

Article

Collaborative Transportation Strategies for the “First-Mile” of Agricultural Product Upward Logistics Under Government Subsidies

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Abstract

Logistics alliance and integrated passenger-freight transit are two widely adopted collaborative logistics modes in rural areas. With the rapid development of agricultural e-commerce, rural “first-mile” logistics has become critical for agricultural products’ upward circulation, but remains constrained by high costs and insufficient service provision. Existing studies mainly focus on a single transportation mode and pay limited attention to logistics service providers’ strategic choice among alternative modes under government intervention. Using a Stackelberg game framework, this study models the interaction among the government, a logistics service provider, and a rural bus company, and analyzes transportation mode choice and subsidy effectiveness. The results show that government subsidies improve rural “first-mile” logistics service levels and stimulate demand for cargo collection services. Transportation mode choice is jointly influenced by market share, service cost coefficient, and subsidy intensity. Large-scale logistics service providers tend to adopt the integrated passenger-freight transit mode when subsidies are insufficient, and prefer the logistics alliance mode when subsidy support becomes adequate. These findings suggest that subsidy policies should consider fiscal capacity and regional operating costs: the integrated passenger-freight transit is more suitable under limited budgets, while the logistics alliance becomes preferable for promoting regional logistics development when sufficient subsidies can be sustained.

Keywords: collaborative transportation; first-mile logistics; integrated passenger-freight transit; sustainable subsidy; rural logistics

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1. Introduction

The upward logistics of agricultural products refers to transporting goods from rural areas to urban and township markets to invigorate rural economies and increase farmers’ income [1]. With the proliferation of e-commerce technologies [2], many farmers now sell products online and rely on logistics service providers (LSPs) instead of delivering goods to offline markets themselves.

However, rural logistics faces persistent challenges due to complex geography, dispersed populations, and uneven demand [3–5]. To reduce costs, most LSPs establish service centers at the township level. This creates a “first-mile” service gap: farmers have to travel long distances to deliver products from their homes to these centers before accessing logistics services [6]. Yet not all farmers can transport agricultural products on their

own, leaving many shipments stuck in rural areas. A few LSPs offer “first-mile” consolidation service, but the additional charges often discourage farmers from consigning goods. This situation creates an “unsustainable dilemma”: poor service quality suppresses logistics demand, while weak demand discourages LSPs from investing in infrastructure, leading to persistent under-provision of services.

Government intervention is critical. A simple ban on “first-mile” charges, though well-intentioned, could worsen service shortages [7]. This reason is that these charges often reflect a market compromise between high logistics costs and insufficient service demand. Sustainable solutions, therefore, require balancing LSP profitability with improved rural logistics accessibility. This study examines how government subsidies and collaborative transportation can alleviate the “first-mile” dilemma and support both operational sustainability and rural economic growth.

Cost constraints are the primary obstacle in rural logistics expansion [8]. To mitigate costs, LSPs often adopt one of two collaborative modes: logistics alliance (LA) and integrated passenger-freight transit (IPFT). The LA mode lowers costs through horizontal co-operation among LSPs to build a joint transportation system and share facilities and routes [9]. The IPFT mode, by contrast, leverages rural passenger transport networks to carry parcels using idle space in buses [10]. Under the IPFT mode, LSPs do not need to incur additional costs for building logistics stations. Instead, they directly cooperate with rural bus companies, as illustrated in Figure 1. Accordingly, the analysis focuses on these two collaborative modes and assumes that LSPs choose between LA and IPFT when providing “first-mile” services, consistent with current practice.

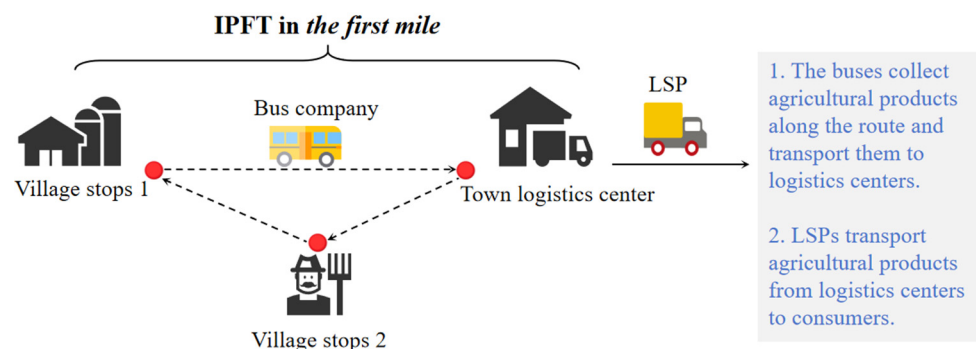


Figure 1. Schematic of the IPFT Mode.

Overall, this study focuses on addressing the following questions: (1) In the context of “first-mile” transportation, what factors influence rural LSPs’ choice of collaborative transportation modes? In particular, do different government subsidy strategies affect this choice? (2) Can government subsidies effectively alleviate the unsustainable dilemma in the “first-mile” phase of agricultural product upward transportation? (3) Considering both subsidy efficiency and effectiveness, how should the government design differentiated subsidy strategies to promote sustainable rural logistics development under fiscal constraints?

To answer these questions, this paper develops a theory-driven analytical framework to examine collaborative transportation and subsidy design in rural “first-mile” logistics. The main contributions of this study can be summarized as follows:

1. This study endogenizes collaborative transportation mode selection in rural “first-mile” logistics. Unlike existing studies that analyze the LA or the IPFT in isolation, the model captures the LSP’s strategic choice between these two modes under government subsidies. It further shows how cost structures, market share, and subsidy intensity jointly shape mode selection.

2. This paper integrates subsidy design and operational decisions within a unified Stackelberg game framework. Specifically, the model jointly considers subsidy recipients, subsidy intensity, pricing, and service level decisions. This setting reveals key equilibrium mechanisms—such as subsidy transmission and revenue equivalence under IPFT—that may be overlooked when subsidy policies or transportation modes are treated as exogenous.
3. This study provides mechanism-based policy insights for differentiated subsidy strategies in rural “first-mile” logistics. The analysis shows how subsidy effectiveness and efficiency depend on regional operating conditions and market structure, offering guidance for designing context-specific and fiscally sustainable subsidy policies.

The remainder of this paper is organized as follows. Section 2 reviews the related literature, and Section 3 introduces the model and assumptions. Section 4 derives equilibrium results and analyzes key drivers, and Section 5 compares subsidy efficiencies. Section 6 presents numerical analyses, followed by conclusions and discussions in Sections 7 and 8, respectively.

2. Literature Review

2.1. Agricultural Product Upward Logistics

Agricultural product upward logistics refers to the process through which agricultural products are collected from rural production sites and transported to township, regional, or urban markets, enabling farmers to participate in modern supply chains and benefit from the development of e-commerce and cold-chain logistics. Compared with downstream or urban logistics systems, agricultural upward logistics is characterized by dispersed production, strong seasonality, and high sensitivity to service quality, especially for fresh and perishable products [6].

In rural logistics systems, the “first-mile” —the process of collecting goods from farmers or rural households and transporting them to township-level consolidation points—has been widely recognized as a critical bottleneck [8]. Existing studies further indicate that inefficiencies in “first-mile” logistics can lead to higher transportation costs, product loss, quality deterioration, and delivery delays [11]. These problems ultimately reduce farmers’ income and discourage participation in e-commerce platforms and formal logistics networks.

To address these challenges, recent research has focused on improving “first-mile” efficiency through routing optimization, pickup scheduling, and cold-chain network design [10]. However, most of this literature implicitly assumes that logistics service arrangements are exogenously given and primarily seek operational improvements within fixed organizational structures.

These limitations suggest that agricultural product upward logistics, particularly at the “first-mile” stage, is not merely an operational optimization problem but also an organizational and institutional one. This insight motivates the examination of collaborative transportation mechanisms that can reduce costs and improve service accessibility in rural logistics systems.

2.2. Collaborative Transportation in the “First-Mile” Stage

Collaborative transportation is widely recognized as an effective organizational approach for improving logistics service accessibility and cost efficiency by coordinating heterogeneous transportation resources. In recent years, this concept has been extended beyond traditional single-carrier systems to include joint delivery arrangements involving drones, riders, and crowdsourced or occasional drivers, particularly in on-demand and takeout delivery markets [12,13].

Although a substantial part of this literature focuses on routing optimization and order assignment, an increasing number of studies adopt an operations management perspective, emphasizing co-sourcing strategies, capacity configuration, pricing, incentive mechanisms, and service stability. For example, Pei et al. (2023) examined drone–human courier co-sourcing and analyzed how pricing and capacity decisions affect operational performance and service reliability [14]. Research on crowdsourced delivery further highlights workforce management and incentive design under uncertain supply, revealing trade-offs between platform profitability and courier welfare [15,16]. These studies suggest that collaborative transportation is not merely a routing problem, but also an organizational and managerial issue involving service level control and coordination among multiple stakeholders. However, this stream of research is largely situated in urban or platform-based contexts, with limited attention to rural logistics systems.

In rural “first-mile” logistics, collaborative transportation has been widely adopted to address the high fixed costs and demand uncertainty inherent in the “first-mile” stage. Existing studies mainly identify two dominant collaborative modes.

The first is the IPFT, which embeds freight services into existing rural passenger transport networks by utilizing idle vehicle capacity. A growing body of research focuses on the operational design and optimization of IPFT systems, including route flexibility, capacity utilization, and multi-stakeholder coordination [17–19]. Recent studies further extend this line of research by emphasizing the institutional and operational feasibility of passenger–freight integration in rural contexts. For example, Xue et al. (2024) highlighted how governance arrangements and public transport institutions support integrated logistics operations at the county level [20]. Similarly, Bing et al. (2025) demonstrated that shared passenger–freight transport can significantly improve service coverage and efficiency in low-density rural areas [21].

The second form of collaboration is the LA, which relies on horizontal cooperation among LSPs to jointly build and operate shared logistics facilities and transportation networks. Early studies examine collaborative savings and cost allocation mechanisms in alliance-based logistics systems [22], while subsequent research extends the analysis to sustainable operation and fair benefit distribution [23,24]. More recently, Parsa et al. (2025) further emphasized that alliance structures are not fixed but can be strategically designed in response to cost structures and demand uncertainty [25].

Despite these advances, existing studies predominantly examine IPFT and LA modes in isolation. Most research treats collaborative transportation structures as exogenously given and focuses on improving operational efficiency within a single mode. However, in real rural logistics markets, LSPs often face both collaboration options simultaneously and must strategically choose between the IPFT and LA modes. Ignoring this strategic choice may lead to incomplete or even misleading policy implications, particularly when government subsidies are involved.

To address this gap, this paper explicitly endogenizes collaborative transportation mode choice by allowing LSPs to strategically select between IPFT and LA modes within a unified analytical framework. In this way, the study moves beyond single-mode analyses and provides a comparative understanding of how different collaborative structures interact with subsidy incentives in rural “first-mile” logistics.

2.3. Government Subsidies and Logistics Service Provision

Government subsidies are a commonly used policy instrument to address market failures in logistics systems, particularly in environments characterized by high operating costs and insufficient service provision. Existing studies show that subsidies can reduce firms’ cost burdens and improve logistics performance in areas such as green logistics, cold-chain transportation, and low-carbon supply chains [26,27].

In rural and agricultural logistics, subsidies are primarily justified by the need to improve service accessibility and support inclusive development. Related research indicates that appropriately designed subsidy schemes can stimulate logistics demand and mitigate welfare losses caused by dispersed consumers and infrastructure constraints [4]. In agricultural product logistics, subsidies are often modeled as instruments that support facility investment and service capability enhancement, especially in cold-chain and “first-mile” logistics networks [28,29]. These studies suggest that subsidies play a role beyond direct cost reduction, as they relax financial constraints and enable higher levels of service investment.

Recent studies further emphasize the incentive role of subsidies in shaping service provision decisions. In the context of rural passenger–freight integrated systems, He and Guan (2023) showed that subsidy-based incentive contracts can effectively improve service quality by aligning the interests of logistics service providers and public transport operators [30]. Related research highlights that subsidy effectiveness depends on its interaction with pricing decisions, service level control, and contractual arrangements among stakeholders, rather than on subsidy intensity alone [17–19].

Another stream of literature examines subsidy allocation and cost-sharing from a multi-agent perspective. Using game-theoretic frameworks, these studies demonstrate that subsidy recipients and cost-sharing mechanisms jointly influence firms’ strategic behavior and system-level outcomes [26]. The results imply that subsidizing different participants within a logistics system may lead to distinct distributional effects, even when total subsidy expenditure is fixed.

Despite these advances, two limitations remain. First, most existing studies analyze subsidy effects within a single transportation or organizational mode, and rarely examine how subsidies influence firms’ strategic choice among alternative collaborative transportation modes. Second, subsidy recipients are usually treated as exogenously determined, and the potential redistribution or equivalence effects arising from subsidizing different stakeholders (e.g., LSPs or bus companies) remain insufficiently explored.

