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Optimal Subsidy Scheme Design for Promoting Intermodal Freight Transport

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Abstract

Waterborne transport is known to have low environmental impacts compared to other modes. This paper investigates the optimal container subsidies for shippers to promote intermodal shipping involving waterways in a regional transportation network. We consider a linear subsidy scheme consisting of a fixed-rate component and a variable component proportional to the sailing distance. The optimal subsidy design problem is formulated as a bilevel program to maximize the intermodal transport split of demand and minimize the subsidy expenditure. Faster methods are developed to solve the optimization problems of two special subsidy forms, i.e., fixed-rate and distance-based schemes. A case study of the Pearl River Delta region in China suggests that an optimally designed subsidy scheme can increase the intermodal split of container transport by 16%. Many insights are unveiled from the case study regarding the performance comparison between different subsidy schemes, the optimal schemes' environmental impacts, and their effects on individual shippers and feeder ports. For example, the subsidy is less effective for shippers originating too far from or too close to the hub port and for highly time-sensitive or time-insensitive goods. Moreover, two commonly-used objectives, maximizing the intermodal split and minimizing the CO_2 emissions, are well aligned as they yield similar solutions. These insights can assist the local governments in determining the appropriate subsidy schemes and better understanding their overall effects.

Keywords: container subsidy; intermodal transport; waterway transport; bilevel programming

1. Introduction

1.1 Background

Governments have been promoting the shift of freight transport from road to more sustainable modes such as rail, maritime, and inland waterways (EC, 2001; Zhang et al., 2015; SCIO, 2016). For example, the European Union targets a 30% shift of long-distance (i.e., over 300 km) freight transport from road to greener modes by 2030 and another 20% by 2050 (COM, 2011). Goals of this kind are ambitious and challenging because road transport still dominates the market of continental freight transport in recent years (Tawfik and Limbourg, 2018).

Inland waterway has been widely considered as a promising alternative to road transport (Meers and Macharis, 2015) for multiple reasons. First, waterway transport is commonly recognized as the most environmentally friendly among major freight transport modes (Wiercx et al., 2019). Promoting waterway transport has become more important than ever because many countries and regions have pledged to achieve carbon neutrality in the next few decades (McKinnon, 2010). Second, shifting the roadway freight transport to waterways can reduce road traffic congestion and pavement deterioration. In addition, inland waterway transport has been viewed as a catalyst for boosting the regional economy (Onuche, 2007). Finally, freight transport through inland waterways still has a large room for improvement (Rogerson et al., 2020). For example, in Sweden, only 0.7% of the export goods were shipped by inland waterways. On the other hand, a major barrier to promoting inland waterway transport is the cost, including the port service charges (Rogerson et al., 2020). Thus, preferential policies such as subsidies are necessary for inducing the shift towards inland waterway freight transport.

The effectiveness of subsidy schemes on inducing demand shift towards intermodal routes (e.g., road + inland waterway) has been demonstrated by many studies (Myles, 1995; Gruber, 2005). Governments seem to be especially interested in this policy instrument (Yang et al., 2020). For example, the Belgian government has allocated an annual budget of 30 million Euros to subsidize the intermodal transport operators (Macharis et al., 2011; Santos et al., 2015). Subsidy instruments also play an important role in the US government's *America's Marine Highway Program* that promotes coastal shipping instead of trucking (DOT, 2011). However, setting up a subsidy policy that ensures both the maximum effectiveness and the minimum financial burden remains a challenge to the governments.

In light of the above, this paper will develop optimal subsidy schemes that maximize the waterway share of freight transport in an intermodal transportation network. We next review the literature in this realm.

1.2 Literature review

Table 1 summarizes the literature on subsidy policies for promoting intermodal freight transport. Here we include the studies related to waterway and rail transport. This is because works on waterway transport only are scarce (Tao, 2013); see column 2 of Table 1.

Table 1. Comparison of studies on the intermodal freight subsidy policies

Authors (Year)	Subsidized Mode	Subsidy recipients	Subsidy scheme	Optimized or not	Assessment metric or objective	Terminal competition
Tsamboulas et al. (2007)	Unspecified	Carriers	Unspecified	No	Intermodal share of transport	No
Macharis and Pekin (2009)	Rail and waterway	Terminal operators	General	No	Hinterland area	Yes
Chen et al. (2014)	Waterway	Carriers	Link-specific	Yes	Minimizing subsi-dy expenditure	Yes
Bouchery and Fransoo (2015)	Rail	Shippers	Fixed-rate and distance-based	No	CO_2 emissions	No
Santos et al. (2015)	Rail	Carriers	General	No	Intermodal share of transport	Yes
Tao et al. (2017)	Rail	Shippers	Fixed-rate	No	CO_2 emissions	No
Kundu and Sheu (2019)	Rail	Shippers	Fixed-rate	Yes	Maximizing social welfare	No
Li and Zhang (2020)	Rail	Shippers	Distance-based	No	CO_2 emissions	Yes
Li et al. (2020)	Waterway	Shippers	Distance-based	Yes	Maximizing port profits	Yes

Column 3 of Table 1 shows that subsidies can be directed to three types of recipients: carriers, terminal operators, and shippers. Qu et al. (2017) found that subsidizing shippers was the most effective in maximizing the modal shift to waterway transport. Hence, our study will focus on this type of subsidy.

Column 4 shows that two simple subsidy schemes were often examined in the literature, including the fixed-rate scheme where the subsidy per unit of cargo (e.g., TEU) is a constant and the distance-based scheme where the subsidy is proportional to the shipping distance. They have also been commonly used in practice (e.g., Pekin et al., 2008; van Leijen, 2019). In addition, Macharis and Pekin (2009) and Santos et al. (2015) studied a more general scheme that combines the two simple schemes (simply termed the "general scheme" in this paper). Unfortunately, most of these studies have only investigated specific schemes with predefined parameters. Only a handful have attempted to derive the optimal subsidy schemes (see column 5 of the table). For example, Chen et al. (2014) developed a bi-level model for minimizing the total subsidy expenditure to a liner company subject to an emission reduction target. Kundu and Sheu (2019) employed a game theoretical framework to model the competition between rail and maritime transport under differentiated subsidies towards shippers. The objective is to determine the optimal subsidy rates for maximizing social welfare. Li et al. (2020) examined the competition between two maritime ports. Each port aims to maximize its profit by providing an optimal subsidy to attract shippers. To their credit, the above-cited works demonstrated how the optimal subsidy schemes could be derived in their own operating environments. However, they cannot be directly applied to maximize the intermodal freight transport in a regional network considering both modal and terminal competitions. Moreover, those studies only focused on finding the optimal subsidy schemes of simple forms, e.g., fixed-rate or distance-based schemes. The optimal design of the more general subsidy schemes has gone unnoticed.

On a related note, the optimal subsidy design problem and the optimal toll design problem for highways, bridges, and tunnels (e.g., Martine et al., 1998; Brotcorne et al., 2001; Castelli et al., 2013; Liu et al., 2014) are alike to some extent. This is because a subsidy can be viewed as a negative toll. However, the toll optimization models in the literature cannot be directly applied to our subsidy design problem because subsidy programs are often subject to budget constraints while toll schemes are not. Incorporating a budget constraint will increase the solution complexity considerably.

1.3 Overview of the paper

This paper fills the above research gap by optimizing a general subsidy scheme to promote intermodal container transport. For simplicity, we focus on regional networks where road and waterway are the two dominant modes, e.g., China's Pearl River Delta region. A bi-level programming model is developed for this purpose. The lower-level problem models each shipper's route and mode choice. The upper-level problem optimizes the general subsidy scheme parameters with a budget constraint for two objectives: maximizing the intermodal split of demand and minimizing the total subsidy expenditure. In addition, we formulate a second model that minimizes CO_2 emissions. This enables us to compare the optimal policies derived under different objectives. To our best knowledge, this is the first study that simultaneously incorporates various features of generality and reality in the optimal subsidy design problem. These features include: (i) the optimization of a general subsidy scheme that can potentially outperform the two commonly-used special ones; (ii) a bi-objective optimization model that not only maximizes the policy's effectiveness but also minimizes the government's expenditure; and (iii) a comparison between different objectives to help the government better understand the effects of the scheme.

Solution approaches are proposed. In particular, we show that the optimal special schemes can be found in polynomial times.

We apply the models to find optimal subsidy schemes for a case study using real-world data. Results show that the optimal general scheme can induce an additional intermodal split of 16% compared to the no-subsidy scenario. More numerical analyses are performed to identify the properties of the shippers and cargo types that are easier to convince by the subsidy, outcomes of the port competition, the sensitivity of the intermodal split to the subsidy budget, and the scheme's cost-effectiveness in view of carbon trading. Managerial insights and their practical implications are discussed.

The rest of the paper is organized as follows. Section 2 describes the bi-level model for optimizing the general subsidy scheme in an intermodal transportation network. The tailored solution algorithms for the optimal general and special subsidy schemes are developed in Section 3. Numerical examples and insights are presented in Section 4. Conclusions and discussions are furnished in Section 5.

2. Problem description and formulations

Section 2.1 introduces the notations used in this paper. The optimal subsidy design problem is described in Section 2.2. Section 2.3 presents the general and two special subsidy schemes. Section 2.4 furnishes a bi-objective, bi-level formulation to maximize the intermodal demand split and minimize the subsidy expenditure. An alternative formulation for minimizing CO_2 emissions is presented in Section 2.5.

