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Abstract

Using the China-Europe freight transportation market as a real-world case, this study utilizes network-based evaluation and optimization models to analyze and improve the efficacy of government subsidies on China Railway Express (CRE). To ensure the completeness and effectiveness of the evaluation and optimization results, we include into the models the full range of CRE service lines, China-Europe liner shipping lines, major highway networks in China and Europe, and all types of containerized freight demands in the market. A multimodal, multicommodity freight transportation network equilibrium model explicitly considering transportation capacity is taken as a subsidy evaluation tool, which can characterize the individual mode-route choice behavior and take into account shipping cost, transit time, capacity-induced congestion surcharge, and unobserved transportation impedances as shippers' decision-making disutility. The evaluation work reveals that the currently implemented subsidy scheme increases the CRE-carried freight volume by 78.7% in total. However, it does not perform equitably well for those CRE lines that experience heavy congestion or depart from coastal regions of China, and it even exacerbates the congestion of some CRE lines. To overcome these unexpected deficiencies, we propose and implement a subsidy optimization model of a bi-term objective and bi-level structure for simultaneously maximizing capacity utilization and minimizing congestion level of all CRE lines. This model embeds the aforementioned network equilibrium model as its submodel in the lower level. From the optimized subsidy scheme, we found that while the government's monthly average subsidy expenditure is lowered by 7.7%, the total revenue loss and total congestion surcharge decrease by 27.7% and 63.9%, respectively, compared to the current subsidy scenario. This result indicates a tripartite win-win-win situation for the government, CRE operator, and cargo shippers. Overall, through such an optimal subsidy design, the social benefit generated by a subsidy expenditure of $1 increases from $0.69 to $1.20 to the entire China-Europe freight transportation market.

Keywords: China Railway Express; subsidy allocation; multimodal multicommodity transportation network; revenue loss; congestion surcharge

1. Introduction

Trade between China and Europe has been steadily growing over the past decades. As of 2022, the trading value between the two economies reached $874.6 billion. The trade relationship between China and Europe holds immense significance on the global scale, which has been greatly benefited from continuous investments on transportation infrastructure for intercontinental freight shipping, including seaports, airports, highways, rail lines, and their affiliated infrastructure components. In particular, China Railway Express[1] (CRE) plays an increasingly important role in the China-Europe freight transportation market.

The CRE network has evolved into an expansive and indispensable system of international freight transportation services. It has solidified its position as the third major freight transportation mode between the two continents, complementing the conventional options of maritime shipping and air freight shipping services. The inauguration of the first China-Europe freight rail transportation service in 2011, linking Chongqing, China, to Duisburg, Germany, marked the inception of this transformative project. Since then, the number of CRE lines have witnessed a remarkable growth. As of the end of 2021, the coverage of the CRE service spans 91 Chinese cities, connecting them with 196 cities in 24 European countries. In 2022, the momentum of the CRE network continued to accelerate, with a record-breaking number of 16,000 CRE trains in operation, representing an impressive 9% increase compared with the preceding year.

In the pre-CRE era, maritime shipping dominated the China-Europe freight transportation market. Eurostat (2021), the statistical office of the EU, reported that in 2020, 93% of the China-Europe trade in weight and 59% in value relied on maritime shipping. This dominance can be attributed to its cost-effectiveness and substantial cargo capacity. In contrast, air freight transportation handles only high-value, time-sensitive goods and have a very low market share due to its high cost and limited capacity (Kundu and Sheu, 2019). Obviously, a significant gap existed between the two modes in the China-Europe freight transportation market. The inception of CRE attempts to fill this gap by introducing a distinctive alternative to both maritime shipping and air freight transportation. CRE stands out from maritime shipping with its mildly high freight rate,

[1] China Railway Express is alternatively called China-Europe Railway Express by some international news agencies. In this paper, we still use the official name of China Railway Express given by its owner, China State Railway Group.

approximately two to three times more expensive than the latter, but offers the advantage of reducing transportation time by half (Yang et al., 2018; Jiang et al., 2018; Zhang and Schramm, 2019). This unique cost-time characteristic positions CRE to largely bridge the gap between maritime shipping and air transportation. A number of recent studies have extensively explored the development prospects and potential of CRE services (e.g., Wen et al., 2019; Lian et al., 2020; Zhou et al., 2021).

However, CRE is facing great marketing challenges, particularly its high freight rate compared to that of maritime transportation. As a result, many CRE lines encounter the issue of low utilization (Hillman, 2018; Besharati, 2017). To boost the attractiveness of CRE services, the Chinese government has taken proactive measures such as offering subsidies to reduce CRE freight rates in the hope of attracting more demand. However, the recently implemented subsidy schemes on CRE encounters a few deficiencies. First, all existing subsidy schemes are city-specific, typically providing a uniform subsidy amount to all CRE lines starting from the jurisdiction of a city. Such a simple subsidy policy overlooks the distinct operational features and competition characteristics of different CRE lines in the market. Second, the China-Europe freight transportation market is a structurally sophisticated, highly competitive economic system involving multiple transportation modes and freight service lines, compounding the complexity of subsidy implementation. Without carefully considering the interaction between different CRE lines and between CRE and other freight transportation services in the market, the efficacy of subsidies will be fall short of the optimal level. The still relatively low CRE market share and competence under the existing CRE subsidies reflect a lack of a systematic subsidy allocation across the entire CRE network.

This paper contributes to the relevant literature in two aspects. First, it evaluates the impacts of the *current subsidy* scheme on multiple levels, including the CRE network, service lines, and transportation paths[2], by using a multimodal multicommodity freight transportation network equilibrium model, as recently developed and tested by Li et al. (2022). This analysis encompasses an exploration of how the subsidy policy influences market share, freight volume, congestion level, and freight rate of CRE services. Second, a subsidy optimization model embedding the aforementioned freight transportation network equilibrium model and a tailored tabu search algorithm are developed and implemented to

[2] A path in this research is defined as a complete shipping itinerary from the origin to the destination that includes at least one railway or seaway line and, typically, a number of truck shipping trips for container pickup, drayage, delivery, and long-haul transportation services.

determine an optimal subsidy allocation plan across different CRE lines, aiming at simultaneously maximizing the capacity utilization and minimizing congestion level of all CRE lines. Using the subsidy optimization model and algorithm, we analyze and compare the performance of the China-Europe freight transportation market and particularly CRE service lines under different subsidy scenarios, including the *optimized subsidy*, *current subsidy*, *no subsidy* scenarios, and accordingly provide a set of useful policy insights and recommendations for enhancing the competitiveness of CRE lines. These research tasks and their relationships can be synthesized in the following methodological framework (see Figure 1).

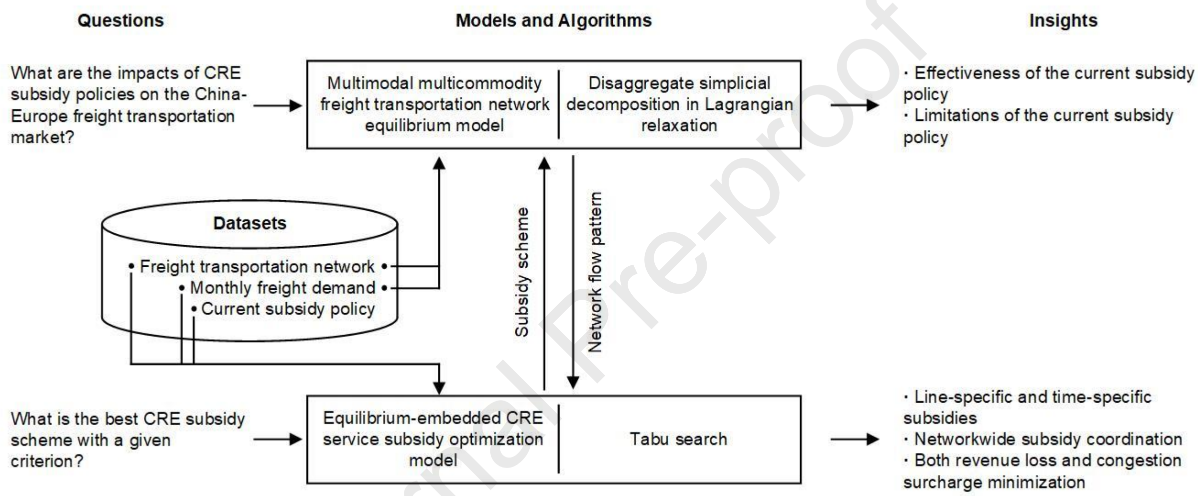


Figure 1 A methodological framework adopted in this study

The subsequent sections of this paper are structured as follows. Section 2 conducts a literature review of descriptive and prescriptive studies on freight subsidies. In Section 3, we elaborate on the sources, composition and construction of the datasets utilized for our study. Section 4 presents a detailed analysis of the impact of the *current subsidy* scheme by using the aforementioned multimodal multicommodity freight transportation network equilibrium model. Section 5 describes and applies the equilibrium-embedded subsidy optimization model for CRE service lines, where the existing and optimized subsidy schemes are analyzed in a comparative manner, based on which managerial insights and policy recommendations for fostering the CRE services are suggested. Finally, the paper is concluded in Section 6.