Addressing these gaps, this study jointly considers subsidy recipient selection and transportation mode choice within a Stackelberg game framework. By comparing subsidy effects across different collaborative modes, the paper reveals how subsidy intensity, recipients, and service control interact to shape equilibrium outcomes, thereby offering new insights into the design of efficient and sustainable subsidy policies for rural “first-mile” logistics.

3. Model Description and Assumptions

We consider a system consisting of the government, an LSP, a rural bus company, and farmers. In this rural area under consideration, public transport services are monopolized by a single bus company, which is consistent with the institutional setting in many rural regions of China, where bus services are typically operated by state-owned enterprises despite long-term financial deficits. In addition, apart from existing bus routes, no specialized cold-chain logistics facilities suitable for fresh agricultural products are available.

Farmers use e-commerce and other online channels to sell agricultural products to consumers. In the absence of collaborative logistics arrangements, farmers must transport goods on their own to town-level logistics service outlets, after which subsequent transportation is completed by the LSP.

To reduce operating costs, the LSP may choose either the LA mode or the IPFT mode to realize door-to-door pickup and complete the “first-mile” service, as illustrated in Figure 2. In the LA mode, the LSP jointly establishes a consolidation system with other LSPs. The total construction cost is denoted by K (e.g., transportation vehicles and express

station construction). Each participating LSP bears a share of this cost in proportion to its market share, so the cost borne by the focal LSP is θK (where θ represents the market share of the LSP). In the IPFT mode, he does not need to invest in a consolidation system; instead, he outsources the “first-mile” service to the bus company and pays an IPFT service fee of w per unit to the latter. Naturally, given the local lack of cold chain capacity, both the LSP and the bus company must incur costs to improve cold chain service level e_i (e_t). Beyond differences in cost composition, the key distinction between the two collaborative transportation modes lies in the LSP’s degree of control over service levels [31]. In the LA mode, the LSP independently determines both the “first-mile” service price p_i and service level e_i . By contrast, in the IPFT mode, the LSP loses control over the consolidation service level. In this case, the LSP only determines the price p_t charged to farmers, while the service level e_t is determined by the bus company.

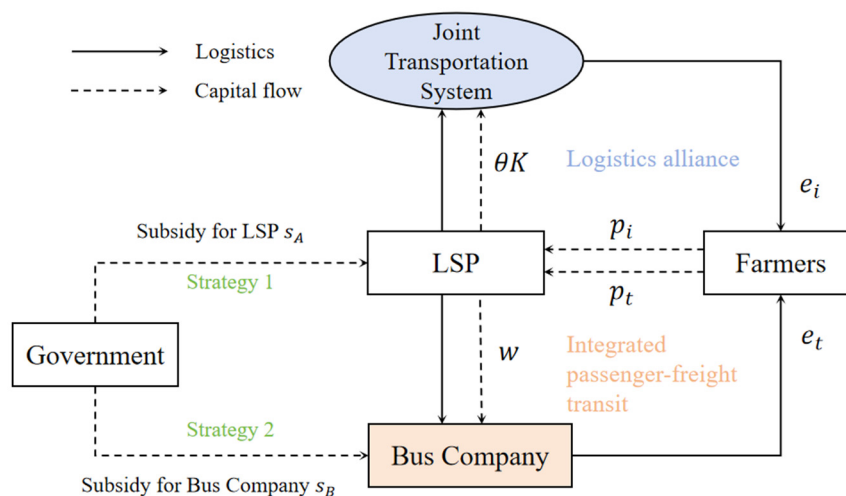


Figure 2. Stakeholder Relationship.

The government uses subsidy measures to promote the development of rural logistics services. To avoid the guidance effect of subsidies exerting adverse impacts on enterprises’ decision-making, the government only determines the subsidy recipients and subsidy intensity, without imposing restrictions on the transportation mode selection. Therefore, the government can choose to subsidize either the LSP or the bus company: it reduces the former’s transportation costs (e.g., costs for personnel operations, facility construction, etc.) by subsidizing the LSP, and helps lower the latter’s operating costs (e.g., costs for the modification of vehicles, route adjustments, etc.) by subsidizing the bus company. Drawing on [32], we fix the subsidy form on a “volume-based subsidy for deliveries”, that is, the total subsidy amount is the product of the unit subsidy amount and the transportation volume. In theory, the combination of two possible subsidy recipients (the LSP or the bus company) and two transportation modes (the LA or IPFT) yields 4 scenarios. However, when the government subsidizes the bus company while the LSP adopts the LA mode, the bus company does not participate in the “first-mile” service. In this case, the subsidy has no practical effect and is therefore regarded as ineffective. Consequently, we only focus on discussing the remaining 3 scenarios.

In this study, superscripts A , B , and N are used to denote the scenarios of government subsidies to the LSP, to the bus company, and no subsidies, respectively. Subscripts i and t are used to denote the scenarios where the LSP chooses the LA mode and the IPFT mode, respectively.

We construct a Stackelberg game in which the sequence of decisions is as follows: (1) the government selects the subsidy recipients and subsidy intensity; (2) given the subsidy

policy, the bus company determines the IPFT service fee w and service level e_t ; (3) the LSP selects the transportation mode and sets pricing p_t under the IPFT mode, or the pricing p_i and service level e_i under the LA mode; (4) the farmers' demand q_i or q_t is realized. Figure 3 illustrates this decision sequence.

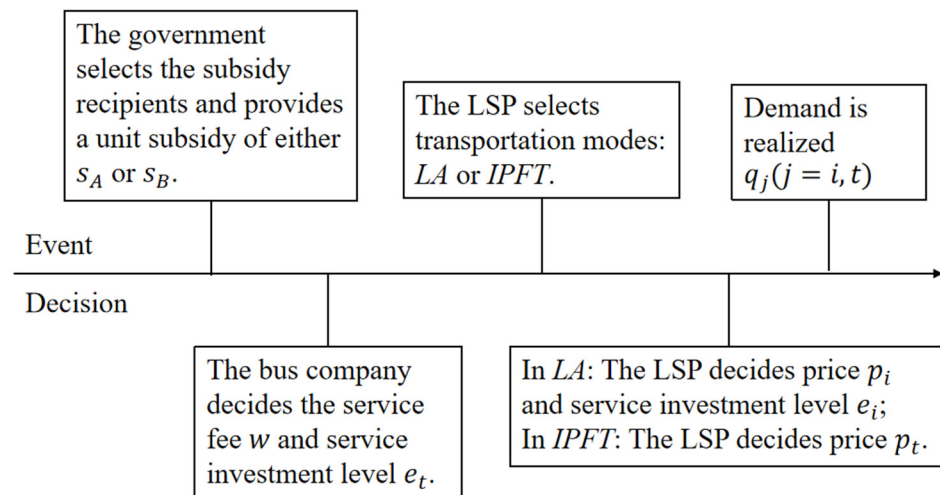


Figure 3. The Sequence of Events and Decisions.

We propose the following assumptions to make the model more specific.

1. Assume that farmers have a sufficient supply of goods to be shipped. Drawing on [33], farmers' demand for the "first-mile" consolidation service is assumed to be influenced by price and service level, such as cold chain capacity and transportation timeliness. Either excessively high logistics prices or poor service levels will both cause farmers to bear losses, thereby suppressing their demand. Accordingly, a linear demand function is adopted to describe farmers' demand for "first-mile" logistics services as $q_j(p_j, e_j) = \theta a - bp_j + \beta e_j, j = i, t$. Herein, a denotes the total market demand, and $\theta \in (0, 1]$ denotes the market share of the LSP [34]. Specifically, $\theta = 1$ indicates that only a sole monopolistic LSP exists in the market. Since the total market demand, as an exogenous constant, does not affect the results. For simplicity, we set $a = 1$; thus, the basic market demand of the LSP is $\theta a \equiv \theta$. Here, b and β respectively represent the sensitivity of demand to price and service level. Furthermore, to keep demand non-negative, in the extreme case where no logistics service improves (i.e., $e = 0$), we assume $q_0 = \theta - bp_j \geq 0$ always holds (i.e., $\theta \geq bp_j$). Since service level decisions are made by different parties under the two transportation modes, operating both modes simultaneously may create inconsistent service standards. Such inconsistency could undermine farmers' evaluation of logistics services. Therefore, it is assumed that the LSP selects only one of the two transportation modes to complete the "first-mile" consolidation service.
2. In the LA mode, the LSP needs to bear the costs of jointly building the transportation system ex-ante in proportion to its market share, and independently determine the price p_i and the service level e_i during the operation process.
3. Although there have been many studies on reasonably evaluating the internal utility of alliances by applying the Shapley value method [24], considering that cooperating enterprises may have differences in services in reality, we characterize the interests of the LSP as two parts: the first part is the benefits obtained by himself in the alliance, and the second part is his corresponding cost sharing (including the ex-ante construction costs and service investment during operation). Therefore, the profit of the LSP

under the LA mode without government subsidies is $\Pi_{LSPi}^{N*} = \max_{p_i, e_i} (p_i - c)q_i(p_i, e_i) - \frac{r}{2}e_i^2 - \theta K$, where α and r are cost conversion coefficients [35,36]. Here, $c = c_0 - \alpha \ln K$ represents the unit operating cost, which conforms to the law of diminishing marginal cost.

4. In the IPFT mode, the LSP needs to pay IPFT service fees to the bus company for the “first-mile” consolidation. At this point, the LSP only determines the final farmer-paid price p_t , while the bus company determines the IPFT service price w and service level e_t . With existing transportation resources and systems, the marginal operating cost of the bus company for basic transportation is normalized to 0, while service level improvements still incur costs proportional to the service level. Hence, the profit of the bus company and the LSP is respectively given by: $\Pi_{BUST}^{N*} = \max_{w, e_t} wq_t(p_t, e_t) - \frac{r}{2}e_t^2$ and $\Pi_{LSPt}^{N*} = \max_{p_t} (p_t - w)q_t(p_t, e_t)$. Notably, since the “first-mile” service investment means are the same, the conversion coefficient for LSP and the bus company is r in both modes.
5. We assume that the government selects only one of the LSP and the bus company to subsidize, which is consistent with the practical characteristic of limited government fiscal resources in rural areas. Furthermore, the assumption of a single subsidy recipient is more in line with the practical logic of “resource inclination” in policy formulation, and helps to facilitate the subsequent analysis of optimal strategies under different subsidy inclinations.

The main parameter symbols and their meanings are shown in Table 1.

Table 1. Main Parameter Symbols and Their Meanings.

Symbols	Meanings
q_j^X	Farmers’ demand, $X = \{A, B, N\}$, $j = \{i, t\}$. ¹
θ	Market share of the LSP.
b	Farmers’ sensitivity coefficient to the price of “first-mile” service.
β	Farmers’ sensitivity coefficient to the service level of “first-mile” service.
w^Y	IPFT service fee, $Y = \{A, B\}$.
p_j^Y	“First-mile” service price, $Y = \{A, B\}$, $j = \{i, t\}$.
e_j^Y	“First-mile” service level, $Y = \{A, B\}$, $j = \{i, t\}$.
r	Cost conversion coefficient for logistics service level.
c	Unit operating cost under the LA mode.
K	Total cost of transportation system construction under the LA mode.
s_Y	Government’s unit subsidy amount, $Y = \{A, B\}$.
S	Government’s total subsidy amount.
U_j^Y	Government’s subsidy efficiency, $Y = \{A, B\}$, $j = \{i, t\}$.
Π_{LSPj}^X	The LSP’s profit, $X = \{A, B, N\}$, $j = \{i, t\}$.
Π_{BUST}^X	The bus company’s profit, $X = \{A, B, N\}$.
Π_{Cj}^X	Farmers’ surplus, $X = \{A, B, N\}$, $j = \{i, t\}$.
Π_{Gj}^X	Social welfare, $X = \{A, B, N\}$, $j = \{i, t\}$.

¹ A denotes government subsidies to the LSP, B denotes government subsidies to the bus company, N no government subsidy. For $j = \{i, t\}$, where i denotes adopting the LA mode and t denotes adopting the IPFT mode.

4. Equilibrium Analysis

In this section, we derive equilibrium outcomes and analyze the underlying mechanisms of the Stackelberg game to explain how subsidy schemes and transportation modes jointly shape firms' strategic behavior and market outcomes.

4.1. Scenario 1: The LA Mode Under Subsidies to the LSP

In Scenario 1, the government provides the LSP with a unit subsidy of s_A , and LSPs establish a joint transportation system to complete the "first-mile" service without the bus company. The profit of the LSP is

$$\Pi_{LSPi}^A = (p_i^A - c + s_A)q_i^A(p_i^A, e_i^A) - \frac{r}{2}e_i^{A2} - \theta K, \quad (1)$$

The LSP chooses p_i and e_i to maximize his profit, and the equilibrium strategy under this scenario is obtained by applying backward induction (the superscript * is to denote optimality). We obtain Proposition 1, and all proof processes are provided in Appendix A.