2.1 Notations

Indices and sets

i	Index of a shipper
I	Set of all shippers
j	Index of a feeder port
J	Set of all feeder ports
H	The hub port

Parameters

$d_{i,r}^{j}$	Travel distance by road between shipper i's origin and feeder port j, km
$d_{i,r}^{H}$	Travel distance by road between shipper i's origin and the hub port, km
$d_{j,w}^{H}$	Sailing distance between feeder port j and the hub port, km
$t_{i,r}^{j}$	Travel time by road between shipper i's origin and feeder port j, h
$t_{i,r}^{H}$	Travel time by road between shipper i's origin and the hub port, h
$t_{j,w}^{H}$	Sailing time between feeder port j and the hub port, h
D_i	Demand of shipper i, TEU
δ_i	Shipper i's value of time, \$/TEU/h
C_r	Variable cost per km of road transport, \$/km/TEU
p_j	Service charge at feeder port j, \$
C_w^j	Variable cost per km of waterway transport departing feeder port j, \$/km/TEU
B	Budget of subsidy, \$
R	Fixed cost rate of road transport, \$/TEU
W	Fixed cost rate of waterway transport, \$/TEU
e_1	CO_2 emission rate for road transport, g/ton-km

e_2 — CO_2 emission rate for waterway transport, g/ton-km

q_i — Weight per TEU for shipper i, ton

q_T — Lightweight of a 20-foot truck, ton

$q_{V,j}$ — Lightweight of a container vessel departing feeder port j, ton

$K_{V,j}$ — Number of TEUs carried by a container vessel departing feeder port j

Decision variables

x_{ij} — Volume of containers shipped from shipper i's origin via feeder port j, TEU

z_0 — Fixed-rate subsidy, \$/TEU

z_1 — Distance-based subsidy rate, \$/km/TEU

2.2 Problem statement

We consider a regional freight transportation network consisting of road and waterway links. The region contains a hub seaport denoted H, where all the export cargos (containers in this paper) are destined. Denote I the set of shippers, and J the set of feeder ports in the region that are connected to the hub port by waterway links. Each shipper $i \in I$ has a demand of D_i (TEUs) to be transported from a distinct origin to H. The shipper can choose between a road-only route (marked by the thick, solid arrow in Figure 1) and $|J|$ intermodal routes. Each intermodal route consists of a road link from the origin to a feeder port (marked by a thin, solid arrow in Figure 1) and a waterway link from that feeder port to the hub port (marked by a dashed arrow). The regional government aims to maximize the total number of TEUs transported via intermodal routes by subsidizing shippers who choose those routes. In addition, the government desires to minimize its total expenditure on subsidy, given that the intermodal demand share is maximized.

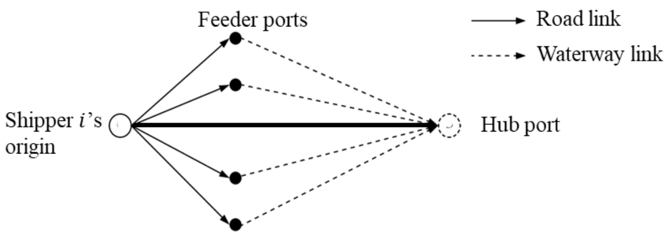

Figure 1. A shipper's route options

Shipping cost and transit time are the two main concerns for shippers (Lam and Gu, 2013; Sheu and Kundu, 2018). The shipping cost per TEU consists of fixed costs (e.g., capital, insurance, and maintenance costs), variable costs related to travel distance (e.g., fuel cost), and service charges at feeder ports. Denote R and W the fixed costs per TEU on road and waterway links, respectively. The R is usually less than W since waterway transport has higher capital and maintenance costs (Macharis and Verbeke, 2004). Further denote C_r the variable cost per TEU per km traveled by road, and C_w^j the variable cost per TEU per km traveled by water from feeder port j to H.[1] We have $C_w^j < C_r$, $\forall j \in J$, since waterway transport uses less fuel and staff per TEU per km traveled. In addition, denote p_j the service charge per TEU at feeder port $j \in J$. Hence, shipper i's shipping cost per TEU via the road-only route is $R + C_r d_{i,r}^H$ (\$/TEU), where $d_{i,r}^H$ denotes the shortest distance by road from shipper i's origin

[1] The variable cost of waterway transport depends on the ship size, which is constrained by the feeder port.

to the hub port H. Similarly, shipper i's shipping cost via the intermodal route that passes through feeder port j is $R + C_r d_{i,r}^j + W + p_j + C_w^j d_{j,w}^H$, where $d_{i,r}^j$ denotes the shortest distance by road from shipper i's origin to port j, and $d_{j,w}^H$ the shortest sailing distance from port j to H.

For simplicity, we assume the travel time on each link is deterministic. Denote $t_{i,r}^H$ the travel time by road from shipper i's origin to H; $t_{i,r}^j$ the travel time by road from shipper i's origin to feeder port j; and $t_{j,w}^H$ the sailing time from port j to H, including the handling time at port j. We have $t_{i,r}^H \leq t_{i,r}^j + t_{j,w}^H$ because road travel is faster. Further denote δ_i the unit time value per TEU for shipper i, which is used to convert the shipping time to a monetary cost. The value of time mainly depends on two factors: (i) the holding cost rate, which is proportional to the value of cargo; and (ii) the cargo's time sensitivity (for example, perishable goods like fruits and vegetables have a higher value of time). Thus, shipper i's time cost is $\delta_i t_{i,r}^H$ (\$/TEU) for the road-only route, and $\delta_i\left(t_{i,r}^j + t_{j,w}^H\right)$ (\$/TEU) for the intermodal route passing through port $j \in J$.

In sum, shipper i's pre-subsidy costs per TEU by road only and by the intermodal route via feeder port j, C_i^H and C_i^j, respectively, are formulated as:

$$C_i^H = R + C_r d_{i,r}^H + \delta_i t_{i,r}^H, \forall i \in I \tag{1}$$

$$C_i^j = R + C_r d_{i,r}^j + W + p_j + C_w^j d_{j,w}^H + \delta_i\left(t_{i,r}^j + t_{j,w}^H\right), \ \forall i \in I, \ j \in J \tag{2}$$

2.3 Subsidy schemes

We consider a general, linear subsidy scheme in the form of $z_0 + z_1 d$, where z_0 denotes the fixed subsidy per TEU transported by waterway, and z_1 the subsidy rate per TEU per km traveled by waterway. The fixed-rate and distance-based schemes are special cases of the general scheme: the former occurs where $z_1 = 0$, and the latter where $z_0 = 0$.

2.4 A bi-objective, bi-level formulation for maximizing intermodal split and minimizing subsidy expenditure

We formulate a bi-level program to optimize the government's primary objective, i.e., maximizing the intermodal transport share (Yin et al., 2020). The lower-level problem determines each shipper's route and mode choice, taking the subsidy scheme as input. The lower-level decision variables, x_{ij}, $i \in I$, $j \in J$, are defined as the volume of containers assigned by shipper i to the intermodal route via feeder port j. And the optimal lower-level solution is denoted by x_{ij}^*, $i \in I$, $j \in J$. The upper-level problem develops the optimal scheme parameters, z_0 and z_1. The bi-level program is given by:

[M1]

$$\max_{z_0, z_1} \sum_{i \in I} \sum_{j \in J} x_{ij}^* \tag{3}$$

subject to:

$$\sum_{i \in I} \sum_{j \in J} x_{ij}^* \left(z_0 + z_1 d_{j,w}^H\right) \leq B \tag{4}$$

$$z_0 + z_1 d_{j,w}^H \leq W + C_w^j d_{j,w}^H + p_j, \ \forall j \in J \tag{5}$$

$$z_0 \geq 0 \tag{6}$$

$$z_1 \geq 0 \tag{7}$$

where

$$x_{ij}^* \in \arg\min_{x_{ij}} \left\{ \sum_{j \in J} \left(C_i^j - z_0 - z_1 d_{j,w}^H \right) x_{ij} + C_i^H \left(D_i - \sum_{j \in J} x_{ij} \right) \right\}, \ \forall i \in I \quad (8)$$

subject to:

$$\sum_{j \in J} x_{ij} \leq D_i, \ \forall i \in I \quad (9)$$

$$x_{ij} \geq 0, \ \forall i \in I, j \in J. \quad (10)$$

The upper-level objective (3) maximizes the split of intermodal transport. Constraint (4) is the budget constraint, where B denotes the prescribed budget. This constraint connects the upper- and lower-level decision variables. Constraint (5) ensures that the subsidy received by any shipper is never greater than its actual waterway transportation cost, so that shippers cannot profit by conducting unnecessary waterway travel. Constraints (6) and (7) ensure the subsidy is nonnegative.

The lower-level objective (8) minimizes each shipper's post-subsidy cost. Constraints (9) and (10) are boundary constraints. To avoid multiple lower-level optima, we assume ties are broken in favor of the upper-level (i.e., the government's) objective. That means a shipper whose intermodal transport cost equals the road-only transport cost will always choose the intermodal route. Thus, we have the following proposition:

Proposition 1. *The lower-level solution for each shipper must be an all-or-nothing assignment of demands; i.e.,* x_{ij}^* *takes the value of 0 or* D_i *for any* $i \in I$, $j \in J$.

In addition, we have the following properties for the optimal solution of **[M1]**. The proofs are omitted because they are self-evident.

Property 1. *The objective of **[M1]** is non-decreasing in the budget* B.

Property 2. *Shipper* $i \in I$ *will choose the road-only route over all the intermodal routes if* $d_{i,r}^H \leq d_{i,r}^{j^*}$, *where* j^* *satisfies* $d_{i,r}^{j^*} = \min\{d_{i,r}^j, j \in J\}$.