2. Relevant research

In the field of freight transportation, subsidy is commonly employed as an incentive tool for stimulating supply or demand increase. Many government agencies utilize it to achieve policy objectives for certain transportation supply or demand management purposes. Freight subsidy studies can be broadly categorized into descriptive and prescriptive ones. This section further reviews these studies with the emphasis of subsidy mode, subsidy purpose, subsidy form, subsidy amount, and modeling forms.

2.1. Descriptive freight subsidy studies

Descriptive studies evaluate existing subsidy policies by constructing models or indicator systems aligned with policy objectives to assess their effectiveness. For instance, Macharis and Pekin (2009) developed a location analysis model to study Belgium's intermodal incentive policies. They recommended integrating policies targeting rail/road and inland waterways/road combinations into a coherent vision to prevent unintended modal shifts between intermodal transportation options. Similarly, Lim and Lee (2013) developed an intermodal freight transportation network model to assess the impact of rail subsidies on increasing the modal share of freight rail in South Korea.

In Europe, Santos et al. (2015) analyzed the effects of rail subsidies aimed at fostering rail-based intermodal freight services; Tsamboulas et al. (2015) evaluated the Ecobonus financial incentive launched by the Italian government for a specific intermodal road-maritime route; Baindur and Viegas (2011) employed an agent-based simulation model incorporating complex supply-demand dynamics to evaluate intercity freight transport policies, finding that intermodal incentive policies could increase the market share of intermodal transportation by 25%–30%; Pittman et al. (2020) identified limited infrastructure capacity as a significant barrier to growing the European rail market share and suggested subsidies as a potential solution.

For Asian cases, Zhu (2021) introduced an evaluation framework applied to the Yiwu-Ningbo container freight corridor, concluding that subsidies were ineffective unless time costs were reduced; Takahashi (2005) conducted a survey in Japan to evaluate the effectiveness of subsidies for achieving modal shift and carbon reduction goals, finding low acceptance among enterprises; Sofiyandi et al. (2023) explored the causal effect of maritime logistics subsidies on food prices in Indonesia, noting an average 3.2% reduction in prices, which dissipated after one year; Jiang et al. (2023) and Qu et al. (2020) studied freight subsidy policies for Chinese ports: Jiang et al. (2023) estimated carbon reduction effects under six subsidy scenarios, while Qu et al. (2020) compared the impacts of various incentive strategies on shippers and port authorities within multimodal transport chains; finally, Yang et al. (2023), using the Three Gorges Dam as a case study, examined the effectiveness of subsidies in promoting transshipment, suggesting that road transport subsidies could help alleviate waterway congestion.

2.2. Prescriptive freight subsidy studies

Prescriptive freight subsidy studies focus on either analyzing existing subsidy policies or assuming government-provided subsidies, aiming to design schemes that align with policy objectives or maximize social benefits. Unlike descriptive studies, prescriptive studies treat subsidy amounts as decision variables.

A review of freight subsidy studies reveals that railways (e.g., Du and Shi, 2017; Yang et al., 2019; Yin et al., 2020b) and waterways (e.g., Chen et al., 2020; Hu et al., 2022) are the primary recipients of subsidies, while subsidies for road freight are rare (e.g., Yang et al., 2023; Perera et al., 2021). This aligns with the strategic goals of subsidy policies, which often aim to promote modal shifts (e.g., Takahashi, 2005; Kundu and Sheu, 2019; Feng et al., 2020; Li et al., 2023). Such policies typically encourage shippers to transition from road transport to rail or waterways due to the latter's lower unit transportation costs and greater environmental benefits. Subsidy programs that increase the market share of rail and water transport help address societal issues such as road congestion and environmental pollution. Additionally, many policies incentivize the development of intermodal transportation (e.g., Macharis and Pekin, 2009; Baindur and Viegas, 2011; Lim and Lee, 2013; Santos et al., 2015) or new freight platforms (e.g., Qu et al., 2020; Cai et al., 2021).

Prescriptive studies often assume specific subsidy forms and scopes. Common forms include fixed-rate subsidies (e.g., Qu et al., 2020; Lu et al., 2021), distance-based subsidies (e.g., Santos et al., 2015; Hu et al., 2022), and subsidies as a percentage of freight rates (e.g., Kundu and Sheu, 2019; Zhang et al., 2018).

Regarding the models used in prescriptive studies, multi-stage models (e.g., Du and Shi, 2017; Kundu and Sheu, 2019) and bi-level models (e.g., Zhang et al., 2018; Yang et al., 2019; Perera et al., 2021) are the most prevalent. These models are often grounded in principles such as user equilibrium principle (e.g., Chen et al., 2020; Li et al., 2022), game theory (e.g., Feng et al., 2020), and random utility theory (e.g., Jiang et al., 2023). The first is a multi-stage integer programming model. These models are typically based on game theory, where government subsidy decisions, carrier pricing or operational decisions, and shipper routing decisions are modeled as two-stage or three-stage games. Equilibrium solutions are sought to account for the interactions among these stakeholders. However, game theory models often struggle with direct subsidy optimization, relying instead on scenario testing with varying subsidy amounts to identify optimal schemes. The second modeling approach is a bi-level programming model. These models feature an upper-level government decision-making layer and a lower-level shipper response layer. The upper-level model aims to minimize subsidy costs (e.g., Yang et al., 2019) or optimize specific policy objectives (e.g., Hu et al., 2022). The lower-level model analyzes shippers' responses to subsidies, using methods like discrete choice models (e.g., Chen et al., 2023) or network flow and equilibrium models to minimize total transportation costs (e.g., Lu et al., 2021). Given the complexity of solving bi-level optimization models, researchers frequently employ heuristic algorithms (e.g., Zhang et al., 2018; Perera et al., 2021; Lu et al., 2021). These algorithms offer practical solutions to otherwise intractable problems.

We also analyzed case studies in prescriptive subsidies, observing a clear distinction in their scope compared to those descriptive studies. Many prescriptive studies focus on small-scale regions, particularly in the context of subsidy optimization for CRE services, often involving a limited number of CRE lines. In contrast, descriptive studies typically adopt a broader scope, analyzing the actual implementation areas of policies as their research cases.

Our analysis narrows its focus to prescriptive studies on CRE subsidy policies, as these align closely with the context of our research and provide a basis for comparative evaluation. Yang et al. (2019) identified inefficiencies in uncoordinated subsidies and proposed a bi-level programming model to explore coordinated subsidy schemes. Kundu and Sheu (2019) applied a game theory model, highlighting that a minimum subsidy of 30% of transportation costs is necessary to encourage shippers with a low value of time of cargoes to shift to CRE services. Similarly, Feng et al. (2020) developed a game theory-based subsidy model, recommending an optimal subsidy ranging between $2,000 and $2,500 per forty-foot equivalent unit (FEU). Gong and Li (2022) investigated subsidy optimization for CRE services and sulfur emissions control in China-Europe liner shipping, establishing a game theory model that addressed both competition and cooperation between CRE and liner shipping. Yin et al. (2020b) proposed a freight subsidy mechanism and formulated a bi-level programming model, concluding that the optimal subsidy should be approximately

14% of the transportation cost. Additional studies have developed CRE subsidy optimization models using game theory approaches, including those by Shi and Du (2017), Feng and Liu (2022), Xie et al. (2020), and Zhang and Xu (2021).

2.3. Research gaps

From the above literature review, we identified a few insufficiencies and shortcomings pertaining to previous research.