Proposition 1. Under government subsidies to the LSP, if the LSP adopts LA mode:

(1) The optimal service level $e_i^{A*} = \frac{(b(s_A - c) + \theta)\beta}{2br - \beta^2\theta}$. (2) The "first-mile" service price $p_i^{A*} = \frac{(c - s_A)(br - \beta^2) + r\theta}{2br - \beta^2}$. (3) The demand $q_i^{A*} = \frac{br(\theta + b(-c + s_A))}{2br - \beta^2}$. (4) The LSP's profit $\Pi_{LSPi}^{A*} = \frac{b^2r(c - s_A)^2 - 2br(c + 2K - s_A)\theta + \theta(2K\beta^2 + r\theta)}{4br - 2\beta^2}$.

It follows from Proposition 1 that the total subsidy expenditure in Scenario 1 is $S_1 = s_A q_i^{A*} = \frac{brs_A(\theta + b(-c + s_A))}{2br - \beta^2}$.

Property 1. Under government subsidies to the LSP, if the LSP adopts LA mode, we have:

(1) $\frac{\partial e_i^{A*}}{\partial s_A} > 0$ and $\frac{\partial q_i^{A*}}{\partial s_A} > 0$. (2) If $\frac{\beta^2}{2b} < r < \frac{\beta^2}{b}$, then $\frac{\partial p_i^{A*}}{\partial s_A} > 0$; if $r \geq \frac{\beta^2}{b}$, then $\frac{\partial p_i^{A*}}{\partial s_A} \leq 0$. (3) There exists a threshold $s_1 = c - \frac{\theta}{b}$: if $0 < s_A \leq s_1$, then $\frac{\partial \Pi_{LSPi}^{A*}}{\partial s_A} < 0$; if $s_A > s_1$, then $\frac{\partial \Pi_{LSPi}^{A*}}{\partial s_A} > 0$. (4) $\frac{\partial p_i^{A*}}{\partial \theta} > 0$, $\frac{\partial e_i^{A*}}{\partial \theta} > 0$ and $\frac{\partial q_i^{A*}}{\partial \theta} > 0$. (5) There exists a threshold $s_1' = s_1 + 2K - \frac{\beta^2 K}{br}$: if $0 < s_A \leq s_1'$, then $\frac{\partial \Pi_{LSPi}^{A*}}{\partial \theta} < 0$; if $s_A > s_1'$, then $\frac{\partial \Pi_{LSPi}^{A*}}{\partial \theta} > 0$.

Property 1 indicates that government subsidies stimulate the LSP to increase investment in service levels and expand farmers' demand. From a game-theoretic perspective, this result arises because the LSP acts as the Stackelberg leader and fully internalizes the impact of service level decisions on market demand when determining prices and service quality. As subsidy intensity increases, financial constraints on service investment are relaxed, enabling the LSP to strategically adjust service levels to stimulate demand rather than relying solely on price reductions.

Property 2. Under government subsidies to the LSP, if the LSP adopts LA mode, then cost of the joint transportation construction K will have the following impacts on the equilibrium:

(1) $\frac{\partial e_i^{A*}}{\partial K} > 0$ and $\frac{\partial q_i^{A*}}{\partial K} > 0$. (2) If $\frac{\beta^2}{2b} < r < \frac{\beta^2}{b}$, then $\frac{\partial p_i^{A*}}{\partial K} > 0$; if $r > \frac{\beta^2}{b}$, then $\frac{\partial p_i^{A*}}{\partial K} < 0$. (3) There exists a threshold $s_1'' = s_1 + \frac{\theta K}{b^2 r \alpha}(2br - \beta^2)$, if $0 \leq s_i \leq s_1''$, then $\frac{\partial \Pi_{LSPi}^{A*}}{\partial K} < 0$; if $s_i > s_1''$, then $\frac{\partial \Pi_{LSPi}^{A*}}{\partial K} > 0$.

Simply put, the magnitude of K not only reflects the construction costs of the transportation system, but also embodies the development level of rural logistics. Property 2 shows that higher construction costs represent larger sunk investments borne by the LSP.

Consequently, the LSP has a stronger incentive to utilize subsidies for improving service levels in order to expand demand and recover fixed costs. As a result, subsidies interact with construction costs by shifting the LSP's optimal trade-off between price and service quality, leading to the observed changes in demand and profitability.

Taken together, Property 1 and Property 2 reveal a “forward-shifting effect” of market share θ and construction cost K on the LSP's profit response to subsidies. Specifically, both θ and K always leads to higher expenditures. Meanwhile, the LSP with a larger market share and more early-stage investments exhibits a more pronounced response to government subsidies (see Figure 4). Thus, when the government subsidizes large-scale LSPs in regions with lower development levels, the subsidy effect will be more significant.

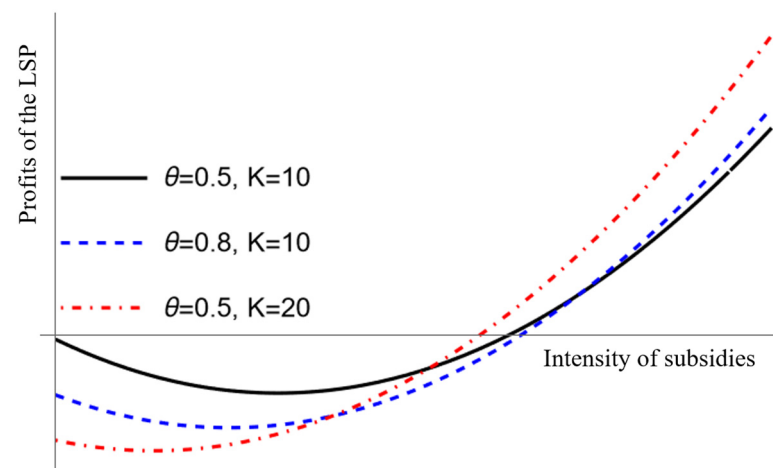


Figure 4. The Forward-shifting Effect on the LSP's Profit.

4.2. Scenario 2: The IPFT Mode Under Subsidies to the LSP

In Scenario 2, the government provides the LSP with a unit subsidy of s_A , and the LSP relies on the bus company to complete the “first-mile” service. The profits of the bus company and the LSP are respectively

$$\Pi_{BUSt}^A = w^A q_t^A(p_t^A, e_t^A) - \frac{r}{2} e_t^{A2}, \quad (2)$$

$$\Pi_{LSPt}^A = (p_t^A - w^A + s_A) q_t^A(p_t^A, e_t^A), \quad (3)$$

In this scenario, the LSP chooses p_t^A , while the bus company chooses w^A and e_t^A , to maximize their respective profits. Just as in Scenario 1, this can be solved by applying backward induction. Notably, for ease of calculation, the pricing of the “first-mile” service is rewritten as $p_t^A = w^A + \delta^A$, where $\delta^A \geq 0$ denotes the unit net profit of the LSP after paying the bus company the IPFT fee w^A . The equilibrium strategies obtained under this scenario are provided in Proposition 2.

Proposition 2. Under government subsidies to the LSP, if the LSP adopts the IPFT mode:

- (1) The bus company's optimal service level $e_t^{A*} = \frac{\beta(\theta + bs_A)}{4br - 2\beta^2}$, and the IPFT service fee $w^{A*} = \frac{r(\theta + bs_A)}{4br - 2\beta^2}$. (2) After paying the IPFT service fee, the LSP can gain the unit net profit $\delta^{A*} = \frac{\theta - bs_A}{2b}$ and the “first-mile” service price $p_t^{A*} = \frac{\theta - bs_A}{2b} + \frac{r(\theta + bs_A)}{4br - 2\beta^2}$, with the demand $q_t^{A*} = \frac{br(\theta + bs_A)}{4br - 2\beta^2}$. (3)

The profit of the bus company and the LSP are respectively $\Pi_{BUSt}^{A*} = \frac{r(\theta + bs_A)^2}{16br - 8\beta^2}$ and $\Pi_{LSPt}^{A*} = \frac{r(\theta + bs_A)^2}{8br - 4\beta^2}$.

Similarly, it follows from Proposition 2 that the total government subsidy expenditure under Scenario 2 is $S_2 = s_A q_t^{A*} = \frac{brs_A(\theta + bs_A)}{4br - 2\beta^2}$.

Property 3. Under government subsidies to the LSP, if the LSP adopts the IPFT mode, we have: (1) $\frac{\partial w^{A*}}{\partial s_A} > 0$, $\frac{\partial e_t^{A*}}{\partial s_A} > 0$ and $\frac{\partial q_t^{A*}}{\partial s_A} > 0$. (2) If $\frac{\beta^2}{2b} < r \leq \frac{\beta^2}{b}$, then $\frac{\partial p_t^{A*}}{\partial s_A} \geq 0$; if $r > \frac{\beta^2}{b}$, then $\frac{\partial p_t^{A*}}{\partial s_A} < 0$. (3) $\frac{\partial \Pi_{LSPt}^{A*}}{\partial s_A} > 0$, $\frac{\partial \Pi_{BUSSt}^{A*}}{\partial s_A} > 0$, $\Pi_{LSPt}^{A*} = 2\Pi_{BUSSt}^{A*}$, and $\frac{\partial \Pi_{LSPt}^{A*}}{\partial s_A} = 2\frac{\partial \Pi_{BUSSt}^{A*}}{\partial s_A}$. (4) $\frac{\partial p_t^{A*}}{\partial \theta} > 0$, $\frac{\partial w^{A*}}{\partial \theta} > 0$, $\frac{\partial e_t^{A*}}{\partial \theta} > 0$, and $\frac{\partial q_t^{A*}}{\partial \theta} > 0$. (5) $\frac{\partial \Pi_{LSPt}^{A*}}{\partial \theta} > 0$, $\frac{\partial \Pi_{BUSSt}^{A*}}{\partial \theta} > 0$, and $\frac{\partial \Pi_{LSPt}^{A*}}{\partial \theta} = 2\frac{\partial \Pi_{BUSSt}^{A*}}{\partial \theta}$.

Proposition 2 and Property 3 indicate that, in the IPFT mode, both the LSP and the bus company benefit from increased subsidy intensity. This outcome results from the strategic response of the bus company to subsidy-induced demand expansion. As the Stackelberg follower in service provision, the bus company adjusts the service level and IPFT fee in response to the LSP's pricing decision, thereby sharing both the costs and benefits associated with higher demand. This pricing and service-level adjustment mechanism enables subsidies to be transmitted across firms within the IPFT structure.

Furthermore, compared with the LA mode, the IPFT mode maintains positive profits for both stakeholders even under relatively low subsidy intensity. This stability can be explained by the separation of decision rights embedded in the IPFT structure. Since the LSP does not directly invest in service capacity and the bus company determines service levels, operational risks are partially shifted away from the LSP. Consequently, subsidies primarily affect demand rather than fixed cost recovery, which explains the relatively smooth and monotonic profit response under the IPFT mode. Figure 5 visually confirms the different profit growth patterns implied by the equilibrium mechanisms discussed above.

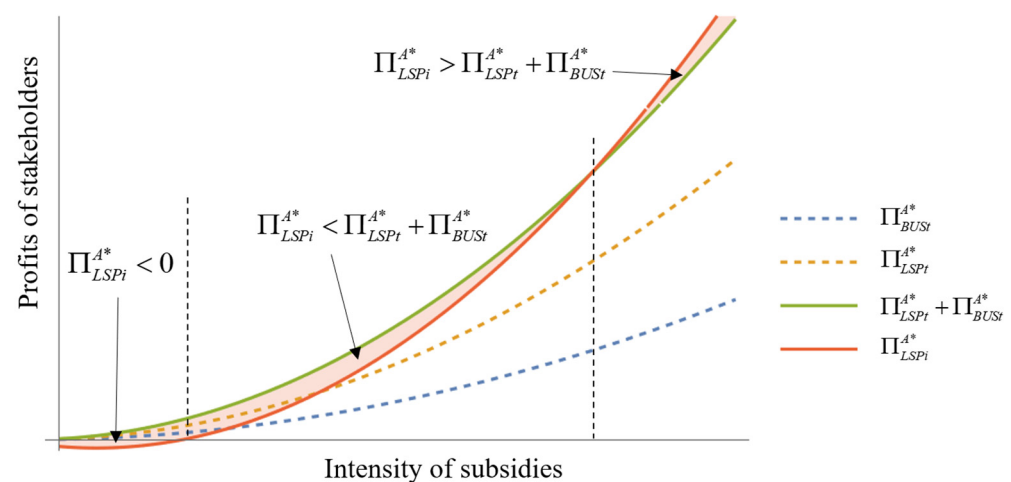


Figure 5. Changes in Stakeholders' Profits with Subsidies Intensity.

