# Optimal Taxes and Subsidies for Sustainable City Logistics: A Multi-Agency Bilevel Game-Theoretic Framework

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## Short summary

Urban freight transport contributes substantially to congestion, pollution, and inefficiency in cities. To mitigate these adverse effects, policymakers are increasingly exploring incentive based mechanisms that promote sustainable transportation modes, such as inland waterways and rail-based scheduled services. The effectiveness of such policies critically depends on the strategic interactions among multiple decision making agencies. This study develops a multi agency game theoretic bilevel framework for sustainable city logistics involving transportation authorities, logistics service providers (LSPs), and end customers. The authority determines tax and subsidy policies under a budget constraint. LSPs respond by optimizing mode choice and pricing strategies, while customers select services through a utility maximizing logit model. A case study of Amsterdam compares three feasible implementation strategies and evaluates their effectiveness in improving system efficiency, promoting sustainable mode adoption, and balancing policy feasibility with economic performance.

**Keywords**: Bilevel optimization, Discrete choice modelling, Environmental impacts on transport, Game-theoretic model, Multi-modal transport, Urban freight transport and city logistics

## 1 Introduction

The growing intensity of urban goods distribution driven by the frequent restocking needs of retailers, restaurants, and service establishments has substantially increased the external costs associated with last mile freight operations in dense urban environments. Freight vehicles are now responsible for approximately 25% of urban $CO_2$ emissions and up to 30% of peak-hour congestion (Savelsbergh & Van Woensel, 2016; European Court of Auditors, 2023).

In response, transportation authorities are increasingly adopting policy instruments aimed at internalizing these externalities and promoting more sustainable freight modes. Among these, incentive-based mechanisms, particularly road usage charges combined with subsidies for lower-emission scheduled alternatives such as inland waterways, metro freight systems, and off-peak deliveries, have gained significant attention (Takman & Gonzalez-Aregall, 2024; Carattini et al., 2018). However, the efficacy of such tax-and-subsidy schemes is highly sensitive to the strategic behavior of logistics actors and the heterogeneous preferences of urban consumers (Jagers et al., 2019; Holguín-Veras et al., 2018).

The design of such fiscal instruments is inherently hierarchical. Public authorities first set tax and subsidy schemes under budgetary and political constraints. Logistics service providers then optimize their multimodal mode allocation and pricing decisions, after which heterogeneous end customers choose services based on cost, reliability, and environmental preferences. Ignoring any of these layers can lead to unintended modal shifts, welfare losses, or inefficient public spending. This highlights the need for modeling frameworks that explicitly capture the full vertical structure of decision making in urban freight systems.

Despite this clear hierarchical structure, most existing studies examine only selected components of the system rather than its full vertical integration. For example, Tundulyasaree et al. (2025) model the relationship between authorities and logistics service providers as a bilevel optimization problem and show that, under deterministic settings, a full subsidy funded by a distance based tax can be socially optimal in a Pickup and Delivery with Scheduled Lines system. Similarly, Tamannaei et al. (2021) adopt a game-theoretic framework to analyse competition between freight transport modes under government intervention, particularly between road and intermodal road rail

systems, demonstrating how pricing and regulatory policies shape modal shares and sustainability outcomes. Other game-theoretic studies consider competition under highly stylised one to one market structures (Ma et al., 2022, 2023).

From a public finance perspective, the literature highlights the importance of revenue recycling in improving the social acceptability of environmental taxation (Jagers et al., 2019). However, these research streams remain fragmented and have yet to be integrated into a unified operational framework. As a result, most approaches still focus on isolated aspects of the system, such as pricing without behavioral demand modeling (Li et al., 2015), policy evaluation without optimization (Comi et al., 2012), or mode choice analysis without routing decisions (Arencibia et al., 2015).

Moreover, limited attention has been given to feasible implementation strategies. Ultimately, a policy mechanism that cannot be put into practice has limited practical value. How incentive based mechanisms can be operationalized, and how they perform relative to existing environmental policies, therefore remains an open question. Existing studies and practices suggest several possible pathways, including direct subsidy schemes for modal shift such as the Dutch SRVB and Modal Shift Subsidy (Netherlands Enterprise Agency (RVO), 2025), government operated scheduled line services within integrated freight transport systems (Ghilas et al., 2016, 2018; Tundulyasaree et al., 2025), and emerging platform based approaches inspired by Mobility as a Service, often referred to as Logistics as a Service (Jittrapirom et al., 2017). However, these alternatives have rarely been examined within a unified framework that captures their behavioral, operational, and policy implications in a comparable manner.