In descriptive studies on freight subsidies, the primary focus has been on evaluating the effects of subsidies on freight volume and energy-saving emissions. However, a significant gap exists in examining the indirect impacts of subsidy policies on the freight transportation market. These indirect effects include changes in network congestion levels, freight service utilization rates, and reductions in freight rates as perceived by various shippers. Moreover, there is a lack of research addressing the evaluation of subsidy policies within large-scale freight transportation networks, particularly those involving multiple transportation modes and diverse categories of goods.

In prescriptive studies, a notable limitation lies in the use of subsidy optimization models. These models often lack a robust, behaviorally grounded component for capturing networkwide freight flow patterns. The heterogeneous preferences and stochastic decision-making processes of shippers across different types of goods are frequently overlooked or inadequately addressed. Additionally, many prescriptive studies propose a single fixed subsidy amount as the optimal solution, offering a uniform subsidy across different CRE lines. This approach is overly simplistic and fails to account for the nuanced requirements of diverse lines, ultimately limiting its effectiveness.

3. Dataset construction and consolidation

Prior to conducting the CRE subsidy evaluation and reallocation work, let us first take a look at how the relevant datasets have been collected, processed and consolidated and key parameters estimated in this study. These datasets include the China-Europe freight transportation service dataset, China-Europe freight demand dataset, and CRE subsidy dataset.

3.1. China-Europe freight transportation service and network dataset

In the China-Europe freight transportation market, typically, goods departing its factory or warehouse in China, first undergo road transportation by trucks to seaports or railway stations, followed by either liner shipping or CRE from China to Europe; in Europe, freight is transported via road transportation networks from seaports or railway stations to its final destinations. The resulting multimodal freight transportation network used in this study encompasses all involving transportation modes, namely, liner shipping services, CRE services, and road transportation.

Firstly, the liner shipping services in the China-Europe freight transportation market are dominated by three major shipping alliances: 2M Alliance, Ocean Alliance, and THE Alliance. As of January 2020, these alliances accounted for 100% of the freight transportation capacity of the Asia-North Europe shipping market and 99% of the freight transportation capacity of the Asia-Mediterranean shipping market. To ensure a comprehensive representation of the liner shipping services, the China-Europe multimodal freight transportation network we developed includes 27 Asia-Europe liner service lines offered by these three alliances. Most details of each liner shipping service line, such as seaport rotation, timetable, vessel capacity, and fleet size, can be obtained from the official websites of these liner shipping companies.

In addition, the container freight rate corresponding to each seaport pair in each liner shipping service line is estimated by the following approach. The container freight rate generally consists of two components: ocean freight rate and seaport charge. We retrieve the ocean freight rates from the liner shipping companies' booking platforms and their online rate query tools. Seaport charges typically include terminal handling charge, booking charge, seal fee, document charge, and other fees, which vary by shipping lines. For Chinese seaports, seaport charges are obtained from a shipping information website named Weiyun[3]; for European seaports, seaport charges are obtained via those liner shipping companies' online rate query tools.

Regarding rail operations in the China-Europe freight transportation market, CRE services involve both state-owned enterprises and private firms. To standardize the operation of railway service lines and consolidate local resources, the Chinese government unified all railway express routes under the brand of CRE since 2016. Notably, some CRE lines operate regularly and adhere to a fixed schedule, while others do not. The China-Europe multimodal freight transportation network we created includes 55 regular rail

[3] Weiyun's website: http://www.weiyun001.com.

service lines operated by CRE as of 2019. The detailed information on CRE lines, including departure stations, arrival stations, border crossings, frequency, transit time, and station-to-station distance, is gathered from the official websites of CRE, governments, media platforms, and online maps.

Furthermore, we estimate the CRE freight rate by the following approach. The rate includes the railway transportation cost, surcharges at railway stations and break-of-gauge stations, and freight forwarding cost. First, due to different railroad systems employed by different countries, the calculation of transportation costs must consider these different parts: The railway transportation cost in China (with the standard gauge), railway transportation cost in Russia, Kazakhstan, Mongolia, and Belarus (with the broad gauge), and railway transportation cost in European countries (with the standard gauge or Iberian gauge). For domestic rail transportation, the rail transportation cost for a twenty-foot equivalent unit (TEU) equals the sum of a fixed cost ($52.47/TEU) and a variable cost that is the product of the unit variable cost ($0.21/TEU·km) and the distance. For overseas rail transportation, according to the published tariff level, the wide-gauge freight rates from Alataw Pass, Khorgas, Erenhot, and Manchuria to Europe are, respectively, $0.35/TEU·km, $0.35/TEU·km, $0.22/TEU·km, and $0.21/TEU·km. Meanwhile, the rail transportation cost for the European section is set as $0.50/TEU·km (Yin et al., 2020a). Second, surcharges at the railway station and the border break-of-gauge station are set as $63.50/TEU and $21.62/TEU, respectively (Alataw Municipal Government, 2023; Mohe Municipal Government, 2023; Erenhot Municipal Government, 2023). Third, the freight forwarding cost is set as $750.00/FEU (Jiang et al., 2018). Fourth, according to our interview with a freight forwarder from JC Trans[4], the service fee is $165.00/FEU.

Lastly, it has been observed that the domestic container transportation within China and interregional container transportation in Europe rely on highway networks. To establish connections between origins and destinations of seaports or railway stations, the China-Europe multimodal freight transportation network incorporates the major highway networks within China and Europe. The key time and cost parameters in the highway network are derived through following estimation. Transportation time is estimated based on an average cruise speed of 100 km/h in China and 80 km/h in Europe; the freight charge for highway transportation in China and Europe is estimated as $1.15/TEU·km (Zhao et al., 2018) and $1.60/TEU·km (Transport Intelligence, 2020), respectively.

[4] JC Trans' website: http://www.jctrans.com.

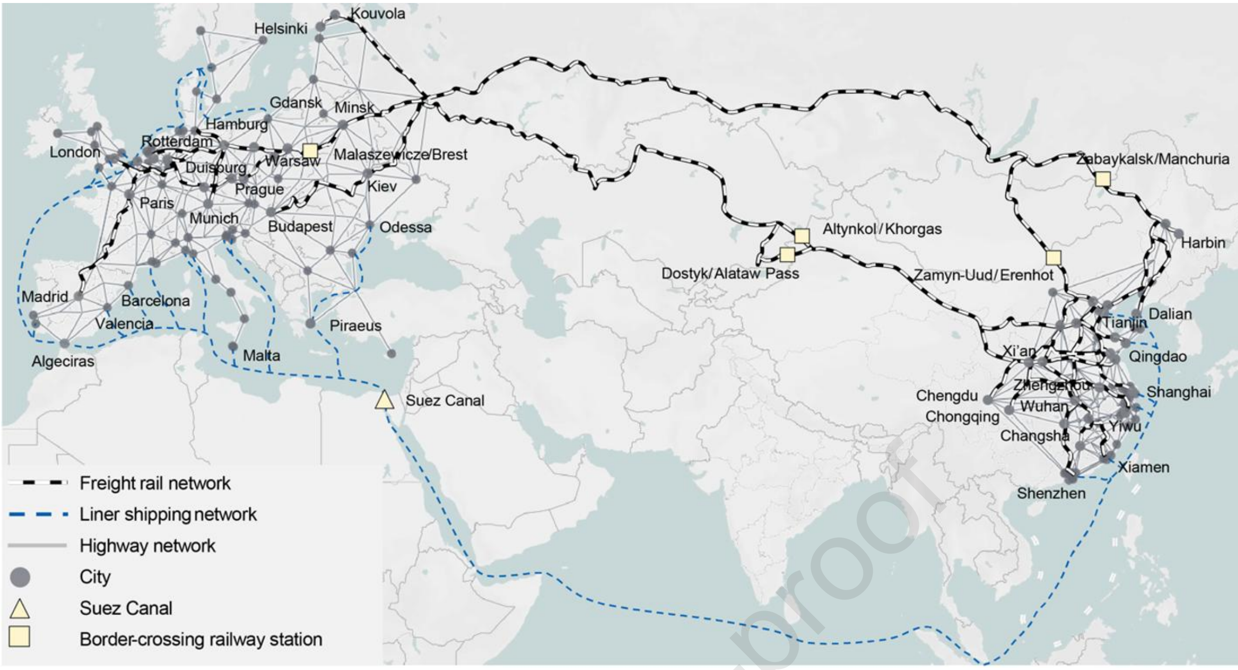


Figure 2 The China-Europe freight transportation network

Figure 2 exhibits the China-Europe multimodal freight transportation network we utilized in this study. The network encompasses 231 nodes, including 50 Chinese cities (as origins), 51 European cities (as destinations), 78 seaport nodes (including the tail nodes and head nodes of all 39 seaport links), 40 railway station nodes, 2 water channel nodes (representing Port Tewfik and Port Said in Egypt), and 10 break-of-gauge station nodes (representing 5 break-of-gauge stations). The network also comprises 46 bottleneck links (39 seaport links, a water channel link, and 5 break-of-gauge station links) with a polynomial cost function, 93 railway service links, and 739 highway network links. The number of liner shipping links varies across quarters due to the change in the liner shipping schedule, which equals to 186, 177, 180 and 171 in the first, second, third and fourth quarters, respectively. More technical details of this multimodal network can be found in Li et al. (2022).