4.3. Scenario 3: The IPFT Mode Under Subsidies to the Bus Company

In Scenario 2, the government provides the bus company with a unit subsidy of s_B , we only discuss the scenario where the LSP adopts the IPFT mode. The profits of the bus company and the LSP are as follows

$$\Pi_{BUSSt}^B = (w^B + s_B)q_t^B(p_t^B, e_t^B) - \frac{r}{2}e_t^{B2}, \quad (4)$$

$$\Pi_{LSPt}^B = (p_t^B - w^B)q_t^B(p_t^B, e_t^B), \quad (5)$$

To maximize their profits, the LSP determines p_t^B , while the bus company decides w^B and e_t^B . Similarly, by defining LSP's unit net profit as $\delta^B = p_t^B - w^B$, we can obtain the equilibrium strategies using backward induction (see Proposition 3).

Proposition 3. *Under government subsidies to the bus company, if the LSP adopts the IPFT mode:*

(1) *The bus company's optimal service level $e_t^{B*} = \frac{(\theta + bs_B)\beta}{4br - 2\beta^2}$, and the IPFT service fee $w^{B*} = \frac{\theta r - 3brs_B + 2s_B\beta^2}{4br - 2\beta^2}$.* (2) *After paying the IPFT service fee, the LSP can gain the unit net profit $\delta^{B*} = \frac{\theta + bs_B}{2b}$ and the "first-mile" service price $p_t^{B*} = \frac{3\theta br - b^2rs_B - \theta\beta^2 + bs_B\beta^2}{4b^2r - 2b\beta^2}$, with the demand $q_t^{B*} = \frac{br(\theta + bs_B)}{4br - 2\beta^2}$.* (3) *The profit of the bus company and the LSP are respectively $\Pi_{BUST}^{B*} = \frac{r(\theta + bs_B)^2}{16br - 8\beta^2}$ and $\Pi_{LSPt}^{B*} = \frac{r(\theta + bs_B)^2}{8br - 4\beta^2}$.*

It follows from Proposition 3 that the total government subsidy expenditure under Scenario 3 is $S_3 = s_B q_t^{B*} = \frac{brs_B(\theta + bs_B)}{4br - 2\beta^2}$.

Property 4. *When the LSP adopts IPFT mode to achieve the "first-mile" service, whether the government subsidizes the LSP or the bus company, under the condition that the subsidy intensity is the same ($s_A = s_B$), there always exists:*

(1) *The "first-mile" service price is the same, $p_t^{A*} = p_t^{B*}$.* (2) *The bus company's service level is the same, $e_t^{A*} = e_t^{B*}$.* (3) *The farmers' demand is the same, $q_t^{A*} = q_t^{B*}$.* (4) *The profits of stakeholders are the same, $\Pi_{LSPt}^{A*} = \Pi_{LSPt}^{B*}$, $\Pi_{BUST}^{A*} = \Pi_{BUST}^{B*}$.*

When the government subsidizes the bus company, one might expect that the bus company would earn higher profits by receiving subsidies directly. However, Property 4 shows that a "revenue equivalence" result arises between the two subsidy strategies under the IPFT mode. This equivalence is driven by the Stackelberg equilibrium structure, in which subsidy benefits are fully transmitted between the LSP and the bus company through adjustments in the IPFT service fee and the final service price. As a result, regardless of the subsidy recipient, equilibrium service prices, service levels, demand, and stakeholder profits remain identical. Therefore, under the IPFT mode, subsidy intensity rather than subsidy allocation determines market outcomes.

Property 5. *If the LSP adopts the IPFT mode, there exists a threshold $s_2 = \frac{r\theta}{3br - 2\beta^2}$, such that when $s_B > s_2$, the bus company may set the IPFT service fee w to a negative value and thus obtain profits through "subsidy fraud". Furthermore, under the condition that the two subsidy intensities are the same ($s_A = s_B = s$), there always exists $w^{A*} > w^{B*}$, and $w^{A*} - w^{B*} = |s|$.*

Property 5 indicates that when the government subsidizes the bus company, it may optimally reduce the IPFT service fee w^{B*} to a negative value to incentivize the LSP to adopt the IPFT mode, a behavior referred to as "subsidy fraud" in this study. This outcome reflects the bus company's strategic use of subsidies to expand demand rather than opportunistic misconduct. By lowering service fees, the bus company reallocates subsidy benefits through equilibrium pricing, which stimulates logistics demand and increases overall welfare despite the apparent distortion in subsidy allocation. Figure 6 provides a more intuitive illustration of the bus company's "subsidy fraud" behavior.

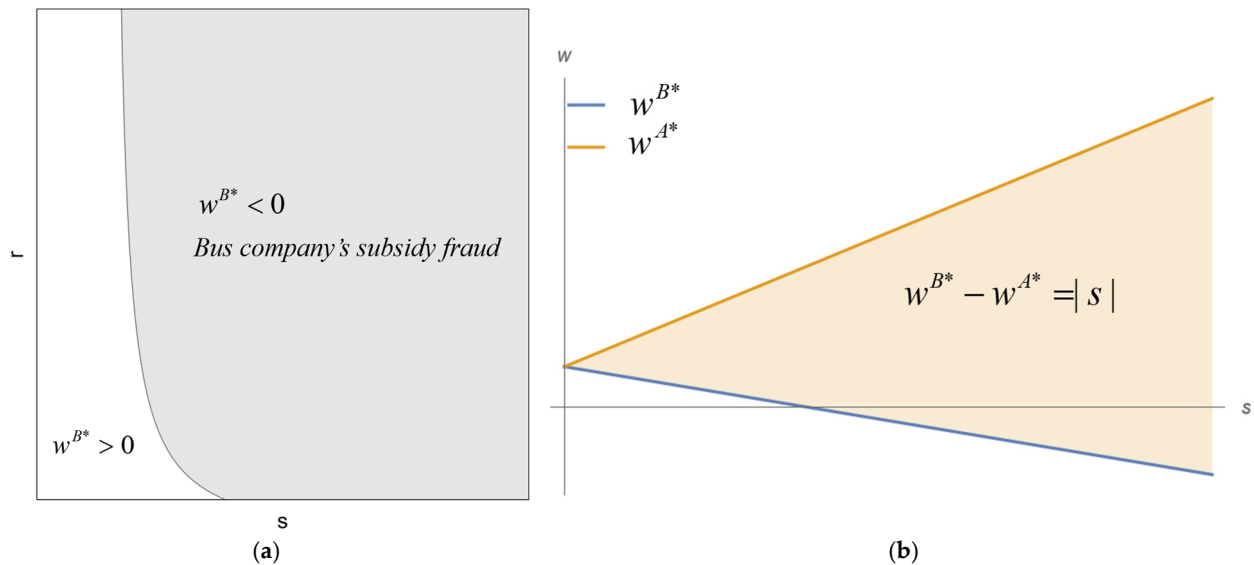


Figure 6. The Bus Company's Subsidy Fraud Behavior. (a) Impacts of subsidy intensity and cost conversion coefficient on the subsidy fraud behavior. (b) Variation in the IPFT service fee with subsidy intensity under two different subsidy recipient scenarios. (Numerical simulation: $b = 1.1$, $\beta = 1$, $r = 0.7$, $\theta = 0.5$).

Within the IPFT mode, Property 6 can be derived by analyzing the optimal unit net profits of the LSP (δ^{A*} and δ^{B*}) under the two subsidy strategies.

Property 6. If the LSP adopts the IPFT mode, there exists:

- (1) $\frac{\partial \delta^{A*}}{\partial s_A} < 0$, $\frac{\partial \delta^{B*}}{\partial s_B} > 0$, $\frac{\partial \delta^{A*}}{\partial \theta} > 0$, and $\frac{\partial \delta^{B*}}{\partial \theta} > 0$. (2) $\delta^{B*} > 0$ holds consistently. Specifically, if $0 < s_A \leq \frac{\theta}{b'}$ then $\delta^{A*} \geq 0$; if $s_A > \frac{\theta}{b'}$ then $\delta^{A*} < 0$. (3) $\delta^{A*} + \delta^{B*} = \frac{\theta}{b}$.

Property 6 describes the price adjustment rule for the LSP. After the bus company determines its optimal IPFT service fee w^{A*} and w^{B*} , the LSP will set its prices as $p_t^{A*} = w^{A*} + \delta^{A*}$ and $p_t^{B*} = w^{B*} + \delta^{B*}$, thereby passing on the costs of IPFT services to farmers and earning a profit margin corresponding to δ^{A*} and δ^{B*} . On the one hand, when the government subsidizes the bus company, the LSP consistently earns a per-unit profit margin of $\delta^{B*} > 0$. On the other hand, when the government subsidizes the LSP, as the subsidy intensity s_A increases, the LSP will set its price below cost (i.e., $p_t^{A*} < w^{A*}$). Such behavior is referred to as “profit concession” in this study. Specifically, when subsidy intensity increases, the LSP optimally sets prices below marginal cost to stimulate demand, while using subsidies to offset cost losses. Notably, the profit concession behavior is also influenced by the price sensitivity b : if b is low, the demand growth stimulated by price reductions will fail to offset cost losses, and the LSP will not engage in profit concession behavior under such circumstances. Figure 7 provides a more intuitive illustration of the LSP's “profit concession” behavior.

Both the “subsidy fraud” behavior of the bus company and the “profit concession” behavior of the LSP reflect a common strategic tendency. When substantial subsidies are available, firms use government support to offset costs while lowering prices to drive demand growth. While market outcomes remain identical under the IPFT mode, the following section further examines whether subsidy efficiency and social welfare performance differ across scenarios, providing a more comprehensive evaluation of subsidy effectiveness.

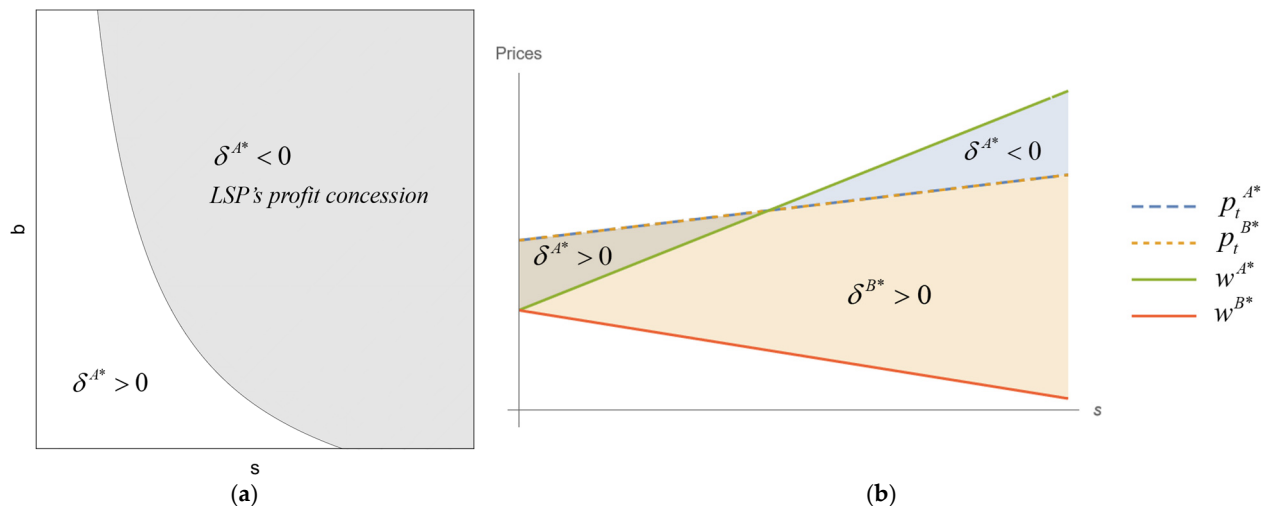


Figure 7. The LSP's Profit Concession Behavior. (a) Impacts of subsidy intensity and price sensitivity coefficient on the profit concession behavior. (b) Variation in the LSP's unit net profit with subsidy intensity under two different subsidy recipient scenarios. (Numerical simulation: $b = 1.1$, $\beta = 1$, $r = 0.7$, $\theta = 0.5$).

5. Comparative Analysis

In this section, we conduct a comparative analysis of subsidy effects and subsidy efficiency across different scenarios. Under identical subsidy intensity and total government expenditure, we identify the key factors driving differences in subsidy performance, thereby providing theoretical support for the design of more efficient subsidy policies.