This study addresses these gaps by introducing a tractable, unified, multi agency game theoretic bilevel framework that captures the decision making process across three stakeholder groups: transportation authorities, LSPs, and customers. The model endogenously determines tax and subsidy levels under a budget constraint, incorporates LSP mode choice and profit maximizing pricing decisions, and embeds a logit based discrete choice model to capture customer responses to service attributes, including price, reliability, and delivery mode. In addition, the framework is used to evaluate and compare three feasible implementation strategies for incentive based city logistics, assessing their relative effectiveness in improving system efficiency, promoting sustainable mode adoption, and balancing policy feasibility with economic performance.

## 2 Methodology

We propose an incentive-based pricing framework to implement a subsidy credit scheme within a city logistics network. The problem is formulated as a bilevel optimization model, where the upper-level (leader) problem corresponds to the transportation authority determining the allocation of subsidies across the network. The lower-level (follower) problem captures the profit-maximizing decisions of LSPs, which are dependent on the customer choice behaviors reacting to the pricing strategies.

Let $r_{i,j}$ denote the subsidy rate for waterway delivery from depot $i \in \mathcal{L}$ to customer $j \in \mathcal{C}$, and let $t_{i,j}$ denote the exogenous tax imposed on road delivery. The quantities delivered by road and water are denoted by $x^r_{i,j}$ and $x^w_{i,j}$, respectively. To ensure that subsidies do not create socially inefficient behavior, the subsidy rate is bounded above by the corresponding waterway delivery cost:

$$r_{i,j} \leq c^w_{i,j}, \qquad \forall (i,j) \in \mathcal{A}^w. \tag{1}$$

Here, $\mathcal{A}$ denotes the set of feasible service connections between LSP depots and customers in the multimodal city logistics network, while $\mathcal{A}^r$ and $\mathcal{A}^w$ denote the subsets of road-based and inland waterway-based connections, respectively.

The authority seeks to promote a modal shift toward inland waterways by maximizing total waterway demand, subject to a budget constraint stating that total subsidy expenditure cannot exceed the available budget plus road tax revenues:

$$\sum_{(i,j)\in\mathcal{A}^w} r_{i,j} x^w_{i,j} - \sum_{(i,j)\in\mathcal{A}^r} t_{i,j} x^r_{i,j} \leq B \tag{2}$$

At the lower level, customer demand is endogenously allocated across LSP services and an outside alternative. Let $y_{i,j}$ denote the expected demand assigned to depot $i$ by customer $j$, and let $\hat{y}_j$ denote the expected demand allocated to the outside alternative. The flow conservation conditions

are

$$x^w_{i,j} + x^r_{i,j} = y_{i,j}, \qquad \forall (i,j) \in \mathcal{A}, \tag{3a}$$

$$\sum_{i \in \mathcal{L}} y_{i,j} + \hat{y}_j = d_j, \qquad \forall j \in \mathcal{C}. \tag{3b}$$

Here, $d_j$ denotes the fixed total demand of customer $j \in \mathcal{C}$. Customer choice is modeled through a multinomial logit structure. The systematic utility of choosing depot $i$ for customer $j$ is specified as

$$V^{\mathsf{LSP}}_{i,j} = \Psi_{i,j} - \beta_c p_{i,j} - \beta_w x^w_{i,j}, \qquad \forall (i,j) \in \mathcal{A}, \tag{4a}$$

$$V^{\mathsf{ALT}}_j = -\beta_c p^{\mathsf{ALT}}_j, \qquad \forall j \in \mathcal{C}. \tag{4b}$$

where $\beta_c$ captures price sensitivity, $\beta_w$ reflects customers' aversion to waterway delivery, and $\Psi i, j$ is an alternative specific constant. The resulting demand shares are

$$\frac{y_{i,j}}{d_j} = \frac{e^{V^{\mathsf{LSP}}_{i,j}}}{\sum_{i \in \mathcal{L}} e^{V^{\mathsf{LSP}}_{i,j}} + e^{V^{\mathsf{ALT}}_j}}, \qquad \forall (i,j) \in \mathcal{A}, \tag{5a}$$

$$\frac{\hat{y}_j}{d_j} = \frac{e^{V^{\mathsf{ALT}}_j}}{\sum_{i \in \mathcal{L}} e^{V^{\mathsf{LSP}}_{i,j}} + e^{V^{\mathsf{ALT}}_j}}, \qquad \forall j \in \mathcal{C} \tag{5b}$$