Property 1 indicates that the government can improve the modal shift by increasing the subsidy budget. However, by Property 2, shippers originating near the hub port can never be convinced to take intermodal routes, regardless of the subsidy level.

[M1] may have multiple optima; i.e., different subsidy schemes may result in the same minimum objective value. However, the shippers' route assignments and government subsidy expenditures under these optimal subsidy schemes may differ. Thus, we formulate the government's secondary objective as minimizing the subsidy expenditure, given that the intermodal transport share is maximized. A second-stage program **[M2]** is thus introduced to identify the expenditure-minimizing scheme:

[M2]

$$\min_{z_0, z_1} \sum_{i \in I} \sum_{j \in J} x_{ij}^* \left(z_0 + z_1 d_{j,w}^H \right) \quad (11)$$

subject to:

$$\sum_{i \in I} \sum_{j \in J} x_{ij}^* = \sum_{i \in I} \sum_{j \in J} \bar{x}_{ij}^* \quad (12)$$

Constraints (4)-(10).

[M2] solves the subsidy design problem again with an extra constraint (12), which specifies that the intermodal share must attain its maximum. In (12), $\bar{x}_{ij}^*$ is the optimal value of x_{ij} obtained by solving **[M1]**.

2.5 The minimal emissions model

The main objective for many governments to implement a subsidy scheme is reducing greenhouse gas (mainly CO_2) emissions. This section proposes a second formulation, denoted **[M3]**, that minimizes CO_2 emissions. Comparing the optimal solutions to **[M3]** and **[M1]** will help the government understand how the two objectives are aligned.

We assume the CO_2 emission per ton of cargo is a linear function of the shipping distance. This assumption has been used in many previous studies (e.g., Qiu and Lam, 2018). Rates of emissions are denoted e_1 (g/ton-km) for road transport and e_2 (g/ton-km) for waterway transport. **[M3]** is formulated as follows:

[M3]

$$\min_{z_0,z_1} e_1 \cdot \sum_{i\in I}\sum_{j\in J} x^*_{ij}\, d^j_{i,r} D_i(q_i+q_T) + e_2\cdot \sum_{i\in I}\sum_{j\in J} x^*_{ij}\, d^H_{j,w} D_i\left(q_i+\frac{q_{V,j}}{K_{V,j}}\right) + e_1\cdot\sum_{i\in I}\left(1-\sum_{j\in J}x^*_{ij}\right) d^H_{i,r} D_i(q_i+q_T) \quad (13)$$

subject to:
Constraints (4)-(10).

where q_i denotes the weight per TEU for shipper $i \in I$; q_T the lightweight of a 20-foot container truck; $q_{V,j}$ the lightweight of a container vessel departing feeder port $j \in J$; and $K_{V,j}$ the number of TEUs carried by that container vessel.

3. The optimal subsidy scheme

Section 3.1 linearizes the bi-level formulation **[M1]** so that the resulting single-level problem can be solved by commercial solvers like CPLEX. Section 3.2 presents efficient methods tailored for optimizing the two special schemes. Insights derived from these methods are discussed.

3.1 The optimal general subsidy scheme

Following the duality theory, we replace the lower-level program with its optimality conditions. The original bi-level problem is thus reformulated as a single-level program. Denote λ_i $(i \in I)$ the dual variable to the lower-level problem. Due to the strong duality theorem, the lower-level program (8)-(10) can be replaced with the following equations:

$$\sum_{j\in J}\left\{x^*_{ij}\left(C^j_i + C^H_i\right) - x^*_{ij}\left(z_0 + z_1 d^H_{j,w}\right)\right\} = D_i\lambda_i,\ \forall i \in I \quad (14)$$

$$\lambda_i \le C^j_i - \left(z_0 + z_1 d^H_{j,w}\right) - C^H_i,\ \forall i \in I, j \in J \quad (15)$$

$$\lambda_i \le 0,\ \forall i \in I \quad (16)$$

where (14) represents the strong duality, and (15)-(16) are constraints of the dual problem.

The nonlinear constraints (4) and (14) must be linearized. To this end, we follow Proposition 1 (see Section 2.4) and introduce binary variables μ_{ij} to indicate the shippers' choice of feeder port. Specifically, $\mu_{ij} = 1$ if shipper $i \in I$ chooses the intermodal route via feeder port $j \in J$, and 0 otherwise. Thus, we have $x^*_{ij} = D_i\mu_{ij}$. The objective function (3) then becomes $\sum_{i\in I}\sum_{j\in J} D_i\mu_{ij}$. In addition, constraints (9-10) are replaced with:

$$\sum_{j\in J}\mu_{ij} \le 1,\ \forall i \in I \quad (17)$$

$\mu_{ij} \in \{0,1\}$. (18)

We further define auxiliary variables y_{ij} to indicate the subsidy per TEU to shipper $i \in I$ when it chooses feeder port $j \in J$; i.e., $y_{ij} = \mu_{ij}(z_0 + z_1 d_{j,w}^H)$ if $\mu_{ij} = 1$, and 0 otherwise. The above nonlinear equation of y_{ij} can be replaced with the following linear constraints:

$$-M(1-\mu_{ij}) \le y_{ij} - (z_0 + z_1 d_{j,w}^H) \le M(1-\mu_{ij}),\ \forall i \in I, \forall j \in J \quad (19)$$
$$-M\mu_{ij} \le y_{ij} \le M\mu_{ij},\ \forall i \in I, \forall j \in J \quad (20)$$

where M is a number greater than or equal to the maximal subsidy level that any shipper can receive. Constraint (5) implies that M can be set to any value no smaller than $\max_{j \in J}\{W + C_w^j d_{j,w}^H + p_j\}$.

Now the bi-level program **[M1]** can be linearized as the following mixed-integer linear program:

[M4]

$$\max_{z_0, z_1, \mu_{ij}, y_{ij}, \lambda_i} \sum_{i \in I} \sum_{j \in J} D_i \mu_{ij} \quad (21)$$

subject to:

$$\sum_{i \in I} \sum_{j \in J} D_i y_{ij} \le B \quad (22)$$
$$\sum_{j \in J} \{\mu_{ij}(C_i^j - C_i^H) - y_{ij}\} = \lambda_i,\ \forall i \in I \quad (23)$$

Constraints (5)-(7), (15)-(20)

where constraint (4) in **[M1]** is replaced with (22), and (14) is replaced with (23). This mixed-integer formulation efficiently exploits the combinatorial structure of the problem, i.e., that the lower-level problem's extremal solutions can be represented by binary variables that indicate demands' route assignments. **[M4]** can be solved by CPLEX.

Accordingly, the expenditure minimization program **[M2]** is reformulated as follows:

[M5]

$$\min_{z_0, z_1, y_{ij}, \mu_{ij}, \lambda_i} \sum_{i \in I} \sum_{j \in J} D_i y_{ij} \quad (24)$$

subject to:

$$\sum_{i \in I} \sum_{j \in J} D_i \mu_{ij} = \sum_{i \in I} \sum_{j \in J} D_i \mu_{ij}^* \quad (25)$$

Constraints (5)-(7), (15)-(20), (22)-(23)

where μ_{ij}^* is the optimal value of μ_{ij} obtained by solving **[M4]**.

3.2 Tailored approaches for two special schemes

Optimal fixed-rate and distance-based schemes can be obtained by solving **[M4]** and **[M5],** given that z_1 or z_0 is set to 0, respectively. They can also be solved via more efficient methods, thanks to the unique properties of these optimal solutions. The following sections explore the properties, tailored solution methods, and insights for the optimal design of the two special schemes.

3.2.1 The optimal fixed-rate scheme

Under this scheme, a shipper only needs to choose between the road-only route and the intermodal route associated with *the lowest pre-subsidy cost*. This is because the intermodal route with the lowest pre-subsidy cost is also the one with the lowest post-subsidy cost under a fixed-rate subsidy. We define a binary function $\psi_i^0(z_0), i \in I$, which takes 1 if shipper i chooses an intermodal route under a fixed-rate subsidy of z_0 and 0 otherwise. We have:

$$\psi_i^0(z_0) = \begin{cases} 0, & z_0 < \Delta c_i \\ 1, & z_0 \geq \Delta c_i \end{cases}, \ \forall i \in I \tag{26}$$

where $\Delta c_i = \max\left\{0, \min_{j\in J}\{C_i^j - C_i^H\}\right\}$ $(i \in I)$ is the minimum subsidy to trigger shipper i's shift from the road-only route to an intermodal alternative. With this, we reformulate the fixed-rate subsidy design problem as follows:

[M6]

$$\max_{z_0} F_0(z_0) = \sum_{i\in I} \psi_i(z_0, 0) D_i \tag{27}$$

subject to:

$$z_0 \sum_{i\in I} \psi_i(z_0, 0) D_i \leq B \tag{28}$$

$$z_0 \leq \min_{j\in J}\{W + C_w^j d_{j,w}^H + p_j\} \tag{29}$$

Constraint (6).

