

| | GOV (C) Subsidy/Incentive | GOV (D) No Subsidy |
|---|---|---|
| OL (A) IWT | **OL**: High profitability<br>**GOV**: High initial cost, but high environmental and social benefits | **OL**: Medium profitability<br>**GOV**: No cost, limited benefits |
| OL (B) Other Modes | **OL**: Medium profitability (carbon tax applied)<br>**GOV**: Low initial cost, but high environmental/social cost | **OL**: High immediate profitability<br>**GOV**: No cost, high environmental/social cost |

Through this simplified matrix, it becomes evident that logistics operators aim to maximize profitability, whereas governmental entities seek to balance short-term fiscal costs against long-term environmental and social benefits. This interaction is formally analyzed using the mathematical formulation presented below.

### Mathematical Formulation of the Non-Cooperative Game

Each player adopts strategies aimed at maximizing utility that is, profit, efficiency, cost reduction, positive environmental impact, and other relevant aspects. Therefore, it is first necessary to define:

- The players (actors in the system);
- The sets of available strategies;
- The payoff functions (return/cost for each actor);
- The resolution of the Nash equilibrium.

These players, in turn, may choose among different strategies. **Table 3** summarizes the players, strategies, and notation adopted in the model:

Table 3. Players, Strategies, and Notation in the Non-Cooperative Game Model

| **Player** | **Strategy** | **Symbol** (Sx) | **Description** |
|---|---|---|---|
| Logistics Operators (O) | Choose Waterway Transport | SOH | Opt for Waterway Transport (IWT) |
| Logistics Operators (O) | Choose Road/Rail Transport | SOR | Opt for Road or Rail Transport |
| Government (G) | Grant subsidies/ investments to IWT | SGS | Support Waterway Transport with subsidies/investments |
| Government (G) | Do not grant subsidies/investments | SGN | No support for Waterway Transport |
| Private Companies (E) | Hire IWT services | SEH | Opt to hire Waterway Transport services |
| Private Companies (E) | Hire road/rail services | SER | Opt to hire Road or Rail Transport services |

The next step consists of defining, for each player, a specific payoff according to the chosen strategies. Thus, the utilities are represented by linear functions, as shown in eqs. (1) - (3):

$$U_O(s_O, s_G, s_E) = R_O(s_O, s_E) - C_O(s_O) + I_O(s_O, s_G) - K_O(s_O) \tag{1}$$

$$U_G(s_O, s_G, s_E) = B_G(s_O, s_E) - S_G(s_G) + \tau_G(s_O, s_G, s_E) \tag{2}$$

$$U_E(s_O, s_G, s_E) = -OC_E(s_O) + PV_E(s_O) - DT_E(s_O) - CT_E(s_O, s_G) \tag{3}$$

where are:

- $R_O(s_O, s_E)$: operator revenue (affected by contracted demand).
- $C_O(s_O)$: operator cost by mode.
- $I_O(s_O, s_G)$: incentive/subsidy under policy $s_G$.
- $K_O(s_O)$: integration/switching/investment cost.
- $B_G(s_O, s_E)$: government benefit (environment + infrastructure/efficiency).
- $S_G(s_G)$: public expenditure under policy $s_G$.
- $\tau_G(s_O, s_G, s_E)$: net fiscal effect (e.g., tax revenue minus admin cost), if modeled.
- $OC_E(s_O)$: logistics cost for the company.
- $PV_E(s_O)$: perceived value (e.g., ESG/reputation or cost advantage).
- $DT_E(s_O)$: delivery-time penalty.
- $CT_E(s_O, s_G)$: carbon charge/tax under policy $s_G$.