Using the logit structure, the LSP price can be written as

$$p_{i,j} = p^{\mathsf{ALT}}_j + \frac{1}{\beta_c}\left(\Psi_{i,j} - \beta_w x^w_{i,j} + \ln(\frac{\hat{y}_j}{y_{i,j}})\right), \qquad \forall (i,j) \in \mathcal{A}. \tag{6}$$

The resulting bilevel optimization formulation is summarized in (7).

$$\max_{\boldsymbol{r}} \quad \sum_{(i,j) \in \mathcal{A}^w} x^w_{i,j} \tag{7a}$$

$$\text{s.t.} \quad \sum_{(i,j) \in \mathcal{A}^w} r_{i,j} x^w_{i,j} - \sum_{(i,j) \in \mathcal{A}^r} t_{i,j} x^r_{i,j} \le B, \tag{7b}$$

$$r_{i,j} \ge 0, \qquad \forall (i,j) \in \mathcal{A}^w, \tag{7c}$$

$$r_{i,j} \le c^w_{i,j}, \qquad \forall (i,j) \in \mathcal{A}^w, \tag{7d}$$

$$(\boldsymbol{x}^w, \boldsymbol{x}^r) \in \underset{\boldsymbol{x}^w, \boldsymbol{x}^r, \boldsymbol{y}, \hat{\boldsymbol{y}}, \boldsymbol{p}}{\arg\min} \sum_{(i,j) \in \mathcal{A}^r} (c^r_{i,j} + t_{i,j}) x^r_{i,j} + \sum_{(i,j) \in \mathcal{A}^w} (c^w_{i,j} - r_{i,j}) x^w_{i,j} - \sum_{(i,j) \in \mathcal{A}} p_{i,j}(x^w_{i,j} + x^r_{i,j}) \tag{7e}$$

$$\text{s.t.} \quad \sum_{i \in \mathcal{L}} y_{i,j} + \hat{y}_j = d_j, \qquad \forall j \in \mathcal{C}, \tag{7f}$$

$$x^w_{i,j} + x^r_{i,j} = y_{i,j}, \qquad \forall (i,j) \in \mathcal{A}, \tag{7g}$$

$$p_{i,j} = p^{\mathsf{ALT}}_j + \frac{1}{\beta_c}\left(\Psi_{i,j} - \beta_w x^w_{i,j} + \ln(\frac{\hat{y}_j}{y_{i,j}})\right), \qquad \forall (i,j) \in \mathcal{A}, \tag{7h}$$

$$x^r_{i,j}, x^w_{i,j} \ge 0, \qquad \forall (i,j) \in \mathcal{A}, \tag{7i}$$

$$p_{i,j} \ge 0, \qquad \forall (i,j) \in \mathcal{A}, \tag{7j}$$

$$y_{i,j} > 0, \qquad \forall (i,j) \in \mathcal{A}, \tag{7k}$$

$$\hat{y}_j > 0, \qquad \forall j \in \mathcal{C}. \tag{7l}$$

The main decision variables of the leader are the subsidies ($r_{i,j}$) provided by the authority. The follower problem characterizes the equilibrium between LSPs and customers, parameterized by the subsidy vector $\boldsymbol{r}$, and incorporates a discrete choice model parameterized by $\boldsymbol{p}$. To solve the model, we reformulate the bilevel problem as a single level program using Karush Kuhn Tucker conditions, following Luan et al. (2025). The resulting nonlinear terms from the logit based demand model are approximated through piecewise linearization, and the final reformulation is solved using a branch and bound algorithm.

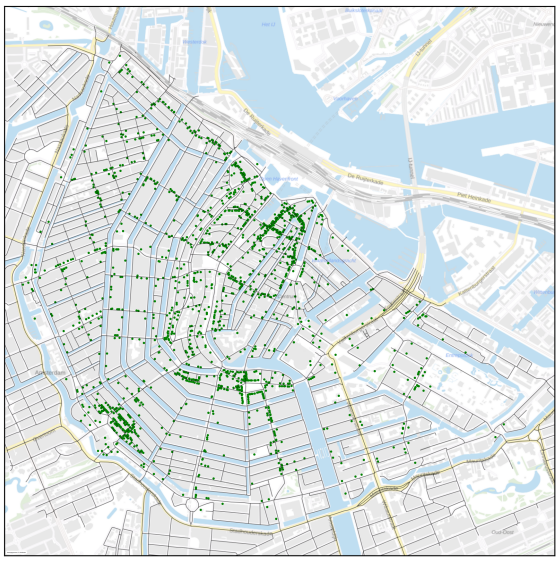


Figure 1: Case Study: Amsterdam City Center. The green dots indicate the locations of HoReCa customers.