[M6] can be solved in a simple way. First, rearrange the sequence $\{\Delta c_i, i \in I\}$ in the ascending order as $\{\Delta c^{(i)}, i = 1,2,\ldots,|I|\}$. For completeness, we specify $\Delta c^{(0)} = 0$ and add that to the above sequence. More than one element in this ordered set can be zero, indicating that some shippers may choose intermodal routes even without subsidy. Denote $i_0 \geq 1$ the index of the first non-zero element in that sequence, i.e., $\Delta c^{(1)} = \Delta c^{(2)} = \cdots = \Delta c^{(i_0-1)} = 0$ and $\Delta c^{(i_0)} > 0$. The shipper corresponding to the i_0-th element in the sequence (for simplicity, we now refer to it by shipper (i_0)) will choose a road-only route without subsidy. Then, when $z_0 = 0$, we have $F_0(0) = \sum_{i=1}^{i_0-1} D^{(i)}$. As z_0 increases from 0 to $\Delta c^{(i_0)}$, shipper (i_0) switches to intermodal transport, and thus $F_0(\Delta c^{(i_0)}) = \sum_{i=1}^{i_0} D^{(i)}$. More shippers will switch as z_0 further increases, such that $F_0(z_0) = \sum_{i=1}^{l} D^{(i)}$ given $l = \max\{i|\Delta c^{(i)} \leq z_0\}$. As an illustration of the above process, Figure 2 shows how the total subsidy expenditure, plotted as a discontinuous, piecewise linear curve with slope $F_0(z_0)$, increases with z_0. The process ends when the expenditure curve crosses the horizontal line marked by budget B. Denote the value of z_0 at this intersection point as $\hat{z}_0$, and $\hat{l} = \max\{i|\Delta c^{(i)} \leq \hat{z}_0\}$. Then the optimal solution to **[M6]** is $z_0^* = \Delta c^{(\hat{l})}$. This is because any z_0 greater than $\Delta c^{(\hat{l})}$ would only yield a higher expenditure, but not a greater objective value. Hence, we have the following theorem:

Theorem 1. *The optimal fixed-rate subsidy* z_0^* *is equal to the largest* $\Delta c^{(l)}$, $l = 1,2,\ldots,|I|$, *such that* $\Delta c^{(l)} \cdot \sum_{i=1}^{l} D^{(i)} \leq B$。

By using Theorem 1, the optimal fixed-rate scheme can be found with time complexity $O(|I|)$. This solution algorithm is especially advantageous when the numbers of shippers and feeder ports, $|I|$ and $|J|$, are very large.

3.2.2 The optimal distance-based scheme

Under this scheme, as z_1 increases, a shipper may first shift from the road-only route to an intermodal one and then to another intermodal route with a longer waterway sailing distance to receive more subsidy. This process is illustrated in Figure 3 for a typical shipper $i \in I$. The figure plots the post-subsidy cost rate per TEU against z_1 for all route options: cost rate of the road-only route as the horizontal line at C_i^H; and that of the intermodal route via feeder port $j \in J$ as the line marked by intercept C_i^j and slope $-d_{j,w}^H$. Therefore, the shipper's minimum cost rate is represented by the lower envelope of all these lines, as shown by the bolded curve in the figure.

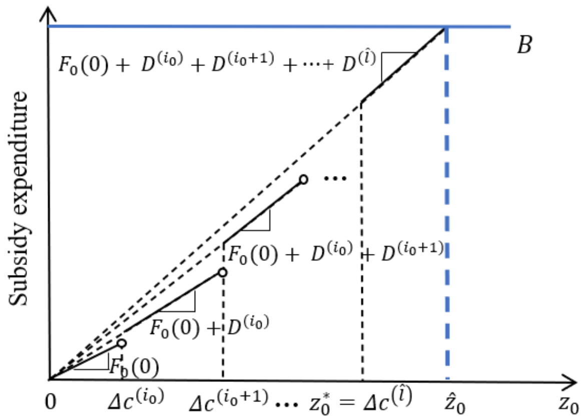

Figure 2. Total subsidy expenditure for a fixed-rate scheme

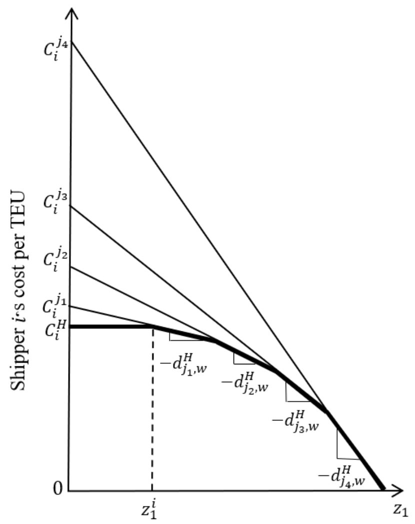

Figure 3. The lower envelope of cost functions

Denote $z_1^i = \max\left\{0, \min_{j \in J}\left\{\frac{C_i^j - C_i^H}{d_{j,w}^H}\right\}\right\}, i \in I$, as the minimum z_1 to induce shipper i to shift to an intermodal route (in Figure 3, z_1^i is located at the first vertex of the bolded, piecewise-linear curve). We have the following theorem:

Theorem 2. *The optimal distance-based subsidy rate,* z_1^*, *belongs to set* $\{z_1^i, i \in I\} \cup \{0\}$.

Theorem 2 can be proved by contradiction. The finite set $\{z_1^i, i \in I\}$ partitions $\mathbb{R}^+ \backslash \{z_1^i, i \in I\}$ into a finite number of open intervals. If $z_1^* \notin \{z_1^i, i \in I\} \cup \{0\}$, then z_1^* must belong to one of those open intervals. Moreover, for a sufficiently small $\epsilon > 0$, $z_1^* - \epsilon$ belongs to the same open interval. Hence, reducing z_1 from z_1^* to $z_1^* - \epsilon$ would not change the objective value (note that the objective value only changes at $\{z_1^i, i \in I\}$). However, it would reduce the subsidy expenditure. This contradicts the fact that z_1^* is the optimal distance-based subsidy rate.

Following Theorem 2, we use the binary search algorithm to find the optimal distance-based scheme. This algorithm also has a time complexity of $O(|I||J|)$. Again, the above approach is especially efficient for solving large-scale problems.

As z_1 increases, a shipper may consecutively switch from feeder ports associated with shorter sailing distances to those with longer distances. In this way, the shipper's post-subsidy cost is further reduced by receiving a higher subsidy. Note that this type of switch does not exist under the fixed-rate scheme. The above phenomenon has two effects on the solution. First, feeder ports located closer to shipper origins (i.e., with shorter road segments) but farther from the hub port (with longer waterway segments) will attract more shippers. This would produce more environmental benefits. Second, as more shippers choose the intermodal routes, the total subsidy expenditure under the distance-based scheme increases faster than under the fixed-rate scheme. Thus, with the same budget, the distance-based scheme may cover fewer shippers than the fixed-rate scheme.

4. Case studies

We apply the proposed models to the Pearl River Delta (PRD) case in Guangdong, China, one of the world's most densely urbanized regions. Numerical experiments are performed on a 3.6 GHz Dual Core PC with 8G bytes of RAM.

Section 4.1 describes the PRD case. Section 4.2 compares the computational efficiency of CPLEX and our proposed algorithms. Section 4.3 examines the optimal general and special schemes of the PRD case. More discussions are furnished regarding: (i) how shippers' mode and route choices depend on their origin locations; (ii) competition between the feeder ports; and (iii) the solution's sensitivity to the subsidy budget and value of time. Section 4.4 furnishes a comparison between the schemes under the intermodal-split-maximizing and emission-minimizing objectives. Finally, we examine the cost-effectiveness of optimal schemes in view of carbon trading in Section 4.5.

4.1 Case description

The government of Guangdong Province plans to promote the waterways of PRD as viable cargo corridors to alleviate local highway congestion and reduce emissions (Department of Transportation of Guangdong, 2020). We use our models to identify the optimal container shipping subsidy program for the government. Since the above-cited government report lacks detailed information, we collect real data from various sources for the case study. The data presented below will be used in the following sections unless otherwise specified.

As the largest container port in the region, the Yantian Port in Shenzhen is designated as the hub port; see the red pentagram in Figure 4. Fourteen feeder ports in the region, including eight seaports and six river ports, are marked by the red asterisks in the figure. Due to the lack of shipper data, we assume that one container shipper is located in each of the 53 cities in PRD. They are plotted as the blue dots in Figure 4. The shippers' demands are calculated by allocating a total demand of 6.53 million TEUs[2] to the 53 shippers in proportion to the gross domestic product of each city in 2019 (Guangdong Bureau of Statistics, 2020a). Each shipper is connected to the hub port by one road-only path and 14

[2] This number is calculated by dividing the container throughput (including both imports and exports) of the Yantian Port in 2019 by 2. Over 98.5% of the Yantian Port's container throughput was carried by trucks and ships. (https://www.yict.com.cn/about-throughput/annual-throughput.html.)

intermodal paths via the 14 feeder ports. Since the actual travel distance data are also unavailable, the travel distance of each roadway and waterway link is estimated by the spheric distance calculated using coordinates of the ports and cities; see Zhou et al. (2021) for a similar estimation method.

Given the limited data, we consider two types of feeder ports with distinct cost rates: seaside ports with a fixed cost rate $C_{p1} \equiv p_j + W$ (for any seaside port j) and a variable cost rate for waterway transport C_{w1}; and riverside ports with a fixed cost rate $C_{p2} \equiv p_j + W$ (for any riverside port j) and a variable cost rate C_{w2}. We estimate the sum of p_j $(j \in J)$ and W, because the two parameters cannot be estimated separately with the limited data. We extract the data of shipping fees per TEU from JCTRANS (http://www.jctrans.com/, in Chinese) for three types of links connecting to the Yantian Port: two types of waterway links starting from seaside ports and riverside ports, respectively, and roadway links. For each type of links, we collected 3-4 data points with different link origins. They were regressed on the travel distances to obtain the parameter values listed in Table 2. The R-squared of the three regression models are 0.79, 0.68, and 0.91, respectively.

