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InnoWaTr

Incentivizing the uptake of inland waterway transport through taxes and subsidies

Report Task 2.6

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Within InnoWaTr, we are investigating how to collaborate along the value chain to make inland waterway transportation feasible. As a part of this, we developed algorithms for analyzing logistics and FFC cooperation. This report describes research on the interaction between a policymaker and a logistics service provider (LSP) cooperating within one freight flow coalition, optimizing the logistics of the LSP and determining government policy which helps to align the LSP's cost minimization goals with the overall goal of maximizing inland waterway utilization.

Executive summary: Frequently, the uptake of inland waterway transportation as a replacement of road transport only works in small geographic areas. A key aspect of the financial feasibility of inland waterway transportation is local regulations interacting with the decision-making of logistics service providers who minimize their own costs. Currently, inland waterway transport (or any other type of scheduled line transport) is still more expensive than road transport. To unlock the environmental benefits of inland waterways by increasing their uptake, public authorities throughout the North-Sea Region and beyond can incentivize logistics service providers using road access charges and subsidies for inland waterways. In this paper, we explore the interrelationship between logistics decision-making and public regulations, and find that fully subsidizing scheduled lines such as inland waterway transport is optimal to minimize driven road-distances. The subsidy can be funded via road access charges. In numerical experiments, we see emission reductions of up to 15%.

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Innovative Applications of O.R.

Optimal taxes and subsidies to incentivize modal shift for inner-city freight transport

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ABSTRACT

With increasing freight demands for inner-city transport, shifting freight from road to scheduled line services such as buses, metros, trams, and barges is a sustainable solution. Public authorities typically impose economic policies, including road taxes and subsidies for scheduled line services, to achieve this modal shift. This study models such a policy using a bilevel approach: at the upper level, authorities set road taxes and scheduled line subsidies, while at the lower level, carriers arrange transportation via road or a combination of road and scheduled lines. We prove that fully subsidizing the scheduled line is an optimal and budget-efficient policy. Due to its computational complexity, we solve the problem heuristically using a bisection algorithm for the upper level and an Adaptive Large Neighborhood Search (ALNS) for the lower level. Our results show that optimally setting the subsidy and tax can reduce the driving distance by up to 15% and substantially increase modal shift, albeit at a higher operational cost due to increased taxes. Furthermore, increased scheduled line frequency and decreased geographical scatteredness of freight orders increase modal shift. We found that an additional budget provides a better trade-off between minimizing distance and transportation costs than solely increasing the subsidy level for the partial subsidy policy. In a Berlin, Germany, case study, we find that up to 2.9% reduction in driving distance can be achieved due to 23.2% scheduled line usage, which amounts to an increase of multiple orders of magnitude, despite only using a few stations for transshipment.

1. Introduction

Integrating scheduled line services for inner-city freight transport can help address the challenges of increasing demand. E-commerce sales are projected to reach \$6.3 trillion with an 8.8% growth in 2024 (Snyder, 2024). This surge in demand for urban transport contributes to air pollution, road congestion, and a decline in quality of life. A promising solution is integrating freight transport into passenger scheduled line services. These services utilize existing urban transportation operating on fixed timetables, such as buses, metros, trams, and barges. During off-peak periods, the spare capacity in these services can be utilized for freight, increasing system efficiency and reducing the impact of road freight vehicles by minimizing road distances (Savelsbergh & Van Woensel, 2016). Nonetheless, implementing this modal shift is difficult because transshipment requires additional time for loading and unloading, as well as handling costs. Therefore, proper incentives are required to encourage carriers to shift the freight off the road.

Carbon taxes and subsidies for modal shift are common economic policies. Takman and Gonzalez-Aregall (2024) reviewed more than 90 European projects for modal shift since 2000 and found that most of these projects target economic policies, including taxes and subsidies, to encourage a shift to railway transportation. According to ex-ante reports, national-level grants and subsidies have shown positive performance, while EU-level policies have had mixed success. Despite total EU funding of around €1.1 billion, the EU's regulatory and financial support for intermodality has not been sufficient for intermodal freight transport to compete effectively with road transportation (European Court of Auditors, 2023). Tax policies often face societal opposition due to higher costs, necessitating reinvesting tax revenue (Jagers et al., 2019). Therefore, the proper settings for these economic policies are crucial to ensure their success.

In this paper, we aim to investigate the effect of road tax and scheduled line service subsidy on increasing the freight modal shift for inner-city freight transport settings. To achieve this, we develop a bilevel model to determine the optimal road tax and scheduled line service subsidy, where the subsidy is derived from recycled tax revenue and a given budget. The upper level of the model represents the perspective of a transportation authority, which aims to minimize total road freight distance by imposing road taxes and setting the scheduled line service subsidy. The lower level represents the perspective of a carrier who aims to minimize transportation costs within the imposed

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system. We analyze the theoretical properties of this model and derive the structure of optimal policies. In addition, we developed a combined ALNS and a bisection method to solve artificially generated instances, as well as a case study based on the city of Berlin.

Our contributions are threefold. First, we propose a novel model for the transportation authority to set policies (tax and subsidy) that factor in the carrier's operational considerations. Second, we analytically show that a policy with a fully subsidized scheduled line achieves the minimum possible driving distance, thereby representing an optimal policy, despite requiring considerable road tax to fund the subsidy. Third, we conduct extensive numerical experiments on realistically sized instances, which show that the optimal policy can substantially increase modal shift, resulting in considerably lower driving distances. However, distance reduction requires high tax levels, resulting in a substantial cost increase for carriers.

The remainder of this paper is structured as follows: In Section 2, we review related research on economic policies in freight transportation and the literature on operating and planning scheduled lines integrated into inner-city freight transport. In Section 3, we describe the problem and introduce the bilevel formulation of the problem. In Section 4, we provide optimal solution properties. Furthermore, Section 5 presents the combined bisection and ALNS for solving the proposed problem. Section 6 outlines the experimental designs and discusses all the numerical experiments. Finally, Section 8 concludes the study.

2. Literature review

This paper relates to (i) research on modal shift in inner-city freight transport as well as (ii) studies on operational planning in inner-city freight transport, focusing on the integration of truck transport and scheduled line services.

2.1. Modal shift regulations

Subsidies and taxes are key public policy tools for promoting modal shift in freight transport (Takman & Gonzalez-Aregall, 2024). They incentivize carriers to adapt their decisions towards more coordinated and sustainable operations. Authorities typically set subsidies and taxes to force carriers to internalize external transport costs, like emissions and congestion (Santos et al., 2010). These policies face two main challenges: political feasibility and economic effectiveness. Political acceptability often encounters societal opposition, but revenue recycling – spending that benefits stakeholders – can increase public support (Carattini et al., 2018; Jagers et al., 2019). For example, Beiser-McGrath and Bernauer (2019) found that most of the US sampled group supports carbon taxes as long as the revenue is invested in new infrastructure, renewable energy, policies for low-income families, and providing tax rebates. Moreover, effectiveness depends on the price levels needed to induce behavior changes. When setting the price, it is crucial to consider the hierarchical relationships between stakeholders, i.e., the decision from a stakeholder has a direct influence on decisions of another.

We can model tax and policy settings using a pricing problem where the leader sets prices for certain activities to maximize benefits. At the same time, the followers choose activities to minimize operating costs (Labbé & Violin, 2016). This model represents taxes as positive prices and subsidies as negative prices. Several studies consider how to allocate a given budget as subsidies, such as intermodal subsidies (Hu et al., 2022), bus service contracts (He & Guan, 2023), and rail freight subsidies (Mohri & Thompson, 2022; Yin et al., 2024). Other studies (Brotcorne et al., 2008; Bruni et al., 2024; Labbé et al., 1998) focus exclusively on the taxation of intermediate hub facilities, tollways, or telecommunication networks without addressing the allocation of the additional revenues generated. We refer to the comprehensive review by Caselli et al. (2024) for recent work adopting this price-setting formulation in various applications.

We focus on literature that combines tax and subsidy settings, i.e.,"tax revenue recycling". Qiu, Xu, Xie, et al. (2020) evaluate a carbon tax and rebate system for air passenger transportation, where airlines pay taxes on emissions and receive subsidies for mitigation improvements. This approach reduces carbon emissions under low transaction costs and fuel price differences. Jiang (2021) analytically evaluates the effects of using aviation tax revenues to subsidize high-speed rail. Counter-intuitively, he found that the policy can lead to undesired effects where air traffic volume increases and high-speed rail volume decreases.

