Contents lists available at GrowingScience

International Journal of Industrial Engineering Computations

homepage: www.GrowingScience.com/ijiec

Game-theoretic modeling of sustainable intermodal freight transportation: Optimal pricing and energy efficiency strategies under government intervention and fuzzy uncertainty

Qian Long[a*] and Qunqi Wu[b]

[a]*College of Transportation Engineering, Chang'an University, Xi'an 710064, China*
[b]*School of Economics and Management, Chang'an University, Xi'an 710064, China*

C H R O N I C L E

Article history:
Received January 12 2025
Received in Revised Format March 18 2025
Accepted April 1 2025
Available online April 2 2025

Keywords:
Fuzzy uncertainties
Sustainable freight transportation
Road-rail transport
Pricing and energy

A B S T R A C T

Sustainable freight transportation plays a pivotal role in addressing pressing environmental challenges while simultaneously fostering socio-economic development. Governmental entities worldwide are increasingly implementing strategic policy interventions to enhance the sustainability of freight transportation systems. A comprehensive understanding of the complex interactions and dynamics between these policy measures and transportation operations is essential for developing effective sustainable transportation strategies. This study aims to explore the impact of government intervention on pricing strategies, and energy-saving level determination in the transportation sector under conditions of fuzzy uncertainty. While the government looks into three distinct strategies, each with two decision variables, transportation enterprises are considering two alternate scenarios for decision-making. It means that twelve distinct scenarios are being considered by the government. Our analyses reveal that: (1) The government's goals of maximizing social welfare and energy saving cannot be aligned with the enterprises' goals of maximizing profits, regardless of whether decision-making is decentralized or centralized. (2) The carbon cap-and-trade mechanism emerges as the most effective strategy for governmental regulation, whereas transportation enterprises demonstrate optimal responsiveness to subsidy-based policy interventions. (3) Centralized decision-making by transportation enterprises yields superior outcomes across multiple dimensions, including LSSC profitability, social welfare enhancement, and energy conservation efficiency, when contrasted with decentralized decision-making paradigms. (4) The implementation of a carbon cap-and-trade policy by the government, combined with increased investments in environmental awareness and centralized decision-making by transportation enterprises, significantly advances both profit objectives and energy-saving targets.

1. Introduction

The sustainability of freight transportation systems is gaining more attention as a result of the sharply growing demand for freight transportation and the escalating environmental issues. A sustainable freight transportation system provides fair and ecologically responsible access to freight facilities (Black, 2004). Road transportation networks serve as a crucial component in freight logistics, accounting for a substantial proportion of cargo movement globally (Bhattacharya et al., 2014). This predominance can be attributed to several distinctive advantages, including operational flexibility (Dadsena et al., 2019), consistent reliability (Demir et al., 2015), and efficient transit capabilities (Jarašūnienė et al., 2022). However, road transportation is unsustainable due to the significant negative externalities it generates, including energy use, accidents, noise, and air pollution (Stenico de Campos et al., 2019). According to the European Commission (EC), shifting freight traffic from road to rail is a crucial policy tactic for establishing a sustainable system that can satisfy the requirements of the contemporary economy, society, and environment (Pittman et al., 2020). However, sustainability is not typically prioritized by transportation enterprises or consumers. The selection of freight transport modalities by consumers is predominantly determined by the pivotal consideration of logistical expenditure (Chen et al., 2017). The primary objective of transportation enterprises is profit maximization. Consequently, governmental intervention in the transportation market through the implementation of incentive-based mechanisms and regulatory sanctions becomes imperative. This strategic intervention is designed to facilitate the

* Corresponding author
E-mail LQ2019023008@163.com (Q. Long)
ISSN 1923-2934 (Online) - ISSN 1923-2926 (Print)
2025 Growing Science Ltd.
doi: 10.5267/j.ijiec.2025.4.002

transition of freight transportation systems toward enhanced operational efficiency and long-term environmental sustainability. Understanding how to balance the objectives of enterprises and the government in intermodal transport networks is necessary to develop sustainable freight transportation.

Government intervention has an significant impact on the sustainability of freight transport (Nkesah, 2023). However, there is little research on sustainable freight transportation that takes into account the influence of government intervention, and it is often fragmented and narrowly focused. For instance, a price game model was conducted by Tamannaei (2021) and Fallahi et al. (2024) to examine competition in freight transportation networks in relation to tax policy. They discovered that whereas environmental and economic sustainability are at odds, social and economic sustainability are compatible. Previous studies have used a single price game model to examine a single intervention strategy. Another significant problem is that many parameters are sometimes unclear because they are difficult to estimate, such as cost, consumer demand, low-carbon preference, product substitution rate, etc. (Zhao et al., 2012). Using certain fuzzy variables is one efficient optimization method for game models. However, little research has been done on the effects of government intervention policies on environmentally friendly freight transportation in game models that account for fuzzy variables.

Given the aforementioned research gap, this study is aimed to examine how government involvement affects energy-saving level decision-making and transportation price while taking fuzzy uncertainty into consideration. This study examines the impact of government policies on sustainability, focusing on two key objectives: minimizing energy consumption (or equivalently, maximizing energy savings) and maximizing social welfare. The government is evaluating three distinct strategies, each characterized by two decision variables, while transportation enterprises are assessing two alternative decision-making scenarios. For the purposes of this study, that translates into twelve scenarios for the government, with the ensuing observations and potential recommendations. As previously said, the subsidy coefficient, carbon tax, carbon cap quota, and the cost of public education on enhancing environmental awareness are the four decision variables. This study addresses three pivotal research questions:

(1) What constitutes the optimal pricing strategy, energy efficiency level, and expected profit margin for transportation enterprises?
(2) What are the government's anticipated optimal outcomes across various policy objectives and strategic implementations?
(3) What scenarios yield optimal results for both governmental bodies and transportation enterprises in terms of pricing mechanisms, market demand, profitability, environmental sustainability, and social welfare enhancement?

The structure of this paper is systematically organized as follows: Section 2 provides a comprehensive literature review, establishing the theoretical foundation for this research. Section 3 presents the problem formulation and research framework. Section 4 presents the development of mathematical models, while Section 5 details the derivation of equilibrium solutions. Section 6 demonstrates the application through a numerical case study, presenting empirical findings and analytical insights. The concluding section synthesizes the research outcomes, discusses theoretical and practical implications, and proposes directions for future research.

2. Literature review

Numerous studies have been conducted on sustainable freight transportation systems; these studies can be broadly categorized into two groups: sustainable development strategies and sustainability assessments. Fulzele and Shankar (2023) developed a performance index to evaluate sustainable freight transportation systems by innovatively integrating the Fuzzy Evidential Reasoning Algorithm (FERA) with the Consensus Model (CM). Their findings revealed that market-leading firms are increasingly prioritizing sustainability in their operational strategies. The study emphasized that a holistic business approach, addressing environmental, economic, and social dimensions, is essential for advancing sustainability goals. An integrated performance assessment framework (PAF) was created by Pathak et al. (2019, 2021) to evaluate the sustainability performance of freight transportation systems. The research on methods for attaining sustainable freight transportation was split into three categories by Nkesah (2023): policy-based management, transport efficiency, and creative technology. According to certain scholars, the transformation of freight transportation through digitization encompasses advancements such as automation, the seamless flow of digital information, the integration of artificial intelligence, and the implementation of the Internet of Things (IoT) is essential for cutting costs, increasing efficiency and service quality, and boosting competitiveness (Jarašūnienė et al., 2022; Pernestål et al., 2020; Wang et al., 2015a; Li & Yu, 2017; Taniguchia et al., 2020). Kontrobayeva et al. (2023) examine the potential for improving road transport efficiency for agricultural goods by switching to new, eco-friendly fuels, lowering maintenance and repair costs by combining transportation companies, and implementing innovations and technologies.