## 3 Case Study

In this section, the proposed methodology is illustrated through a case study of HoReCa supply in the city center of Amsterdam, where urban freight distribution combines road transport with inland waterway transport as a potential sustainable alternative. The study area includes 1,635 HoReCa establishments, shown in Figure 1. We compare three implementation strategies: the Dutch Subsidy Scheme for the Sustainability of Inland Vessels (SRVB), Scheduled Lines (SL), and Logistics as a Service (LaaS). Under SRVB, an LSP receives a subsidy whenever a delivery is shifted from road to waterway transport. Under SL, waterway transport is provided through predefined government operated scheduled services, each associated with a subsidy level. Under LaaS, route choices are directly observable, allowing the authority to design route specific subsidies. This provides the highest level of flexibility among the three strategies.
To facilitate comparison, we use a modified network configuration shown in Figure 2. Customers are filtered based on proximity to transfer points so that direct or near direct waterway delivery is feasible, yielding 96 customers in the final sample. Under LaaS and SRVB, customers can be served fully by waterway when that mode is selected. Under SL, however, transhipment remains necessary because scheduled services are fixed and do not provide direct access to all customers. The red triangle in Figure 2 denotes the LSP depot, and different depot locations are examined later. Throughout the results section, waterway usage is reported as a percentage, which can also be interpreted as the expected share of waterway deliveries.

***Analysis 1: Comparison of implementation strategies***

We first compare the three implementation strategies across different authority budget levels. Unless otherwise stated, the case study assumes a road tax of €0.2 per unit, a customer price sensitivity parameter of $\beta_c = 1$ per euro, and a customer disutility parameter for waterway delivery of $\beta_w = 0.02$ per unit. Delivery costs are assumed to be distance dependent, with a unit cost of €1 per kilometer for both road and waterway transport. The alternative service price is fixed at €3.2 per unit. Figure 3 presents the resulting waterway usage percentages for budgets ranging from €10 to €140.
All three strategies improve sustainability outcomes as the authority's budget increases, but their performance differs substantially. SRVB performs poorly under low budget levels because the available subsidy is spread uniformly across all potential waterway deliveries, resulting in weak incentives. Its performance improves as the budget rises, but soon reaches saturation because the subsidy for each waterway delivery cannot exceed the corresponding service cost. SL follows a similar pattern but generally performs better than SRVB, since subsidies can be differentiated across scheduled services. In some intermediate budget ranges, SL slightly outperforms LaaS. However, its fixed service structure also limits further gains. Overall, LaaS delivers the strongest performance

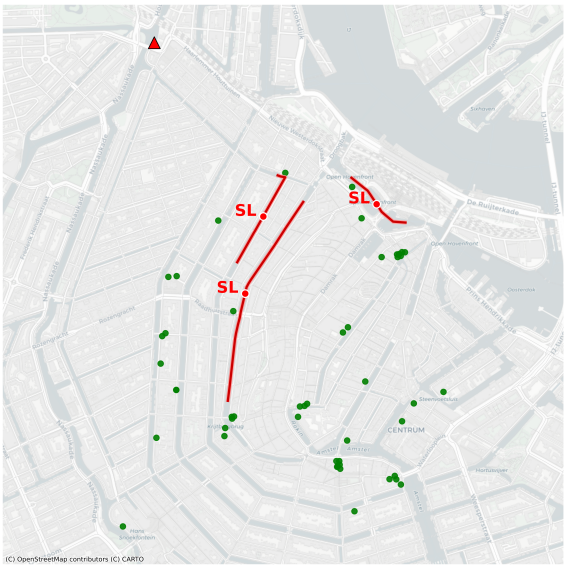



Figure 2: Modified network configuration. The green dots indicate the locations of the selected customers. The red lines denote the predetermined scheduled lines. The red triangle represents the LSP depot.

across most budget levels. Its route specific subsidy design allows meaningful improvements even under limited budgets and supports continued gains as the budget increases. These results highlight the flexibility and effectiveness of LaaS as a policy instrument for sustainable urban freight transport.

***Analysis 2: Sensitivity to the alternative service price***

We next examine how the three strategies respond to changes in the exogenous price of the alternative service. Figure 4 presents the results for alternative prices ranging from €2.0 to €3.9 per unit. From a policy perspective, a desirable implementation strategy should remain effective under changing market conditions.
Among the three strategies, LaaS shows the highest robustness. Its performance varies only slightly across different alternative price levels, indicating strong resilience to external market fluctuations. SRVB is the most sensitive strategy, with performance becoming increasingly dispersed as the authority's budget rises. SL displays an intermediate level of robustness. Its outcomes are more stable than those of SRVB but more sensitive than those of LaaS. The stepwise pattern observed under SL reflects its discrete service structure, since subsidies are tied to a limited set of predetermined scheduled lines. Overall, the sensitivity analysis confirms that LaaS delivers the most stable sustainability improvements across a broad range of market conditions.