3.2. China-Europe freight demand dataset

A complete freight transportation demand dataset for the year of 2019 for the China-Europe freight transportation market was compiled by month and categorized into nine distinct categories. The demand data is labelled with the origin and destination cities or regions and commodity types.

Figure 3 exhibits the monthly freight demand rates from China to Europe and their commodity composition in 2019. The demand rate and composition exhibit a significant fluctuation across months, where the demand rate in July, which appears as the highest, is 53% higher than that in February, which contributes the lowest. For this reason, throughout the following subsidy evaluation and optimization work, we typically elaborate only the freight flow results from February and July as two representative months, although the results for all other months are obtained as well.

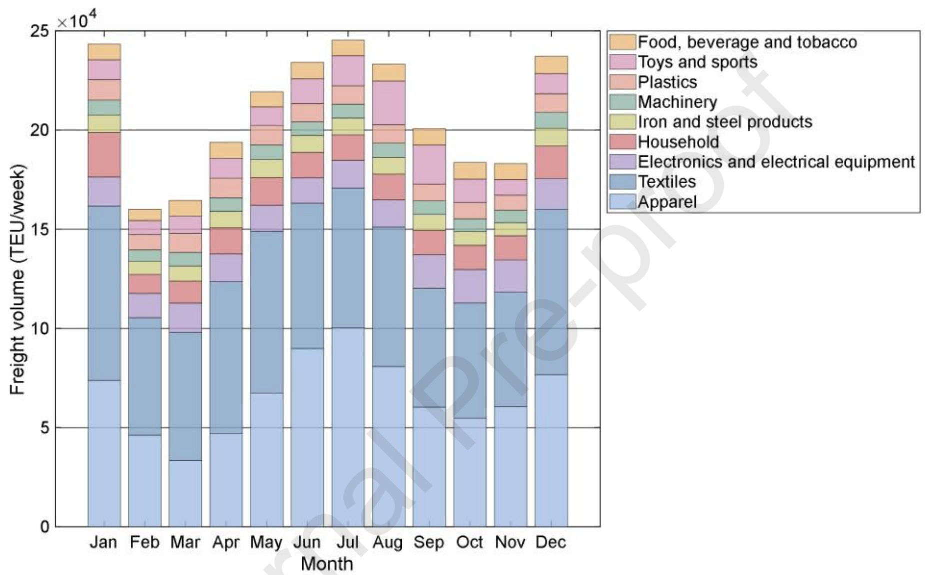


Figure 3 Monthly freight demand rates of nine commodity types in the China-Europe freight transportation market

The cargo exports from China to the 28 EU countries in 2019 constituted over 98% of China's total exports to Europe in terms of monetary value. Recognizing the significance of other European trading partners such as Ukraine, Norway, Switzerland, and Belarus, this study encompasses a total of 32 European countries (comprising 28 EU countries and 4 other European countries) as export destinations. On the other hand, we identify 20 provinces, municipalities, and autonomous regions in China as cargo origin regions in terms of their trading relationship with European countries, which collectively contribute to over 90% of China's exports to Europe in terms of monetary value. In total, 51 cities in the above European countries and 50 cities in the above Chinese provinces, municipalities, and autonomous regions are identified as freight destinations and origins, respectively, for this study.

The raw data of China-Europe freight demand was provided by the General Administration of Customs of China, in the format of the basic trade information of a shipment: Export date, harmonized system (HS) code, trading partner, location of the exporter, and monetary value. In order to get the export value of each commodity from a Chinese city to a European city, we first disaggregate the export value in proportion to the population size of cities in each European country to get the export value from each Chinese province to each European city. Then, we disaggregate the data in proportion to the total export value in each Chinese province to obtain the export values of individual China-Europe city pairs.

For the purpose of consolidation, we use *equivalent monetary value* (EMV) of a full container load, where a container is referred to as a TEU, to transform the monetary values of cargoes into TEU volumes. It is evident that different commodity categories have different EMV values. We systematically classify demand into nine distinct groups based on 2-digit and 4-digit level HS codes, each with a unique EMV, as shown in Table 1. As a result, we calculated the converted freight volume (in TEU) for each origin-destination pair of the China-Europe freight transportation network, as in nine distinct commodity categories.

Table 1 Commodity categories

Commodity	Level of time sensitivity	Equivalent monetary value ($/TEU)	Devaluation rate (per day)
Food, beverage, and tobacco	High	7,557	2.500%
Apparel	Medium	15,810	0.125%
Electrical and electronic equipment	Medium	202,020	0.125%
Household	Medium	35,255	0.125%
Toys and sports	Medium	27,137	0.125%
Textiles	Low	3,675	0.025%
Iron and steel products	Low	22,522	0.025%
Machinery	Low	107,116	0.025%
Plastics	Low	10,802	0.025%

On the other hand, our demand categorization also characterizes the heterogeneity of shippers in the China-Europe freight transportation market, reflecting the time sensitivity of different cargo types. Specifically, the nine commodity categories are of three levels of time sensitivity: High, medium, and low, each with a different depreciation rate, as shown in Table 1.

We further define the value of time, v_m, of each commodity category m as follows, according to the formula suggested by Lian et al. (2020):

$$v_m = \omega_m d_m + \frac{\omega_m r}{n} \tag{1}$$

where ω_m is the monetary value of commodity m (\$/TEU), d_m is the devaluation rate of commodity m due to the commodity obsolescence/deterioration, n is the number of days in a year, and r is the opportunity cost of shipper's capital. Following the standard practice in intertemporal logistics cost modeling (Lian et al., 2020), we set r as the 2019 annual interest rate on 5-year Chinese government bonds.

3.3. CRE subsidy dataset

The Chinese government has provided subsidies for CRE for years to address the challenge that the market share of CRE is not as high as expected. The CRE subsidy dataset is formed by collecting CRE subsidy policy data from two sources. First, we gathered statistical bulletins, fiscal budget reports, and solicitations for proposals on CRE subsidy policies published on government websites. Second, we retrieved and reviewed CRE subsidy policy reports from international trade information websites.

The CRE subsidy policy originated from the requirements outlined by the Ministry of Finance of China in "Work Requirements for Regulating the Financial Subsidy Funds for China Railway Express". Local governments design and implement individual subsidy schemes on the basis of this requirement, leading to region-to-region variations of subsidy policies. For instance, the Harbin Municipal Government provides a subsidy of $3,000/TEU for the CRE line named "Haxinou", while the Zhengzhou Municipal Government subsidizes the local CRE operating company in the form of tax refunds and land allocation, with an annual subsidy expenditure of approximately $16 million. Among all CRE subsidy forms, the fixed subsidy amount based on freight volume (in $/TEU) is the most widely adopted due to its ease of implementation. In order to facilitate the inclusion of subsidy policies from different regions into the China-Europe freight transportation network, we standardize all subsidy schedules to this form. For other forms of subsidy schedules, we calculate the subsidy amount per TEU by dividing the total subsidy expenditure in a region by the freight volume receiving the subsidy. Figure 4 summarizes the monthly subsidy expenditures in 2019 for the entire CRE system, while Figure 5 depicts the standardized subsidy value for a single container departing from all departure cities of CRE service lines in the same year.