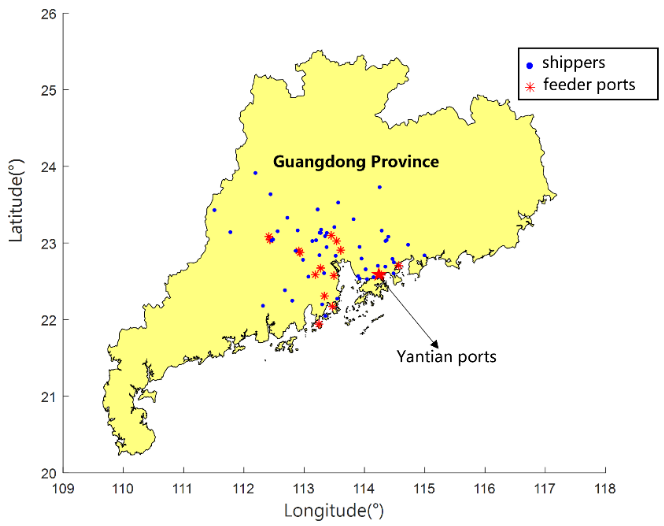

Figure 4. Locations of shippers and ports in Guangdong Province

Table 2. Cost parameters

C_{w1} ($/km/TEU)	0.73
C_{w2} ($/km/TEU)	0.42
$(p_j + W)_1$ ($/TEU)	132.21
$(p_j + W)_2$ ($/TEU)	81.37
R ($/TEU)	77.27
C_r ($/km/TEU)	1.52

We assume the truck speed is 70 km/h (Bektaş and Laporte, 2011), and the vessel speed is 22.22 km/h (equivalent to 12 knot/h; see Norlund and Gribkovskaia, 2013). The travel time on each link is thus derived by dividing the distance by the speed. A shipper's value of time is randomly generated from a uniform distribution with support $[0.07, 14.80]$ $/TEU/h (Zhao et al., 2018; Yang et al., 2020). An additional cost rate of 0.25 $/TEU/h is added to each shipper's value of time to account for the cost borne by complying with ports' sulfur emission regulation.[3]

[3] This cost rate is estimated as follows. For a typical 600-TEU vessel, the fuel consumption is 28.0 ton/day

4.2 Computational efficiency of the solution algorithms

Before examining the PRD case, we first perform an extensive and unbiased comparison between solution algorithms. This section examines 15 instances where the numbers of shippers and feeder ports vary between 1000-5000 and 10-15, respectively. These numbers represent reasonable sizes for regional shipping networks (Guangdong Bureau of Statistics, 2020b; Zhao et al., 2020). In each instance, each shipper's demand, longitude, and latitude of its origin are randomly generated from uniform distributions with support $[50,150]$ TEU, $[109.5,117.3]°$, and $[20.3,25.5]°$, respectively. (Note that the magnitude of the number of containers will not affect the solution algorithms' performance.) The budget is set to \$310,000. Other parameter values are the same as described in Section 4.1.

Table 3. Runtimes of the proposed algorithms, CPLEX, and the PSO heuristic method

Number of shippers	Number of feeder ports	Fixed-rate				Distance-based				General		
		Tailored algorithm (s)	CPLEX (s)	PSO (s)	Gap^p (%)	Tailored algorithm (s)	CPLEX (s)	PSO (s)	Gap^p (%)	CPLEX (s)	PSO (s)	Gap^p (%)
1000	10	0.0011	1.9858	0.1329	0.26	0.0046	2.2841	0.8564	14.95	6.1356	0.8718	3.12
1500	10	0.0025	1.8733	0.2039	0.13	0.0045	4.7375	1.1613	10.61	12.2051	1.1486	1.98
2500	10	0.0010	4.5268	0.3306	0.09	0.0070	19.6217	1.7618	5.56	35.1862	1.7372	1.14
3500	10	0.0017	11.1593	0.6762	0.05	0.0106	43.8470	2.5804	4.42	72.2932	2.5697	1.25
5000	10	0.0020	18.8264	1.2234	0.28	0.0159	154.6123	3.4796	3.76	185.8363	3.4260	0.78
1000	12	0.0009	1.4829	0.1496	0.41	0.0034	2.6749	0.8447	9.58	8.6110	0.8205	2.38
1500	12	0.0009	2.6773	0.2155	0.23	0.0047	6.3243	1.1960	7.55	18.3808	1.1834	1.34
2500	12	0.0011	5.6180	0.3922	0.07	0.0073	20.9557	1.7999	4.16	46.0184	1.7632	0.99
3500	12	0.0017	12.6138	0.7070	0.04	0.0105	41.5369	2.5967	3.06	126.0792	2.5186	0.91
5000	12	0.0021	23.3466	1.2423	0.11	0.0162	173.8749	3.4927	2.18	268.0506	3.4393	0.54
1000	15	0.0010	1.8394	0.1546	0.20	0.0031	3.8340	0.8540	8.61	14.7473	0.8315	1.67
1500	15	0.0010	3.2497	0.1890	0.11	0.0044	9.5352	1.1745	7.18	34.0495	1.1876	1.81
2500	15	0.0011	11.4632	0.4283	0.06	0.0080	28.5362	1.8316	3.64	118.9376	1.7650	1.24
3500	15	0.0016	18.1714	0.7193	0.04	0.0108	85.7501	2.5956	2.63	286.3538	2.5357	0.79
5000	15	0.0020	36.6905	1.2694	0.17	0.0155	110.9011	3.5590	1.99	686.8979	3.4751	0.50

Table 3 presents the runtimes for the 15 instances under each of the three subsidy schemes. For the fixed-rate and distance-based schemes, we compare the runtimes and solution quality of the tailored method (Sections 3.2.1 and 3.2.2), CPLEX (using the approach in Section 3.1), and a partical swarm optimization (PSO) algorithm. For the general scheme, the runtimes and solution quality are compared between CPLEX and PSO. Gap^p indicates the percentage gap between the objective values of the exact solution (CPLEX and tailored methods) and the heuristic (PSO). Key parameters of the PSO algorithm take values used in previous works (Chen et al., 2019; Zhen et al., 2020). The population size and the maximum iteration number are set to 20 and 75, respectively.

The table shows that, for the two special schemes, our tailored methods are generally over 100 times faster than PSO, and the latter is 3-50 times faster than CPLEX. In addition, PSO renders an

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(Bernacki, 2021). If it uses the low-sulfur fuel (VLSFO), the cost would be \$128.5 higher than using a regular fuel (IFO380) for each ton of fuel; see World Bunker Prices (2021). To comply with the sulfur emission regulation at ports, a vessel will switch to VLSFO when it is navigating in the proximity of a port. We assume each vessel spends one hour navigating near a port. Then the additional cost rate is $\frac{128.5\times28}{600\times24}=0.25$ \$/TEU/h.

objective value gap up to 15%. Further examination of the results shows that as the problem size (mainly the number of shippers) increases, the CPLEX runtime grows muchs faster than the tailored algorithms. Thus, the tailored algorithms should be used for optimizing the special subsidy schemes. They are especially advantageous for solving large-scale problems; see Section 3.2. On the other hand, the last three columns of Table 3 show that CPLEX can still find the optimal general subsidy fairly efficiently for medium-sized problems. This demonstrates the computational feasibility of our models for practical applications. Although PSO is significantly faster than CPLEX, the PSO solution is sub-optimal with a gap up to 3%.

4.3 Optimal subsidy schemes for the PRD case

We now focus on the PRD case and assume $B = \$1.02 \times 10^8$ (roughly equivalent to 660 million CNY). Section 4.3.1 presents the optimal solutions of the PRD case under the three subsidy schemes. Section 4.3.2 investigates the origin locations of shippers that switch to intermodal routes under the optimal subsidy and the container volumes served by each feeder port. Section 4.3.3 examines the sensitivity of maximum intermodal split to the subsidy budget and shippers' values of time.

4.3.1 Optimal subsidy schemes

The three optimal schemes for the PRD case are summarized in Table 4. Compared against the no-subsidy scenario, the three schemes increase the intermodal transport share by 14.31-15.99%, with a total expenditure of about $\$1.0 \times 10^8$. The general subsidy scheme is slightly more effective than the two special schemes in inducing the shift toward intermodal routes. However, this is at the cost of a modestly larger expenditure.

Table 4. The optimal subsidy schemes for the PRD case

	Optimal scheme	Intermodal share	Minimal expenditure ($)
No subsidy	\	19.36%	\
Fixed-rate subsidy	$z_0^* = 21.68$ $/TEU	34.22%	0.97×10^8
Distanced-based subsidy	$z_1^* = 0.13$ $/km/TEU	33.67%	1.00×10^8
General subsidy	$z_0^* = 20.27$ $/TEU $z_1^* = 0.011$ $/km/TEU	35.35%	1.01×10^8

4.3.2 Shippers' route choices and feeder port competition

We now examine the properties of shippers that are motivated by the optimal general subsidy to switch from road-only to intermodal routes. Figure 5 colors the 53 shipper origins by the way they are affected by the subsidy: the grey dots represent shippers choosing the intermodal transport even with no subsidy; the blue dots represent those motivated by the subsidy to choose the intermodal transport; and the white dots represent those who still choose road-only under the subsidy. Locations of the hub and feeder ports are also plotted for reference. The figure shows that all the grey dots are located at moderate-to-far distances from the hub port because a shipper with a longer travel distance can enjoy more cost reduction by water transport (recall that $C_w^j < C_r,\ \forall j \in J$). On the other hand, most white dots are located close to the hub since those shippers prefer road-only to avoid the intermodal detour and transfer costs. They are either impossible or very costly to convert by subsidy. Note that this is consistent with Property 2 in Section 2.4. Finally, the blue dots are located moderate distances from the hub, indicating that those originating neither too far nor too close from the hub are prone to be convinced by subsidy. Locations of the three classes of shippers are not distinctly separated because the distance from the hub is not the only factor that affects their choices. Other factors in play include the proximity to feeder ports, demand volume, and value of time of each shipper. The figure unveils that the subsidy directed to the "grey" shippers is unproductive because they will choose intermodal routes anyway. This finding implies that a location-dependent subsidy scheme can be potentially more cost-effective. For example, one can apply subsidies only to shippers originating within a certain distance from the hub port. Another possibility is nonlinear schemes, where the subsidy rate per TEU per km decreases with the total waterway travel distance. Such a scheme can reduce the subsidy directed to those "grey" shippers.