Some researchers found effective transportation planning (Tacken et al., 2014) such as the aggregation of merchandise (Arvidsson et al., 2013), increasing load factor (Makan & Heyns, 2018; Santén, 2017) and minimize idle trips (Wehner, 2018) can better utilize internal resources to improve transportation efficiency, and some scholars found that multimodal transportation can reduce environmental impact and achieve environmental sustainability. According to (Liljestrand, 2016), intermodal mobility lowers the climate effect from the shippers' point of view by 27% to 31% for road-to-rail transportation and 27% to 53% for road-to-sea transportation. One issue that is very important to sustainable freight transportation is government intervention. Duan and Heragu (2015), Fahimnia et al. (2015), and Zhou et al. (2018) evaluated a government tax policy on a tactical supply chain and intermodal freight transportation, respectively. To assess how government tax decisions affected emissions reduction, they conducted a comprehensive analysis of the trade-off between cost efficiency and emission reduction. According to Wang et al. (2015b), societal welfare can be enhanced by enacting fair carbon-emission fees. Kundu and Sheu (2019) carried out an extensive study on how government subsidy initiatives influence shippers' transition from maritime to rail transport. Their research examined the broader implications of these subsidies and pinpointed effective strategies to encourage diverse shippers to switch between the two modes of transportation. In order to determine if the establishment of a carbon market results in the Porter effect, Qi et al. (2021) investigates how a carbon trading pilot policy affects an industry's low-carbon worldwide competitiveness. Road truck routing is presented by Li et al. (2015) as part of the carbon emission trading arrangement. Additionally, the cap and trade mechanism's truck routing choice is more successful in cutting carbon emissions. A few academics While researching government intervention programs, some academics also take government sustainability goals into account. Rasti-Barzoki and Moon (2017) conducted a comprehensive study examining the dynamic interactions between two competing supply chains—one characterized by environmentally friendly practices and the other by conventional non-green operations—within the context of government intervention and policy influence. By taking into account the government's economic, social, and environmental objectives, Tamannaei et al. (2021) conducted a comprehensive analysis of competitive dynamics between traditional road transportation systems and multimodal road-rail transportation networks under carbon pricing mechanisms.

To the best of our knowledge, there are few studies on how government intervention affects the development of sustainable freight. Few studies compare the effects of various intervention policies on freight enterprise decision-making and government sustainability goals, most existing research focuses on a single intervention policy or price game model. As a result, our research makes two primary contributions to the body of knowledge on freight transportation. In order to properly study the game behaviors between government and freight transportation enterprises, an enhanced game model that takes fuzzy factors into account is first built. Second, a thorough examination of the ways in which government intervention affects enterprises' decision-making about equilibrium pricing and energy-saving levels is provided, along with a comparison of the effects of three distinct strategies.

3. Problem formulation

We analyze a Logistics Service Supply Chain (LSSC) comprising one road-based enterprise and one rail-based enterprise, both functioning within a unified government framework (refer to Fig. 1). In stage 1, the government aims to reduce emissions by implementing policies such as carbon taxation, carbon cap and trade, and subsidies. According to these policies, transportation providers decide on the cost of transportation services and the level of energy savings in stage 2. Road transport enterprise, as a logistics service integrator (LEI), decides to merge certain of its operations with road-rail intermodal transportation and calculates the transportation price P with an energy-saving level of e. In the process of road-rail intermodal transportation, the percentage of rail transportation is β, and the percentage of road-rail intermodal transportation in the whole road transportation business is γ.

The problem is based on the following assumptions:

Assumption 1: All decision parameters are nonnegative, informations in the game process are transparent and symmetrical. All participating parties are completely rational with the goal of maximizing their own profits.
Assumption 2: The transportation cost does not involve storage costs, only considering fuel cost and transfer costs. The unit transportation cost for road transportation is c_r , and the unit transportation cost for rail transportation is c_t , $c_r > c_t$.
Assumption 3: Carbon emissions per unit of demand for road transportation is e_r , carbon emissions per unit of demand for rail transportation is e_t , $e_r > e_t$.

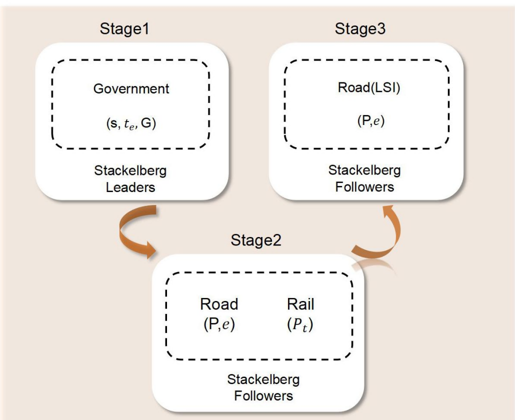

Fig. 1. The framework of the issue

4. Model Formulation

The aforementioned issue is presented for the government and transportation enterprises, respectively, in the next two subsections. To keep things simple, the following notations in table1 are used in this study (i=1,2,3 stands for subsidy policy, carbon tax policy, and carbon cap-and-trade policy, respectively):

Table 1
The definition of parameters in this study

Parameters	Meanings (Superscript D denotes decentralized decision-making, C denotes centralized decision-making)
e_r/e_t	Carbon emission per unit of transported product of road /rail transport
$\tilde{a}$	The market base for the demand (fuzzy variable)
$\tilde{\sigma}$	The price of one unit to raise public awareness of environmental issues (fuzzy variable)
$\tilde{k}$	Investment coefficient of energy saving (fuzzy variable)
b	Self-price sensitivity of the demands
c_r	Cost per unit of road freight volume which includes transloading costs.
c_t	Cost per unit of rail freight volume
e	Unit energy saving level (unit carbon emission reduction level)
γ	Percentage of rail transport in road-rail transportation
β	Percentage of road-rail transport in road transportation operation
F	Upper bound of the government’s energy saving goal
M	The lower bound of expected profit (EP)
N	The minimum threshold for the government's social welfare objective.
Decision variables	
t_e	The amount of tax on a unit of carbon emission
P_e	Unit carbon trading price
s	Subsidy coefficient
η	Environmental awareness
G	Carbon quota per unit of freight volume
P_t	Rail transport price
P	Road transport price
Demand, profits, government goals	
q	The market base for the demand
π_i^C	Profit of the road-rail intermodal logistics services supply chain in CDM
π_{ti}^D/π_{ri}^D	Profit of rail/road transportation enterprises in DDM
ES^D/ES^C	Energy saving under centralized/decentralized decision-making
SW^D/SW^C	Social welfare under centralized/decentralized decision-making

4.1 Transportation enterprise

In line with the studies conducted by Deyan Yang (2017) and Ghosh and Shah (2015), we posit that consumer demand is influenced by two key factors: the level of energy efficiency e and the transportation cost P. This relationship is modeled using a practical fuzzy linear formulation, which illustrates that higher energy-saving measures correlate with a reduction in transportation expenses. Specifically, the demand function is $q = \tilde{\alpha} - bP + \eta e$, where $E[\tilde{\alpha} - bP] > 0, E[\tilde{\alpha}] > 0$,the initial unit carbon emissions of intermodal road- rail transportation is $e_0^D = (1-\beta)e_r + \beta[(1-\gamma)e_r + \gamma e_t] = (1-\gamma\beta)e_r + \gamma\beta e_t$, the unit transportation cost of road transport after combined transport is $C^D = (1-\beta)c_r + \beta(1-\gamma)c_r = (1-\gamma\beta)c_r$.