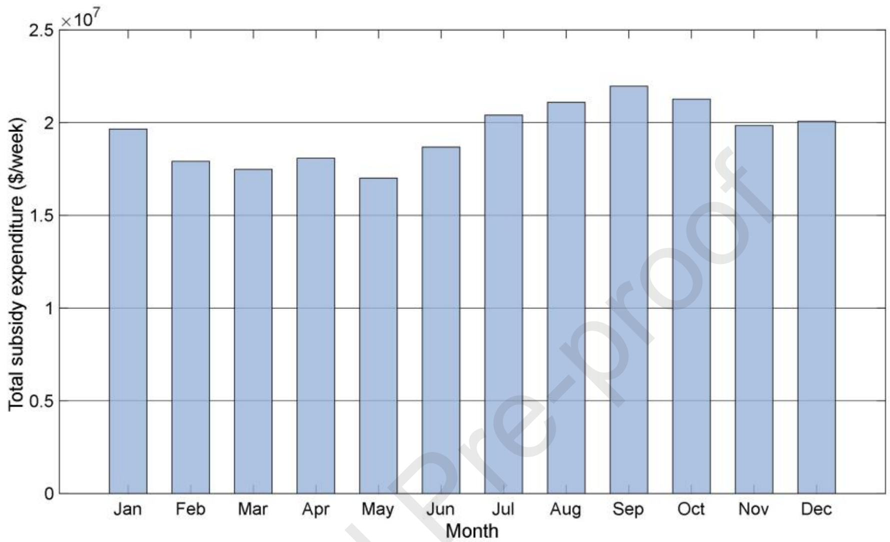


Figure 4 Monthly subsidy expenditures for the CRE system

Figure 5 Standardized subsidy values for a container from departure cities of CRE service lines

4. Subsidy evaluation

Subsidy evaluation relies on a freight transportation network flow model that can explicitly take into account multiple disutility components (including transportation time, freight rate, and shipping subsidy), freight transportation modes (such as freight rail, liner ships, and trucks), freight transfer processes (at railway stations, break-of-gauge stations, and seaports), and commodity types. Below we first review such a model and then discuss the subsidy evaluation results from applying it to the China-Europe freight transportation network.

4.1. Freight transportation network flow model

Evaluating the impact of subsidies on the CRE system resorts to solving a multimodal multicommodity freight transportation network equilibrium problem. A convex programming model for this problem was recently developed by Li et al. (2022) and further discussed in Wang and Xie (2025). The model is of the following mathematical form:

$$\text{minimize} \quad B\big(\mathbf{f}, \mathbf{t}_b(\mathbf{f})\big) + C(\mathbf{f}, \bar{\mathbf{t}}_a, \mathbf{t}_b(\mathbf{f}), \bar{\mathbf{c}}, \bar{\mathbf{s}}) + E(\mathbf{f}) \tag{2}$$

$$\text{subject to} \quad \boldsymbol{\Xi}\mathbf{f} = \bar{\mathbf{q}} \tag{3}$$

$$\boldsymbol{\Delta}\mathbf{f} \leq \bar{\mathbf{u}} \tag{4}$$

$$\mathbf{f} \geq \mathbf{0} \tag{5}$$

where $\mathbf{f}$ denotes the path flow rates, the primal decision variables of the model, $\bar{\mathbf{t}}_a$ denotes the fixed transportation times of rail service lines, liner shipping lines, and highway networks, $\mathbf{t}_b$ denotes the variable transportation times such as flow-dependent delays occurring at bottleneck facilities (i.e., seaports, water channels, and break-of-gauge railway stations), $\bar{\mathbf{c}}$ denotes the freight rates of rail service lines, liner shipping lines, and highway networks, $\bar{\mathbf{s}}$ denotes the rail subsidies, $\bar{\mathbf{q}}$ denotes the freight demand rates from origins to destinations, $\boldsymbol{\Xi}$ is the origin/destination-path incidence matrix, $\bar{\mathbf{u}}$ denotes the capacity values of rail service lines and liner shipping lines, and $\boldsymbol{\Delta}$ is the link-path incidence matrix.

The objective function in (2) consists of three terms: $B(\cdot)$ is the well-known Beckmann transformation (Beckmann et al., 1956) that is used to quantify the queueing or waiting delay occurring at freight transportation or transfer bottlenecks in the network, $C(\cdot)$ represents the sum of all constant costs in the system, including fixed transportation times, freight rates, and rail subsidies associated with highway networks, liner shipping lines, and CRE service lines, and $E(\cdot)$ is the entropy term of path flow rates. In the set of constraints, the constraints in (3) set the flow conservation within each origin-destination pair, the constraints in (4) impose the physical capacities of link segments of rail service lines and liner shipping lines, and the constraints in (5) guarantee the nonnegativity of all categorized path flow rates.

Alternatively, the problem could be also written as a complementarity system of equations and inequalities, which will be more conveniently used as part of the constraints of the subsidy optimization problem we will introduce later on:

$$\Phi(\bar{\mathbf{t}}_a, \mathbf{t}_b(\mathbf{f}^*), \boldsymbol{\mu}^*, \bar{\mathbf{s}}, \bar{\mathbf{c}}) = \mathbf{f}^* \tag{6}$$

$$\Theta(\mathbf{f}^*, \boldsymbol{\mu}^*, \bar{\mathbf{u}}) \geq \mathbf{0} \tag{7}$$

where $\boldsymbol{\mu}$ denotes the link-specific dual variables corresponding to the capacity constraints in (4), as generally interpreted as the queueing or waiting delays of individual shippers before obtaining space from their desired rail service lines or liner shipping lines, and the definition of all other variables and parameters is the same as given previously.

In the above complementarity problem, the nonlinear equations in (6) include the mode-route choice probability functions and flow conservation equations, while the nonlinear inequalities in (7) synthetically depict the primal constraint-dual variable complementarity relationship between the capacity constraints in (4), $\boldsymbol{\Delta}\mathbf{f} \leq \bar{\mathbf{u}}$, and waiting delay variables $\boldsymbol{\mu}$. It is noted that both primal variables $\mathbf{f}$ and dual variables $\boldsymbol{\mu}$ are included in the complementarity formulation, the optimal values of which are highlighted by asterisk marks.

Overall, either of the above problem formulations describes in a mathematical way the spatial distribution of containerized freight flow rates across all available transportation modes and service lines in the China-Europe freight transportation market. A prominent feature of these formulations is that they account explicitly for individual shippers' mode-route choices, congestion effects due to bottleneck facilities, and demand queues resulting from the limited capacities of rail service and liner shipping lines. By solving the convex programming or complementarity problems, we can systematically evaluate the quantitative impacts of CRE subsidies on different levels, identifying both the strengths and limitations of the *current subsidy* scheme, and assessing its economic implications. This problem can be solved by the subgradient algorithm or iterative balancing algorithm, embedding a disaggregate simplicial decomposition algorithm (Larsson and Patriksson, 1992) for solving the subproblem obtained from relaxing the capacity constraints. Readers who are interested in knowing more about the algorithmic details of the iterative balancing procedures are suggested to refer to Zeng and Xie (2025), respectively. In this study, the iterative balancing algorithm is employed and coded in C++ for solving the freight transportation network equilibrium problem sketched in (2)-(5).

4.2. Impact on the entire CRE system

In the current freight transportation market, traditional China-Europe liner shipping and emerging CRE services represent the two dominant competing modes. Government subsidies are strategically designed to lower the actual CRE freight rates to shippers, thereby enhancing its competitiveness and incentivizing a modal shift from seaway to railway. A key measure of subsidy effectiveness is the volume of cargos diverted from the liner shipping to CRE. Table 2 shows that, compared to the *no subsidy* scenario, the *current subsidy* scheme boosts the CRE freight volume by 2,823 TEUs per week on average over the entire year, with a monthly increasing percentage ranging from 62% to 109%.