Thus, the Nash equilibria are defined. It is important to emphasize that a Nash Equilibrium corresponds to a state in which no player has an incentive to unilaterally change their strategy. Therefore, a set of strategy profile denoted by $s*$ represents the equilibrium condition, as shown in Equation (4):

$$\begin{gathered}\boldsymbol{s}^{*} \in \boldsymbol{S_O} \times \boldsymbol{S_G} \times \boldsymbol{S_E} \text{ is a Nash equilibrium if} \\ \boldsymbol{U_i}\left(\boldsymbol{s}_i^{*}, \boldsymbol{s}_{-i}^{*}\right) \geq \boldsymbol{U_i}\left(\boldsymbol{s_i}, \boldsymbol{s}_{-i}^{*}\right), \forall \boldsymbol{s_i} \in \boldsymbol{S_i}, \forall \boldsymbol{i} \in \{\boldsymbol{O}, \boldsymbol{G}, \boldsymbol{E}\}.\end{gathered} \tag{4}$$

For clarity, all variables used in the payoff formulation are explicitly defined. For the logistics operator, ROR represents operational revenue, COC denotes operational cost, GI corresponds to government incentives, and IC represents integration or switching costs. For the freight-generating company, OC denotes operational cost, PV represents perceived value, DT corresponds to delivery time, and CT denotes the carbon tax applied to road transport. These variables capture both economic and operational factors influencing the strategic decisions of each agent.

To illustrate the mathematical formulation of the game, we can add simulated values for the agents' payoffs, based on real or estimated data. This will help demonstrate how different variables affect the equilibrium. Table 4 presents an illustrative example of the payoff structure for the logistics operator under the proposed policy scenario.

Table 4. Example of Payoff for the Logistics Operator

| **Strategy** | **Operational Revenue** | **Operational Cost** | **Government Incentives** | **Integration Cost** | **Payoff (UO)** |
|---|---|---|---|---|---|
| Use IWT | 120 | 40 | 60 | 10 | 130 |
| Use Railway | 150 | 50 | 0 | 20 | 80 |

Table 5 shows the corresponding payoff structure for the freight-generating company, highlighting the impact of policy instruments on decision-making. Together, Table 4 and Table 5 illustrate how policy instruments reshape incentives across agents:

Table 5. Example of Payoff for the Private Company

| **Strategy** | **Operational Cost (OC)** | **Perceived Value (PV)** | **Delivery Time (DT)** | **Carbon Tax (CT)** | **Payoff (UE)** |
|---|---|---|---|---|---|
| Use IWT | 40 | 45 | 5 | 0 | 0 |
| Use Road | 70 | 30 | 25 | 15 | -80 |

This section presents the results of the simulations in a summarized manner, as well as the analysis of the strategic behaviors observed among the agents. Different combinations of policies and modal choices are explored to identify stability and evaluation when publics investments are made. The model relies on simplified payoff structures and simulated parameters, which may introduce measurement inaccuracies. In particular, uncertainties related to hydrological variability, seasonal navigability, and operational disruptions are not explicitly modeled and may affect real-world outcomes. Additionally, non-cooperative game theory assumes rational decision-making and may not fully capture institutional frictions such as licensing disputes, political constraints, or perceived socio-environmental risks. These limitations should be considered when interpreting the results. For clarity, the main abbreviations used throughout the model are listed in the Abbreviations section before the References.

## RESULTS AND DISCUSSION

### Nash Equilibrium Analysis

Best responses across the strategy profiles are analyzed to identify Nash equilibria, defined as outcomes in which no player can improve its payoff through unilateral deviation. Table 6 summarizes the equilibrium payoffs under the policy scenario combining subsidies and carbon taxation. The results indicate that the equilibrium configuration emerges when inland waterway transport is supported by subsidies and selected by both logistics operators and freight-generating companies. In this configuration, the incentives align across agents, resulting in higher payoffs and a stable strategic outcome.

Table 6. Game Results Matrix (With Subsidies and Taxes).

| Logistics Operator Strategy | Government Strategy | Company Strategy | UO (Logistics Operator) | UG (Government) | UE (Private Company) |
|---|---|---|---|---|---|
| **IWT** | Subsidy | IWT | 135 | 70 | 0 |
| **Railway** | No Subsidy | Road | 80 | 20 | -80 |
| **Road** | Carbon tax (Road) | Railway | 90 | 30 | -50 |

Nash Equilibrium (Scenario with Subsidies): Based on the simulation, the Nash equilibrium occurs when the payoffs cannot be improved by any agent changing their strategy unilaterally, given the behavior of the others.