Because limiting the analysis to a single origin–destination pair abstracts the details of delivery, such as multiple pickups and delivery points, consolidation effect, time window, Qiu, Xu, Ke, et al. (2020) explore a more complex pollution routing problem with up to 100 nodes. They propose using road tax revenues for funding allowances based on reduced road freight emissions. This policy effectively reduces emissions while controlling additional costs for carriers. Our work extends upon this stream of literature by investigating the solution structure of our bilevel formulation, allowing us to evaluate optimal policy settings, and by further numerical analyses. Unlike Qiu, Xu, Xie, et al. (2020) and Jiang (2021), we consider a more realistically sized problem instead of a single OD pair. Additionally, we investigate the solution structure of our bilevel formulation, allowing us to evaluate optimal policy settings.

Very few studies consider the interaction between stakeholders in the context of using the scheduled line services for inner-city freight transport. Ma et al. (2022) propose an analytical model to characterize the strategic interaction between a metro operator and a logistics company in a metro-integrated logistics system. The model considers both cooperative and non-cooperative markets. The metro operator sets the freight price, while the logistics company choose their transportation plan, opting for either road transport or metro modes. They show that the metro-integrated logistics system can benefit the operators and logistics companies. In an extension, Ma et al. (2023) additionally permit outsourcing where a carrier hires a freight carrier for the road freight transport. However, both studies analyzed a stylized model using a single origin–destination pair. Compared to their work, we integrate the operational decision-making of the carrier as a response to the policy.

To summarize, we contribute to this literature stream by addressing a more realistically-sized problem considering policy settings and multi-modal transportation channels.

2.2. Last-mile delivery using scheduled lines

Several studies have investigated planning to use scheduled line services for inner-city freight transportation. The scheduled line services may include inland waterway, bus, tram, or metro services. Since these services are commonly passenger-oriented, the literature also refers to these services as freight-on-transit. For a comprehensive overview of the literature on freight-on-transit, we refer the reader to recent literature reviews by Cleophas et al. (2019), Elbert and Rentschler (2022), and Cheng et al. (2023). We focus our review on the operational level studies on the last-mile delivery using the scheduled line services. For synchronization of routing with schedules in other applications, please refer to Soares et al. (2024). Two primary approaches model the operation planning of this application: the two-echelon system and the Pickup and Delivery Problem with Time Windows and Scheduled Lines (PDPTW-SL).

The two-echelon system involves delivering freight from distribution centers to city areas using scheduled line services, followed by last-mile delivery via city freighters from public transport stations. Key studies in this area include Masson et al. (2017), Schmidt et al. (2024), and Mo et al. (2023), which abstract the first echelon decisions and model them as replenishment nodes with fixed demands. They address the problem as a pickup and delivery problem with time windows, employing various algorithms like ALNS and Branch-Price-and-Cut. Wang et al. (2024) take a different approach by explicitly modeling the first echelon routing decision, connecting satellites via public transport, and using city freighters for the second echelon, i.e., for the last-mile delivery.

The PDPTW-SL approach, proposed by Ghilas et al. (2016b), involves a carrier organizing last-mile delivery by choosing between vehicles alone or a mix of vehicles and public transit systems. Their computational results on small instances show that public transport can reduce operational costs by up to 20%. To handle larger instances, Ghilas et al. (2016a) developed an ALNS algorithm capable of solving instances with up to 100 transportation requests. Additionally, Ghilas et al. (2018) proposed a Branch-and-Price method to solve instances with up to 50 transportation requests. De Maio et al. (2024) relaxed the capacity constraints of public transport and introduced a destroy-and-repair neighborhood search heuristic to handle up to 500 requests. Similarly, He et al. (2023) extended the PDPTW-SL to allow multiple trips for vehicles and incorporated practical constraints such as driver workload and driving distance limits. Others adopt sample average approximation to tackle the stochastic version of the PDPTW-SL with stochastic freight demands (Ghilas et al., 2016) and scheduled line capacity (Mourad et al., 2021).

However, these studies assume tactical decisions related to scheduled line services, such as departure time scheduling or capacity, and focus solely on the carrier's perspective, neglecting interactions with other stakeholders like transportation authorities. The literature contains few tactical studies on inner-city freight transport, including train scheduling (Hörsting & Cleophas, 2023; Ozturk & Patrick, 2018) and station capacity determination (Fontaine et al., 2021). This gap hinders a comprehensive understanding of stakeholder interactions. In this study, we address this gap by incorporating the role of a transportation authority in setting road taxes and subsidies for scheduled line services and investigating the carrier's response in the PDPTW-SL setting.

3. Problem description and formulation

This section first presents the problem narrative of setting the road tax and the scheduled line subsidy, and then the mathematical formulation. Next, we present some properties of the proposed problem and its optimal solutions.

3.1. Problem narrative

We consider the problem of determining a tax and subsidy policy to incentivize a modal shift away from emission-intensive road transport. The transportation authority sets fuel or access taxes per unit driving distance for road vehicles. It subsidizes freight transportation on scheduled lines such as urban light rail or inland waterway transportation. Given tax and subsidy levels, a carrier directly transports goods with a truck or utilizes scheduled lines to minimize total costs. Due to the leader–follower structure, we model the policy-setting problem as a Stackelberg game.

The transportation authority aims to promote a modal shift. In most European cities, public authorities oversee public transport operations and can levy local taxes. After passenger transport, scheduled lines have a remaining capacity that can be used for freight transport at a predefined cost. The authority has a budget of B available to subsidize the scheduled line, reducing the fare by s. Further subsidies must be financed through distance-based road access taxes at the rate of t. Using tax revenues to subsidize public transport services is a common policy in many countries. For instance, in the 1990s, cordon tolls, a form of congestion pricing, in three Norwegian cities funded public transport in the larger Oslo area (Aasness & Odeck, 2023; Odeck & Bråthen, 2002). Similarly, congestion tax revenues in Singapore, London, Stockholm, Milan, and Gothenburg have also been used to subsidize public transport (The International Transport Forum, 2024).

The carrier builds routes to transport exogenous requests, including a pickup location, delivery location, and time window. Freight demands remain constant regardless of tax and subsidy levels since the carrier maintains consistent customer pricing. This is typically the case in competitive markets, where carriers are, in essence, price-takers. The carrier will utilize the scheduled line for an order if it reduces transportation costs and is feasible concerning the time windows. In this case, the goods is transported to a transshipment point by a truck, waits there for the next available scheduled line (subject to its capacity), is transported to the next transshipment point, and is picked up by a truck. The routes depend on the authority's policy (s, t).

Since this paper focuses on the operational level, we consider strategic and tactical decisions regarding the scheduled line service, such as network design and operating schedule, as given. We acknowledge that the effectiveness of the delivery scheme also depends on these decisions, as demonstrated by Ghilas et al. (2016b). In the following, we first detail a carrier's decision problem and then formulate the bilevel road tax-and-subsidy setting problem.

3.2. Carrier decision model

The carrier decides how to ship their transportation requests through their network, using direct transportation by truck or transshipping some requests via a scheduled line. The carrier's joint decision for all their requests can be modeled as a Pickup and Delivery Problem with Time Windows and Scheduled Line (PDPTW-SL), as introduced by Ghilas et al. (2016b). We only provide a conceptual description of the model as our bilevel formulation applies to other carrier models involving multiple transportation modes. The decisions include the routing plan for road vehicles and the shipment amount allocated to the scheduled line. Constraints include typical routing and flow constraints from the PDPTW problem, accounting for vehicle capacity limits and time windows for requests. Additionally, we consider the scheduled line capacity and the service's running schedule, ensuring time synchronization between road vehicles and scheduled line services. The objective is to minimize transportation costs, which are composed of road and scheduled line costs. Unlike the approach in Ghilas et al. (2016b), the carrier considers tax as part of the routing costs, and the scheduled line is partially subsidized. We will explain this further in the following section.

3.3. Bilevel road tax-and-subsidy setting model

Then, the bilevel model is given by:

$$\min_{s,t} \quad d^*(s,t) \tag{1}$$

$$\text{subject to} \quad s f^*(s,t) - t\phi d^*(s,t) = B \tag{2}$$

$$0 \leq s \leq 1, \quad 0 \leq t, \tag{3}$$

$$\left(d^*(s,t), f^*(s,t), x^*(s,t)\right) \in \underset{(d,f,x)\in\mathcal{X}}{\arg\min} \, (1+t)\,\phi d + (1-s)\, f. \tag{4}$$

Table 1 summarizes the notations. Eq. (1) represents the objective of the transportation authority: minimizing the total driving distance. Constraint (2) defines the budget constraint, where the difference between the total subsidy and the total tax revenue is equal to the given budget. Constraint (3) specifies the subsidy and tax ranges. Finally, constraint (4) defines that $(d^*(s,t), f^*(s,t), x^*(s,t))$ are the optimal solutions for the lower-level problem introduced in Section 3.2 with the objective function under tax and subsidy policy. Lower-level solutions are the routing solutions that comply with demand fulfillment, vehicle capacity, requested time windows, and time synchronization with the scheduled line service. We assume that even if multiple feasible lower-level solutions exist for one input s, t, the carrier will select the same

Table 1
Notations.