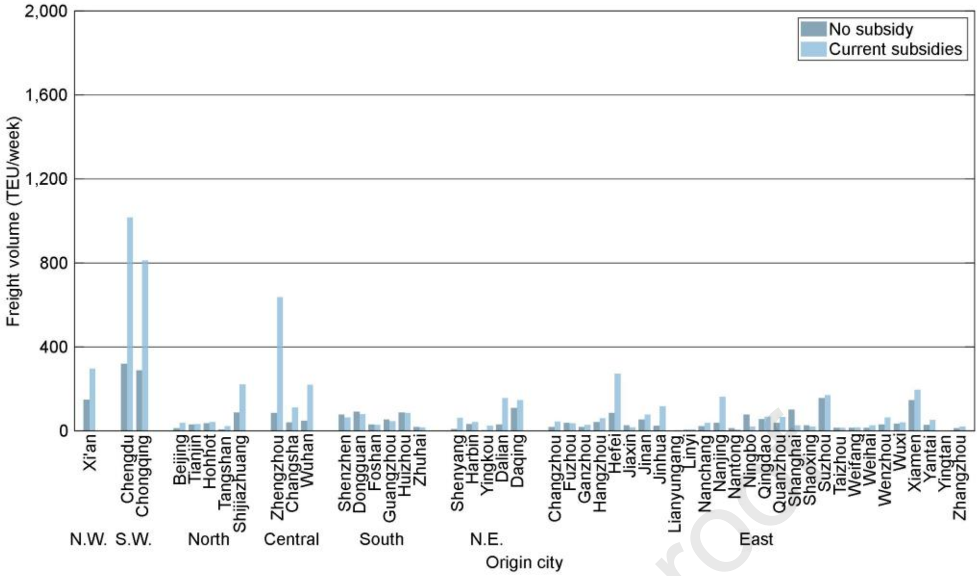
Table 2 Monthly total freight volume changes due to the current subsidy scheme

Month of the year of 2019	Total freight volume without subsidy (TEU/week)	Total freight volume with the current subsidy scheme (TEU/week)	Freight volume change
January	3,663.47	6,507.93	+78%
February	2,815.39	5,894.80	+109%
March	2,988.73	5,773.87	+93%
April	3,343.31	6,012.94	+80%
May	3,528.99	5,723.50	+62%
June	3,773.75	6,217.25	+65%
July	3,917.51	6,721.00	+72%
August	3,871.88	6,923.78	+79%

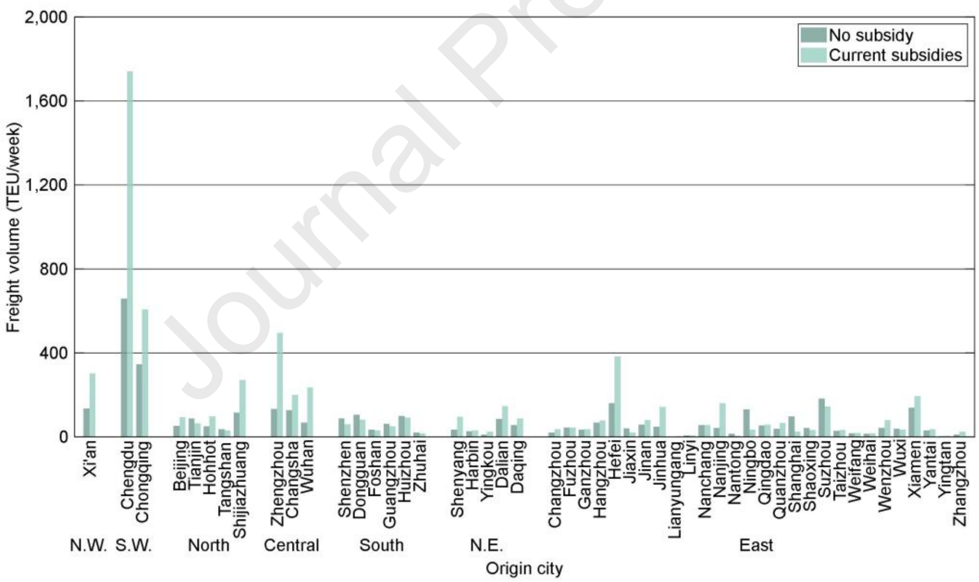
September	4,084.98	7,118.66	+74%
October	3,856.71	6,919.74	+79%
November	3,593.00	6,499.35	+81%
December	3,595.14	6,598.42	+84%

A further analysis of the spatial distribution of shifted freight demand by origin city, shown in Figure 6, indicates a notable demand concentration in inland Chinese cities, including Chengdu, Chongqing, Zhengzhou, Xi'an and Hefei. In contrast, some coastal cities like Yingkou, Yantai, and Hangzhou see only small shifts from the China-Europe liner shipping to CRE, while others like Shanghai, Ningbo and Shenzhen even see a significant amount of freight demand shifted from CRE to the liner shipping. The latter phenomenon reflects the complex competition situation of the freight demand from different Chinese cities for the limited capacity of CRE lines. On the destination side, however, the shifted freight demand is quite evenly distributed across European cities without an apparent geographical difference. This suggests that the influence of the subsidies on shippers' mode choices is more strongly associated with origin cities rather than destination cities.

In the pre-CRE era, inland shippers had to transport goods to the seaports located along the southeastern coast of China via roadway or railway before loading goods onto China-Europe liner ships, incurring additional transportation costs and time. CRE offers a rail-based land transportation option for freight demand between Chinese origin cities to European destination cities, largely reducing transportation cost, time and distance, particularly for the freight destined to cities in inland Europe. Such a shortcut obviously drives the interest of inland shippers in switching from conventional liner shipping to CRE, especially when the CRE services are subsidized.



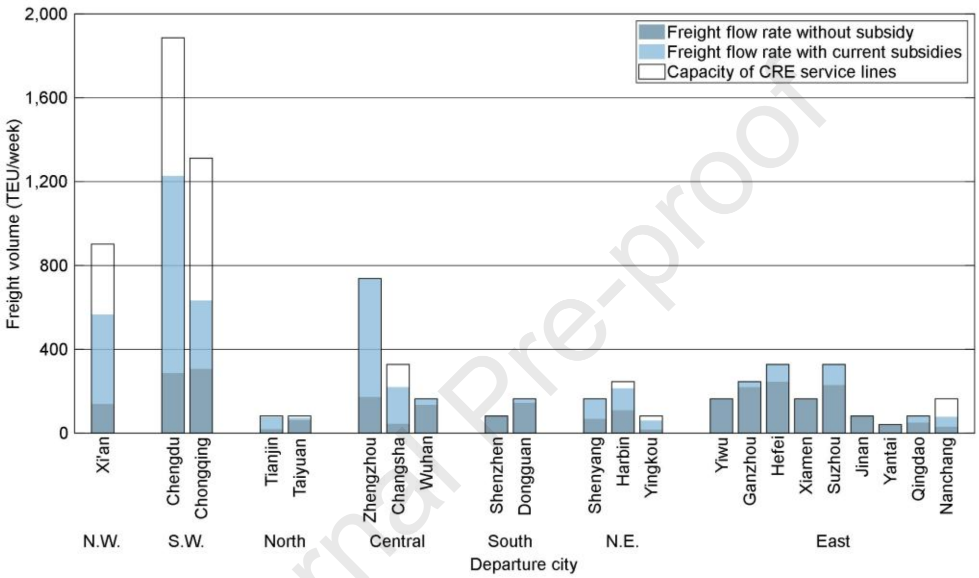
(a) February 2019



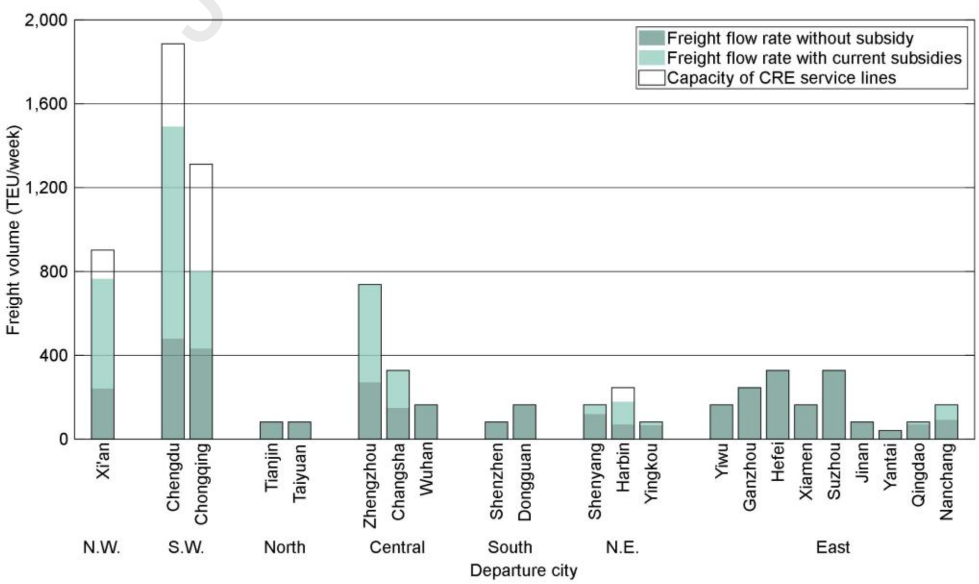
(b) July 2019

Figure 6 Shifted freight demand from liner shipping to CRE across origin cities under the *current subsidy* scheme

The capacity of individual CRE lines also plays a crucial role in enabling modal shifts. Only lines with a surplus capacity can effectively absorb the additional freight demand induced by subsidies. Notably, CRE lines originating from inland China typically offer a greater capacity than those in coastal areas, making them being at a better position to attract shifted demand. Figure 7 illustrates changes of the CRE market share across departure cities under the *no subsidy* and *current subsidy* scenarios. CRE services departing from hinterland cities, particularly Chengdu, Chongqing, Xi'an, Zhengzhou, and Changsha, capture significantly more freight demand than those from coastal regions. This increase in freight volume reinforces the position of Chinese hinterland cities in the CRE market, with coastal cities merely playing a secondary role.