## Equilibrium Simulations

To further explore the model behavior, alternative policy scenarios were simulated by varying subsidy levels and carbon taxation. In the illustrative case, the inland waterway subsidy is set to 60 units and the carbon tax applied to road transport is set to 15 units.

Under these conditions, the payoff structure shifts significantly, favoring inland waterway transport. The results reported in Table 6 demonstrate how coordinated policy instruments can alter incentives and drive the system toward a more sustainable equilibrium.

- IWT Subsidy: 60
- Road Transport Carbon Tax: 15

With these values, the payoff for each agent is recalculated, as shown in the tables above.

## Parametric and Graphical Analysis of Results

To extend the analysis beyond discrete payoff tables, a parametric evaluation of policy instruments was conducted. The subsidy level for inland waterway transport and the carbon tax applied to road transport were treated as continuous variables.

Figure 3 shows the variation in the logistics operator's payoff as a function of the subsidy level. The results reveal a nonlinear relationship, with diminishing returns as subsidies increase. An optimal range can be identified around intermediate subsidy levels, indicating that excessive incentives may reduce overall efficiency.

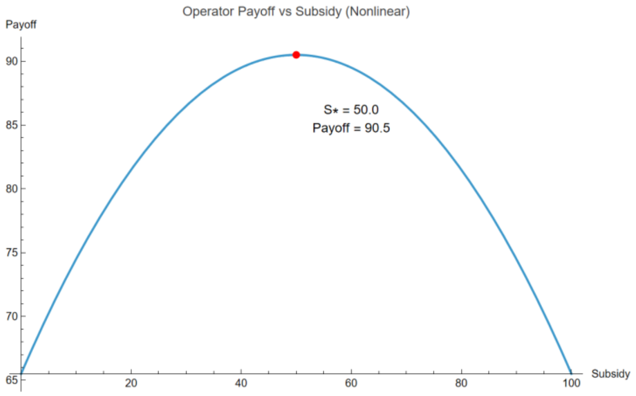

Figure 3. Logistics operator payoff as a function of subsidy level. The nonlinear concave relationship reveals diminishing returns to subsidies. The red marker denotes the optimal subsidy level (S* = 50), corresponding to the maximum payoff, highlighting the existence of a policy optimum.

This implies that policy effectiveness is subject to diminishing marginal returns, meaning that increasing subsidies beyond a certain threshold may lead to inefficient allocation of public resources without proportional gains in system performance. This also suggests that optimal policy design should prioritize efficiency over scale of intervention.

**Figure 4** shows the payoff of freight-generating companies as a function of carbon taxation. The results reveal a nonlinear decreasing relationship, indicating that increases in carbon taxation progressively reduce the payoff associated with road-based transport.

Unlike the logistics operator case, no internal optimum is observed within the analyzed range. Instead, the highest payoff occurs at the lowest taxation level, suggesting that carbon taxation operates primarily as a regulatory constraint rather than an optimization instrument. This reinforces its role in discouraging high-emission transport modes rather than enhancing system efficiency.