First, under the same subsidy policy environment, we analyze the influencing factors and variation characteristics of subsidy effects. To ensure comparability across different scenarios, this study considers a specific case: both the total government expenditure and the unit subsidy strategy are consistent across the three scenarios, i.e., $S_1 = S_2 = S_3$. From the government's perspective, policy evaluation should account for more than firms' profits. In particular, farmers' surplus—viewed as consumer surplus from “first-mile” services—and government subsidy expenditure must also be considered. Therefore, we define social welfare as follows: $\Pi_{Gj}^{X*} = \Pi_{LSPj}^{X*} + \Pi_{BUSj}^{X*} + \Pi_{Cj}^{X*} - s_X q_j^{X*}$, where $j = \{i, t\}$ and $X = \{A, B\}$. Here, Π_{LSPj}^{X*} denotes the profit of the LSP, Π_{BUSj}^{X*} denotes the profit of the bus company, $s_X q_j^{X*}$ represents the total government subsidy expenditure, and Π_{Cj}^{X*} denotes farmers' surplus, which satisfies [37]

$$\Pi_{Cj}^{X*} = \int_{p_i^*}^{p_i^{max}} (\theta - bp_i + \beta e_j^*) dp_i = \frac{(\theta - bp_j^* + \beta e_j^*)^2}{2}, \quad (6)$$

Specifically, the social welfare of Scenario 1 is given by $\Pi_{Gi}^{A*} = \Pi_{LSPi}^{A*} + \Pi_{Ci}^{A*} - s_A q_i^{A*}$, that of Scenario 2 is $\Pi_{Gt}^{A*} = \Pi_{LSPt}^{A*} + \Pi_{BUSt}^{A*} + \Pi_{Ct}^{A*} - s_A q_t^{A*}$; and that of Scenario 3 is $\Pi_{Gt}^{B*} = \Pi_{LSPt}^{B*} + \Pi_{BUSt}^{B*} + \Pi_{Ct}^{B*} - s_B q_t^{B*}$. Furthermore, in practice, subsidies may produce counterproductive effects, and not all subsidy policies yield positive outcomes. Therefore, we define the social welfare of two baseline scenarios without government subsidies as $\Pi_{Gi}^{N*} = \Pi_{LSPi}^{N*} + \Pi_{Ci}^{N*}$ (for LA mode) and $\Pi_{Gt}^{N*} = \Pi_{LSPt}^{N*} + \Pi_{BUSt}^{N*} + \Pi_{Ct}^{N*}$ (for IPFT mode), respectively. These baseline scenarios are incorporated into the comparative analysis, ultimately leading to the derivation of Proposition 4.

Proposition 4. Under the same subsidy policy, there exist thresholds r_1 , r_2 and r_3 such that:

- (1) If $r < r_1$, then $\Pi_{Gt}^{A*} = \Pi_{Gt}^{B*} > \Pi_{Gi}^{A*}$, with $\Pi_{Gi}^{A*} > \Pi_{Gi}^{N*}$ and $\Pi_{Gt}^{A*} > \Pi_{Gt}^{N*}$.
- (2) If $r_1 < r < r_2$, then $\Pi_{Gt}^{A*} = \Pi_{Gt}^{B*} < \Pi_{Gi}^{A*}$, with $\Pi_{Gi}^{A*} > \Pi_{Gi}^{N*}$ and $\Pi_{Gt}^{A*} > \Pi_{Gt}^{N*}$.
- (3) If $r_2 < r < r_3$, then $\Pi_{Gt}^{A*} = \Pi_{Gt}^{B*} > \Pi_{Gi}^{A*}$, with $\Pi_{Gi}^{A*} < \Pi_{Gi}^{N*}$.
- (4) If $r > r_3$, then $\Pi_{Gt}^{A*} = \Pi_{Gt}^{B*} < \Pi_{Gi}^{A*}$, with $\Pi_{Gi}^{A*} < \Pi_{Gi}^{N*}$.

Proposition 4 indicates that, under identical subsidy intensity and total government expenditure, differences in social welfare across scenarios are primarily driven by the cost conversion coefficient r . The cost conversion coefficient r captures regional logistics operating difficulty, with higher values corresponding to higher transportation and service costs (e.g., remote and sparsely populated plateaus, mountainous areas, and deserts). In regions with lower operating costs, the IPFT mode benefits from existing transport capacity and avoids fixed investment, allowing subsidies to translate more directly into demand expansion. By contrast, when operating costs are high, the LA mode becomes relatively more effective. Full control over service decisions allows LSPs to internalize service investments and recover fixed costs through demand growth. When r is excessively high, however, subsidy-induced service improvements are largely absorbed by operating costs, rendering market-based subsidies ineffective regardless of the transportation mode.

Figure 8 illustrates how the welfare dominance conditions derived in Proposition 4 vary with the LSP's market share θ and the cost conversion coefficient r . When the cost conversion coefficient r is fixed, if the market share of the LSP θ is relatively large, the IPFT mode is more conducive to social welfare; conversely, if the market share θ is relatively small, the LA mode is more conducive to social welfare. This result arises because, in the LA mode, larger LSPs bear a greater share of initial construction costs, whereas smaller LSPs benefit from a lighter cost burden.

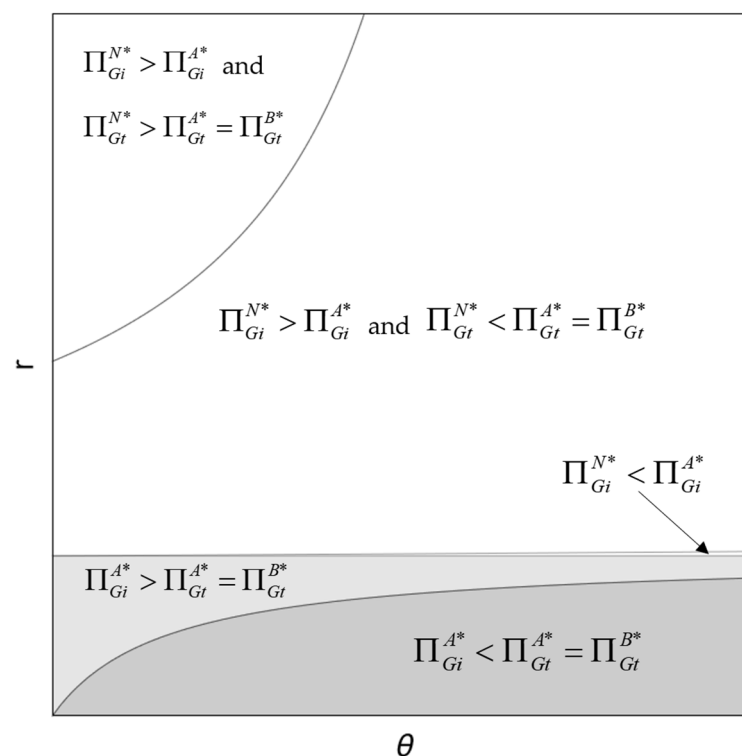


Figure 8. Variation in Social Welfare with r and θ .

Then we analyze the impact of different subsidy intensities on subsidy effects. Subsidy efficiency is defined as the ratio of social welfare to government subsidy expenditure [6]. Specifically, we denote the subsidy efficiency under the three scenarios as U_i^A , U_t^A , and U_t^B respectively, i.e.: $U_i^A = \Pi_{Gi}^{A*} / (s_A \cdot q_i^{A*})$, $U_t^A = \Pi_{Gt}^{A*} / (s_A \cdot q_t^{A*})$, and $U_t^B = \Pi_{Gt}^{B*} / (s_B \cdot q_t^{B*})$. Through a horizontal comparison under the condition that the subsidy intensities are equal (i.e., $s_A = s_B = s$), we derive Proposition 5.

Proposition 5. Regarding subsidy efficiency, there exist threshold s_3 and s_4 with $s_3 < s_4$, such that:

(1) If $0 < r < \frac{\beta^2}{(2-b)b}$, then: when $s_3 < s < s_4$, $U_i^A < U_t^A = U_t^B$; when $s < s_3$ or $s > s_4$, $U_i^A \geq U_t^A = U_t^B$. (2) If $r > \frac{\beta^2}{(2-b)b}$, then: when $s_3 < s < s_4$, $U_i^A > U_t^A = U_t^B$; when $s < s_3$ or $s > s_4$, $U_i^A \leq U_t^A = U_t^B$.

Proposition 5 characterizes subsidy efficiency by comparing welfare gains relative to fiscal expenditure. Unlike Proposition 4, which focuses on welfare levels, subsidy efficiency captures how effectively government spending is transformed into social welfare under different transportation modes. The results show that subsidy efficiency is jointly determined by subsidy intensity and the cost conversion coefficient r , leading to non-monotonic efficiency patterns across modes. On the one hand, in regions with low operational difficulty, the bus company can utilize existing transportation networks to convert subsidies into service improvements at relatively low marginal cost, resulting in higher efficiency under the IPFT mode at moderate subsidy levels. As the unit subsidy increases further, government spending no longer effectively incentivizes the company to improve service efficiency. Instead, high subsidies enable the LSP to cover expensive upfront construction costs, gradually making the LA mode's subsidy efficiency higher than that of the IPFT mode. On the other hand, if service operating costs are high, the government subsidy burden rises, shifting thresholds negatively. In this case, the LA mode becomes more efficient than the IPFT mode due to its greater autonomy in service quality control.

Figure 9 further validates the efficiency patterns implied by Proposition 5 under different combinations of subsidy intensity and market share. Overall, the IPFT mode yields higher subsidy efficiency for the LSP with a larger market share, which aligns with the conclusions of Proposition 4. Notably, in regions with high service costs, excessive unit subsidy intensity may result in negative subsidy efficiency, which indicates that excessive government subsidy input could lead to resource waste. Therefore, adopting a uniform or “broad-brush” subsidy strategy in regions with high logistics costs may lead to fiscal inefficiency and limited improvements in local logistics development.

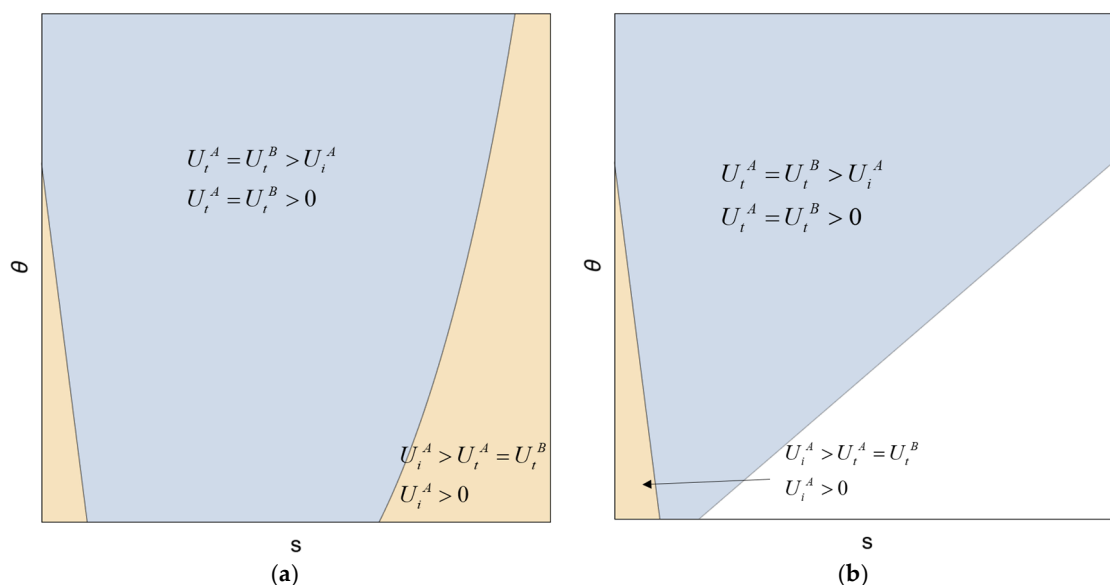


Figure 9. Variation in Subsidy Efficiency with s and θ . (a) $0 < r < \frac{\beta^2}{(2-b)b}$. (b) $r > \frac{\beta^2}{(2-b)b}$.

6. Numerical Analysis

In this section, we analyze how the total subsidy budget and key parameters—specifically the LSP's market share and the regional cost conversion coefficient r —affect equilibrium outcomes, under the condition that total subsidy expenditure is held constant (i.e., $S_1 = S_2 = S_3 = S$).

Numerical analysis is conducted using a representative parameter setting: $b = 1.1$, $\beta = 1$, $r = 0.7$, $\theta = 0.5$ and $c = 1$. In rural areas of China, farmers have relatively low disposable income and are more sensitive to price changes (b is slightly larger than β). Meanwhile, to ensure the numerical values meet constraint $2br > \beta^2$, we first set r and θ to 0.7 and 0.5, respectively, and subsequently vary these values for sensitivity analysis.

These parameter values are chosen to represent rural regions with heterogeneous operating conditions and market structures. Lower values of r correspond to plains or peri-urban areas, whereas higher values represent remote or mountainous regions with higher service costs. A larger θ indicates a more concentrated logistics market in which the LSP holds a stronger market position.

6.1. Numerical Results Under Different Subsidy Budget Levels

First, we examine how variations in the total subsidy budget affect enterprises' profits, farmers' surplus, and social welfare, as illustrated in Figure 10.