Symbol	Description
$\mathcal{X}$	Set of feasible lower-level solutions
B	Parameter for the authority's available budget
ϕ	Parameter for unit distance cost
s	Upper-level decision variable for the scheduled line subsidy
t	Upper-level decision variable for the road tax
d	Lower-level decision variable for the total driving distance
f	Lower-level decision variable for the total flow cost on the scheduled line
x	Lower-level decision variables for routing

solution deterministically. The carrier's strategy can either be cooperative (see, e.g. Dempe, 2024) or adversarial (see, e.g. Liu et al., 2018; Tsoukalas et al., 2009). Moreover, with the term $(1-s)$, we ensure that the provided subsidy does not exceed the total flow cost on the scheduled line service to prevent unnecessary modal shifts. For the complete version of the specific lower-level problem adopted in this paper, please refer to Ghilas et al. (2016b).

4. Properties of the optimal policy

We begin by outlining the properties of the model defined in Section 3.3. Subsequently, we derive a condition for the optimal policy and explore its associated properties. All proofs are provided in Appendix. For notational brevity, we assume that $\phi = 1$.

We first examine the effects of changing s and t, subject to a budget of B. Proposition 1 shows that the objectives of the transportation authority and carrier's objectives are inherently conflicting; it is impossible to improve one party without worsening the other. Then, we show that increasing taxes cannot increase the driving distance (Proposition 2). On the other hand, Example 1 shows that increasing the subsidy level can increase distances. Notwithstanding, we show that if the transportation authority sets the tax rate optimally, driving distance does decrease in the subsidy level (Proposition 3), such that an optimal solution exists that fully subsidizes the scheduled line (Proposition 4). Moreover, Proposition 5 specifies the impact of increasing the authority's budget on the cost of the carrier.

Proposition 1.
For a given budget B, the carrier's total cost decreases if and only if the driving distance is increasing, i.e., for two feasible solutions $\langle s_1, t_1, d_1^\star, f_1^\star \rangle$, $\langle s_2, t_2, d_2^\star, f_2^\star \rangle$,

$$d_1^\star < d_2^* \iff \left(1+t_1\right) d_1^\star + \left(1-s_1\right) f_1^\star > \left(1+t_2\right) d_2^\star + \left(1-s_2\right) f_2^\star \quad (5)$$

The following proposition shows that, with a fixed budget, the transportation authority cannot worsen its objective by increasing the tax rate.

Proposition 2. *For a given budget B, the driving distance is non-increasing in the tax level t, i.e., for two feasible solutions $\langle s_1, t_1, d_1^\star, f_1^\star \rangle$, $\langle s_2, t_2, d_2^\star, f_2^\star \rangle$ with $t_1 < t_2$, it holds that $d_1^\star \geq d_2^\star$.*

Note that it is impossible to increase the tax level indefinitely to keep reducing driving distance since the solution should remain feasible, and the subsidy level can be at most 1. We have shown that increasing the tax level reduces the driving distance but increases the carrier's costs. On the other hand, increasing the subsidy level, $s_1 < s_2$, at a given budget B *can* result in increased distances, $d_1^\star < d_2^\star$, thereby counteracting the goals of the policymaker, as Example 1 shows.

Example 1. Assume that the budget $B = 0$ and that the lower-level problem has only two feasible routing solutions ($\mathcal{X} = \{\langle d_1 = 15, f_1 = 20\rangle, \langle d_2 = 20, f_2 = 5\rangle\}$) due to the time window, vehicle capacity, and other constraints. Under the policy $(s_1 = 0.5, t_1 = 2/3)$, the first solution is optimal for the carrier, resulting in a distance 15. However, under the policy $(s_2 = 0.6, t_2 = 0.15)$, with a higher subsidy level *but lower tax*, the second solution is optimal for the carrier, resulting in distance 20.

However, we can show that if the transportation authority selects the tax rate optimally given the subsidy level, the driving distance *does* decrease in the subsidy, as shown by Proposition 3. It immediately follows that the transportation authority can minimize distance by fully subsidizing the scheduled line, as formalized in Proposition 4.

Proposition 3. *For a given budget B and subsidy level s, let $d^*(s)$ denote the lowest driving distance over all tax rates t. Then, $d^*(s)$ decreases monotonically in s.*

Proposition 4. *Let f^{full} denote the scheduled line costs of the carrier under the policy $(s = 1, t = 0)$. If $B \leq f^{full}$, there exists an optimal where $s = 1$. If $B > f^{full}$, the problem is infeasible.*

After identifying the structure of an optimal policy, we now turn to the efficiency of the budget. We show that the carrier's routing decision is independent of the budget if $s = 1$ and that an increase in budget directly and by an equal amount decreases the carrier's cost (Proposition 5).

Proposition 5. *Under the optimal policy, increasing the budget does not influence the carrier's optimal routing decision but decreases its total cost, i.e., for any two optimal policies with $s_1 = s_2 = 1$ with their corresponding budget $B_1 < B_2 \leq f^{full}$ and total carrier cost C_1, C_2, it holds that*

$$B_1 + C_1 = B_2 + C_2$$

5. Solution algorithm

Given a policy (s, t), we solve the lower-level problem using the ALNS algorithm for PDPTW-SL developed in Ghilas et al. (2016a). We are aware that a Branch-and-Price algorithm for PDPTW-SL is proposed by Ghilas et al. (2018), but use ALNS to be able to solve larger problem sizes. The Branch-and-Price algorithm can only solve instances with up to 40–50 requests, depending on the instance type. Ghilas et al. (2016a) demonstrate that the proposed ALNS generally obtains high-quality solutions for PDPTW-SL instances with 100 requests, and is often capable of finding optimal solutions in smaller instances. Moreover, Molenbruch et al. (2021) only manage to find a better solution for some instances when benchmarked against this ALNS algorithm. Consequently, the ALNS proposed by Ghilas et al. (2016a) is particularly effective for solving instances of more realistic sizes. Since the orders transported by the carrier may vary daily, we aggregate the results of various demand scenarios to compute the total subsidy and tax revenue.

The optimal policy for the transportation authority is computed according to Proposition 4. We also perform tests that do not use a full subsidy. Given some subsidy level $s < 1$, we compute the tax rate that satisfies the budget constraint using a bisection search. We start with initial guesses for the tax rate that, respectively, undershoot and overshoot the budget constraint and continue refining these guesses until the constraint is sufficiently met. For an algorithm overview, refer to Algorithm 1.

In Section 4, we showed that multiple feasible tax rates may exist for a given subsidy level, implying that Algorithm 1 may result in a suboptimal solution. However, the algorithm performs well in numerical experiments, as seen in the next section.

Algorithm 1 Tax rate search.

Initialize variables a, b, and ϵ (where a and b define the tax interval, and ϵ is the tolerable error).
Input initial guesses x_0 and x_1 such that $f(x_0) \cdot f(x_1) < 0$. ($f(\cdot)$ - solving scenarios of lower problems using ALNS given a tax value and return average budget)
Initialize maximum number of iterations N.
$n \leftarrow 0$ ▷ Initialize iteration counter
while $\left| f\left(\frac{x_0+x_1}{2}\right) \right| > \epsilon$ and $n < N$ and $f\left(\frac{x_0+x_1}{2}\right) \neq B$ **do** ▷ B - Total budget
    $x_2 \leftarrow \frac{x_0+x_1}{2}$
    if $f(x_0) \cdot f(x_2) < 0$ **then**
        $x_1 \leftarrow x_2$
    else
        $x_0 \leftarrow x_2$
    end if
    $n \leftarrow n+1$ ▷ Increment iteration counter
end while

6. Numerical experiments

This section presents the findings from a series of numerical experiments with the bilevel model. We describe the experimental design and then discuss the benefits and consequences of optimal policies for transportation authorities and carriers. Moreover, we conduct a sensitivity analysis to assess the impact of the scatteredness of order and scheduled line frequency on optimal policy settings, transportation authority, and carrier objectives. Moreover, we explore the trade-off between total driving distance and the cost of carriers for policies with different subsidy levels. Finally, we conclude the section with a case study based on the city of Berlin.