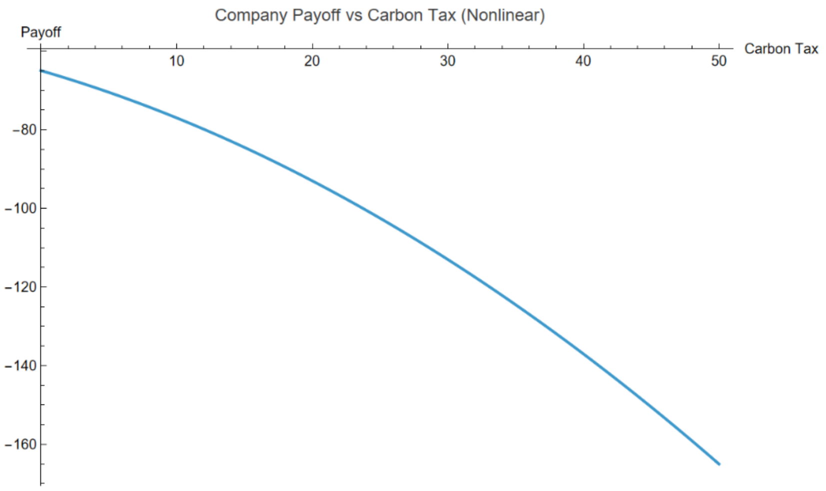

Figure 4. Payoff of freight-generating companies as a function of carbon taxation. The nonlinear decreasing relationship indicates that higher taxation consistently reduces payoff, reinforcing its role as a regulatory instrument.

**Figure 5** presents the strategic payoff landscape as a function of subsidy levels and carbon taxation. The color gradient represents the magnitude of the logistics operator’s payoff, while the highlighted region denotes policy combinations that achieve at least 90% of the maximum payoff.

The results reveal that optimal outcomes are not confined to a single point but instead emerge within a well-defined region in the policy space. This region is centered around moderate subsidy levels and low carbon taxation, indicating that effective policy design does not require precise parameter tuning but rather the identification of robust combinations of incentives.

The shape of the highlighted region reflects the nonlinear structure of the payoff function. In particular, the curvature along the subsidy axis indicates diminishing returns, while the sharper contraction along the carbon tax axis suggests a stronger negative impact of taxation on system performance. This asymmetry implies that increases in carbon taxation reduce the payoff more rapidly than equivalent increases in subsidies improve it.

The red marker indicates the global maximum of the payoff function, corresponding to the optimal policy configuration. However, the existence of an extended near-optimal region suggests that policymakers may operate within a range of acceptable parameter values while still achieving high levels of performance.

From a strategic perspective, this result reinforces the importance of coordinated policy instruments. Rather than relying on a single mechanism, such as subsidies or taxation alone, the combination of moderate incentives and regulatory pressure creates a stable environment in which inland waterway transport becomes the dominant strategy.

Overall, the analysis highlights that the transition toward more sustainable transport systems is governed by nonlinear interactions between policy variables, and that robust policy regions are more relevant than isolated optimal points in practical decision-making contexts. These findings are consistent with theoretical expectations from nonlinear systems, in which equilibrium configurations emerge from the interaction of competing forces rather than from linear optimization of isolated variables.