4.1.1 Decentralized decision-making model

The game can be broken down into three stages in the decentralized decision-making (DDM) model: the government determines the unit transportation service's subsidy coefficient, carbon tax coefficient, and carbon cap quota in stage 1; the rail transport enterprise determines the agreed-upon price P_t of the unit transportation service based on the government's decision in the stage 2; and the road transport enterprise determines the unit price P of based on the decisions of the government and the rail transport enterprise in the stage 3.The following is how the businesses' profit functions under various policy scenarios:

The expected profit function of rail transportation enterprise is as follow：

$$E[\pi_{t1}^{D}] = \beta(E[\widetilde{\alpha}] - bP + \eta e)(P_t - \gamma c_t + s) \tag{1}$$

$$E[\pi_{t2}^{D}] = E[\pi_{t3}^{D}] = \beta(E[\widetilde{\alpha}] - bP + \eta e)(P_t - \gamma c_t) \tag{2}$$

The expected profit function of road transportation enterprise is as follow：

$$E[\pi_{r1}^{D}] = (E[\widetilde{\alpha}] - bP + \eta e)(P - (1-\gamma\beta)c_r - \beta P_t) - \frac{1}{2}E[\tilde{k}]e^{D2} \tag{3}$$

$$E[\pi_{r2}^{D}] = (E[\widetilde{\alpha}] - bP + \eta e)(P - (1-\gamma\beta)c_r - \beta P_t - t_e) - \frac{1}{2}E[\tilde{k}]e^{D2} \tag{4}$$

$$E[\pi_{r3}^{D}] = (E[\widetilde{\alpha}] - bP + \eta e)(P - (1-\gamma\beta)c_r - \beta P_t + P_e(G - (e_0^D - e^D))) - \frac{1}{2}E[\tilde{k}]e^{D2} \tag{5}$$

4.1.2 Centralized decision-making models

According to the model of centralized decision-making (CDM), enterprises that provide road and rail transportation decide to integrate their operations to create a supply chain for intermodal logistics services. They then use centralized decision-making to maximize the logistics service supply chain's profit. (β is assumed to be 1 for CDM as, in accordance with Corollary 4, greater is better for road and rail transportation enterprises.) When the government makes decisions, its aim is to maximize energy savings and social benefit.

There are three stages to the game: the government determines the carbon tax coefficient, the subsidy coefficient, and the carbon cap quota for the unit transportation service in stage 1. The decision makers in the intermodal logistics services supply chain (logistics service integrators, i.e., road transportation enterprise) jointly decide on the price of a unit of transportation service based on the government's determination in the ideal state of full information disclosure within the supply chain as P_t in stage 2. According to this model, the intermodal logistics service's supply chain's carbon emissions per unit is $e_0^C = (1-\gamma)e_r + \gamma e_t$, The transportation cost of the intermodal logistics services unit is $c^C = (1-\gamma)c_r + \gamma c_t$. The expected profits of road-rail intermodal logistics services supply chain is as follow:

$$E[\pi_1^c] = (E[\widetilde{\alpha}] - bP + \eta e)(P - (1-\gamma)c_r - \gamma c_t + s) - \frac{1}{2}E[\tilde{k}]e^{C2} \tag{6}$$

$$E[\pi_2^c] = (E[\widetilde{\alpha}] - bP + \eta e)(P - (1-\gamma)c_r - \gamma c_t - t_e) - \frac{1}{2}E[\tilde{k}]e^{C2} \tag{7}$$

$$E[\pi_3^c] = (E[\widetilde{\alpha}] - bP + \eta e)(P - (1-\gamma)c_r - \gamma c_t + P_e(G - (e_0^c - e^c))) - \frac{1}{2}E[\tilde{k}]e^{C2} \tag{8}$$

4.2 The government

Based on the problem definition, we focus on two objectives: maximizing energy efficiency and optimizing social welfare. The energy savings target is determined by multiplying the transportation demand by the energy savings achieved per unit, as follows:

$$ES^D = e^D q^D \tag{9}$$

$$ES^C = e^C q^C \tag{10}$$

In previous research, social welfare improvements are quantified by applying the consumer surplus factor to the disparity between perceived and actual costs (Rasti-Barzokia and Moon, 2020). Here, however, we use the approach described in Sheu and Chen (2012) to include consumer surplus, producer surplus and transportation-related environmental costs in social welfare metrics. The environmental cost in this context primarily refers to the cost spent by the government to increase consumer awareness of environmental issues, as follows:

$$SW^D = \frac{1}{2}q^{D2} + (\pi_{ti}^D + \pi_{ri}^D) - \eta E[\widehat{\sigma}] \tag{11}$$

$$SW^C = \frac{1}{2}q^{C2} + \pi_i^C - \eta E[\widehat{\sigma}] \tag{12}$$

It is clear that a transportation system will cease to exist in the cutthroat transportation market if economic activity fails to meet the rate of return that the system requires (Adler, 2001). In light of sustainability, road and rail transportation companies may anticipate a minimal level of acceptable profits. Therefore, the government has two limitations for each of these goals that are connected to the others. These thresholds are lower bounds on profits and social welfare, respectively, because, taking scenario 2 as an example, the government's environmental goal (i.e., energy conservation) is to maximize energy saving while taking into account the enterprise's expected profit and social welfare. When pursuing social welfare enhancement, the government must consider both the minimum acceptable expected profit and the upper limit of achievable energy savings. When the government wants to maximize social welfare, it must take into account the minimum acceptable expected profit and the maximum energy saving. In this case, we take the enterprise's profit without government intervention, social welfare, and total carbon emissions as the critical values of the revenue, social welfare, and environmental protection objectives, respectively. Table 2 shows the models of the various scenarios.

Table 2
The twelve scenarios for the government

Goal	Constrains	Decision-making Structures					
		DDM			CDM		
		s	t_e	G	s	t_e	G
ES	EP SW	$\mathrm{MaxES}(P, P_t, s)$ $EP \geq M$ $SW \geq N$	$\mathrm{MaxES}(P, P_t, t_e)$ $EP \geq M$ $SW \geq N$	$\mathrm{MaxES}(P, P_t, G)$ $EP \geq M$ $SW \geq N$	$\mathrm{MaxES}(P, s)$ $EP \geq M$ $SW \geq N$	$\mathrm{MaxES}(P, t_e)$ $EP \geq M$ $SW \geq N$	$\mathrm{MaxES}(P, G)$ $EP \geq M$ $SW \geq N$
	Scenario	2	4	6	8	10	12
SW	EP ES	$\mathrm{MaxSW}(P, P_t, s)$ $EP \geq M$ $ES \leq F$	$\mathrm{MaxSW}(P, P_t, t_e)$ $EP \geq M$ $ES \leq F$	$\mathrm{MaxSW}(P, P_t, G)$ $EP \geq M$ $ES \leq F$	$\mathrm{MaxSW}(P, s)$ $EP \geq M$ $ES \leq F$	$\mathrm{MaxSW}(P, t_e)$ $EP \geq M$ $ES \leq F$	$\mathrm{MaxSW}(P, G)$ $EP \geq M$ $ES \leq F$
	Scenario	1	3	5	7	9	11

5. Equilibrium solutions

To solve this game, standard backward induction is employed. The problem at hand has the following chronology. For every possible situation, the government determines the decision variables during the first period. In the secondary period, transportation operators strategically determine both their energy efficiency investment levels and service pricing structures.

5.1 Equilibrium results under DDM

Proposition 1:The equilibrium values of transport prices, transport demand and expected profits for road and rail transport companies are as follows：

$$P_i^{D*} = \begin{Bmatrix} \dfrac{6E[\tilde{k}]E[\tilde{\alpha}] + (2bE[\tilde{k}] - H_i^2)B_i}{(8bE[\tilde{k}] - H_i^2)}, i = 1,2 \\ \dfrac{(6E[\tilde{k}] - P_e H_i)E[\tilde{\alpha}] + (2bE[\tilde{k}] - \eta H_i)B_i}{(8bE[\tilde{k}] - H_i^2)}, i = 3 \end{Bmatrix} \tag{13}$$

$$P_{ti}^{D*} = \frac{8E[\tilde{k}](E[\tilde{\alpha}] - bA_i) + H_i^2(A_i - B_i)}{2\beta(8bE[\tilde{k}] - H_i^2)} \tag{14}$$

$$q^{D*} = \frac{2bE[\tilde{k}](E[\tilde{\alpha}] - bB_i)}{8bE[\tilde{k}] - H_i^2} \tag{15}$$

$$e^{D*} = \frac{H_i(E[\tilde{\alpha}] - bB_i)}{8bE[\tilde{k}] - H_i^2} \tag{16}$$

$$\pi_{ti}^{D*} = \frac{8b(E[\tilde{k}])^2 (E(\tilde{\alpha}) - bB_i)^2}{(8bE[\tilde{k}] - H_i^2)^2} \tag{17}$$

$$\pi_{ri}^{D*} = \frac{E[\tilde{k}](E(\tilde{\alpha}) - bB_i)^2}{2(8bE[\tilde{k}] - H_i^2)} \tag{18}$$

where

$H_{1,2}=\eta, H_3=\eta+bP_e$ $A_1=(1-\gamma\beta)c_r-\gamma\beta c_t+\beta s$ $B_1=(1-\gamma\beta)c_r+\gamma\beta c_t-\beta s$