6.1. Experimental design

We derive our instances from the largest instances used by Ghilas et al. (2016a), with 100 transportation goods and three scheduled line stations. Compared to the original instances, we assume all stations also serve as vehicle depots. We generate instances that vary across three dimensions: order location geography, order allocation, and time window length. Fig. 1 illustrates three order location cases: *Intercity* (Inter), *Metropolitan* (Metro), and *City*. The scheduled line stations are spaced twice as far apart in the Intercity case compared to the Metropolitan case, and twice as far apart in the Metropolitan case compared to the City case. For the first two cases, orders are sampled within a certain radius of the three stations, while in the *City* case, orders are sampled from the centroid of the scheduled line service. All instances can be found at Tundulyasaree et al. (2025).

'Order allocation' defines the process of matching pickup and delivery locations. We examine two cases: 'Different' (Diff) and 'Random' (Rand). In the 'Different' scenario, we pair pickup and delivery locations from whose closest scheduled line station is different. Conversely, 'Random' involves a selection process for pickup and delivery locations. We also distinguish the time window length into two cases: 'Tight' (T) and 'Wide' (W), representing 45 and 60 time units, respectively.

To ensure fair cost comparison, the scheduled line cost per demand varies based on the distance between stations and the vehicle cost to cover the same distance, preventing the scheduled line service from being significantly cheaper than the vehicle cost. The cost per unit distance is 0.25, and the cost per unit of freight on the train is 0.1 per unit distance.

Our algorithm settings are similar to those in Ghilas et al. (2016a) due to the shared problem. However, based on testing, we increased the number of iterations from 10k to 30k to ensure better solution quality. When optimizing the tax and subsidy rate, we use the obtained routing solution without tax and subsidy as a starting solution for the lower-level model.

6.2. Optimal policies for the transportation authority and the carrier

We identify the benefits and consequences of the optimal policy by comparing the results under the optimal policy to the base scenario, where there is no intervention. Table 2 compares the base and optimal policy on the modal shift level and the objective of the transportation authority and carrier. Since the authority's budget is zero, the tax columns show the required tax level to achieve the total scheduled line subsidy. Other columns show the average value of performance metrics obtained from ten randomly generated scenarios. This approach ensures the metrics are not overestimated and account for any variability due to scenario-specific errors.

Result 1. *The optimal policy results in high road distance savings due to substantial freight modal shifts, particularly in the wide time window and distinct order pair instances.*

Table 2 shows that the optimal policy reduces driving distances by 4.3% to 15% across all instances. This reduction is attributed to the increased modal shift from road vehicles to the scheduled line. Additionally, carriers can achieve greater shifts when the time window is wide, and the pickup and delivery nodes are in different clusters. A wide time window provides the extra travel time needed for the modal shift. Furthermore, when order pairs are in different clusters, the distances are greater, leading to higher cost savings from the modal shift.

Result 2. *Since the optimal policy requires more vehicles, we recommend carriers utilize smaller vehicles.*

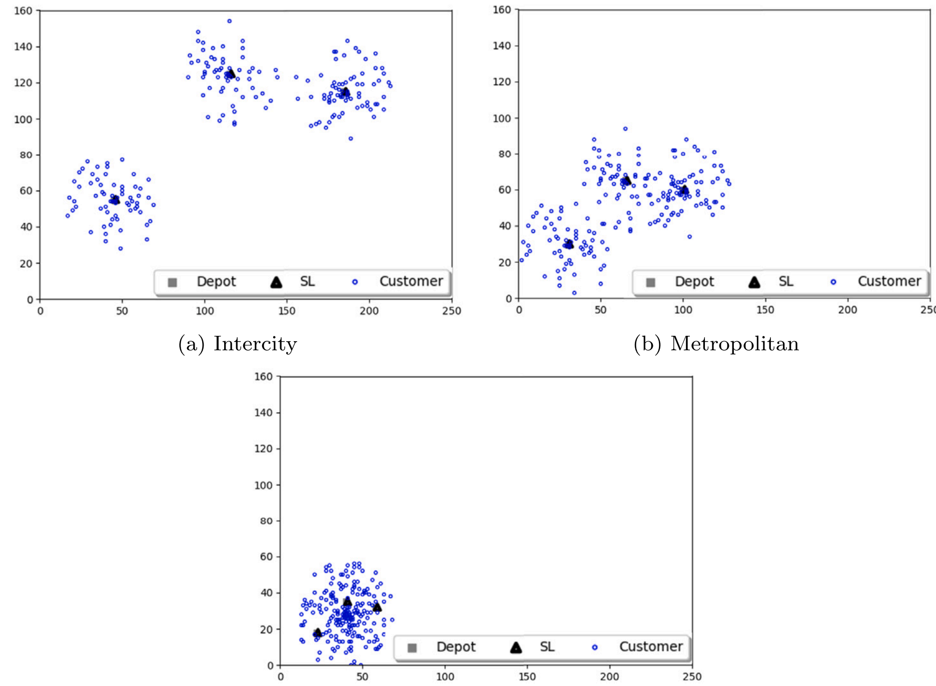
Table 3 shows the maximum load and the number of vehicles for each instance under both the base and optimal policies. Under the optimal policy, carriers use more vehicles to accommodate the increased modal shift. This increase may be due to time windows, capacity, and spatial patterns of requests. This finding aligns with Ghilas et al. (2016a), who observed that instances with higher modal shifts, such as clustered instances, require more vehicles under the PDPTW-SL scheme. However, the maximum vehicle capacity utilization mostly decreases, especially if the time window is wide and the instances involve different clusters. Consequently, carriers can use smaller vehicles.

Result 3. *Under the optimal policy, carriers face higher operational costs due to increased tax levels, particularly in instances with wide time windows.*

As shown in Table 2, the percentage increase in operational costs is higher with elevated tax levels, ranging from 17.6% to 46.1%. This increase is large for wide time window settings, where the modal shift is high. However, the transportation authority can offset this increase using its budget (Proposition 5).

6.3. Number of transported goods

In this section, we evaluate the effect of the number of transported goods on the benefits and consequences of the optimal policy. We experimented with Inter-Rand-W due to its highest relative driving distance saving as observed in Table 2. Table 4 compares the base and optimal policies across different number of orders. When the number of orders exceeds 100, the relative saving in driving distance decreases. This is likely due to the higher density of requests in the area, which causes the base distance to grow more slowly. Conversely, the relative saving seems to fluctuate with fewer orders due to the large differences between base cases. Further, the level of modal shift does not depend on the number of orders.



(c) City

Fig. 1. Different order location geographies.

Table 2
Base versus optimal (Opt) policy under budget-neutral conditions ($B = 0$).

Instance	Driving distance			%Modal shift		Operation cost			Tax
	Base	Opt	%	Base	Opt	Base	Opt	%	
Inter-Diff-T	7094.0	6414.4	−9.6	8.9	40.1	1968.0	2451.8	24.6	0.53
Inter-Diff-W	6290.0	5409.0	−14.0	9.4	59.7	1772.2	2573.8	45.2	0.90
Inter-Rand-T	6406.3	5785.5	−9.7	6.2	28.4	1728.5	2035.3	17.8	0.41
Inter-Rand-W	5592.4	4755.2	−15.0	10.0	46.1	1601.3	2161.9	35.0	0.82
Metro-Diff-T	4481.4	4253.6	−5.1	8.7	39.2	1210.3	1473.8	21.8	0.39
Metro-Diff-W	4105.2	3840.5	−6.4	6.1	49.2	1091.0	1483.4	36.0	0.55
Metro-Rand-T	4170.4	3990.1	−4.3	6.4	29.7	1109.3	1304.3	17.6	0.31
Metro-Rand-W	3809.9	3570.8	−6.3	5.7	43.1	1009.7	1344.8	33.2	0.51
City-*-T	2327.3	2283.1	−1.9	1.8	9.6	591.3	620.1	4.9	0.09
City-*-W	2115.9	2070.4	−2.2	1.5	10.8	535.7	571.0	6.6	0.10

Table 3
Max vehicle capacity utilization and # Vehicles under base versus optimal (Opt) policy under budget-neutral conditions ($B = 0$).

Instance	Max vehicle capacity utilization			#Vehicles		
	Base	Opt	%	Base	Opt	%
Inter-Diff-T	9.5	9.4	−1.1	21.9	26.8	22.4
Inter-Diff-W	11.0	9.4	−14.5	19.6	27.8	41.8
Inter-Rand-T	8.3	7.9	−4.8	20.3	24.2	19.2
Inter-Rand-W	10.3	9.0	−12.6	18.5	24.4	31.9
Metro-Diff-T	9.5	9.0	−5.3	17.3	24.7	42.8
Metro-Diff-W	11.4	10.1	−11.4	15.0	24.7	64.7
Metro-Rand-T	9.0	8.8	−2.2	15.9	21.3	34.0
Metro-Rand-W	10.6	9.4	−11.3	14.9	22.9	53.7
City-*-T	8.8	8.8	0.0	10.8	13.2	22.2
City-*-W	10.5	10.8	2.8	8.8	11.7	33.0

6.4. Number of scheduled line services

We further evaluate the impact of the number of scheduled lines on driving distance, modal shift, and operation cost. So far, all instances are defined with three stations with fully connected services. We extend the scheduled line network by adding a station in the middle between the previous stations and adding one or two pairs of scheduled line services. Hereafter, we denote #SL as the number of (bi-directional) scheduled line service pairs. We select the metropolitan case as the test case due to the potential for modal shift and the proximity of requests, making an additional station potentially beneficial. Table 5 shows the impact of the number of scheduled line services.