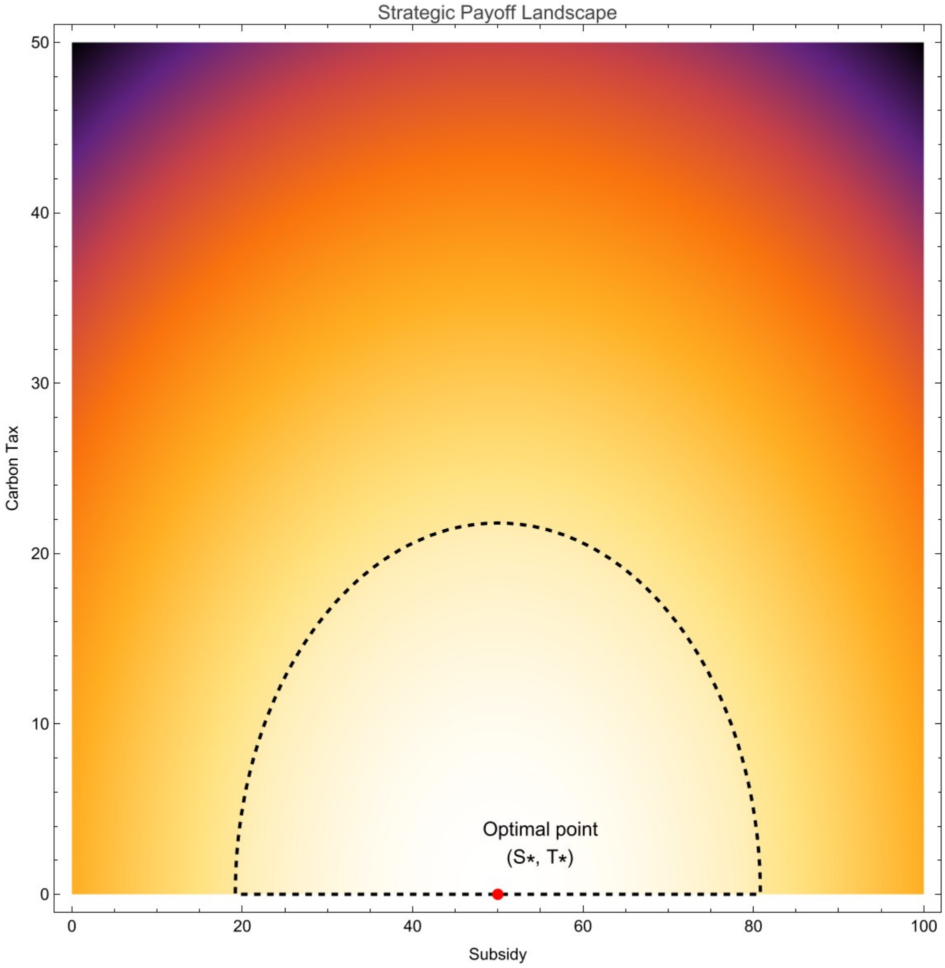

Figure 5. Strategic payoff landscape as a function of subsidy and carbon taxation. The color gradient represents the magnitude of the logistics operator’s payoff. The shaded region indicates policy combinations that achieve at least 90% of the maximum payoff, defining a robust zone of near-optimal performance. The red marker denotes the optimal policy point (S*, T*).

**Figure 6** provides a three-dimensional representation of the payoff surface, offering a comprehensive view of the interaction between subsidy levels and carbon taxation. The surface exhibits a well-defined peak corresponding to the optimal policy configuration.

The curvature of the surface confirms the presence of diminishing returns with respect to subsidies and a stronger negative effect associated with carbon taxation. The steeper gradient along the taxation axis indicates that increases in carbon taxes reduce system performance more rapidly than equivalent increases in subsidies improve it.

The red marker identifies the global maximum of the payoff function, representing the optimal combination of policy instruments. The optimal solution can also be derived analytically from first-order conditions, reinforcing the consistency of the graphical representation.

These results highlight that equilibrium outcomes emerge from the interaction of policy variables, reinforcing the importance of coordinated and balanced policy design in promoting sustainable transport systems.