## 4 Conclusion and perspectives

This study develops a multi-agency game theoretic framework to analyse incentive-based policies for sustainable city logistics, with a particular focus on promoting modal shifts toward inland waterways. The framework captures the strategic interactions among transportation authorities, LSPs, and end customers. It is formulated as a bilevel optimization model in which the authority maximizes the share of waterway deliveries under a budget constraint, while the lower level captures the operational and pricing decisions of the LSP together with customer responses represented through a discrete choice model.
A case study based on central Amsterdam is used to compare three implementation strategies: SRVB, Scheduled Lines, and Logistics as a Service. The results show that all three strategies improve sustainability outcomes as the available budget increases, but LaaS performs best across most budget levels because it enables more flexible and targeted subsidy design. The sensitivity analysis further shows that LaaS is more robust to variations in the alternative service price, whereas SRVB is the most sensitive and SL shows intermediate performance. Overall, the findings

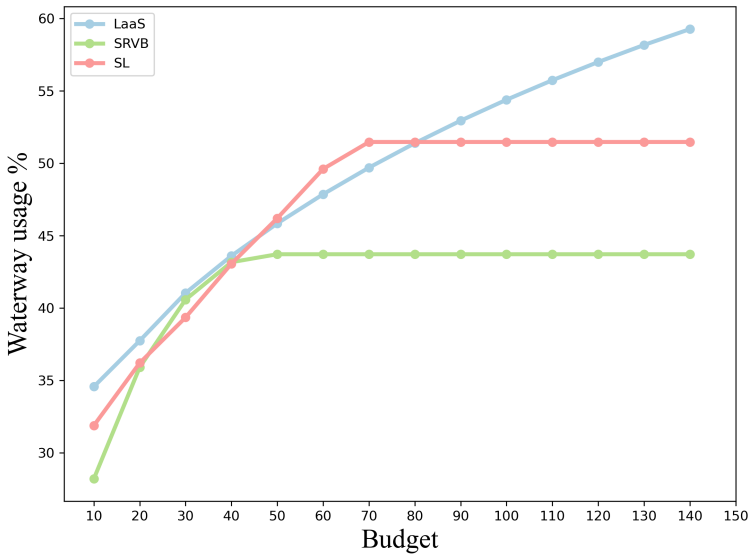



Figure 3: Waterway usage percentages under the three implementation strategies across authority budget levels.

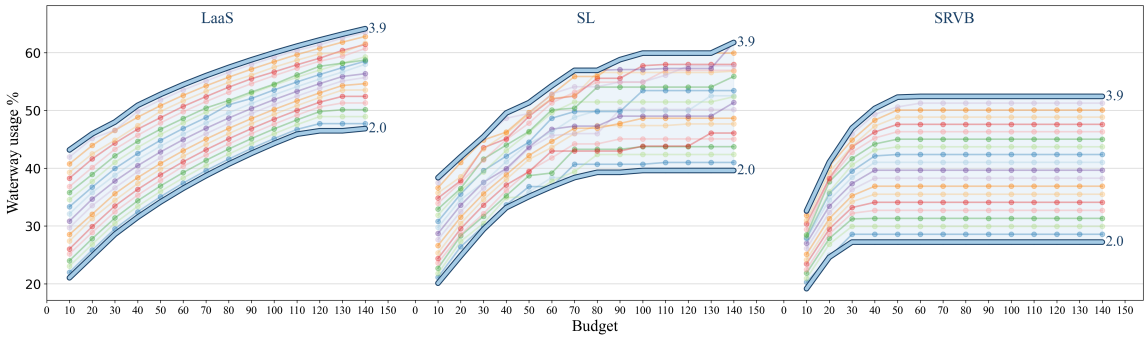



Figure 4: Waterway usage percentages under three implementation strategies across authority budget levels and alternative service prices. Different colors indicate different alternative service prices, varying from €2.0 to €3.9 per unit. The lower and upper bounds of this range (€2.0 and €3.9) are highlighted.

suggest that flexible and behaviorally informed incentive mechanisms are more effective and robust than rigid subsidy schemes in supporting sustainable modal shifts in city logistics.
Future research may extend the framework to competitive settings with multiple heterogeneous LSPs and richer customer behavior. It would also be valuable to examine practical deployment issues related to digital coordination platforms, including data availability, institutional coordination, and stakeholder acceptance.

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