With increasing scheduled line services, carriers can further decrease operation costs and reduce driving distances, which also benefits the transportation authority. However, in this context, the benefits do not substantially exceed the original case with three scheduled line pairs. This highlights that increasing #SL may not immediately lead to great benefits. Moreover, we can also observe that the modal shift does not necessarily increase with the number of services. This is sensible because, for example, inefficient modal shifts may lead to further driving distances.

6.5. Order scatteredness and scheduled line services frequency

The effectiveness of the PDPTW-SL scheme is influenced by the spatial distribution of requests and the configuration of scheduled line services (Ghilas et al., 2016b). Consequently, it is important to assess the impact of these factors on optimal policy implementation. This section evaluates the effects of order scatteredness and scheduled line

Table 4
Impact of the number of transported goods.

#Orders	Tax	Driving distance			%Modal shift		Operation cost		
		Base	Opt	%	Base	Opt	Base	Opt	%
25	0.55	1773.1	1521.1	−14.2	13.4	41.9	505.5	590.2	16.8
50	0.68	2987.6	2610.0	−12.6	11.7	43.1	869.0	1093.3	25.8
75	0.71	4290.0	3716.5	−13.4	11.6	42.3	1258.0	1585.4	26.0
100	0.82	5592.4	4755.2	−15.0	10.0	46.1	1601.3	2161.9	35.0
125	0.69	6437.9	5656.7	−12.1	9.7	36.7	1884.6	2394.8	27.1
150	0.84	7512.3	6629.7	−11.7	11.2	43.7	2244.2	3047.7	35.8
175	0.78	8430.9	7482.4	−11.2	12.1	39.9	2563.5	3338.9	30.2
200	0.77	9743.9	8840.7	−9.3	9.7	40.6	2862.4	3906.5	36.5

Table 5
Impacts of number of scheduled line services (#SL).

Instance	#SL	Tax	Driving distance			%modal shift		Operation cost		
			Base	Opt	%	Base	Opt	Base	Opt	%
Metro-Diff-W	3	0.55	4105.0	3841.0	−6.4	6.1	49.2	1091.0	1483.4	36.0
	4	0.54	4101.6	3846.4	−6.2	5.1	50.3	1076.5	1484.7	37.9
	5	0.54	4092.3	3805.5	−7.0	5.1	51.3	1073.0	1461.0	36.2
Metro-Diff-T	3	0.39	4481.0	4254.0	−5.1	8.7	39.2	1210.3	1473.8	21.8
	4	0.36	4461.4	4235.0	−5.1	8.1	36.8	1199.1	1437.8	19.9
	5	0.38	4454.1	4238.8	−4.8	8.3	39.3	1190.1	1458.4	22.5
Metro-Rand-W	3	0.51	3810.0	3571.0	−6.3	5.7	43.1	1009.7	1344.8	33.2
	4	0.38	3795.9	3576.0	−5.8	6.0	33.6	1003.4	1236.5	23.2
	5	0.43	3781.1	3551.6	−6.1	6.0	39.5	992.2	1267.7	27.8
Metro-Rand-T	3	0.31	4170.0	3990.0	−4.3	6.4	29.7	1109.3	1304.3	17.6
	4	0.33	4152.3	3932.9	−5.3	6.0	32.1	1099.6	1311.3	19.3
	5	0.30	4144.7	3930.8	−5.2	5.6	31.1	1091.5	1280.2	17.3

frequency on policy settings and stakeholders' objectives. From Table 2, we observe the highest difference in the modal shift between the intercity and metropolitan areas with the different clusters and wide time windows. Therefore, we choose this instance for further analysis.

Order scatteredness refers to distances between the pickup and delivery points. We vary the scatteredness level (k) by multiplying the original coordinates by ($k/2+0.5$). The Intercity and Metropolitan cases correspond to k equaling 1 and 0, respectively. For each scatteredness level, we generate 10 sets of 10 scenarios.

Fig. 2 illustrates the impact of order scatteredness by comparing the performance of base and optimal policies. Each box plot represents the distribution of measures: %modal shift, driving distance, tax, and total cost of the system from different instances. We found instances become infeasible if $k > 1.2$ due to the time windows. Generally, the variability of the measures across instances is limited. As order scatteredness increases, the average optimal modal shift decreases from 98.3% to 38.3%. On the other hand, under the base policy, the modal shift gradually increases, levels off, and then decreases. The main contributor to this behavior is the time window: The tight time windows combined with high order scatteredness make it impossible to shift these goods to the scheduled line. A sensitivity experiment (see Fig. 3) for different time window widths and different scatteredness verifies this: For all time window widths, the optimal policy results in a decreasing modal shift for higher scatteredness, before becoming infeasible. The base policy first increases the modal shift, and then levels off and decreases before becoming infeasible. Consequently, the time windows make modal shift impossible.

As orders are farther apart, some orders are not feasible for a detour via transferred nodes. In the first phase, it is likely that as the orders scatter, the modal shift provides cost savings until the time window becomes a limitation. Despite this decrease in the modal shift, the distance saving increases until the scatteredness level of 0.8, after which the saving decreases. For the policy settings, the tax trends resemble the optimal modal shift trend. In addition, the system's total cost increases with the scatteredness level. Under the optimal policy, the rate of increased cost seems to be slower with the decreasing modal shift.

Next, we vary the frequency of scheduled line services to assess their impact on policy settings and stakeholder objectives. Similar to the previous sensitivity analysis, we use the same instance, varying scheduled line frequency from 1 to 10 services per hour. We generate 10 sets of instances for each frequency level, with 10 scenarios each. Fig. 4 shows the results for all performance measures, with each box representing the distribution of measure values.

As shown in Fig. 4(a), the optimal policy increases the average modal shift from the base scenarios, starting from less than 10% and reaching up to a maximum of 60% with increasing scheduled line frequency. The modal shift appears to saturate after the frequency reaches 6, as higher frequencies do not further reduce the request waiting time at the station. Additionally, as the modal shift increases, the driving time under the optimal policy decreases with rising frequency. The relative driving time savings between the base and optimal policies also grow with increasing frequency. However, a higher tax is required with the increased modal shift, resulting in higher total system costs and increasing the carrier's cost burden. Overall, the measures do not change much for the same settings. Therefore, we conclude that improving the services without any strategic changes can increase the modal shift to a certain extent.

6.6. A trade-off between minimizing driving distances and minimizing operation costs under different policies

In this section, we explore various policies under different budget levels. We analyze how driving distances and operation cost change with varying subsidy and tax levels to understand the impact on stakeholders. The subsidy levels range from 0 to 1 in increments of 0.1, and we consider three budget levels for the authority, represented as a percentage (0%, 25%, and 50%) of f^{full}, the required budget to fully subsidize the scheduled line service. We apply Algorithm 1 to determine the solutions for each scenario.