(a) February 2019



(b) July 2019

Figure 7 Freight volume change of departure cities of CRE service lines under the *current subsidy* scheme

4.3. Impact on CRE service lines

The China-Europe containerized freight transportation network examined in this study comprises 55 CRE service lines in total, on which we analyze the volume and congestion changes caused by the *current subsidy* scheme as follows.

For quantifying the impact of the *current subsidy* scheme, the *occupancy rate* of CRE service lines is used as a basic measure, which is defined as the percentage of the capacity of a CRE service line occupied by cargos. For discussion convenience, we divide occupancy rate into four categories: 0%–30%, 30%–60%, 60%–99%, and ⩾99%, and refer to lines that fall into these four categories as lowly utilized lines, moderately utilized lines, highly utilized lines and saturated lines, respectively. To graphically illustrate the change of the occupancy rate of CRE service lines due to the imposition of subsidies, we accordingly construct a 4 × 4 matrix where each cell indicates the number of CRE lines pertaining to a specific change of occupancy category.

As evidenced in Figure 8, the matrix quantifies cargo volume shifts in all occupancy rate changes between the *no subsidy* and *current subsidy* scenarios. Notably, the *current subsidy* scheme exhibits a substantial effect on enhancing the occupancy rate of those pre-subsidy unsaturated lines. For example, in July 2019, 22 pre-subsidy unsaturated lines became saturated with the current subsidies imposed. Specifically, under the *current subsidy* scheme, all 7 pre-subsidy highly utilized lines become saturated, while 15 out of 25 pre-subsidy moderately or lowly utilized lines become saturated, indicating that the *current subsidy* scheme is more conducive to helping those lines that already have a relatively high occupancy rate to achieve full capacity utilization. On the other hand, we also noticed that the occupancy rates of 9 CRE service lines in February 2019 and 5 lines in July 2019 remain below 60% under the *current subsidy* scheme, which indicates that these lines are relatively irresponsive to the *current subsidy* scheme.

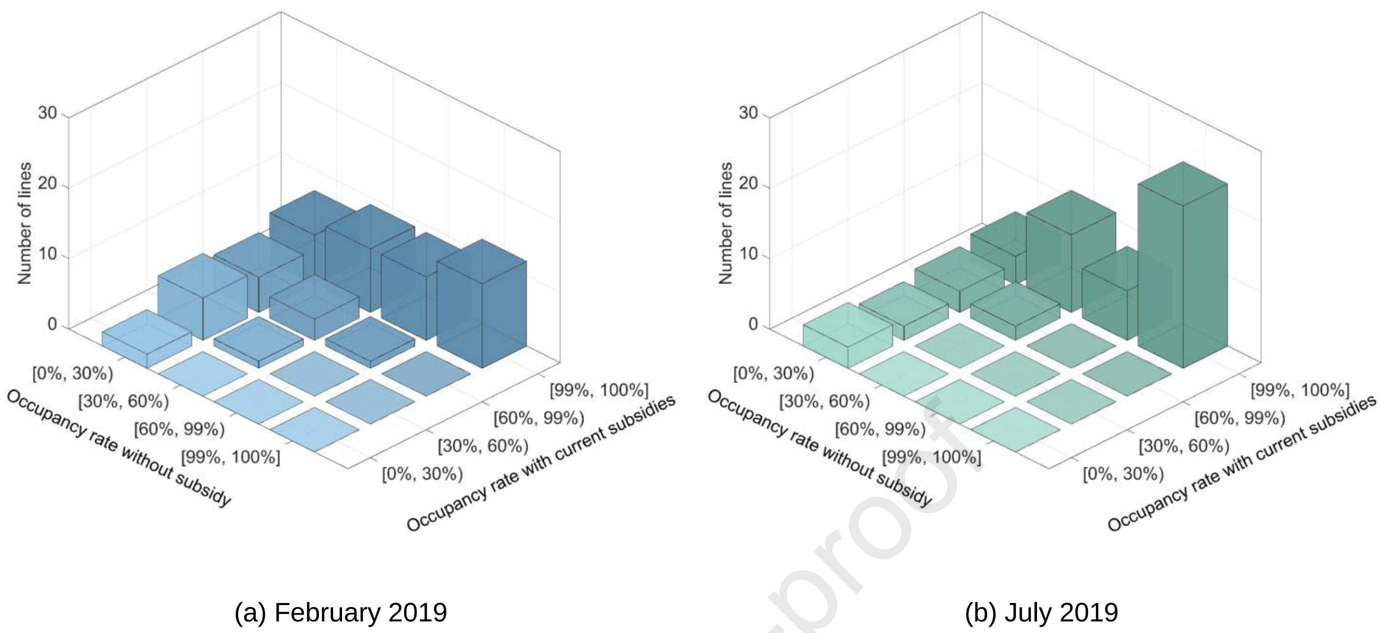
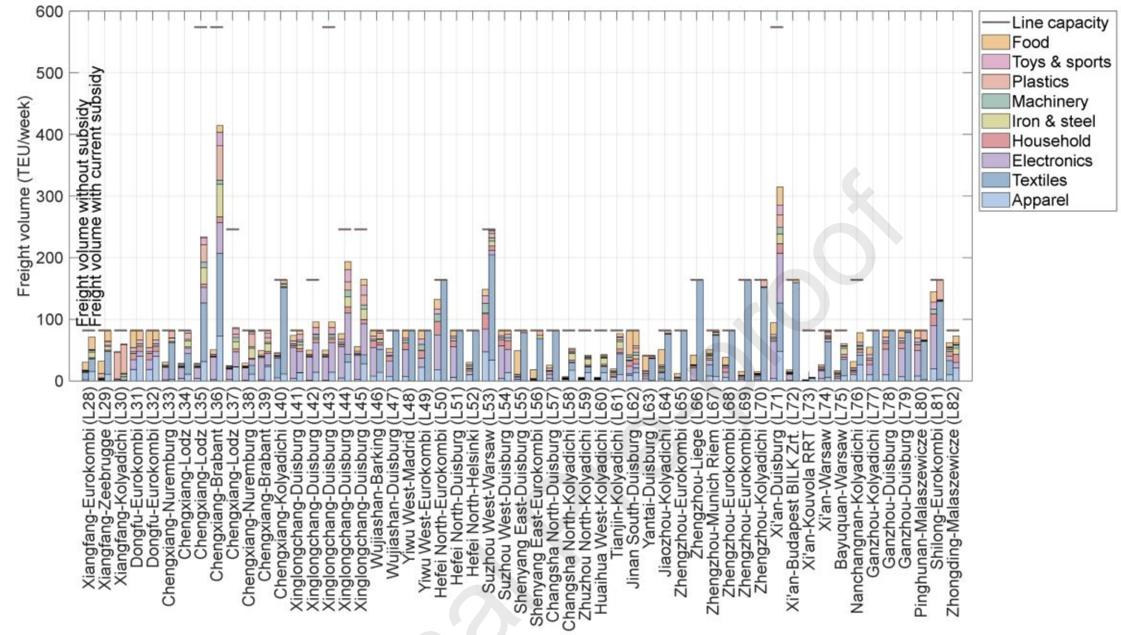
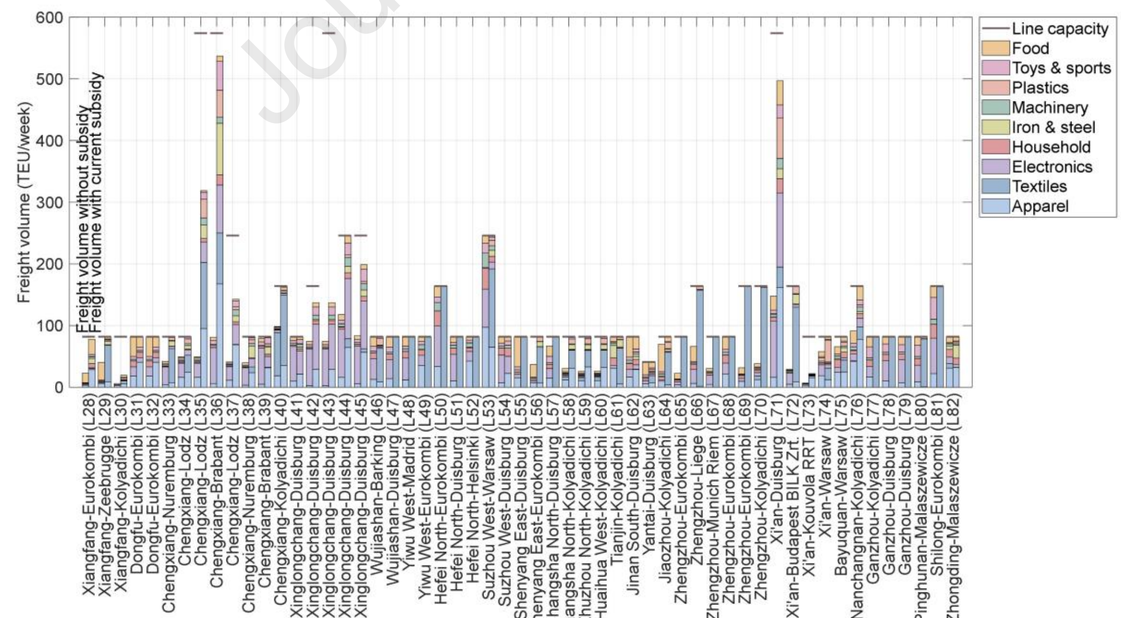