$A_2=(1-\gamma\beta)c_r-\gamma\beta c_t+t_e$ $B_2=(1-\gamma\beta)c_r+\gamma\beta c_t+t_e$ $A_3=(1-\gamma\beta)c_r-\gamma\beta c_t-P_e(G-e_0^D)$

$B_3=(1-\gamma\beta)c_r+\gamma\beta c_t-P_e(G-e_0^D)$

It is evident from Eqs. (13)–(18):

Corollary 1:

(1) When $\eta^2<2bE\left[\tilde{k}\right]$, then $\frac{\partial P_1^{D*}}{\partial s}<0$, when $2bE\left[\tilde{k}\right]<\eta^2<8bE\left[\tilde{k}\right]$, then $\frac{\partial P_1^{D*}}{\partial s}>0$

(2) When $\eta^2<4bE\left[\tilde{k}\right]$, then $\frac{\partial P_{t1}^{D*}}{\partial s}<0$, when $4bE\left[\tilde{k}\right]<\eta^2<8bE\left[\tilde{k}\right]$, then $\frac{\partial P_1^{D*}}{\partial s}>0$

(3) When $\eta^2<2bE\left[\tilde{k}\right]$, then $\frac{\partial P_2^{D*}}{\partial te}<0$, when $2bE\left[\tilde{k}\right]<\eta^2<8bE\left[\tilde{k}\right]$, then $\frac{\partial P_2^{D*}}{\partial te}>0$

(4) When $\eta(\eta+bp_e)<2bE\left[\tilde{k}\right]$, then $\frac{\partial P_3^{D*}}{\partial G}<0$, when $\eta(\eta+bp_e)>2bE\left[\tilde{k}\right]$, then $\frac{\partial P_3^{D*}}{\partial G}>0$

(5) $\frac{\partial P_{t3}^{D*}}{\partial G}>0$, $\frac{\partial P_{t1}^{D*}}{\partial te}<0$.

Corollary 1 shows the pricing of rail transportation exhibits a direct correlation with the quantity of carbon allowances and an inverse relationship with the carbon tax coefficient. Under the condition where $\eta^2<2bE\left[\tilde{k}\right]$, the introduction of subsidy policies leads to a reduction in road transportation prices, whereas the application of carbon tax policies results in an increase. Conversely, when $2bE\left[\tilde{k}\right]<\eta^2<8bE\left[\tilde{k}\right]$, these effects are inverted. Furthermore, when $\eta^2<4bE\left[\tilde{k}\right]$, an increase in subsidies decreases rail transportation prices; however, when $4bE\left[\tilde{k}\right]<\eta^2<8bE\left[\tilde{k}\right]$, the same increase in subsidies elevates rail transportation prices. Regarding carbon quota credits, they are inversely proportional to road transportation prices when $\eta(\eta+bp_e)<2bE\left[\tilde{k}\right]$, but this relationship reverses when $\eta(\eta+bp_e)>2bE\left[\tilde{k}\right]$. These observations highlight that the thresholds of consumer environmental awareness and energy-saving investment coefficients significantly influence equilibrium transportation prices, varying with different intervention policies. Therefore, it is crucial to manage the thresholds of these variables effectively to achieve desired outcomes in transportation pricing strategies.

Corollary 2:

$$\frac{\partial q^{D*}}{\partial s}>0, \frac{\partial q^{D*}}{\partial t_e}<0, \frac{\partial q^{D*}}{\partial G}>0$$

Corollary 2 shows that while carbon tax coefficients are inversely correlated with equilibrium demand, subsidy and carbon quota coefficients are positively correlated with it. This is because rising subsidies and carbon quotas favor transportation prices, which in turn impact demand.

5.2 Equilibrium results under CDM

Proposition 2: The equilibrium values of transport prices, transport demand and expected profits of road and rail transportation enterprise under centralized decision-making are shown as follow:

$$P_i^{C*}=\begin{cases}\dfrac{E[\tilde{k}]E[\tilde{\alpha}]+(bE[\tilde{k}]-H_i^2)D_i}{(2bE[\tilde{k}]-H_i^2)}, i=1,2\\[2ex] \dfrac{(E[\tilde{k}]-P_eH_i)E[\tilde{\alpha}]+(bE[\tilde{k}]-\eta H_i)D_i}{(2bE[\tilde{k}]-H_i^2)}, i=3\end{cases} \tag{19}$$

$$q^{C*}=\frac{bE[\tilde{k}](E[\tilde{\alpha}]-bD_i)}{2bE[\tilde{k}]-H_i^2} \tag{20}$$

$$e^{C*} = \frac{H_i(E[\tilde{\alpha}] - bD_i)}{2bE[\tilde{k}] - H_i^2} \tag{21}$$

$$\pi_i^{C*} = \frac{E[\tilde{k}](E(\tilde{\alpha}) - bD_i)^2}{2(2bE[\tilde{k}] - H_i^2)} \tag{22}$$

where

$H_{1,2} = \eta, H_3 = \eta + bP_e$

$D_1 = (1-\gamma)c_r + \gamma c_t - s$

$D_2 = (1-\gamma)c_r + \gamma c_t + t_e$

$D_3 = (1-\gamma)c_r + \gamma c_t - P_e(G - e_0^C)$

It is evident from Eqs. (18)–(21):

Corollary 3:

(1) When $\eta^2 < bE\left[\tilde{k}\right]$, then $\frac{\partial P_1^{C*}}{\partial s} < 0, \frac{\partial P_2^{C*}}{\partial t_e}$, when $bE\left[\tilde{k}\right] < \eta^2 < 2bE\left[\tilde{k}\right], \frac{\partial P_1^{C*}}{\partial s} > 0, \frac{\partial P_2^{C*}}{\partial t_e} < 0$

(2) $\frac{\partial P_3^{C*}}{\partial G} > 0$, $\frac{\partial q^{C*}}{\partial t_e} < 0$, $\frac{\partial q^{C*}}{\partial G} > 0$, $\frac{\partial q^{C*}}{\partial s} > 0$.

Corollary 3 shows that when $\eta^2 < 2bE\left[\tilde{k}\right]$, an increase in subsidies leads to a reduction in the price of intermodal transportation, while the implementation of a carbon tax policy results in a price increase. Conversely, when $bE\left[\tilde{k}\right] < \eta^2 < 2bE\left[\tilde{k}\right]$, this relationship is inverted, and an increase in carbon quota credits elevates the equilibrium price. Regarding equilibrium demand, similar to corollary 2, the application of a carbon tax policy exerts a negative impact on equilibrium demand.

5.3 The optimal strategy of government

In the preceding sections, we examined the optimal strategies for transportation enterprises to respond to government policy. In the decision-making framework analyzing the government's diverse objectives and preferences, the government acts as the Stackelberg leader, while the road and rail transport enterprises function as followers. After substituting Eqs. (15)-(18) and (19)-(21) into Eq. (9)-(11) respectively, the objective functions of the government are obtained, respectively, as follow:

$$ES^D = \frac{2bE[\tilde{k}]H_i(E(\tilde{\alpha}) - bB_i)^2}{(8bE[\tilde{k}] - H_i^2)^2} \tag{23}$$

$$ES^C = \frac{bE[\tilde{k}]H_i(E(\tilde{\alpha}) - bD_i)^2}{(2bE[\tilde{k}] - H_i^2)^2} \tag{24}$$

$$SW^D = \frac{E[\tilde{k}](4b^2E[\tilde{k}]+24bE[\tilde{k}] - H_i^2)(E(\tilde{\alpha}) - bB_i)^2}{2(8bE[\tilde{k}] - H_i^2)^2} - \eta E[\tilde{\sigma}] \tag{25}$$

$$SW^C = \frac{E[\tilde{k}](b^2E[\tilde{k}]+1)(E(\tilde{\alpha}) - bB_i)^2}{2(2bE[\tilde{k}] - H_i^2)^2} - \eta E[\tilde{\sigma}] \tag{26}$$

Corollary 4:

$\frac{\partial \pi_{ti}^{D*}}{\partial \beta} > 0$, $\frac{\partial \pi_{ri}^{D*}}{\partial \beta} > 0$.