To illustrate the trade-off effect, we select the instance with the highest modal shift, referred to as Inter-Diff-W. Fig. 5 depicts the trade-off between stakeholders' objectives. For each budget, each point

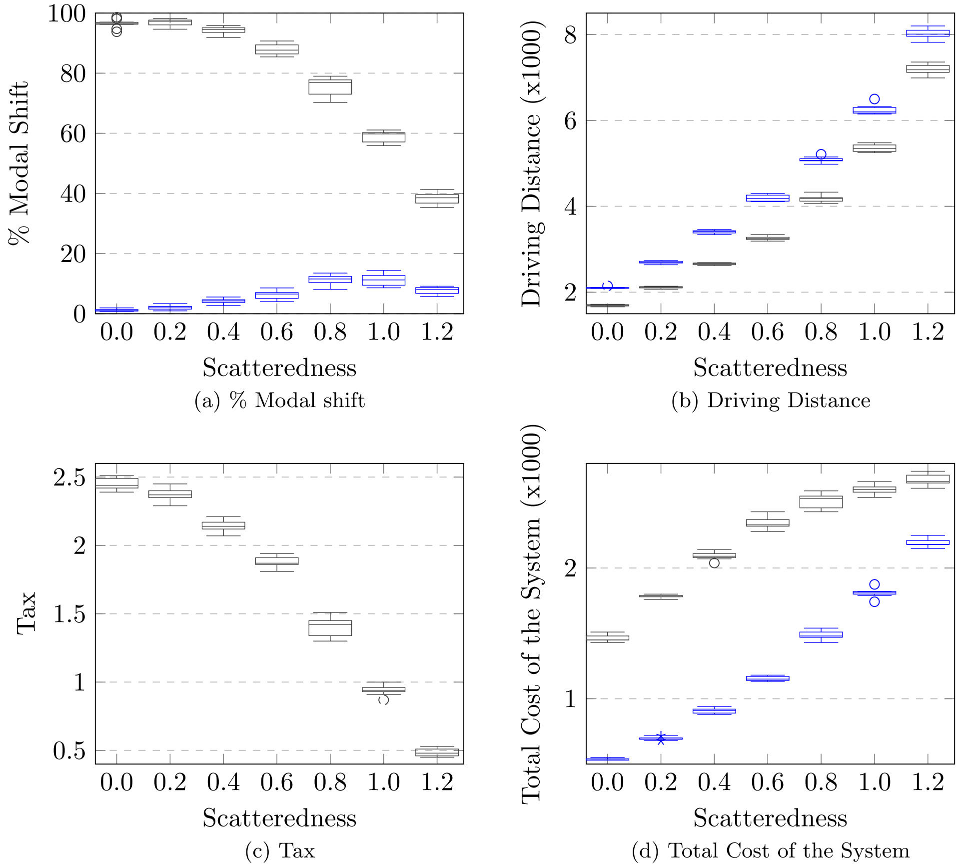


Fig. 2. Distribution of measures across scatteredness levels: base (blue) vs. optimal (dark gray) policies. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

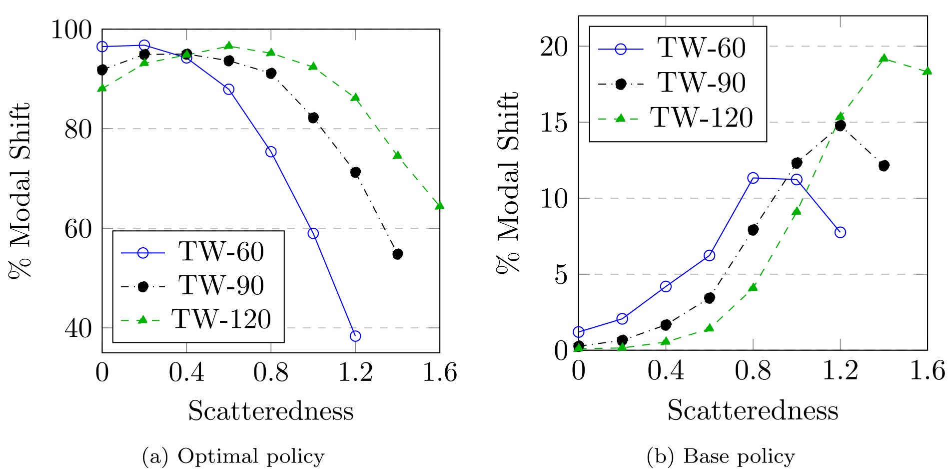


Fig. 3. Effect of time window on the modal shift for each policy.

depicts a different subsidy level with the corresponding tax level. Solutions are plotted as points on the graph and connected to approximate a Pareto front. To ensure solution quality, the best solution from a lower subsidy level is used as the initial solution for a higher subsidy level. Infeasible points that do not meet budget constraints have been omitted. Additionally, we include the point for the base scenario.

Fig. 5 reveals three key observations. First, for each budget level, increasing the subsidy decreases the distances but increases operation costs. From lowest to optimal subsidy, the distance decreases from 3.9 to 5.1% while the cost of the carrier changes between 15.6 and 28.5%. The increased cost is due to the higher taxes required for larger subsidies. While the authority benefits more from higher subsidy levels, it must also consider the burden on carriers. This finding supports Proposition 2, which states that increasing taxes while maintaining the budget level ensures no worse driving distance.

Second, if the budget level increases while the subsidy level remains unchanged, distances tend to increase, and operation costs decrease. The distance increase is rather small, with an increase of less than 1% on average, while the cost savings range from 13.3 to 28.9%. This is due to the reduced tax burden associated with a higher budget.

Third, in support of the analytical result in Proposition 5, we observe that increasing the budget level by some amount ΔB can reduce

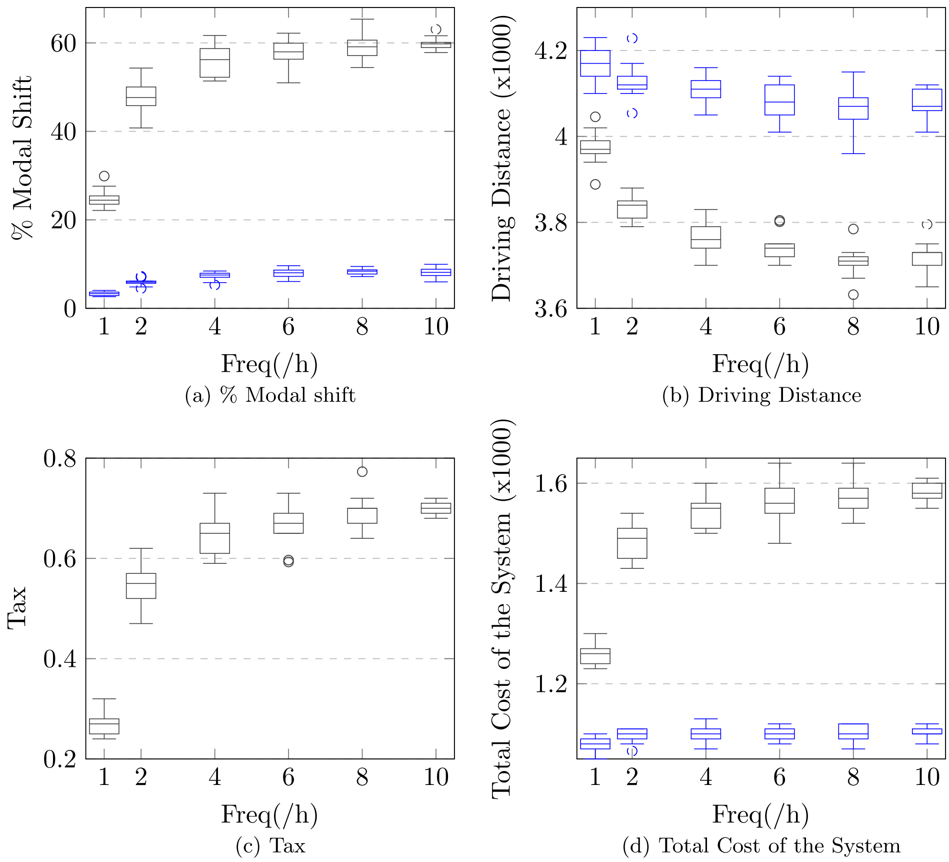


Fig. 4. Distribution of measures across train frequencies: base (blue) and optimal (dark gray) policies. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

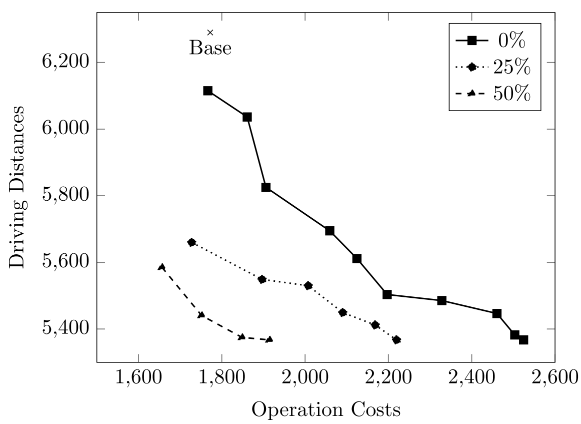


Fig. 5. Trade-off between transportation authority and carrier for policies with partial subsidy and optimal policy with different budgets.

the carriers' costs by more than ΔB in practice, even though at the expense of a higher increase in driving distance.