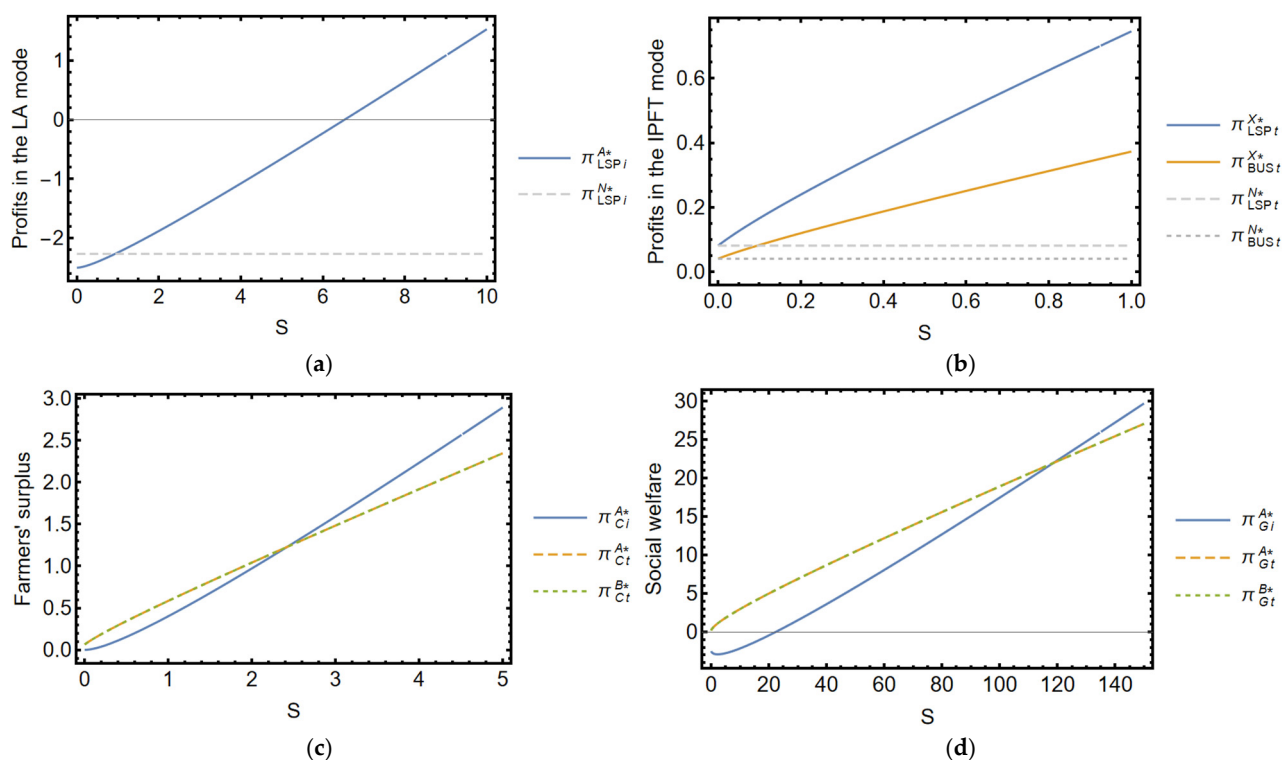


Figure 10. Impact of Total on the Profits of Stakeholders. (a) The impact on the LSP's profits in the LA mode. (b) The impact on the logistics enterprises' profits in the IPFT mode. (c) The impact on the farmers' surplus. (d) The impact on social welfare.

Figure 10a illustrates the LSP's profit changes in the LA mode. The LSP must bear the construction costs of the joint transportation system in proportion to market share, which imposes a fixed-cost burden on initial profits. Low subsidies only partially cover unit operating costs, leaving LSPs with negative or meager profits. When total subsidies are sufficiently large, both operating and construction costs are fully covered. This encourages LSPs to enhance service levels and leads to rapid profit growth.

Figure 10b shows that logistics enterprises maintain positive profits under the IPFT mode across all subsidy budget levels. Moreover, due to the game equilibrium and profit transfer, the LSP's profits are consistently twice those of the bus company, consistent with Property 3 and Property 4.

Farmers' surplus is essentially the net service utility after deducting payment costs. As depicted in Figure 10c, improvements in service levels offset price effects, sustaining growth in farmers' surplus. Moreover, high subsidies drive significantly higher service levels in the LA mode, leading to the surplus exceeding that in the IPFT mode.

Figure 10d shows social welfare variations: as total subsidies increase, the LA mode's social welfare overtakes IPFT's. In the LA mode, low subsidy levels only partially offset fixed-cost losses, whereas higher subsidies stimulate profit and surplus growth that eventually exceeds subsidy expenditure. In contrast, the IPFT mode is constrained by service control, slowing stakeholders' income growth and letting the LA mode overtake in social welfare.

The results in Figure 10 indicate that the effectiveness of subsidy policies depends strongly on the total subsidy budget. When fiscal resources are limited, the IPFT mode delivers positive profits and stable welfare gains by avoiding large upfront construction costs, making it a suitable short-term policy option. As the subsidy budget increases, the LA mode becomes increasingly attractive, since sufficient subsidies allow logistics service providers to internalize fixed costs and translate fiscal support into higher service levels and welfare. These results suggest that IPFT can serve as a transitional policy option under budget constraints, while logistics alliances become preferable when long-term subsidy support can be sustained.

6.2. Sensitivity Analysis of Key Parameters

We next conduct sensitivity analysis focusing on social welfare by varying the cost conversion coefficient r and the LSP's market share θ , as shown in Figure 11.

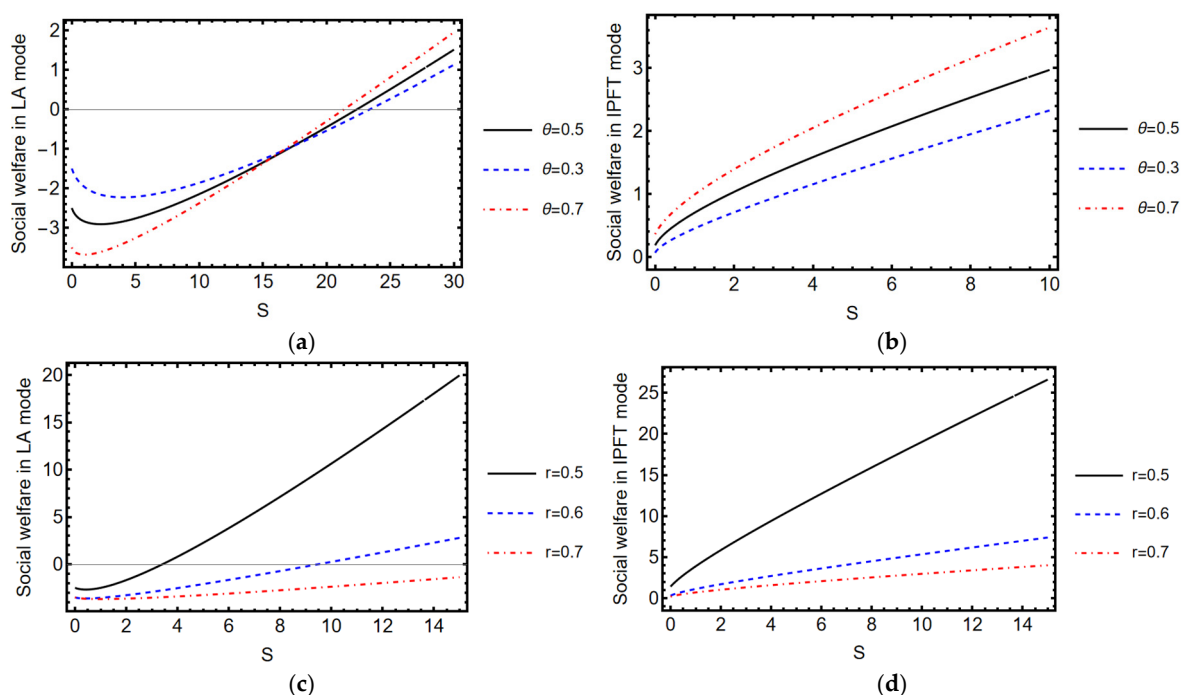


Figure 11. Impact of θ and r on the Social Welfare. (a) The impact of θ in the LA mode. (b) The impact of θ in the IPFT mode. (c) The impact of r in the LA mode. (d) The impact of r in the IPFT mode.

Figure 11a,b depict the impact of LSP's market share θ on social welfare. In the LA mode, large-scale LSPs bear a bigger share of construction costs, dragging profits more noticeably. When subsidies fully cover costs, scale advantages emerge and drive rapid growth in social welfare. In the IPFT mode, θ directly determines base demand, thus a larger θ results in a greater demand growth driven by subsidies. Nevertheless, since LSPs cannot independently optimize service levels in the IPFT mode, social welfare growth is driven solely by demand, maintaining a moderate growth rate.

Figure 11c,d illustrate the impact of the cost conversion coefficient r on social welfare. Overall, r characterizes regional operational difficulty, and higher r indicates higher operating costs. In the LA mode, higher operating costs cause a larger share of subsidies to be absorbed by cost coverage, leading to a decline in welfare conversion efficiency. In the IPFT mode, the bus company can moderately increase service fees to share service costs, making the mode more resilient to r and avoiding a sharp decline in social welfare.

The sensitivity analysis highlights the importance of regional heterogeneity in subsidy design. In regions with high operating costs, increasing subsidies yields diminishing welfare gains, implying that uniform subsidy expansion may lead to fiscal inefficiency. In such contexts, IPFT-based subsidies that rely on existing transport networks are more robust. Conversely, in regions with lower operating costs or more fragmented markets, subsidizing logistics alliances can generate higher long-term welfare by enabling service quality improvements. These results indicate that rural "first-mile" subsidy policies should be region-specific rather than uniformly implemented.

7. Discussion

7.1. Transportation Mode Selection Under Government Subsidies

The analysis indicates that transportation mode selection between the LA mode and IPFT modes is driven not only by cost minimization, but also by strategic trade-offs involving fixed-cost exposure, risk-sharing, and control over service quality.

When the subsidy intensity is relatively low, LSPs—especially those with larger market shares—tend to prefer the IPFT mode. This preference arises because IPFT allows LSPs to avoid large upfront construction costs and transfers part of the operational risk to bus companies, thereby ensuring non-negative profits under limited policy support. This result helps explain why IPFT is frequently observed and widely promoted in rural contexts, especially under local fiscal constraints, as documented in county-level case studies such as the Lianhua County practice [20].

As subsidy intensity increases, the LA mode becomes more attractive. Full control over service levels and pricing enables LSPs to transform subsidies more effectively into service improvements and demand expansion. In contrast to prior logistics alliance studies that typically treat alliance structures as exogenously given and focus on internal coordination mechanisms such as cost allocation and cooperation stability [22,23], this study highlights how subsidy policies can endogenously induce LSPs to switch between collaborative modes.

From a policy perspective, these results suggest that IPFT can function as a risk-buffering or transitional solution under limited fiscal capacity, while logistics alliances become more attractive as subsidy support strengthens.

7.2. Mechanisms Through Which Subsidies Alleviate the "First-Mile" Dilemma

The analysis confirms that government subsidies can effectively alleviate the unsustainable dilemma in rural "first-mile" logistics, characterized by mutually reinforcing low service levels and weak demand. Importantly, the effect of subsidies does not primarily operate through direct price reductions.

Instead, subsidies relax financial constraints and induce firms' strategic behavior. In equilibrium, LSPs may lower prices to stimulate demand while using subsidies to offset cost losses, and bus companies under the IPFT mode may strategically adjust service fees. These behaviors should be interpreted as equilibrium outcomes of strategic interaction, functioning as transmission mechanisms that translate public subsidies into higher service levels and expanded logistics participation.

This mechanism differs from much of the existing subsidy literature, which models subsidies mainly as direct cost reducers or price suppressors and evaluates their effectiveness through price and demand responses [4]. In imperfect rural logistics markets, however, the present results indicate that subsidies mainly operate through incentive realignment and equilibrium adjustment rather than mechanical price pass-through. Accordingly, evaluating subsidy performance requires attention not only to price changes, but also to service quality indicators such as cold-chain capacity, delivery timeliness, and service coverage.

7.3. Revenue Equivalence Under the IPFT Mode

A notable theoretical finding is the revenue equivalence between subsidizing LSPs and subsidizing bus companies under the IPFT mode. When subsidy intensity is identical, equilibrium service prices, service levels, demand, and stakeholder profits remain unchanged, regardless of the subsidy recipient.

This revenue equivalence arises from the strong price-transmission mechanism embedded in IPFT collaboration, whereby subsidies received by either the LSP or the bus company are fully reallocated through service fees and final logistics prices. Existing studies on integrated passenger–freight systems emphasize the role of subsidy allocation in shaping firms' incentives and welfare outcomes [18,30]. Building on this literature, the present analysis further shows that, under the IPFT mode, subsidy intensity plays a more prominent role than subsidy allocation in determining equilibrium outcomes. This result holds when effective contractual pricing mechanisms are in place.