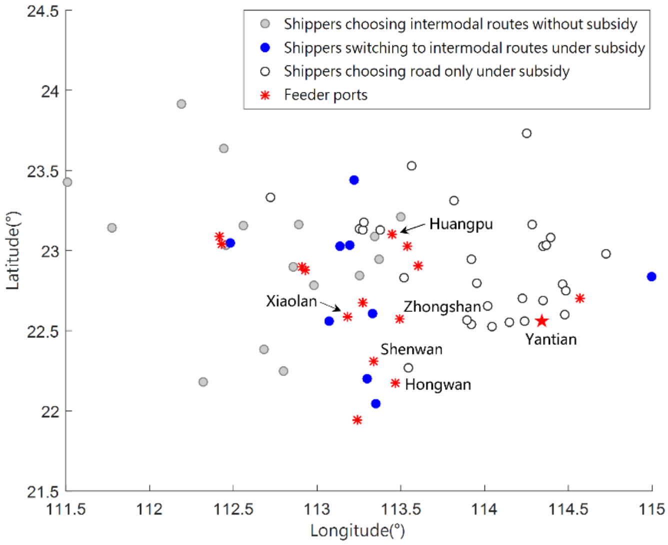

Figure 5. Origin locations of three classes of shippers

Figure 6 compares the container throughputs of eleven feeder ports under the no-subsidy scenario and the three optimal subsidy schemes. The other three feeder ports are excluded because their throughputs are 0. The figure shows that subsidy schemes significantly improved the throughputs of five ports: Zhongshan, Xiaolan, Huangpu, Hongwan, and Shenwan. Their locations are marked in Figure 5. It turns out that the five ports exhibit some common properties. First, they are located neither too close nor too far from the hub. And second, each of them is located adjacent to some "blue" or "grey" shippers, who switch from road-only or other feeder ports to that feeder port under the subsidy. Distinct schemes have largely different effects on three of the five ports, Zhongshan, Xiaolan, and Huangpu. For example, Zhongshan gains the maximum throughput growth under the fixed-rate scheme, while Xiaolan is the biggest winner under the distance-based scheme. This is because Xiaolan is located 33km (24%) farther from the hub than Zhongshan. A longer waterway link is likely to attract more shipping demand under a distance-based scheme. Finally, although the general scheme outperforms the two special ones in terms of the total intermodal share, special schemes may produce greater throughputs for a specific feeder port (e.g., Huangpu and Zhongshan). The above findings unveil how complicated the port competition under a subsidy scheme could be.

4.3.3 Sensitivity analysis

The optimal solutions presented in Table 4 imply that an arbitrarily settled budget B could be redundant. To see how B affects our objective, we let B vary from 0 to $\$4.0 \times 10^8$. Figure 7 plots the optimal intermodal split (in terms of the percentage of the total demand) against B under the general scheme as the dark blue curve. The non-decreasing trend of the curve is consistent with Property 1 in Section 2.4. In addition, the figure shows that the intermodal split grows at a decreasing pace as the budget increases. For example, the intermodal split grows sharply from 30% to 39% (i.e., a 9% increase) with an additional budget of $\$7.05 \times 10^7$, but it would require another additional budget of $\$2.05 \times 10^8$ to attain the next 9% increase (i.e., from 39% to 48%); see the illustration by the dashed light-blue lines. The reason is simple: when the subsidy rates are increased to attract more shippers (i.e., the white dots in Figure 5), those who presently choose intermodal routes will also receive greater subsidies. This renders converting every new shipper to intermodal routes increasingly expensive. Similar trends were observed for the two special schemes; see the red dashed curve (which largely overlaps with the dark blue curve) and the black solid curve in Figure 7. When the budget increases, the intermodal split under the distance-based scheme grows even slower than under the other two schemes. This is because when the distance-based subsidy rate increases, a subsidized shipper would reap more profits due to both the higher subsidy per km and a longer waterway link to which it would switch. Thus, an even greater subsidy expenditure is needed to convince new shippers. Note that this is consistent with the finding in Section 3.2.2.

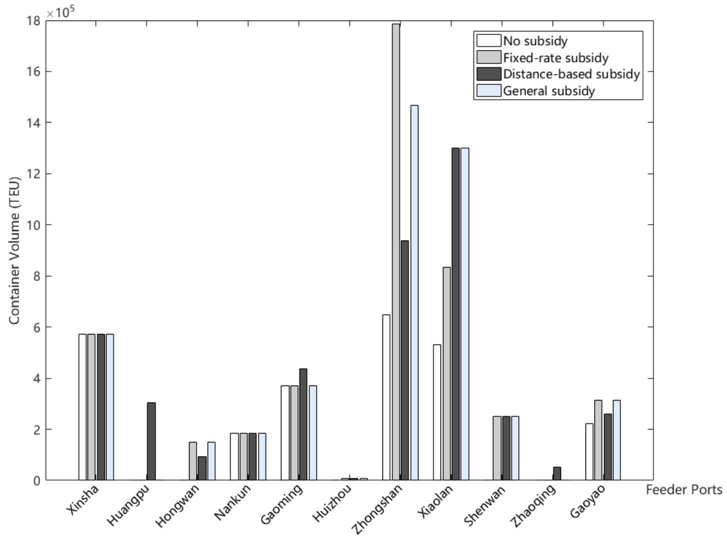

Figure 6. Intermodal freight volume at the feeder ports

Another parameter that may significantly affect the effectiveness of a subsidy scheme is the shippers' values of time. For simplicity, we now assume all the shippers have the same value of time and let it vary from 0 to 15 \$/TEU/h. The budget is fixed at $\$1.02 \times 10^8$. Figure 8 plots the optimal intermodal share under the general scheme against the value of time as the blue curve. As expected, the intermodal share drops from 55% to 19% as the time value grows since waterway transport is much slower than road travel. Figure 8 also plots the intermodal share increase incentivized by the subsidy as the black curve. The curve shows that when the value of time is low (< 2 \$/TEU/h), the subsidy is ineffective because many shippers will choose the intermodal routes even without subsidy, despite the longer travel times. As the shippers become more time-sensitive, the subsidy's effectiveness first improves and then declines; see the black curve. It improves first because more shippers choosing the intermodal routes do so only if they can be compensated by the subsidy. However, as the value of time grows beyond 12 \$/TEU/h, nearly all the intermodal shippers are induced by the subsidy; i.e., no shipper would choose intermodal routes if no subsidy is provided. Thus, the black curve starts to decline together with the blue one. The above results suggest that the government should direct the subsidy to cargos with medium time values. Low-time-value cargos like mineral products will choose waterway transport even without subsidy, while subsidizing high-time-value cargos like perishable food products would be too costly to be effective.

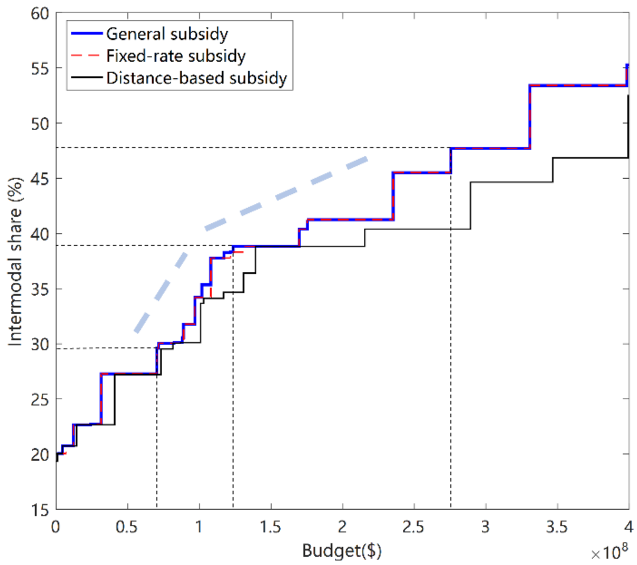

Figure 7. Sensitivity of the intermodal split to the subsidy budget

4.4 Comparison between intermodal split maximization and emission minimization

For simplicity, we use medium-sized container ships with a capacity of 600 TEU. The lightweight of a truck is $q_T = 14$ tons (Hilgers and Achenbach, 2021), and the lightweight of a container ship is $q_{V,j} = 5000$ tons, $\forall j \in J$ (Wen et al., 2017). We further assume the average weight of a 20-foot container is 17 tons (Wang et al., 2021). The emission rates are set to $e_1 = 145$ g/ton-km for road transport and $e_2 = 8.5$ g/ton-km for waterway (NTM, 2020). We let B vary from 0 to $\$1.4 \times 10^8$. Other parameter values are the same as in Section 4.1. The emission minimizing program **[M6]** is similarly solved as presented in Section 3.1.