7. Case study

This section evaluates the optimal policy in a real-world setting for practical insights. The German federal government conducted a feasibility and economic analysis to introduce freight transport to the scheduled line system in Berlin Metro Report International (2025). Consequently, we believe that a case study in Berlin is valuable to support decision-making for the project. Our focus is on illustrating the benefits of the optimal policy in improving modal shifts to scheduled line services and showing the impact of service costs and frequency levels on the schemes' effectiveness. We obtain order locations and corresponding distances from Sartori and Buriol (2020). The locations were extracted from real addresses, and the corresponding distances were derived from the routing solution. The remaining parameters are generated as follows:

- Data Sampling: We randomly sampled 100 requests from 5000 Berlin locations in a random instance, four depot locations (using delivery company depot locations and one imaginary location in the central area), and 40 vehicles.
- Scheduled Line Service Network: We selected a part of the S-Bahn Berlin light rail with 5 transfer nodes and 14 direct connections. The average headway is 10 min per train for all lines.
- The demand for each order is uniformly generated between 5 and 10. The time window is 1 h. The vehicle capacity is 25 units, while the available train capacity is 60 units. We assume the vehicle speed is 60 km/h. The vehicle cost is €1.24 /km (Comité national routier, 2021), and the cost of transporting on the scheduled line service per demand is €2 and €4, respectively.

Based on this setting, a scenario is shown in Fig. 6. Black circles indicate pickup and delivery locations, while the pink and red ones refer to depots and train stations. The dotted line shows the bidirectional service connections between the stations.

Table 6 presents the average results of 10 scenarios comparing the base and optimal policies for the case study, with varying costs

Table 6
Results of the Berlin case study, where base versus optimal (Opt) policy.

Train cost	Driving distance			%Modal shift		Operation cost			#Vehicles		Tax
	Base	Opt	%	Base	Opt	Base	Opt	%	Base	Opt	
2	3376.5	3341	−1.1	19.9	29.4	4446	4529	1.9	25.5	26.4	9.3
4	3449.9	3349	−2.9	4.0	23.2	4385	4766	8.7	24.4	25.7	14.8

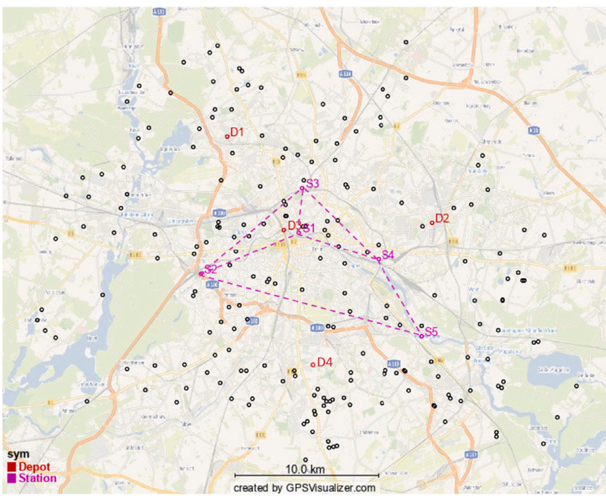


Fig. 6. A Berlin case study.

of transporting a demand unit on the scheduled line. The authority achieves greater driving distance savings when the cost of transporting on the scheduled line is higher. This is due to differences in the base scenarios. When the cost of using the scheduled line is low, the carrier already achieves a relatively low driving distance, although not as low as the driving distance in the base scenario. The optimal policy provides a 1.1% distance saving with a higher modal shift. Conversely, when the scheduled line cost is high, the carrier uses it less often, resulting in a 4.0% modal shift. Under the optimal policy, the modal shift increases to 23.2%, and the driving distance saving is approximately 2.9%. However, this saving comes with an increase in operational costs. This may prompt the authority to allocate an additional budget to alleviate the cost burden on the carrier.

8. Conclusions

This study investigates the impact of an integrated road tax and scheduled line service subsidy policy on promoting a freight modal shift from road to more sustainable modes for inner-city freight transportation. Road tax revenues partly fund the subsidy to overcome political and economic challenges. We formulate a bilevel problem to capture the interaction between the transportation authority and carrier. The upper level determines the policy, tax, and subsidy levels from an available budget, while the lower level involves carriers' routing decisions based on the given policy. We identify a condition for the optimal policy and derive its properties. Moreover, we show the benefits and consequences of optimal policies for each player. Since the PDPTW-SL scheme at the lower level depends on the tactical network decision, we also test the impact of train frequency and order scatteredness on stakeholders' objectives. However, depending on the budget, the optimal policy may burden the carrier. We also show the trade-off between minimizing driving distance and operation cost under non-optimal policies. Finally, we validate our approach with a Berlin case study using open data from Sartori and Buriol (2020).

We show that the optimal policy for the proposed problem is when the scheduled line services are fully subsidized. Moreover, under this policy, the budget does not influence the carrier's decision but can directly reduce their costs. In addition to the theoretical findings, we conducted extensive numerical tests. We show that the optimal policy can reduce the driving distance by up to 15% and substantially increase the modal shift at higher operation costs from the tax level. Moreover, the scheme shows higher driving distance savings and modal shifts with higher train frequency up to a certain level. Furthermore, we numerically show that with an additional budget, the carrier can save more costs than the budget with the partial subsidy policy at the cost of a higher distance for the authority. We can achieve driving distance savings and high modal shift for the case study with suitable cost settings.

The findings of this study have significant implications for future practice. To address the issue of insufficient incentives for modal shifts under current economic regulations, we recommend recycling road tax revenue to subsidize scheduled line services. Such a policy may garner more political and societal support than a pure tax or pure subsidy policy, as the tax paid by carriers is also returned to carriers through subsidies. Our study demonstrates the policy's effectiveness in creating a trade-off in transportation costs for carriers, leading to reduced driving distances and increased modal shifts. The optimal policy setting is also budget-efficient, ensuring that the authority's additional budget can alleviate the carriers' burden. It is important to recognize the impact that strategic and tactical decisions have on the effectiveness of such a policy. Our study shows that the frequency and number of available scheduled line services affect the policy's effectiveness.

Future research could focus on developing an exact algorithm to solve this bilevel program. Since the current work omits the initial cost of using more vehicles, we cannot address the trade-offs when the modal shift is higher. Incorporating vehicle costs can tackle this. Investigating scenarios with multiple carriers and evaluating the impact of policies on different carriers would also provide more practical insights. We can see which carrier would feel the impact of the policy and to what extent.

CRediT authorship contribution statement

Krissada Tundulyasaree: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Layla Martin:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Rolf Nelson van Lieshout:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Tom Van Woensel:** Writing – review & editing, Supervision, Conceptualization.

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Appendix. Proofs

Lemma 1. *The carrier's driving distance decreases if and only if the amount on the scheduled line increases, i.e. for two feasible solutions* $\langle s_1, t_1, d_1^\star, f_1^\star\rangle$, $\langle s_2, t_2, d_2^\star, f_2^\star\rangle$, *it holds that* $d_1^* < d_2^* \iff f_1^* > f_2^*$.

Proof. This immediately follows from the optimality of the carriers decisions. If both $d_1^* < d_2^*$ and $f_1^* < f_2^*$, the second solution is dominated by the first, and can therefore never be a solution to the lower level problem. □

Proposition 1.

For a given budget B, the carrier's total cost decreases if and only if the driving distance is increasing, i.e., for two feasible solutions $\langle s_1, t_1, d_1^\star, f_1^\star\rangle$, $\langle s_2, t_2, d_2^\star, f_2^\star\rangle$,

$$d_1^\star < d_2^* \iff (1+t_1)\, d_1^\star + (1-s_1)\, f_1^\star > (1+t_2)\, d_2^\star + (1-s_2)\, f_2^\star \quad (A.1)$$

Proof. Let $\langle s_1, t_1, d_1^\star, f_1^\star\rangle$ and $\langle s_2, t_2, d_2^\star, f_2^\star\rangle$ be two feasible solutions for the problem with $0 \le s_1, s_2 \le 1$ the subsidy in either solution, $0 \le t_1, t_2$ the associated tax level, and $d_1^\star$ and $d_2^\star$ the driving distance in either solution and $f_1^\star$ and $f_2^\star$ the cost of using the scheduled line services. We start by rewriting the second equation in the proposition:

$$\begin{aligned} &(1+t_1)\, d_1^\star + (1-s_1)\, f_1^\star > (1+t_2)\, d_2^\star + (1-s_2)\, f_2^\star \\ \iff\ & d_1^\star + f_1^\star - t_1 d_1^* + s_1 f_1^* > d_2^\star + f_2^\star - t_2 d_2^* + s_2 f_2^*. \end{aligned}$$

Using that $B = s_1 f_1^\star - t_1 d_1^\star = s_2 f_2^\star - t_2 d_2^\star$, we can further rewrite as

$$\begin{aligned} & d_1^\star + f_1^\star - B > d_2^\star + f_2^\star - B \\ \iff\ & d_1^\star + f_1^\star > d_2^\star + f_2^\star. \end{aligned}$$