Corollary 4 shows that the equilibrium expected profit of a road and rail transportation firm increases with the percentage of road-rail transport in road transportation operation. Thus taking $\beta = 1$, we can get:

Corollary 5:

$\pi_{ti}^{D*} + \pi_{ri}^{D*} < \pi_i^{C*}, e^{D*} < e^{C*}, SW^D < SW^C, ES^D < ES^C, q^{D*} < q^{C*}$

Corollary 5 shows that the equilibrium values of social welfare, energy saving level, demand, total energy saving, and the expected profit of the LSSC under CDM are all higher than the equilibrium values under DDM when the road transportation enterprise determines its entire business volume to road-rail intermodal transportation.

6. Numerical example

This section presents a numerical example to analyze the issue and learn more about the players' variables. Some of the data, including the unit carbon emission and the sensitivity factor by the unit transportation cost, are provided in the study (Tian et al., 2023) and in other studies (de Rus and Socorro, 2014, Austin, 2015; Tamannaei et al. 2021). To generate triangular fuzzy numbers for several more hard-to-value factors, we used the approach given in Cheng (2004). The relationships between linguistic expressions and triangular fuzzy variables are established based on expert knowledge and practical insights (see to Table 3). Considering the case where the transportation freight market scale ã is large, the per-unit cost associated with enhancing public awareness of environmental issues $\tilde{\sigma}$ is Medium, the investment coefficient of energy saving $\tilde{k}$ is large. With Table 3, $\tilde{\alpha}$ =(800 1000 1200), $\tilde{\sigma}$ =(2000 4000 6000), $\tilde{k}$ =(150 200 250). By applying fuzzy theory (Wang et al., 2015a,b), these fuzzy variables' predicted values are as follows: $E[\tilde{\alpha}]=1000, E[\tilde{\sigma}]=4000, E[\tilde{k}]=200$, of course, there are other parameters such as $c_r=4.7, c_t=1, e_r=97, e_t=12, \gamma=0.4, b=1.9$.

Table 3
Relationship between linguistic expression and triangular fuzzy variable

	Linguistic expression	Triangular fuzzy variable
Market Scale $\tilde{\alpha}$	large (about 1000)	(800 1000 1200)
	Medium (about 600)	(400 600 800)
The cost coefficient for increasing the public's environmental awareness $\tilde{\sigma}$	High (about 8000)	(6000 8000 10000)
	Medium (about 4000)	(2000 4000 6000)
Investment coefficient of energy saving $\tilde{k}$	large (about200)	(150 200 250)
	Medium (about 120)	(80 120 150)
	Small (about 50)	(20 0 80)

6.1 Equilibrium solutions and feasible region

For each scenario, the feasible regions are distinctly illustrated in Fig. 2 and Fig. 3, respectively. The areas delineated by yellow, blue, and red lines correspond to the boundaries for profits, energy savings, and social welfare, respectively, depicting the feasible region shaped by the two constraints across the 12 potential scenarios. Additionally, the contour plot highlights the governmental objectives for each scenario. Table 4 presents the equilibrium solutions, demonstrating that governmental goals and policies exert a substantial influence on transportation costs, energy efficiency, demand, profits, energy conservation levels, and social welfare. These impacts are further elaborated in the subsequent discussion.

Table 4
The equilibrium solutions for the twelve scenarios

	Decision variables				Function							
					Rail		Road				Government	
	η	S	t_e	G	P_{ti}^{D*}	π_{ti}^{D*}	P_i^{D*}	q^{D*}	e^{D*}	π_{ri}^{D*}	S^D	ES^D
DDM	3.40	20.00	**	**	254.13	70972.37	391.73	259.66	1.16	35351.25	126435.28	**
	4.00	20.00	**	**	253.53	71181.46	392.33	260.04	1.37	35403.16	**	355.90
	3.60	**	8.03	**	260.21	63928.66	398.89	246.44	1.18	31824.16	111719.16	**
	4.00	**	8.60	**	260.16	63900.67	399.40	246.39	1.30	31782.16	**	319.50
	3.25	**	**	50.00	241.01	54833.76	385.98	228.24	4.40	25481.26	93361.77	**
	4.00	**	**	50.00	242.98	55719.18	384.12	230.01	4.67	25686.16	**	1072.59
	Decision variables				Rail-road						Government	
	η	S	t_e	G	P_i^{C*}	π_i^{C*}	e^{C*}	q^{C*}	**	**	SW^C	ES^C
CDM	3.30	20.00	**	**	257.99	142915.54	4.56	524.97	**	**	267512.28	**
	4.00	20.00	**	**	259.88	143897.17	5.56	528.47	**	**	**	2939.76
	1.67	**	20.00	**	274.95	121379.48	2.11	481.11	**	**	230432.90	**
	4.00	**	10.10	**	274.62	128429.49	5.25	499.26	**	**	**	2623.82
	4.00	**	**	50.00	678.53	137698.35	24.99	616.69	**	**	311851.62	**
	4.00	**	**	50.00	678.53	137698.35	24.99	616.69	**	**	**	15412.36

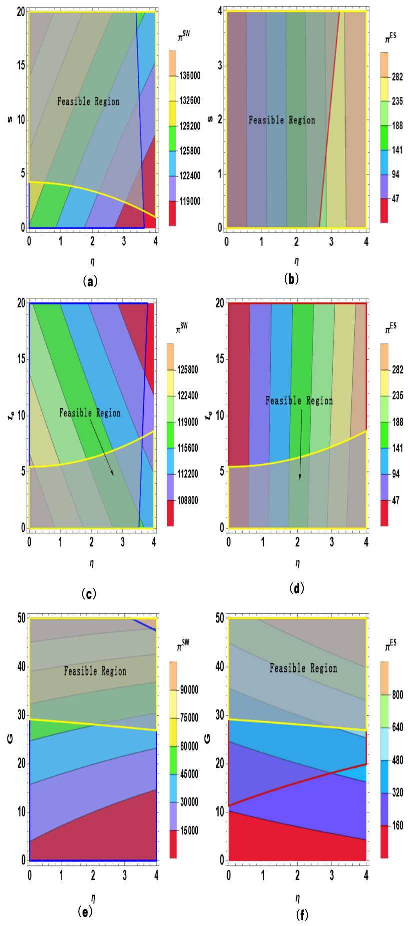

Fig. 2. The optimal governmental strategies for each scenario1-6

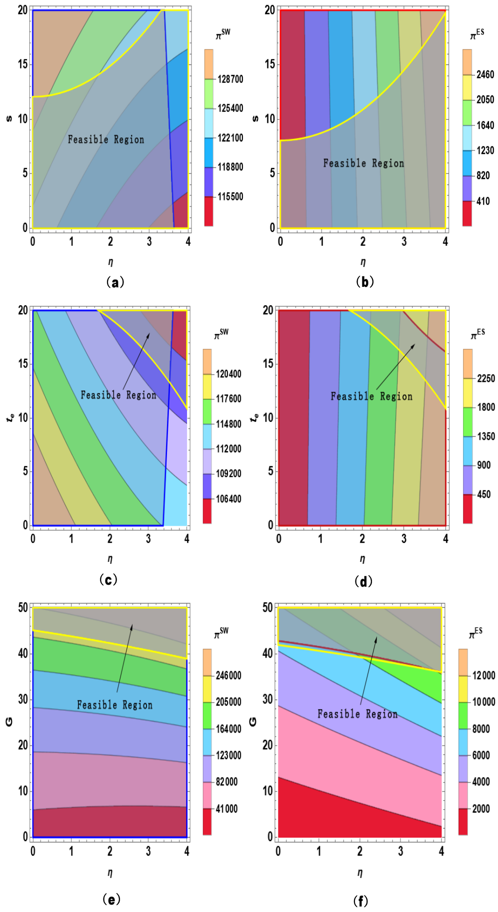

Fig. 3. The optimal governmental strategies for each scenario7-12

6.2 Parametric sensitivity analysis

Fig. 4-5 show the effect of parameters k and η on the profit, prices, SW and ES. k means investment coefficients for energy saving， η means environmental awareness. Fig. 4(a)–(c) show the effect of k on the equilibrium outcomes. The equilibrium price of road transport and rail transport increase as the energy saving investment coefficient increases when implementing carbon cap-and-trade policy, while the equilibrium price decreases in other scenarios. The investment coefficient k is negatively correlated with equilibrium profits, social welfare and energy saving level in all scenarios. Equilibrium profit, equilibrium social welfare and energy saving levels have the largest thresholds for k when enterprises make centralized decision while the government implements a carbon cap and trade policy.