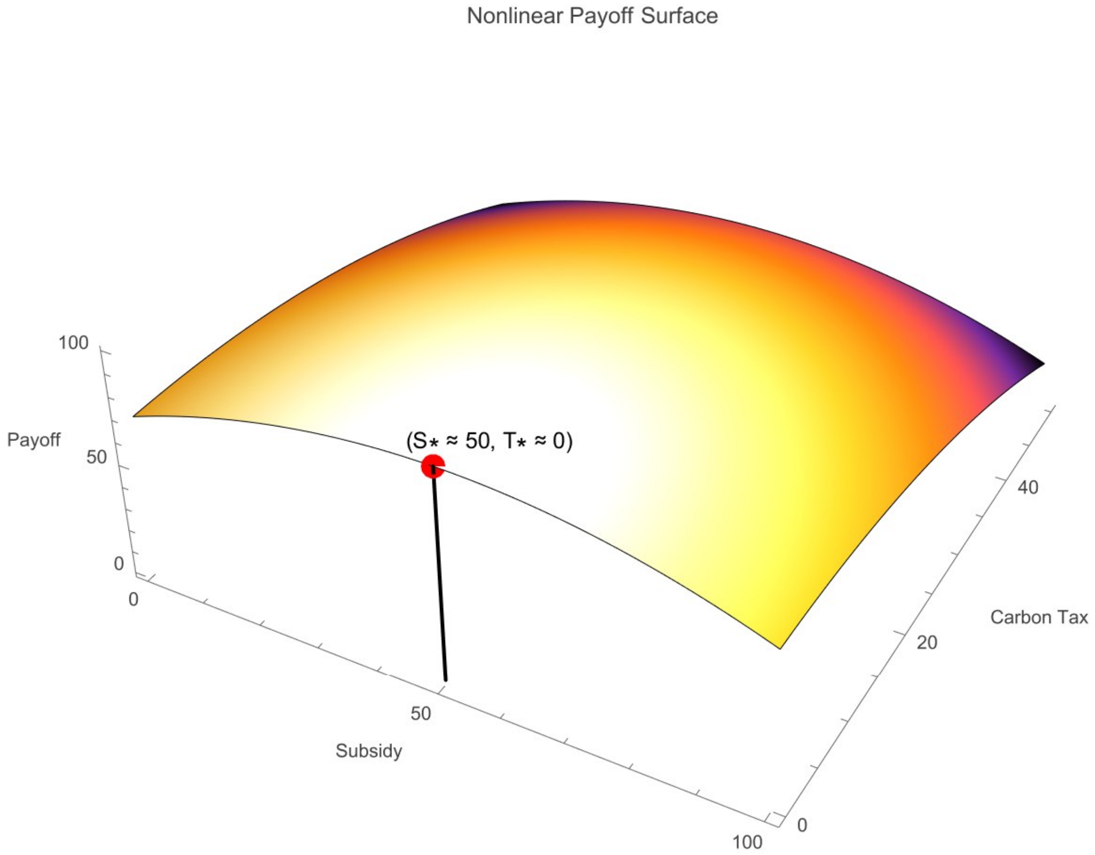

Figure 6. Three-dimensional representation of the logistics operator's payoff as a function of subsidy and carbon taxation. The surface illustrates the nonlinear structure of the payoff function, with a well-defined peak corresponding to the optimal policy combination (S* ≈ 50, T* ≈ 0). The red marker indicates the global maximum within the analyzed domain , while the surrounding smooth region highlights the robustness of near-optimal outcomes.

From a policy perspective, this indicates that effective intervention does not require precise calibration of parameters, but rather the identification of robust regions in the policy space where desirable outcomes emerge. This reduces implementation uncertainty and enhances the robustness of policy design in real-world applications.

## Discussion of Strategic Implications

The results demonstrate that the transition toward inland waterway transport is driven by coordinated policy mechanisms rather than isolated interventions. The combination of subsidies and carbon taxation alters the strategic environment by simultaneously increasing the attractiveness of waterway transport and penalizing less sustainable alternatives.

From the perspective of logistics operators, subsidies reduce perceived risks and improve expected returns, encouraging investment in inland waterway infrastructure and services. For freight-generating companies, carbon taxation increases the relative cost of road-based logistics, shifting preferences toward lower-emission transport options.

The nonlinear structure of the payoff functions indicates that policy effectiveness is not proportional to the magnitude of intervention. Instead, there exists a range of policy configurations that maximize system performance, reinforcing the importance of calibrated and balanced policy design.

Moreover, the results highlight that equilibrium outcomes emerge from the interaction of agents operating under institutional and economic constraints. This supports the applicability of game theory as a framework for analyzing sustainable logistics transitions.

These findings are consistent with the theory of induced innovation, according to which external incentives influence technological and operational change. More broadly, the results suggest that policy effectiveness in freight transport systems is inherently nonlinear and depends on the alignment of incentives across multiple stakeholders.

Importantly, the proposed framework can be directly mapped into measurable sustainability indicators, such as emission intensity ($g \cdot CO_2/(t \cdot km)$), logistics cost efficiency, and modal share. This enables alignment with SDG monitoring frameworks and supports the translation of strategic outcomes into quantifiable policy-relevant metrics.