Therefore, we continue by proving the following equivalence:

$$d_1^\star < d_2^* \iff d_1^\star + f_1^\star > d_2^\star + f_2^\star.$$

($\implies$) Since the carrier makes optimal decisions under both policies, it holds that

$$\begin{aligned} &(1+t_2)d_2^* + (1-s_2)f_2^* \le (1+t_2)d_1^* + (1-s_2)f_1^* \\ \iff\ & d_2^* + f_2^* - d_1^* - f_1^* \le t_2(d_1^* - d_2 *) + s_2(f_2^* - f_1^*). \end{aligned}$$

Given that $d_1^\star < d_2^\star$, by Lemma 1 it holds that $f_1^\star > f_2^\star$, so the right hand side of the above equation is negative. Thus

$$\begin{aligned} & d_2^* + f_2^* - d_1^* - f_1^* < 0 \\ \iff\ & d_1^* + f_1^* > d_2^* + f_2^*. \end{aligned}$$

($\Longleftarrow$) We now start with the optimality of the first lower level solution:

$$\begin{aligned} &(1+t_1)d_1^* + (1-s_1)f_1^* \le (1+t_1)d_2^* + (1-s_1)f_2^* \\ \iff\ & d_1^* + f_1^* - d_2^* - f_2^* \le t_1(d_2^* - d_1^*) + s_1(f_1^* - f_2^*). \end{aligned}$$

Given that $d_1^\star + f_1^\star > d_2^\star + f_2^\star$, the left hand side of the above equation must be positive. Therefore, at least one of the terms on the right hand side should be positive. By Lemma 1, both terms have the same parity, and must therefore both be positive. We conclude that $d_2^* > d_1^*$. □

Proposition 2. *For a given budget B, the optimal driving distance d^* decreases in the tax level t, i.e., for two feasible solutions* $\langle s_1, t_1, d_1^\star, f_1^\star\rangle$, $\langle s_2, t_2, d_2^\star, f_2^\star\rangle$ *with* $t_1 < t_2$, *it holds that* $d_1^\star \ge d_2^\star$.

Proof. We distinguish two cases for the subsidy level.

Case I: $s_1 \ge s_2$. It follows from the lower level optimality of the first solution that

$$\begin{aligned} (1+t_1)d_1^* + (1-s_1)f_1^* &\le (1+t_1)d_2^* + (1-s_1)f_2^* \\ &\overset{t_1<t_2}{<} (1+t_2)d_2^* + (1-s_1)f_2^* \\ &\overset{s_1\ge s_2}{<} (1+t_2)d_2^* + (1-s_2)f_2^*. \end{aligned}$$

Applying Proposition 1, we find that $d_1^* > d_2^*$.

Case II: $s_1 < s_2$. We use proof by contradiction and assume that $d_1^* < d_2^*$. We again start from the lower-level optimality of the first solution:

$$\begin{aligned} &(1+t_1)\, d_1^\star + (1-s_1)\, f_1^\star \le (1+t_1)\, d_2^\star + (1-s_1)\, f_2^\star \\ \iff\ & (1+t_1)\,(d_2^\star - d_1^\star) \ge (1-s_1)\,(f_1^\star - f_2^\star) \\ & (1+t_1)\,(d_2^\star - d_1^\star) \overset{s_1<s_2}{>} (1-s_2)\,(f_1^\star - f_2^\star). \end{aligned} \quad (A.2)$$

Analogously, the second solution is optimal given subsidy rate s_2 and tax level t_2:

$$\begin{aligned} &(1+t_2)\, d_2^\star + (1-s_2)\, f_2^\star \le (1+t_2)\, d_1^\star + (1-s_2)\, f_1^\star \\ \iff\ & (1+t_2)\,(d_2^\star - d_1^\star) \le (1-s_2)\,(f_1^\star - f_2^\star) \end{aligned} \quad (A.3)$$

which with (A.2) becomes

$$\begin{aligned} &(1+t_1)\,(d_2^\star - d_1^\star) > (1+t_2)\,(d_2^\star - d_1^\star), \\ &\overset{t_1<t_2}{\iff} d_2^* - d_1^* < 0 \end{aligned} \quad (A.4)$$

leading to a contradiction with the assumption $d_1^\star < d_2^\star$. □

Proposition 3. *For a given budget B and subsidy level s, let $d^*(s)$ denote the lowest driving distance over all tax rates t. Then, $d^*(s)$ decreases monotonically in s.*

Proof. Let $\langle s, t^*, d^\star(s), f^\star(s)\rangle$ denote the solution with the lowest driving distance given subsidy level s, and let $\langle s, t_2, d_2^\star, f_2^\star\rangle$ denote any other feasible solution with the same subsidy level, so $d_2^* > d^\star(s)$. Now consider a higher subsidy level $s' > s$ and new tax level $t' = (s' f^\star(s) - B)/d^\star(s) > t^*$. By the optimality of the first solution, we have that

$$\begin{aligned} (1+t')d^\star(s) + (1-s')f^\star(s) &= d^\star(s) + s' f^\star(s) - B + f^\star(s) - s' f^\star(s) \\ &= d^\star(s) + s f^\star(s) - B + f^\star(s) - s f^\star(s) \\ &= (1+t^*)d^\star(s) + (1-s)f^\star(s) \\ &\le (1+t^*)d_2^* + (1-s)f_2^* \\ &= d_2^* + s(\frac{d_2^*}{d^*(s)} f^*(s) - f_2^*) + f_2 - \frac{d_2^*}{d^*(s)} B \\ &\le d_2^* + s'(\frac{d_2^*}{d^*(s)} f^*(s) - f_2^*) + f_2 - \frac{d_2^*}{d^*(s)} B \\ &= d_2^* + \frac{t' d^\star(s) + B}{f^\star(s)} \frac{d_2^*}{d^*(s)} f^*(s) - s' f_2^* \\ &\quad + f_2 - \frac{d_2^*}{d^*(s)} B \\ &= (1+t')d_2^\star + (1-s')f_2^\star. \end{aligned}$$

In other words, there exists a tax rate t' such that solution $\langle s', t', d^\star(s), f^\star(s)\rangle$ is preferred by the carrier over all alternative solutions with a higher driving distance. Therefore, the minimum driving distance at the increased subsidy level s' is at most $d^\star(s)$, i.e. $d^\star(s) \ge d^\star(s')$. □

Proposition 4. *Let f^{full} denote the scheduled line costs of the carrier under the policy ($s = 1, t = 0$). If $B \le f^{full}$, there exists an optimal where $s = 1$. If $B > f^{full}$, the problem is infeasible.*

Proof. Let d^{full} denote the driving distance under policy ($s = 1, t = 0$). Under this policy, the carrier only minimizes driving distance, so d^{full} is a lower bound on the optimal distance.

If $B \le f^{full}$, the transportation authority can fully subsidize the scheduled line and set a tax rate of $t = (f^{full} - B)/d^{full} \ge 0$, which results in a driving distance of d^{full}, attaining the lower bound.

Now assume that $B > f^{\text{full}}$ and that there exists a feasible solution (s, t, d^*, f^*). By the budget constraint, we have that $B = sf^* - td^* \leq sf^* \leq f^*$, contradicting the assumption that $B > f^{\text{full}}$. □

Proposition 5. *Under the optimal policy, increasing the budget does not influence the carrier's optimal routing decision but decreases its total cost, i.e., for any two optimal policies with $s_1 = s_2 = 1$ with their corresponding budget $B_1 < B_2 \leq f^{\text{full}}$ and total carrier cost C_1, C_2, it holds that*

$$B_1 + C_1 = B_2 + C_2$$

Proof. Let $\langle s_1, t_1, d_1^\star, f_1^\star \rangle$ and $\langle s_2, t_2, d_2^\star, f_2^\star \rangle$ be two optimal solutions for the policy maker's problem with $s_1 = s_2$ the subsidy in either solution, t_1, t_2 the associated tax level, $d_1^\star$ and $d_2^\star$ the driving distance in either solution and $f_1^\star$ and $f_2^\star$ the total cost of putting freight on the scheduled line, such that $B_1 < B_2$ are their corresponding given budgets.

Provided that $s_1 = s_2 = 1$, the carrier's problem reduces to minimizing driving distance, resulting in $d_1^* = d_2^*$ and $f_1^* = f_2^*$, and therefore

$$d_1^\star + f_1^\star = d_2^\star + f_2^\star.$$

Subtracting and adding the corresponding budgets (2) on both sides yields

$$\underbrace{d_1^\star + f_1^\star - (s_1 f_1^\star - t_1 d_1^\star)}_{C_1} + B_1 = \underbrace{d_2^\star + f_2^\star - (s_2 f_2^\star - t_2 d_2^\star)}_{C_2} + B_2$$

which is equivalent to the original statement. □

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