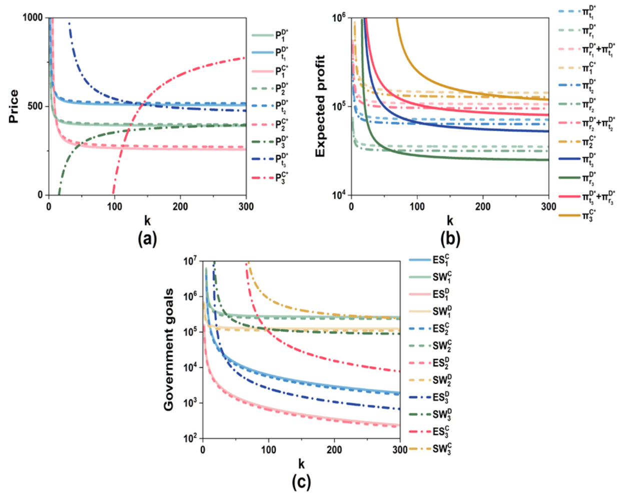

Fig. 4. The effect of k on equilibrium results

Fig. 5(a)–(c) shows the affect of η on equilibrium outcomes. The equilibrium price, profit, social welfare, and energy-saving level are all correlated positively with consumers' environmental awareness. The equilibrium price and profit of road transport enterprises are most obviously affected when adopting the carbon cap and trade policy and under a centralized strategy; the effect of η on the equilibrium value of the energy-saving level is more noticeable, especially in situations where carbon tax and subsidy policies are adopted.

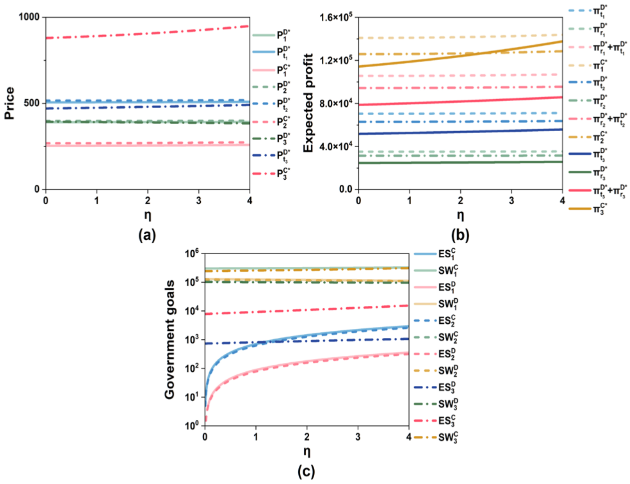

Fig. 5. The effect of η on equilibrium results

6.3 Result and insight

In this subsection, several findings and revelations from examining the aforementioned numerical example are presented. Fig. 6(a) shows the equilibrium profit for each scenario. The maximum equilibrium value of profit for road and rail transport enterprises occurs in scenario 2 and scenario 8, in which the government implements a subsidy policy with the goal of maximizing energy savings. When transportation enterprises make decentralized decisions, the minimum equilibrium value of profit for road and rail transport enterprises occurs in scenario 5, in which the government implements a carbon cap and trade policy with the goal of maximizing social welfare. The minimum equilibrium value of profit for road and rail transport enterprises occurs in scenario 9, in which the government implements a carbon quota exchange mechanism with the goal of maximizing social welfare, while transportation enterprises make centralized decisions. The equilibrium price for each scenario is shown in Fig. 6(b). When combined with Table 5, we discover that the lowest equilibrium price for road and rail transportation occurs in scenario 6 and 5, in which the government implements a carbon quota exchange mechanism with the goal of maximizing energy saving and social welfare respectively, while the transportation enterprises make decentralized decisions. The highest equilibrium price for road and rail transportation occurs in scenario 4 and 3, in which the government implements a carbon tax policy with the goal of maximizing energy saving and social welfare respectively, while the transportation enterprises make decentralized decisions. The minimum equilibrium price for road-rail transportation is observed in Scenario 7, where the government adopts a subsidy policy aimed at optimizing social welfare, and transportation enterprises operate under a centralized decision-making structure. The highest equilibrium price for road - rail transportation occurs in scenario11 and 12, in which the government implements a carbon cap and trade policy while the transportation enterprises make centralized decisions. Therefore, we can conclude that:

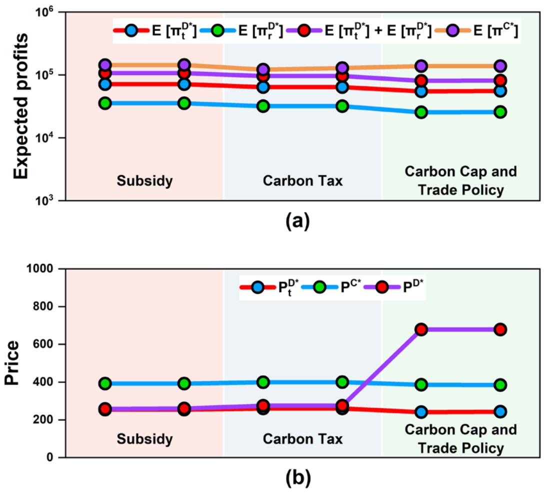

Fig. 6. The equilibrium results of price and expected profits.

Corollary 6: When the government implements the subsidy policy and aims for maximum energy savings, the equilibrium profit of the transportation enterprises adds advantages. When the transportation enterprises are under a centralized strategy, it is contradictory to play the price advantage and pursue the optimal profit; however, when the transportation enterprises are under a decentralized strategy, the equilibrium price could be close to the minimum equilibrium price in the case of the largest equilibrium profit of the transportation enterprises.

The equilibrium demand and equilibrium energy saving level under each scenario is shown in Fig. 7, where scenarios 1-6 are decentralized strategies and scenarios 7–12 are centralized strategies. Corollary 4 is demonstrated by the proof that, under the identical intervention policy, enterprises that make centralized decisions have higher equilibrium demand and energy saving level than making decentralized decisions. Under decentralized decision-making by enterprises, Scenario 2 achieves the highest equilibrium demand, while Scenario 6 attains the greatest equilibrium energy-saving level. Conversely, under centralized decision-making, Scenarios 11 and 12 yield the maximum equilibrium demand and energy-saving levels, respectively. We can conclude that:

Corollary 8: When the government implements the carbon cap and trade policy, enterprises need to save as much energy as possible. The carbon cap-and-trade policy increases the potential demand for transportation when enterprises make centralized decisions, while the subsidy policy increases the potential demand for intermodal transportation when enterprises make decentralized decisions.

Fig7 shows the comparison results of equilibrium social welfare and energy saving levels. Social welfare and energy-saving equilibrium values are lower in decentralized decision-making than in centralized decision-making. Out of all scenarios, scenarios 11 and 12 have the highest social welfare equilibrium values and the biggest energy savings level. Scenarios 1 and 6 have the highest social welfare equilibrium values and the biggest energy savings level in decentralized decision-making, respectively. Thus, we can deduce that:

Corollary 9: The government can implement carbon cap and trade policy to maximize energy efficiency and enact subsidy policy to maximize social welfare when enterprises make decentralized decisions. The government enacts the carbon cap and trade policy when enterprises make centralized decisions, which can accomplish both goals at once.