Figure 9 plots the CO_2 emissions against budget B for solutions under the two objectives as the dashed and solid blue curves, respectively. Comparison unveils that the gap between the two curves is capped by 5%, and is especially small (i.e., $< 0.7\%$) for $B \leq \$8 \times 10^7$. This result indicates that the two objectives are well aligned in terms of CO_2 emissions, especially for lower budget levels. Moreover, the differences between the intermodal shares under the two objectives are also small, i.e., less than 0.6%; see the dashed and solid black curves in Figure 9. Thus, maximizing intermodal split is an acceptable objective, even if the government's primary goal is reducing emissions. Governments may prefer maximizing intermodal split to minimizing CO_2 emissions for two reasons. First, in addition to reducing CO_2 emissions, some governments may desire to mitigate roadway traffic congestion. And second, the intermodal split can be more accurately measured, while the estimation of CO_2 emissions is often subject to multifarious uncertainties (McKinnon, 2007). Using an easy-to-measure objective can help the government better understand the effectiveness of an implemented subsidy scheme.

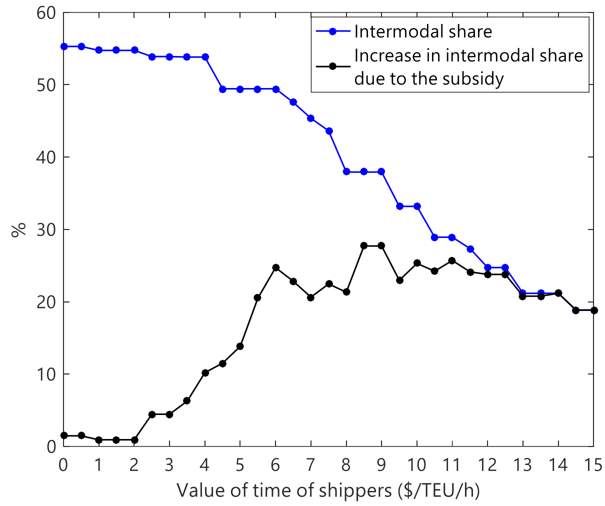

Figure 8. Sensitivity of the intermodal split to the value of time

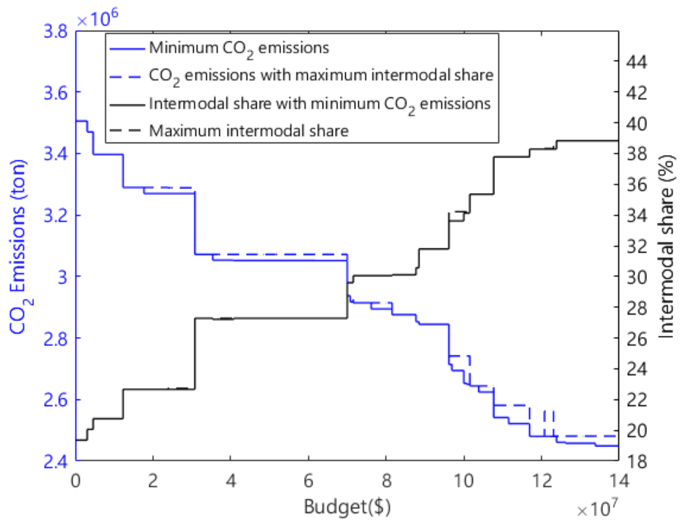

Figure 9. Comparison of the two objectives

4.5 Profitability of the optimal subsidy scheme in view of carbon trading

We further examine the cost-effectiveness of optimal subsidy schemes in view of carbon trading. Figure 10 plots the monetary value of the CO_2 emission saving minus the subsidy expenditure (i.e., the net saving) against the budget. A carbon price of \$71/ton is used.[4] The optimal subsidy schemes were obtained by maximizing the intermodal split (minimizing CO_2 emissions would produce similar results). The figure shows that the net saving of the optimal scheme is not a monotonic function of the budget. This is reasonable since the net saving is the difference between the monetary value of CO_2 emission reduction and the subsidy expenditure. Although the emission reduction and the expenditure both decrease with the budget, their difference is not necessarily so. On a coarse scale, the net saving generally declines as the budget grows. Thus, setting a large budget (i.e., $B > 6.96 \times 10^7$ \$ in our

[4] This is the carbon price used by the European Union; see EMBER (https://ember-climate.org/data/carbon-price-viewer/). We use this price instead of the Chinese carbon price because the latter was considered to be significantly underestimated (Tang et al., 2020). In contrast, the EU price is determined by the EU Emission Trading System, which has been operating for over 10 years with a proven track record.

case) would not be profitable and financially sustainable.[5] A maximal intermodal shift (compared to the no-subsidy scenario) of 7.92% is achieved when keeping a nonnegative net saving. This is attained when the budget exceeds $\$3.07 \times 10^7$.

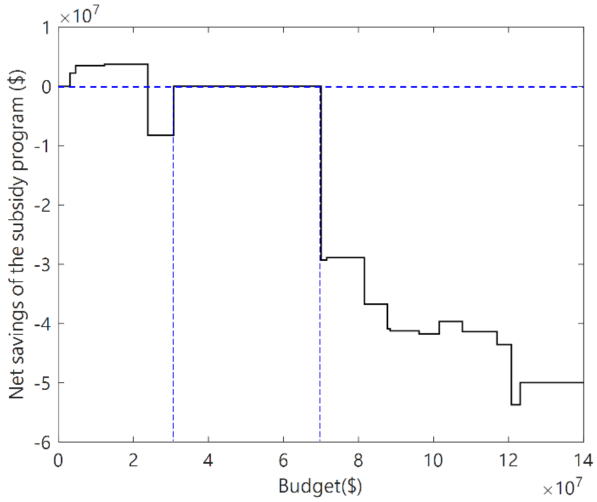

Figure 10. Net savings of the subsidy program measured by the carbon price

5. Conclusions

This paper examines the optimal subsidy design problem for promoting the utilization of regional waterways. We used a linear subsidy scheme and formulated a bilevel model to maximize the intermodal transport share and minimize the subsidy expenditure, accounting for the interactions between the local government and individual shippers. The nonlinear model was linearized and solved by CPLEX. We further developed more efficient algorithms for solving the optimal design of two commonly-used special schemes: one where the subsidy rate is fixed and the other where the rate is proportional to the travel distance. Compared to CPLEX, these latter algorithms can save 80-99% of the computation time. This advantage renders them especially suitable for solving larger-scale problems. They also unveiled useful insights into the government's choice of subsidy schemes, which were verified by our numerical case studies. For example, the distance-based scheme tends to cost more than the fixed-rate one when the number of subsidized shippers increases. Hence, the fixed-rate scheme may be more cost-effective under a limited budget.

Our case study of the PRD region revealed that a 16% increase in intermodal split could be realized by implementing a subsidy consisting of a fixed rate of 20.27 \$/TEU plus a distance-based rate of 0.011 \$/km/TEU. A closer look into the shippers' mode choices unveiled that the subsidy only affected the shippers originating within a medium range of distances from the hub port. Thus, location- or area-dependent schemes and nonlinear distance-based schemes can potentially be more cost-effective. Further analysis showed that the subsidy was the most effective for goods moderately sensitive to the travel time (see Figure 8). This also implies that offering differentiated, cargo-type-based subsidy rates would be better. These more sophisticated schemes will be explored in future research.

Our comparison between two commonly-used objectives, maximizing the intermodal split and minimizing the greenhouse gas emissions, unveiled that the two are highly aligned. This finding

[5] However, to achieve carbon neutrality, governments often value the CO_2 emission reduction higher than its monetary value.

justified the validity of using the former objective in policy-making.

Our models can benefit the local governments by assisting them with subsidy policy-making. For example, the models can produce results similar to Figure 7, which can help determine the appropriate budget for a target intermodal split. On the other hand, subsidizing waterway transport would inevitably hit the trucking industry. To reduce the negative impacts on trucking companies, the government can provide incentives to redirect trucks to serve the links between shipper origins and feeder ports or regions not served by waterways.

Admittedly, the models presented in this paper have several limitations. For example, the simplified, cost-based model for shippers' mode and route choices failed to capture the effects of other factors such as the procurement process, safety, and business preferences. A more sophisticated choice model, e.g., a logit model, can be incorporated to account for these factors. In addition, our simple cost functions can be revised to include more realistic features. For example, the port handling fee can be estimated as a function of the container volume (Wang and Pallis, 2014), given that more operational data are available. Costs related to potential port congestion can be included as well. Our future research will focus on these directions.

References

Bektaş, T., Laporte, G. (2011). The pollution-routing problem. Transportation Research Part B: Methodological, 45(8), 1232-1250.

Bernacki, D. (2021). Assessing the Link between Vessel Size and Maritime Supply Chain Sustainable Performance. Energies, 14(11), 2979.

Bouchery, Y., Fransoo, J. (2015). Cost, carbon emissions and modal shift in intermodal network design decisions. International Journal of Production Economics, 164, 388-399.

Brotcorne, L., Labbé, M., Marcotte, P., Savard, G. (2001). A bilevel model for toll optimization on a multicommodity transportation network. Transportation Science, 35(4), 345-358.

Castelli, L., Labbé, M., Violin, A. (2013). A network pricing formulation for the revenue maximization of European air navigation service providers. Transportation Research Part C: Emerging Technologies, 33, 214-226.

Chen, K., Yang, Z., Notteboom, T. (2014). The design of coastal shipping services subject to carbon emission reduction targets and state subsidy levels. Transportation Research Part E: Logistics and Transportation Review, 61, 192-211.

Chen, W., Panahi, M., Tsangaratos, P., Shahabi, H., Ilia, I., Panahi, S., Ahmad, B. B. (2019). Applying population-based evolutionary algorithms and a neuro-fuzzy system for modeling landslide susceptibility. Catena, 172, 212-231.