It should be noted that this result relies on simplifying assumptions (e.g., linear demand and relatively low marginal operating costs for bus companies), but these assumptions are broadly consistent with institutional characteristics of rural public transport systems and the operational logic of bus-based logistics integration [17]. From a policy perspective, the result suggests that, under the IPFT mode, subsidy intensity and service regulation may play a more prominent role than the specific choice of subsidy recipient.

7.4. Regional Heterogeneity and Adaptive Subsidy Design

The comparative and numerical analyses demonstrate that subsidy effectiveness and efficiency vary substantially across regions. In regions with relatively low operating costs, subsidizing the LA mode yields higher long-term social welfare when fiscal resources are sufficient, as subsidies can be effectively transformed into service quality improvements.

Conversely, in regions with high operating costs or harsh geographic conditions, the IPFT mode exhibits greater resilience and higher subsidy efficiency under a limited budget. Several studies, including recent case-based analyses of urban–rural bus systems with shared passenger–freight services, advocate IPFT as a cost-effective solution for rural logistics development under budget constraints [21]. However, the present results indicate that its relative advantage is conditional on regional operating costs and fiscal constraints. This finding underscores the necessity of differentiated subsidy strategies rather than uniform policy prescriptions.

From an operational perspective, these findings indicate the feasibility of staged and adaptive subsidy approaches under heterogeneous regional conditions. In the initial stage, local governments may prioritize IPFT-based subsidies by contracting rural bus

companies to provide “first-mile” services, with subsidy eligibility linked to observable service indicators such as pickup frequency, route coverage. As logistics demand expands, market conditions stabilize, and subsidy support can be sustained over time, policy emphasis may gradually shift toward LA, enabling LSPs to invest in dedicated infrastructure and achieve higher service quality. When operating costs are extremely high, the marginal welfare gains from subsidies decline sharply, suggesting that market-based subsidy instruments alone may be insufficient to improve logistics accessibility. In such cases, complementary non-market interventions may be required.

In practice, county-level transportation authorities and agricultural bureaus can serve as primary implementing agencies, while subsidy disbursement may be conditional on periodic performance assessments. Monitoring mechanisms may include service quality audits, demand growth benchmarks, and cost-efficiency evaluations, ensuring that subsidy allocation dynamically responds to regional conditions rather than remaining fixed over time.

8. Conclusions

This paper investigates how government subsidies and collaborative transportation strategies can alleviate the unsustainable dilemma of rural “first-mile” logistics in agricultural product transportation. Using a Stackelberg game framework, the study derives equilibrium outcomes under alternative transportation modes and subsidy strategies. The results show that transportation mode selection and subsidy effectiveness jointly depend on market structure, regional operating conditions, and fiscal capacity, providing a clear basis for differentiated policy design.

From a sustainability perspective, the findings indicate that government subsidies alleviate the rural “first-mile” logistics dilemma not by mechanically lowering prices, but by reshaping firms’ strategic incentives and improving service accessibility. In equilibrium, subsidies relax financial constraints and are transformed into higher service levels, expanded logistics participation, and increased rural welfare. By jointly considering enterprise profits, farmers’ surplus, and government expenditure, the analysis provides an integrated assessment of economic viability, social inclusion, and fiscal sustainability in rural logistics systems. The results suggest that well-designed subsidy policies can enhance service quality and demand while avoiding excessive fiscal burdens, thereby supporting the long-term sustainability of rural logistics development.

Moreover, the study highlights the importance of differentiated and region-specific subsidy strategies. Subsidy effectiveness and efficiency vary systematically with regional operating conditions, market structure, and fiscal capacity, implying that no single subsidy approach is universally optimal. Adaptive subsidy frameworks, rather than uniform or broad-brush subsidy policies, are therefore more likely to support the resilience, inclusiveness, and long-term sustainability of rural logistics systems. From an international perspective, the applicability of these findings can be benchmarked by examining whether other regions exhibit comparable “first-mile” cost pressures, underutilized passenger transport networks, and fiscal constraints.

Admittedly, this study relies on theoretical modeling and numerical simulations rather than direct empirical data from specific regions. As a result, the analysis does not aim to provide case-specific policy prescriptions. Instead, the proposed framework is designed to uncover general equilibrium mechanisms through which subsidy intensity, subsidy recipient, and collaborative transportation structures interact in rural “first-mile” logistics. These mechanism-based insights provide a conceptual foundation for future empirical studies and policy evaluations using regional data, pilot program outcomes, or survey-based evidence.

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Abbreviations

The following abbreviations are used in this manuscript:

LSP	Logistics Service Provider
LA	Logistics Alliance
IPFT	Integrated Passenger-Freight Transit

Appendix A

Prerequisite Assumption. For the model to have a meaningful equilibrium, we assume the core parameter constraint $2br - \beta^2 > 0$. This ensures non-zero denominators in subsequent derivations and guarantees the strict concavity of the profit function with respect to decision variables.

Proof of Proposition 1. First, assume that e_i^A is known; then the optimal unit “first-mile” service price p_i^{A*} can be determined first, i.e., $\Pi_{LSPi}^{A*} = \max_{p_i^A} (p_i^A - c + s_A)(\theta - bp_i^A + \beta e_i^A) - \frac{r}{2} e_i^{A2} - \theta K$ (A1). Since $\partial^2 \Pi_{LSPi}^A / \partial (p_i^A)^2 < 0$, confirming that Π_{LSPi}^A is strictly concave in p_i^A , the maximum is uniquely determined by setting $\partial \Pi_{LSPi}^A / \partial p_i^A = 0$ and solve for the results: $p_i^{A*}(e_i^A) = \frac{(c-s_A)b+\theta+e_i^A\beta}{2b}$ and $q_i^{A*}(e_i^A) = \frac{1}{2}(b(s_A - c) + \beta e_i^A + \theta)$. Substitute the above results back into Formula (A1) to convert it into a univariate function of e_i^A : $\Pi_{LSPi}^{A*} = \max_{e_i^A} \frac{1}{4b} [b^2(c - s_A)^2 + (\theta + \beta e_i^A)^2 - 2b(e_i^{A2}r + e_i^A(c - s_A)\beta + (c - s_A + 2K)\theta)]$ (A2). Similarly, it is easy to prove that e_i^A is concave with respect to Formula (A2). Set the first-order derivative of Formula (A2) with respect to e_i^A equal to 0, and solve for the optimal e_i^{A*} . Substitute e_i^{A*} back into the relevant expressions to obtain p_i^{A*} , q_i^{A*} and Π_{LSPi}^{A*} . □

Proof of Property 1. (1) $\frac{\partial e_i^{A*}}{\partial s_A} = \frac{b\beta}{2br - \beta^2} > 0$ and $\frac{\partial q_i^{A*}}{\partial s_A} = \frac{b^2r}{2br - \beta^2} > 0$. By setting $\frac{\partial p_i^{A*}}{\partial s_A} = \frac{br}{2br - \beta^2} - 1 = 0$ and solving for r , we obtain $r_0 = \frac{\beta^2}{b}$. Thus, if $\frac{\beta^2}{2b} < r < \frac{\beta^2}{b}$, then $\frac{\partial p_i^{A*}}{\partial s_A} > 0$; if $r \geq \frac{\beta^2}{b}$, then $\frac{\partial p_i^{A*}}{\partial s_A} \leq 0$. (2) $\frac{\partial \Pi_{LSPi}^{A*}}{\partial s_A} = \frac{br(b(-c+s_A)+\theta)}{2br - \beta^2}$, and $\frac{\partial^2 \Pi_{LSPi}^{A*}}{\partial s_A^2} = \frac{b^2r}{2br - \beta^2} > 0$. By setting $\partial \Pi_{LSPi}^{A*} / \partial s_A = 0$, we find the threshold $s_1 = c - \frac{\theta}{b}$. To ensure s_1 is meaningful, we assume $c > \frac{\theta}{b}$ which is consistent with the reality of high operation costs in rural logistics. Thus, when $0 < s_A < s_1$, $\partial \Pi_{LSPi}^{A*} / \partial s_A < 0$; when $s_A > s_1$, $\partial \Pi_{LSPi}^{A*} / \partial s_A > 0$. (3) $\frac{\partial p_i^{A*}}{\partial \theta} = \frac{r}{2br - \beta^2} > 0$,

$\frac{\partial e_t^{A*}}{\partial \theta} = \frac{\beta}{2br - \beta^2} > 0$ and $\frac{\partial q_t^{A*}}{\partial \theta} = \frac{br}{2br - \beta^2} > 0$. (4) Similar to (2), by setting $\frac{\partial \Pi_{LSPt}^{A*}}{\partial \theta} = 0$, we obtain the threshold $s_1' = s_1 + 2K - \frac{\beta^2 K}{br}$, and $\frac{\partial^2 \Pi_{LSPt}^{A*}}{\partial \theta^2} > 0$. $\square$

Proof of Property 2. Substitute $c = c_0 - \alpha \ln K$ into the equilibrium solution of Proposition 1, we obtain: $\frac{\partial e_t^{A*}}{\partial K} = \frac{b\alpha\beta}{2bKr - K\beta^2} > 0$ and $\frac{\partial q_t^{A*}}{\partial K} = \frac{b^2 r \alpha}{2bKr - K\beta^2} > 0$. By setting $\frac{\partial p_t^{A*}}{\partial K} = \frac{\alpha(-br + \beta^2)}{K(2br - \beta^2)} = 0$ and solving for r , we get $r_0 = \frac{\beta^2}{b}$. Thus, the sign of $\frac{\partial p_t^{A*}}{\partial K}$ is opposite on either side of r_0 . Furthermore, $\frac{\partial \Pi_{LSPt}^{A*}}{\partial K} = \frac{b^2 r(-c_0 + s_A)\alpha + br(-2K + \alpha)\theta + K\beta^2\theta + b^2 r \alpha^2 \ln K}{K(2br - \beta^2)}$. By setting $\partial \Pi_{LSPt}^{A*} / \partial K = 0$, we solve for the threshold $s' = \frac{K(2br - \beta^2)\theta}{b^2 r \alpha} + c_0 - \frac{\alpha}{b} - \alpha \ln K = s_1 + \frac{\theta K}{b^2 r \alpha}(2br - \beta^2)$. Therefore, there exists a threshold s' such that the sign of $\frac{\partial \Pi_{LSPt}^{A*}}{\partial K}$ is opposite on either side of s' , which completes the proof. $\square$

Proof of Propositions 2 and 3. First, the bus company determines the service fee w^{A*} and service level e_t^{A*} . Combined with her profit formula and the relation $p_t^A = w^A + \delta^A$, we obtain: $\Pi_{BUST}^{A*} = \max_{w, e_t} (w + s_A)(\theta - bw^A - b\delta^A + \beta e_t^A) - \frac{m}{2} e_t^{A^2}$ (A3). Since $\frac{\partial^2 \Pi_{BUST}^{A*}}{\partial e_t^{A^2}} < 0$ and $\frac{\partial^2 \Pi_{BUST}^{A*}}{\partial w^{A^2}} < 0$, confirming that Π_{BUST}^{A*} is strictly concave in e_t^A and w^A , we set the first-order derivatives of Formula (A3) with respect to w^A and e_t^A to zero respectively, and solve for the results: $w^{A*}(\delta^A) = \frac{r(\theta - b\delta^A)}{2br - \beta^2}$ and $e_t^{A*}(\delta^A) = \frac{\beta(\theta - b\delta^A)}{2br - \beta^2}$. Substitute the above results back into the profit formula of the LSP, and we get: $\Pi_{LSPt}^{A*} = \max_{\delta^A} (\delta^A + s_A) \frac{br(\theta - b\delta^A)}{2br - \beta^2}$ (A4). Given $\frac{\partial \Pi_{LSPt}^{A*}}{\partial \delta^A} = \frac{br(a - b(s_A + 2\delta^A))}{2br - \beta^2}$ and $\frac{\partial^2 \Pi_{LSPt}^{A*}}{\partial \delta^{A^2}} = \frac{2b^2 r}{-2br + \beta^2} < 0$, we set the first-order derivative of Formula (A4) with respect to δ^A to zero, and solve for $\delta^{A*} = \frac{\theta - bs_A}{2b}$. Substitute the expression of δ^{A*} back into w^{A*} , e_t^{A*} , p_t^{A*} , q_t^{A*} , Π_{BUST}^{A*} and Π_{LSPt}^{A*} respectively, which completes the proof. Proposition 3 can be proven similarly. $\square$