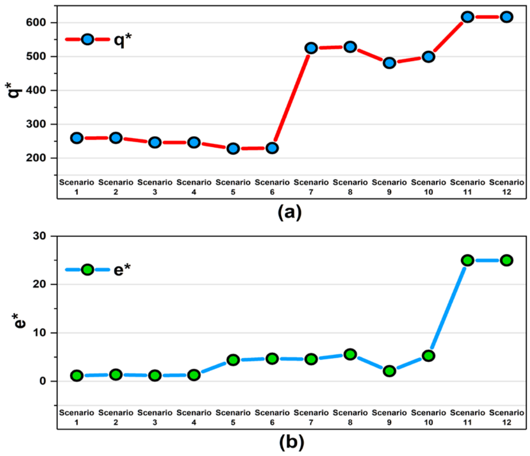

Fig. 7. The equilibrium results of q and e

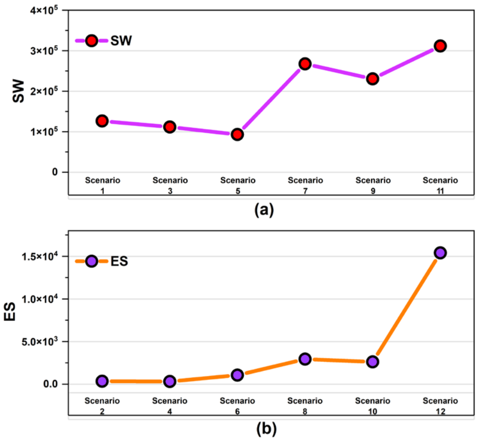

Fig. 8. The equilibrium results of SW and ES

Insight 1: The goals of the government and the enterprise can't be achieved at the same time when enterprises make decentralized decisions. The government could adopt a subsidy policy if it seeks to maximize social welfare, in which case enterprises' profits are suboptimal. The government could adopt a carbon quota exchange policy if it seeks to maximize energy savings, although at this point, the enterprises' equilibrium profit is approaching its minimum value. When the government adopts a subsidy policy, it can maximize the equilibrium value of potential transportation demand and the equilibrium value of enterprises' profits. When the government adopts a carbon tax policy, it makes the equilibrium price the highest. Whatever the government's goals, the equilibrium profits of rail and road transportation enterprises are at their lowest when a carbon cap-and-trade policy is adopted. When enterprises make decentralized decisions, the best intervention strategy is the subsidy policy; if the government seeks to optimize social welfare, the carbon tax policy is the suboptimal intervention strategy; if the government seeks to maximize energy efficiency, the carbon cap and trade policy is the suboptimal intervention strategy.

Insight 2: The pursuit of profit maximization by transportation enterprises and the goals of the government cannot be synchronized when transportation enterprises make centralized decisions. While the government can adopt a subsidy policy to increase transportation enterprises' equilibrium profits, the social welfare and energy-saving equilibrium values are not optimal. The government can adopt a carbon quota exchange policy to optimize both social welfare and energy efficiency;

however, this approach results in the highest equilibrium energy-saving level, necessitating substantial investments from transportation enterprises in energy conservation and emission reduction, while their equilibrium profits remain suboptimal. When prioritizing social welfare optimization, the Carbon pricing mechanism represents a suboptimal intervention approach; conversely, when aiming to maximize energy efficiency, the carbon cap and trade policy is a suboptimal intervention strategy.

Insight 3: If the transportation enterprise invests in energy savings and emission reduction after the government implements the carbon cap and trade policy, it must control the threshold of investment coefficients for energy saving. The carbon cap and trade policy and the energy saving investment will raise the enterprises' operating costs, which will raise the price of transportation significantly and lower enterprises' profits, which will then impact social welfare and the level of energy conservation.

Insight 4: Appropriate investment and promotion of enhancing consumer environmental awareness can improve the equilibrium profit of the intermodal logistics service supply chain. When enterprises make centralized decisions and the government enacts a carbon cap and trade policy, enhancing public environmental awareness can effectively improve energy conservation, which is especially obvious when subsidies and carbon tax policy are implemented.

7. Conclusion

Freight transportation is critical for the overall transportation system to develop sustainably. With the goal to improve the environmental, social, and economic sustainability dimensions of freight transport systems, governments often intervene in policies such as taxes and subsidies. Studying the way governments and policy recipients interact, as well as how interventions affect each other's goals, is necessary. In freight transportation systems, future market demand and related variables frequently become uncertain due to insufficient or inaccessible planning data. This study employs triangular fuzzy variables to represent such uncertainties. By analyzing twelve game-theoretical scenarios, we investigate the impact of different government interventions on pricing strategies, energy-saving decisions, and the profitability of road transport enterprises, rail enterprises, and road-rail intermodal logistics service supply chains (LSSCs). The findings offer valuable managerial implications.

The analysis yields four key managerial implications, outlined below: First, the government's goals of maximizing social welfare and energy saving cannot be aligned with the enterprises' goals of maximizing profits, regardless of whether decision-making is decentralized or centralized. Second. The government's optimal policy is the carbon quota policy, while the transportation enterprises' optimal policy is the subsidy policy. Third, The profit of LSSC, social welfare, and energy-saving levels are higher when the transportation enterprises make centralized decisions than when they make decentralized decisions. Finally, the implementation of a carbon cap-and-trade policy by the government, coupled with increased investments in environmental awareness initiatives and centralized decision-making by transportation enterprises, significantly advances both profit objectives and energy-saving targets.

Theoretical contributions: To the best of our knowledge, limited research exists on determining transportation pricing and energy-saving levels in alignment with government initiatives focused on social welfare and energy conservation. This research advances prior studies in several ways. Firstly, it extends existing work on transportation pricing by developing a novel transport demand function incorporating triangular fuzzy variables and energy-saving levels. Secondly, it investigates and contrasts the impact of varying governmental objectives and intervention approaches on transportation pricing, energy efficiency, and the profitability of transport enterprises. Thirdly, the study employs a system dynamics methodology to illustrate the causal relationships among problem variables and integrates game theory into the analysis. Lastly, it conducts a comprehensive numerical analysis, yielding multiple significant findings.

Despite the insights on pricing and energy saving level decision-making of freight transportation under government intervention in an uncertain environment, this research also has some limitations. First of all, this paper primarily discusses the game behavior of single road enterprise and single rail enterprise. In fact, there are many game players in a competitive market, and subsequent studies can consider multi-subject game behavior. Finally, this paper only considers the impact of a single intervention policy. In real life, the subsidy, carbon tax, and carbon quota policies may be implemented at the same time, and the game behavior of multiple intervention policies implemented at the same time can be considered in the follow-up research.

References

Adler, N. (2001). Competition in a deregulated air transportation market. *European Journal of Operational Research, 129*, 337–345.

Arvidsson, N., Woxenius, J., & Lammgård, C. (2013). Review of Road Hauliers' Measures for Increasing Transport Efficiency and Sustainability in Urban Freight Distribution. *Transport Reviews, 33*(1), 107–127. doi:org/10.1080/01441647.2013.763866.

Austin, D. (2015). *Pricing freight transport to account for external costs*. In: Congressional Budget Office. Washington, DC, pp. 1－44.

Bhattacharya, A., Kumar, S.A., Tiwari, M., Talluri, S. (2014). An intermodal freight transport system for optimal supply chain logistics. *Transportation Research Part C: Emerging Technologies, 38,* 73–84.

Black, W.R. (2004). Sustainable Transport: Definitions and Responses, Integrating Sustainability into the Transportation Planning Process. *Transportation Research Board*, pp. 35–43. http://onlinepubs.trb.org/Onlinepubs/conf/CP37.pdf

Chen, X., Zhu, X., Zhou, Q., & Wong, Y. D. (2017). Game-Theoretic Comparison Approach for Intercontinental Container Transportation: A Case between China and Europe with the B&R Initiative. *Journal of Advanced Transportation, 2017*(1), 3128372.

Cheng, C. B. (2004). Group opinion aggregation based on a grading process: A method for constructing triangular fuzzy numbers. *Computers & Mathematics with Applications, 48*(10), 1619–32. doi: 10.1016/j.camwa.2004.03.008 .

Dadsena, K.K., Sarmah, S.P., & Naikan, V.N.A. (2019). Risk evaluation and mitigation of sustainable road freight transport operation: a case of trucking industry. *International Journal of Production Research, 57*(19), 6223–6245. doi:org/ 10.1080/00207543.2019.1578429.

de Rus, G., & Socorro, M.P. (2014). Access pricing, infrastructure investment and intermodal competition. *Transportation Research Part E: Logistics and Transportation Review, 70*, 374–387.