To further operationalize this connection, the payoff structure can be associated with emission-based indicators. Let emission intensity be defined as Em ($g \cdot CO_2/(t \cdot km)$) for each transport mode m. The expected emissions associated with a given strategy profile can be approximated as follows:

$$E = \sum_{m} s_m \cdot E_m \tag{5}$$

where $s_m$ represents the share of freight allocated to mode m, endogenously determined by the equilibrium of the game. Since the payoff functions incorporate costs, incentives, and carbon taxation, changes in the equilibrium strategy profile directly affect $s_m$, thereby influencing total emission intensity. This establishes a direct link between strategic interaction outcomes and measurable sustainability indicators, allowing the model to be interpreted not only in terms of economic performance but also environmental impact.

In comparison with existing studies in the literature, the present model introduces relevant conceptual and methodological advances. Previous works, such as [11], primarily focus on competition between transport modes under predefined regulatory conditions, typically considering government intervention as an external parameter. In contrast, this study explicitly models government agencies as strategic players within the game, allowing policy instruments such as subsidies and carbon taxation to emerge as endogenous elements of the equilibrium structure.

Furthermore, while most existing approaches are limited to bimodal or operator–shipper interactions, the proposed framework incorporates a tripartite structure, capturing the interdependence between logistics operators, freight-generating companies, and public authorities. This enables a more realistic representation of decision-making processes in freight transport systems, particularly in emerging economies where institutional and policy dynamics play a central role. As a result, the model moves beyond static comparisons of transport modes and provides a framework for analyzing how coordinated policy design influences equilibrium outcomes, modal shifts, and sustainability performance. This distinction is particularly relevant in the context of sustainable transport planning, where policy effectiveness depends on dynamic interactions rather than isolated optimization of individual agents. In this sense, the model provides a bridge between micro-level strategic decisions and macro-level sustainability performance metrics.

## CONCLUSIONS

This study developed a non-cooperative, tripartite game-theoretic model to represent strategic interactions among logistics operators, government agencies, and freight-generating companies in the context of inland waterway freight transport competitiveness. By structuring payoffs around operational revenues and costs, policy incentives, demand responses, and perceived value, the model provides a transparent and analytically consistent framework for examining how individual decisions aggregate into equilibrium outcomes under different policy scenarios.

The results demonstrate that the limited adoption of inland waterway transport in emerging economies is primarily driven by misalignment of incentives rather than purely technical constraints. When policy instruments such as subsidies and carbon taxation are coordinated, the system transitions toward equilibrium configurations in which inland waterways become the dominant strategy. Importantly, this transition is governed by nonlinear dynamics, with diminishing returns to subsidies and asymmetric effects of carbon taxation, reinforcing the need for balanced and well-calibrated policy design.

From a sustainability perspective, the proposed framework enables direct linkage between strategic decision-making and measurable performance indicators, including emission intensity ($gCO_2$/ton-km), modal share, and logistics cost efficiency. This connection allows the model to support evidence-based policy evaluation and aligns its outcomes with Sustainable Development Goals related to infrastructure, efficiency, and climate action. In this sense, the model contributes not only to theoretical analysis but also to the practical design of sustainable transport policies.

Moreover, the results highlight that effective policy intervention does not depend on precise parameter optimization, but rather on the identification of robust regions in the policy space where desirable outcomes emerge. This insight reduces implementation uncertainty and enhances the applicability of the model in real-world decision-making contexts, particularly in emerging economies characterized by institutional and infrastructural constraints.

Although the model relies on stylized parameters, the adopted values reflect realistic operational conditions and are consistent with orders of magnitude reported in the literature. This ensures that the results capture plausible strategic behavior while maintaining analytical clarity. Future research may focus on empirical calibration using corridor-specific data, incorporation of uncertainty factors such as hydrological variability, and extension of the framework to include multimodal contracts and dynamic policy adjustments.

Overall, this study provides a structured and policy-relevant analytical framework for understanding how coordinated incentives can drive sustainable transitions in freight transport systems, offering both conceptual insights and practical guidance for decision-makers.