COM. (2011). WHITE PAPER: Roadmap to a Single European Transport Area – Towards a Competitive and Resource Efficient Transport System, Brussels, Belgium.

Department of Transportation of Guangdong, 2020. Guangdong Waterway Development Plan (2020-2035). http://td.gd.gov.cn/attachment/0/407/407024/3147982.pdf (Accessed on 24th July 2021).

DOT. (2011). Department of Transportation, the USA. America's Marine Highway Report to Congress April 2011. https://maritime.dot.gov/sites/marad.dot.gov/files/docs/intermodal-systems/marine-highways/3051/maradamhreporttocongress.pdf (Accessed on 30th October 2019).

EC. (2001). European Commission, Luxembourg. WHITE PAPER: European Transport Policy for 2010: Time to Decide.

EMBER. (n.d.) https://ember-climate.org/data/carbon-price-viewer/ (Accessed on 14th August 2021).
Gruber, J. (2005). Public Finance and Public Policy. Macmillan.
Guangdong Bureau of Statistics. (2020a). Guangdong Statistical Yearbook 2020. China Statistics Press, Beijing, China.
Guangdong Bureau of Statistics. (2020b). Research on the Innovation-driven Development of Industrial Economy in the Guangdong-Hong Kong-Macao Greater Bay Area. http://stats.gd.gov.cn/attachment/0/384/384305/2853067.pdf (Accessed on 17th November 2021.)
Hilgers, M., Achenbach, W. (2021). Equipment for Typical Truck Application Areas. In Vocational Vehicles and Applications (pp. 35-41). Springer Vieweg, Berlin, Heidelberg.
JCTRANS. (n.d.). http://www.jctrans.com/ (Accessed on 14th July 2021).
Kundu, T., Sheu, J.B. (2019). Analyzing the effect of government subsidy on shippers' mode switching behavior in the Belt and Road strategic context. Transportation Research Part E: Logistics and Transportation Review, 129, 175-202.
Lam, J. S. L., Gu, Y. (2013). Port hinterland intermodal container flow optimisation with green concerns: a literature review and research agenda. International Journal of Shipping and Transport Logistics, 5(3), 257-281.
Li, D., Qu, Y., Ma, Y. (2020). Study on the impact of subsidies for overlapping hinterland shippers on port competition. Transportation Research Part A: Policy and Practice, 135, 24-37.
Li, L., Zhang, X. (2020). Reducing CO_2 emissions through pricing, planning, and subsidizing rail freight. Transportation Research Part D: Transport and Environment, 87, 102483.
Liu, Z., Wang, S., Meng, Q. (2014). Toll pricing framework under logit-based stochastic user equilibrium constraints. Journal of Advanced Transportation, 48(8), 1121-1137.
Macharis, C., Caris, A., Jourquin, B., Pekin, E. (2011). A decision support framework for intermodal transport policy. European Transport Research Review, 3(4), 167-178.
Macharis, C., Pekin, E. (2009). Assessing policy measures for the stimulation of intermodal transport: a GIS-based policy analysis. Journal of Transport Geography, 17(6), 500-508.
Macharis, C., Verbeke, A. (2004). Intermodaal binnenvaartvervoer. Economische en strategische aspecten van het intermodaal binnenvaartvervoer in Vlaanderen, Leuven: Garant, 176 blz.
Martine L., Marcotte, P., Savard, G. (1998). A bilevel model of taxation and its application to optimal highway pricing. Management Science, 44(12-Part-1), 1608-1622.
McKinnon, A. (2007). CO_2 Emissions from Freight Transport in the UK. Report prepared for the Climate Change Working Group of the Commission for Integrated Transport, 57.
McKinnon, A. (2010). Green logistics: the carbon agenda. Electronic Scientific Journal of Logistics, 6(3).
Meers, D., Macharis, C. (2015). Prioritization in modal shift: determining a region's most suitable freight flows. European Transport Research Review, 7(3), 1-12.
Myles, G. D. (1995). Public Economics. Cambridge University Press.
Norlund, E. K., Gribkovskaia, I. (2013). Reducing emissions through speed optimization in supply vessel operations. Transportation Research Part D: Transport and Environment, 23, 105-113.
NTM, (2020). Network for Transport Measures. Road cargo transport baselines 2020 China.
Onuche, H. A. (2007). Assessment of Inland water transport at the Lokoja Crossing Port. M.Sc. thesis, Benue State University, Makurdi.
Pekin, E., Macharis, C., Caris, A., Janssens, G. K., Crépin, T., Jourquin, B. (2008). Integrated decision support tool for intermodal freight transport. In Nectar Cluster Meeting on Freight Transport and Intermodality, 1-13.

Qiu, X., Lam, J. S. L. (2018). The value of sharing inland transportation services in a dry port system. Transportation Science, 52(4), 835-849.

Qu, C., Wang, G. W. Y., Zeng, Q. (2017). Modelling port subsidy policies considering pricing decisions of feeder carriers. Transportation Research Part E: Logistics and Transportation Review, 99, 115-133.

Rogerson, S., Santén, V., Svanberg, M., Williamsson, J., Woxenius, J. (2020). Modal shift to inland waterways: dealing with barriers in two Swedish cases. International Journal of Logistics Research and Applications, 23(2), 195-210.

Santos, B. F., Limbourg, S., Carreira, J. S. (2015). The impact of transport policies on railroad intermodal freight competitiveness – the case of Belgium. Transportation Research Part D: Transport and Environment, 34, 230-244.

SCIO. (2016). The State Council Information Office, China. WHITE PAPER: Development of China's Transport.

Sheu, J. B., Kundu, T. (2018). Forecasting time-varying logistics distribution flows in the One Belt-One Road strategic context. Transportation Research Part E: Logistics and Transportation Review, 117, 5-22.

Tang, B. J., Ji, C. J., Hu, Y. J., Tan, J. X., Wang, X. Y. (2020). Optimal carbon allowance price in China's carbon emission trading system: Perspective from the multi-sectoral marginal abatement cost. Journal of Cleaner Production, 253, 119945.

Tao X. (2013). A Model to Evaluate the Modal Shift Potential of Subsidy Policy in Favor of Sea-Rail Intermodal Transport. In TLGB 2012(153-159). Springer, Berlin, Heidelberg.

Tao, X., Wu, Q., Zhu, L. (2017). Mitigation potential of CO_2 emissions from modal shift induced by subsidy in hinterland container transport. Energy Policy, 01, 265-273.

Tawfik, C., Limbourg, S. (2018). Pricing problems in intermodal freight transport: Research overview and prospects. Sustainability, 10(9), 3341.

Tsamboulas, D., Vrenken, H., Lekka, A. M. (2007). Assessment of a transport policy potential for intermodal mode shift on a European scale. Transportation Research Part A: Policy and Practice, 41(8), 715-733.

van Leijen, M. (2019). Chinese subsidies for the New Silk Road on a decline. RailFreight.com. https://www.railfreight.com/specials/2019/10/01/chinese-subsidies-for-the-new-silk-road-on-a-decline/ (Accessed on 29th July 2021)

Wang, G. W., Pallis, A. A. (2014). Incentive approaches to overcome moral hazard in port concession agreements. Transportation Research Part E: Logistics and Transportation Review, 67, 162-174.

Wang, T., Meng, Q., Wang, S., Qu, X. (2021). A two-stage stochastic nonlinear integer-programming model for slot allocation of a liner container shipping service. Transportation Research Part B: Methodological, 150, 143-160.

Wen, M., Pacino, D., Kontovas, C. A., Psaraftis, H. N. (2017). A multiple ship routing and speed optimization problem under time, cost and environmental objectives. Transportation Research Part D: Transport and Environment, 52, 303-321.

Wiercx, M., van Kalmthout, M., Wiegmans, B. (2019). Inland waterway terminal yard configuration contributing to sustainability: Modeling yard operations. Research in Transportation Economics, 73, 4-16.

World Bunker Price, (2021). https://shipandbunker.com/prices (Accessed on 26th July 2021).

Yang, J., Luo, M., Shi, M. (2020). Optimal subsidies for rail containers: a bi-level programming solution. Maritime Policy & Management, 47(2), 172-187.

Yang, Z., Sun, Y., Lee, P. T. W. (2020). Impact of the development of the China-Europe Railway Express – A case on the Chongqing international logistics center, Transportation Research Part A: Policy and Practice, 136, 244-261.

YICT. (n.d.). https://www.yict.com.cn/about-throughput/annual-throughput.html (Accessed on 24th July 2021).

Yin, C., Lu, Y., Xu, X., Tao, X. (2020). Railway freight subsidy mechanism based on multimodal transportation. Transportation Letters, 1-12.

Zhang, M., Janic, M., Tavasszy, L. A. (2015). A freight transport optimization model for integrated network, service, and policy design. Transportation Research Part E: Logistics and Transportation Review, 77, 61-76.

Zhao, Y. R., Yang, Z. Z., Theo, N. (2018). Roles of China Railway Express in Sino-Euro trade transportation system. Journal of Dalian Maritime University, 44(3), 33-40.

Zhao, Y., Zhu, Q., Kou, Y., Lun, Y. V. (2020). Quantitative evaluation of dual operational-environmental port performance in the Pearl River Delta. International Journal of Shipping and Transport Logistics, 12(3), 212-229.

Zhen, L., Wu, Y., Wang, S., Laporte, G. (2020). Green technology adoption for fleet deployment in a shipping network. Transportation Research Part B: Methodological, 139, 388-410.

Zhou, Y., Kundu, T., Goh, M., Sheu, J. B. (2021). Multimodal transportation network centrality analysis for Belt and Road Initiative. Transportation Research Part E: Logistics and Transportation Review, 149, 102292.