Demir, E., Bektas¸, T., & Laporte, G. (2014). A review of recent research on green road freight transportation. *European Journal of Operational Research, 237*(3), 775 –793. doi:org/10.1016/j.ejor.2013.12.033.

Duan, X., & Heragu, S. (2015). *Carbon emission tax policy in an intermodal transportation network*. In Proceedings of the IIE Annual Conference, Nashville, TN, USA (Vol. 30, pp. 566-574).

Fallahi, N., Hafezalkotob, A., Raissi, S., & Ghezavati, V. (2024). A game theoretic approach to sustainable freight transportation: competition between green, non-green and semi-green transportation networks under government sustainable policies. *Environment, Development and Sustainability, 26*(4), 9711-9758. doi:10.1007/s10668-023-03115-1k

Fahimnia, B., Sarkis, J., Choudhary, A.K., & Eshragh, A. (2015). Tactical supply chain planning under a carbon tax policy scheme: A case study. *International Journal of Production Economics, 164*, 206-215.doi:10.1016/J.IJPE.2014.12.015

Fulzele, V., & Shankar, R. (2023). Performance measurement of sustainable freight transportation: a consensus model and FERA approach. *Annals of Operations Research, 324*(1), 501-542.

Ghosh, D., & Shah, J. (2015). Supply chain analysis under green sensitive consumer demand and cost sharing contract. *International Journal of Production Economics, 164*, 319-329.https://doi.org/10.1016/j.ijpe.2014.11.005

Jarašūnienė, A., Čižiūnienė, K., & Petraška, A. (2022). Sustainability promotion by digitalisation to ensure the quality of less-than-truck load shipping. *Sustainability*, *14*(19), 12878. doi:org/10.3390/su141912878.

Kontrobayeva, Z., Salykov, B., & Issintayev, T. (2023). Improving the Efficiency of Road Transport During the Carriage of Agricultural Goods. *Geomate Journal, 25*(109), 213-220.

Kundu, T., & Sheu, J. B. (2019). Analyzing the effect of government subsidy on shippers' mode switching behavior in the Belt and Road strategic context. *Transportation Research Part E: Logistics and Transportation Review, 129*, 175-202.

Li, J., Lu, Q., & Fu, P. (2015). Carbon footprint management of road freight transport under the carbon emission trading mechanism. *Mathematical Problems in Engineering, 2015*(1), 814527. doi:org/10.1155/2015/814527

Li, Y., & Yu, Y. (2017). The use of freight apps in road freight transport for CO 2 reduction. *European Transport Research Review, 9*, 1-13. doi:org/10.1007/ s12544-017-0251-y.

Liljestrand, K. (2016). Improvement actions for reducing transport's impact on climate: A shipper's perspective. *Transportation Research Part d: Transport and Environment 48,* 393–407. doi:org/10.1016/j.trd.2016.08.021.

Makan, H., & Heyns, G. J. (2018). Sustainable supply chain initiatives in reducing greenhouse gas emission within the road freight industry. *Journal of Transport and Supply Chain Management 12,* a365. doi:org/10.4102/jtscm.v12i0.365.

Nkesah, S. K. (2023). Making road freight transport more Sustainable: Insights from a systematic literature review. *Transportation Research Interdisciplinary Perspectives, 22*, 100967. doi:org/10.1016/j.trip.2023.100967

Pathak, D. K., Shankar, R., & Choudhary, A. (2021). Performance assessment framework based on competitive priorities for sustainable freight transportation systems. *Transportation Research Part D: Transport and Environment, 90*, 102663.

Pathak, D. K., Thakur, L. S., & Rahman, S. (2019). Performance evaluation framework for sustainable freight transportation systems. *International Journal of Production Research, 57*(19), 6202-6222.

Pernestål, A., Engholm, A., Bemler, M., & Gidofalvi, G. (2020). How will digitalization change road freight transport? Scenarios tested in Sweden. *Sustainability, 13*(1), 304. doi:org/10.3390/su13010304.

Pittman, R., Jandová, M., Król, M., Nekrasenko, L., & Paleta, T. (2020). The effectiveness of EC policies to move freight from road to rail: Evidence from CEE grain markets. *Research in Transportation Business & Management, 37*, 100482. doi:org/10.1016/j.rtbm.2020.100482.

Qi, S. Z., Zhou, C. B., Li, K., & Tang, S. Y. (2021). The impact of a carbon trading pilot policy on the low-carbon international competitiveness of industry in China: An empirical analysis based on a DDD model. *Journal of Cleaner Production, 281*, 125361. doi:org/10.1016/j.jclepro.2020.125361

Rasti-Barzoki, M., & Moon, I. (2020). A game theoretic approach for car pricing and its energy efficiency level versus governmental sustainability goals by considering rebound effect: A case study of South Korea. *Applied energy, 271*, 115196. doi:org/10.1016/j.apenergy.2020.115196.

Santén, V. (2017). Towards more efficient logistics: increasing load factor in a shipper's road transport. *The International Journal of Logistics Management, 28*(2), 228–250. doi:org/10.1108/ijlm-04-2015-0071.

Sheu, J. B., & Chen, Y. J. (2012). Impact of government financial intervention on competition among green supply chains. *International Journal of Production Economics, 138*(1), 201-213. doi:org/10.1016/j.ijpe.2012.03.024.

Stenico de Campos, R., Tadeu Simon, A., & Felipe de Campos, M. (2019). Assessing the impacts of road freight transport on sustainability: A case study in the sugar-energy sector. *Journal of Cleaner Production, 220*, 995–1004. doi:org/10.1016/j.jclepro.2019.02.171.

Tacken, J., Sanchez Rodrigues, V., & Mason, R. (2014). Examining CO2e reduction within the German logistics sector. *The International Journal of Logistics Management, 25*(1), 54-84.doi:org/10.1108/ijlm-09-2011-0073.

Tamannaei, M., Zarei, H., & Rasti-Barzoki, M. (2021). A game theoretic approach to sustainable freight transportation: Competition between road and intermodal road–rail systems with government intervention. *Transportation Research Part B: Methodological, 153*, 272-295. doi:10.1016/j.trb.2021.09.002.

Taniguchia, E., Thompsonb, R.G., Qureshi, A.G. (2020). Modelling city logistics using recent innovative technologies. *Transportation Research Procedia, 46*, 3–12.

Tian, P., Mao, B., Tong, R., Zhang, H., & Zhou, Q. (2023). Analysis of carbon emission level and intensity of China's transportation industry and different transportation modes. *Advances in Climate Change Research, 19*(3), 347.

Wang, M., Liu, K., Choi, T. M., & Yue, X. (2015a). Effects of carbon emission taxes on transportation mode selections and social welfare. *IEEE Transactions on Systems, Man, and Cybernetics: Systems, 45(*11), 1413-1423.

Wang, Y., Sanchez Rodrigues, V., & Evans, L. (2015b). The use of ICT in road freight transport for CO2 reduction–an exploratory study of UK's grocery retail industry. *The International Journal of Logistics Management, 26*(1), 2-29. doi"org/ 10.1108/ijlm-02-2013-0021.

Wehner, J. (2018). Energy Efficiency in Logistics: An Interactive Approach to Capacity Utilisation. *Sustainability, 10*(6), 1727. doi:org/10.3390/su10061727.

Yang, D., & Xiao, T. (2017). Pricing and green level decisions of a green supply chain with governmental interventions under fuzzy uncertainties. *Journal of Cleaner Production, 149,* 1174-1187.doi:org/10.1016/j.jclepro.2017.02.138.

Zhao, J., W. Tang, R. Zhao, and J. Wei. (2012). Pricing decisions for substitutable products with a common retailer in fuzzy environments. *European Journal of Operational Research, 216*(2), 409–19. doi:10.1016/j.ejor.2011.07.026.

Zhou, Y., Fang, W., Li, M., & Liu, W. (2018). Exploring the impacts of a low-carbon policy instrument: A case of carbon tax on transportation in China. *Resources, Conservation and Recycling, 139*, 307-314. doi:org/10.1016/j.resconrec.2018.08.015.