## ACKNOWLEDGMENT

The authors acknowledge the financial support provided by FAEPEX–UNICAMP (Agreement No. 519.287 – T.A. UNICAMP/PRP/FAEPEX, Incentive Program for New Faculty at the University of Campinas), CAPES (Coordination for the Improvement of Higher Education Personnel, Ministry of Education, Brazil), and CNPq (National Council for Scientific and Technological Development) under Grant No. 401609/2025-1 (Call CNPq/MCTI No. 44/2024 – Track A).

## ABBREVIATIONS

| | |
|---|---|
| OL | Logistics Operator |
| G | Government Agency |
| E | Freight-Generating Company |
| IWT | Inland Waterway Transport |
| ROR | Operational Revenue (Operator) |
| COC | Operational Cost (Operator) |
| GI | Government Incentives |
| IC | Integration / Switching Cost |
| OC | Operational Cost (Company) |
| PV | Perceived Value |
| DT | Delivery Time |
| CT | Carbon Tax |

## REFERENCES

1. Calderón-Rivera, N., Bartusevičienė and I., Ballini, F., Sustainable development of inland waterways transport: A review, *Journal of Shipping and Trade*, Vol. 9, No. 3, 2024, https://doi.org/10.1186/s41072-023-00162-9.
2. Rodrigue, J.-P., *The Geography of Transport Systems*, 5th ed., Routledge, London, UK, 2020, https://doi.org/10.4324/9780429346323.
3. Vilarinho, A., Liboni, L. B., Cezarino, L. O., Durán Micco, J., Mommens, K. and Macharis, C., Challenges and opportunities for the development of inland waterway transport in Brazil, Sustainability, Vol. 16, No. 5, 2136, 2024, https://doi.org/10.3390/su16052136.
4. Barros, B. R. C. de, Carvalho, E. B. de and Brasil Junior, A. C. P, Budget performance and governance in infrastructure project management: The case of Brazilian inland waterway transport, *Cadernos EBAPE.BR*, Vol. 21, No. 5, 2023, https://doi.org/10.1590/1679-395120210135x.
5. Castro, C. N., O Agronegócio e os desafios da infraestrutura de transporte na região Centro-Oeste (in Portuguese, Agribusiness and the challenges of transportation infrastructure in the Central West region), Chap. 8, Institute for Applied Economic Research (Ipea), 2017, https://repositorio.ipea.gov.br/handle/11058/9031, [Accessed: May. 08, 2026].
6. Hensher, D. A. and Brewer, A. M., *Transport: An Economics and Management Perspective*, Oxford University Press, Oxford, UK, 2000.
7. Fudenberg, D. and Tirole, J., *Game Theory*, MIT Press, Cambridge, MA, USA, 1991.
8. Osborne, M. J. and Rubinstein, A., *A Course in Game Theory*, MIT Press, Cambridge, MA, USA, 1994.
9. United Nations, Sustainable Development Goal 9: Industry, innovation and infrastructure, United Nations, n.d., https://sdgs.un.org/goals/goal9, [Accessed: May. 08, 2026].
10. United Nations, Sustainable Development Goal 13: Climate action, United Nations, n.d., https://sdgs.un.org/goals/goal13, [Accessed: May. 08, 2026].
11. International Transport Forum, Mode choice in freight transport: A logistics perspective, Report, OECD Publishing, Paris, France, 2022, https://doi.org/10.1787/3e69ebc4-en.
12. Tamannaei, M., Zarei, H. and Rasti-Barzoki, M., A game theoretic approach to sustainable freight transportation: Competition between road and intermodal road–rail systems with government intervention, *Transportation Research Part B: Methodological*, Vol. 153, pp. 272-295, 2021, https://doi.org/10.1016/j.trb.2021.09.002.
13. Maevsky, O., Kovalchuk, M., Brodsky, Y., Stanytsina, V. and Artemchuk, V., Game-theoretic modeling in regulating greenhouse gas emissions, *Heliyon*, Vol. 10, No. 9, e30549, 2024, https://doi.org/10.1016/j.heliyon.2024.e30549.

Paper submitted: 27.12.2025
Paper revised: 03.04.2026
Paper accepted: 15.04.2026