Proof of Property 3. $\frac{\partial w^{A*}}{\partial s_A} = \frac{br}{4br - 2\beta^2} > 0$, $\frac{\partial e_t^{A*}}{\partial s_A} = \frac{b\beta}{4br - 2\beta^2} > 0$, and $\frac{\partial q_t^{A*}}{\partial s_A} = \frac{b^2 r}{4br - 2\beta^2} > 0$. For $\frac{\partial p_t^{A*}}{\partial s_A} = \frac{br}{4br - 2\beta^2} - \frac{1}{2}$, set $\frac{\partial p_t^{A*}}{\partial s_A} = 0$ and solve for r , we obtain $r = \frac{\beta^2}{b}$. Thus, the sign of $\frac{\partial p_t^{A*}}{\partial s_A}$ varies with the value of r . Given $\frac{\partial \Pi_{LSPt}^{A*}}{\partial s_A} = \frac{br(bs_A + \theta)}{8br - 4\beta^2} > 0$ and $\frac{\partial \Pi_{BUST}^{A*}}{\partial s_A} = \frac{br(bs_A + \theta)}{4br - 2\beta^2} > 0$, it is thus easy to derive that $\Pi_{LSPt}^{A*} = 2\Pi_{BUST}^{A*}$ and $\frac{\partial \Pi_{LSPt}^{A*}}{\partial s_A} = 2\frac{\partial \Pi_{BUST}^{A*}}{\partial s_A}$. Additionally, $\frac{\partial p_t^{A*}}{\partial \theta} = \frac{1}{2b} + \frac{r}{4br - 2\beta^2} > 0$, $\frac{\partial w^{A*}}{\partial \theta} = \frac{r}{4br - 2\beta^2} > 0$, $\frac{\partial e_t^{A*}}{\partial \theta} = \frac{\beta}{4br - 2\beta^2} > 0$, and $\frac{\partial q_t^{A*}}{\partial \theta} = \frac{br}{4br - 2\beta^2} > 0$. Since $\frac{\partial \Pi_{LSPt}^{A*}}{\partial \theta} = \frac{r(bs_A + \theta)}{8br - 4\beta^2} > 0$ and $\frac{\partial \Pi_{BUST}^{A*}}{\partial \theta} = \frac{r(bs_A + \theta)}{4br - 2\beta^2} > 0$, we have $\frac{\partial \Pi_{LSPt}^{A*}}{\partial \theta} = 2\frac{\partial \Pi_{BUST}^{A*}}{\partial \theta}$. $\square$

Proof of Property 4. Combining the conclusions of Propositions 2 and 3, if we set $s_A = s_B = s$, it is thus easy to derive that $p_t^{A*} - p_t^{B*} = 0$, $e_t^{A*} - e_t^{B*} = 0$, $q_t^{A*} - q_t^{B*} = 0$, $\Pi_{LSPt}^{A*} - \Pi_{LSPt}^{B*} = 0$ and $\Pi_{BUST}^{A*} - \Pi_{BUST}^{B*} = 0$, which completes the proof. $\square$

Proof of Property 5. Combining the conclusions of Propositions 2 and 3, if we set $s_A = s_B = s$, we obtain $w^{A*} = \frac{r(\theta + bs)}{4br - 2\beta^2}$ and $w^{B*} = \frac{\theta r - 3brs + 2s\beta^2}{4br - 2\beta^2}$. It is thus easy to derive that $w^{A*} - w^{B*} = s$. By setting $w^{B*} = 0$, we get the threshold $s_2 = \frac{r\theta}{3br - 2\beta^2}$. Moreover, since $\frac{\partial w^{B*}}{\partial s_B} = -1 + \frac{bm}{4bm - 2\beta^2} < 0$, thus when $s_B > s_2$, $w^{B*} < 0$, which completes the proof. $\square$

Proof of Property 6. It follows from Propositions 2 and 3 that $\delta^{A*} = \frac{\theta - bs_A}{2b}$ and $\delta^{B*} = \frac{\theta + bs_B}{2b}$, thus $\delta^{A*} + \delta^{B*} = \frac{\theta}{b}$ holds constantly. We have $\frac{\partial \delta^{A*}}{\partial s_A} = -\frac{1}{2} < 0$, $\frac{\partial \delta^{B*}}{\partial s_B} = \frac{1}{2} > 0$, $\frac{\partial \delta^{A*}}{\partial \theta} =$

$\frac{1}{2b} > 0$, and $\frac{\partial \delta^{B*}}{\partial \theta} = \frac{1}{2b} > 0$. By setting $\delta^{A*} = 0$ and solving for s_A , we obtain $s_A = \frac{\theta}{b}$. Thus, when $s_A > \frac{\theta}{b}$, $\delta^{A*} < 0$, which completes the proof. $\square$

Proof of Proposition 4. By setting $S_1 = S_2 = S_3$, we obtain $s_A^* = s_B^* = 2c - \frac{\theta}{b}$. Substituting these into $\Pi_{Gj}^{X*}, X = \{A, B, N\}, j = \{i, t\}$, yields:

$$\begin{array}{l} \Pi_{Gi}^{A*} = \frac{b^2 c^2 r((-6+b)br + 3\beta^2) + 2(2br - \beta^2)(b(c-2K)r + K\beta^2)\theta}{2(-2br + \beta^2)^2} \\ \Pi_{Gt}^{A*} = \frac{bcr(bc((-2+b)br + \beta^2) + 4br\theta - 2\beta^2\theta)}{2(-2br + \beta^2)^2} \\ \Pi_{Gt}^{B*} = \frac{bcr(bc((-2+b)br + \beta^2) + 4br\theta - 2\beta^2\theta)}{2(-2br + \beta^2)^2} \\ \Pi_{Gi}^{N*} = \frac{b^2 c^2 r(b(10+b)r - 5\beta^2) - 2(b^2((8+b)c + 4K)r^2 - 4b(c+K)r\beta^2 + K\beta^4)\theta + r(b(6+b)r - 3\beta^2)\theta^2}{2(-2br + \beta^2)^2} \\ \Pi_{Gt}^{N*} = \frac{r\theta(-7\beta^2\theta + b^2r(-16c + \theta) + 2b(4c\beta^2 + 7r\theta))}{8(-2br + \beta^2)^2} \end{array}$$

It can be observed that $\Pi_{Gt}^{A*} = \Pi_{Gt}^{B*}$ holds constantly; thus, it is only necessary to compare the magnitudes of four cases: Π_{Gi}^{A*} , Π_{Gt}^{A*} , Π_{Gi}^{N*} and Π_{Gt}^{N*} .

First, compare Π_{Gi}^{A*} and Π_{Gt}^{A*} . By setting $\Pi_{Gi}^{A*} - \Pi_{Gt}^{A*} = 0$, we obtain $r_1 = \frac{K\beta^2\theta}{b^2c^2 + 2bK\theta}$. Given $\frac{\partial(\Pi_{Gi}^{A*} - \Pi_{Gt}^{A*})}{\partial r} = \frac{b^2c^2\beta^2}{(-2br + \beta^2)^2} > 0$, when $r < r_1$, $\Pi_{Gi}^{A*} < \Pi_{Gt}^{A*}$; when $r > r_1$, $\Pi_{Gi}^{A*} > \Pi_{Gt}^{A*}$.

Second, compare Π_{Gi}^{A*} and Π_{Gi}^{N*} . By setting $\Pi_{Gi}^{A*} - \Pi_{Gi}^{N*} = 0$, we obtain $r_2 = \frac{\beta^2(4bc - 3\theta)}{b(8bc - (6+b)\theta)}$.

Meanwhile, $\frac{\partial(\Pi_{Gi}^{A*} - \Pi_{Gi}^{N*})}{\partial r} = \frac{\beta^2(2bc - \theta)(-4bc(-2br + \beta^2) - 2b(3+b)r\theta + 3\beta^2\theta)}{2(2br - \beta^2)^3}$ and $\frac{\partial^2(\Pi_{Gi}^{A*} - \Pi_{Gi}^{N*})}{\partial r^2} = -\frac{b\beta^2(2bc - \theta)(8bc(2br - \beta^2) - (4b(3+b)r + (-6+b)\beta^2)\theta)}{(-2br + \beta^2)^4}$. Since $8bc(2br - \beta^2) - (4b(3+b)r + (-6+b)\beta^2)\theta > 8bc((2br - \beta^2)c - br)$, $\frac{\partial^2(\Pi_{Gi}^{A*} - \Pi_{Gi}^{N*})}{\partial r^2} < 0$ over the interval $r \in [\frac{\beta^2c}{b(2c-1)}, +\infty)$.

Setting $\frac{\partial(\Pi_{Gi}^{A*} - \Pi_{Gi}^{N*})}{\partial r} = 0$, we get $r' = \frac{\beta^2(4bc - 3\theta)}{8b^2c - 2b(3+b)\theta} > \frac{\beta^2c}{b(2c-1)}$. Thus, $\Pi_{Gi}^{A*} - \Pi_{Gi}^{N*}$ decreases with r when $r > r'$. It is easy to know that $r_2 > r'$; therefore, when $r' < r < r_2$, $\Pi_{Gi}^{A*} > \Pi_{Gi}^{N*}$; when $r > r_2$, $\Pi_{Gi}^{A*} < \Pi_{Gi}^{N*}$.

Third, compare Π_{Gt}^{A*} and Π_{Gt}^{N*} . By setting $\Pi_{Gt}^{A*} - \Pi_{Gt}^{N*} = 0$, we obtain $r_3 = \frac{\beta^2(-2bc + 7\theta)}{b(2(-2+b)bc + (14+b)\theta)}$. Given $\frac{\partial(\Pi_{Gt}^{A*} - \Pi_{Gt}^{N*})}{\partial r} = -\frac{\beta^2(2bc - \theta)(2bc(2(-1+b)br + \beta^2) + (2b(7+b)r - 7\beta^2)\theta)}{8(2br - \beta^2)^3}$ and $2bc(2(-1+b)br + \beta^2) + (2b(7+b)r - 7\beta^2)\theta > (2bc + 1)\beta^2b > 0$, $\frac{\partial(\Pi_{Gt}^{A*} - \Pi_{Gt}^{N*})}{\partial r} < 0$ holds constantly. Therefore, when $r < r_3$, $\Pi_{Gt}^{A*} > \Pi_{Gt}^{N*}$; when $r > r_3$, $\Pi_{Gt}^{A*} < \Pi_{Gt}^{N*}$.

Finally, compare the magnitudes of r_1 , r_2 and r_3 . $r_1 - r_2 = -\frac{\beta^2(4bc^3 + \theta(-3c^2 + K\theta))}{(8bc - (6+b)\theta)(bc^2 + 2K\theta)}$. Since $r_1 > 0$ and $r_2 > 0$ must hold, $4bc^3 + \theta(-3c^2 + K\theta) > K\theta^2 > 0$, so $r_1 - r_2 < 0$. $r_2 - r_3 = \frac{4\beta^2(2b^2c^2 - bc\theta + \theta^2)}{(8bc - (6+b)\theta)(2(-2+b)bc + (14+b)\theta)}$. Since $r_2 > 0$ and $r_3 > 0$ must hold, $2(-2+b)bc + (14+b)\theta < 0$; meanwhile, $2b^2c^2 - bc\theta + \theta^2 > \theta^2 > 0$, so $r_2 - r_3 < 0$. This completes the proof. $\square$

Proof of Proposition 5. Assuming that $s_A = s_B = s$, according to the definition of subsidy efficiency $U_j^X, X = \{A, B\}, j = \{i, t\}$, we obtain

$$\begin{array}{l} U_i^A = \frac{b^2r(c-s)(br((2+b)c - (-2+b)s) - (c+s)\beta^2) - 2(b^2r^2((2+b)c + 4K - bs) - b(c+4K)r\beta^2 + K\beta^4)\theta + r(b(2+b)r - \beta^2)\theta^2}{2brs(2br - \beta^2)(b(-c+s) + \theta)} \\ U_t^A = \frac{bs((-2+b)br + \beta^2) + (b(6+b)r - 3\beta^2)\theta}{4bs(2br - \beta^2)} \\ \Pi_{Gt}^{N*} = \frac{bs((-2+b)br + \beta^2) + (b(6+b)r - 3\beta^2)\theta}{4bs(2br - \beta^2)} \end{array}$$

It is easy to know that $U_t^A = U_t^B$ holds constantly; thus, it is only necessary to compare the magnitude relationship between U_t^A and U_t^A . Construct the function $f(s) = U_t^A - U_t^A$; after rearrangement, it can be known that $f(s)$ is a quadratic function with respect to s , and there exist two analytical solutions:

$$s_{3,4} = \frac{\sqrt{r}(bc(b(2+3b)r-\beta^2)-2((-2+b)br+\beta^2)\theta) \pm \sqrt{b^2c^2r(b(6+b)r-3\beta^2)^2+16K(-2br+\beta^2)^2((-2+b)br+\beta^2)\theta}}{2b\sqrt{r}((-2+b)br+\beta^2)}.$$

When $0 < r < \frac{\beta^2}{(2-b)b}$, $f(s)$ opens upwards; when $r > \frac{\beta^2}{(2-b)b}$, $f(s)$ opens downwards. Therefore, there exist two thresholds $s_3 < s_4$ such that the subsidy efficiency changes with the subsidy intensity s . This completes the proof. $\square$

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