Figure 8 Occupancy rate change of CRE service lines due to the *current subsidy* scheme

Under the *current subsidy* scheme, the number of unsaturated lines decreases from 43 to 18 in February 2019 and from 32 to 10 in July 2019. Figure 9 compares the categorized freight volumes of all CRE service lines under the *no subsidy* and *current subsidy* scenarios. In both months, the *current subsidy* scheme increases the freight volumes of pre-subsidy unsaturated lines. In February 2019, for instance, for the 18 lines that remain unsaturated with the current subsidies (e.g., Line 37, Line 44, and Line 71), the freight volume of high-value goods (e.g., food and electronics) does not change much, while a large number of commodities of other categories are likely to shift to these lines to take advantage of their unused capacity. Among the 25 lines that become saturated due to the *current subsidy* scheme and the 12 lines that were already saturated under the *no subsidy* scenario, the commodity composition exhibits more or less changes. On some CRE lines like Line 39 and Line 54, the volume and proportion of high-value goods show a slight change, while many other CRE lines like Line 69 and Line 78 are completely dominated by goods with the lowest value of time (i.e., textiles) under the *current subsidy* scheme. The commodity composition change relates to different shippers' responses to the competition for the limited capacity of CRE service lines. Specifically, textile shippers are likely to shift to those lines with low freight rates and high subsidy levels to save their shipping expenditure, regardless of the fierce capacity competition, while other shippers of high-value goods may be thus reluctant to choose these lines considering the possible prolonged waiting delays. This delay, attributed to the limited capacity of CRE service lines, is termed as capacity-induced delay, measured in days. In the freight transportation network model, the Lagrangian multipliers associated with the capacity constraints, $\boldsymbol{\mu}$, indicate that such delays, which, when multiplied by the value of time of goods, can be interpreted as *congestion surcharge* (in \$).



(a) February 2019



(b) July 2019

Figure 9 Freight volume increase and commodity composition change caused by the *current subsidy* scheme

4.4. Impact on CRE transportation paths

A CRE-based transportation path represents a complete itinerary from an origin city to a destination city, encompassing all transportation and transshipment stages: The long-haul rail transportation along a CRE line, road transportation by trucks, and cargo loading, unloading, and drayage processes. Figure 10 illustrates an example CRE-based transportation path from Shanghai, China, to Hamburg, Germany. Each CRE-based path is a mode-route option that implies a CRE service as its primary long-haul mode. While a single CRE service line can serve multiple CRE transportation paths that share its capacity, each CRE-based path uses only one CRE line. Shippers may have access to multiple paths that meet their requirements but vary in transit times and freight rates and typically favor those paths with shorter times and lower rates.

Figure 10 An example CRE-based transportation path from Shanghai, China to Hamburg, Germany

In this section, we focus on shippers transporting goods from Chongqing, China, to Hamburg, Germany, to analyze their available transportation paths, the impact of subsidies on generalized transportation costs, and the effects on shippers' mode-route choices. In this origin-destination example, 124 containers are shipped weekly, carrying primarily electronic equipment (76% of the volume), machinery (14%), textiles (4%), apparel (3%), and other goods (3%) making up the remainder. The China-Europe market provides 16 liner shipping lines and 10 CRE service lines for these shipments.

Using the freight transportation network equilibrium model, we combined the 16 liner shipping lines with highway networks, creating 103 seaway-based transportation paths from Chongqing, China to Hamburg, Germany, with their freight rates between \$2,863 and \$5,278 per TEU and transit times ranging from 27 to 53 days. Meanwhile, combining the 10 CRE lines with road transport produces 12 distinct CRE paths connecting the same origin-destination pair. Without subsidies, the freight rates carried by the CRE paths range from \$4,376 to \$6,026 per TEU and their transit times are from 16 to 20 days; under the current subsidies, the effective freight rates drop to the level between \$1,376 and \$2,922, which significantly increase their attractiveness in the market. Figure 11 presents a scatter plot showing the shift of the competitiveness of these CRE paths, in which the horizontal axis represents freight rate and the vertical axis represents transit time. This plot clearly shows that, with the current subsidies, the set of CRE paths turns to be more competitive than the seaway paths in both monetary cost and transit time.

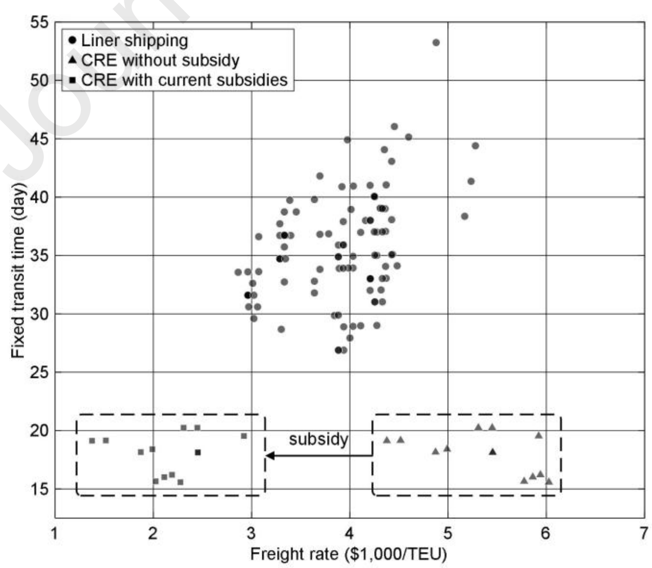


Figure 11 Freight rate and transit time of all available railway-based and seaway-based paths from Chongqing, China to Hamburg, Germany

Shippers' mode-route choice depends on both freight rates and transit times. In the freight transportation network equilibrium model, these factors are combined into the generalized transportation cost through the value of time defined in (1). While subsidies reduce freight rates, they do not impact transit times, so their effectiveness in lowering generalized transportation costs varies by commodity. Taking all CRE-based paths using Line 71 (from Xi'an, China to Duisburg, Germany) as an example, Table 3 shows how subsidies reduce the generalized transportation costs of nine commodity categories in two example months, February and July 2019.

Table 3 Generalized transportation cost change of nine commodity categories with an example CRE line from Chongqing, China to Duisburg, Germany

(a) February 2019

Commodity category	Average generalized transportation cost without any subsidy ($/TEU)	Average generalized transportation cost with subsidies ($/TEU)	Percentage of cost change due to subsidies (%)
Apparel	5,957.5	3,157.4	-47%
Textiles	4,428.4	1,967.8	-56%
Electronics	11,033.9	8,279.9	-25%
Household	6,552.5	3,624.0	-45%
Iron & steel	5,167.9	2,350.4	-55%
Machinery	6,177.2	3,280.3	-47%
Plastics	4,848.0	2,370.2	-51%
Toys & sports	6,339.0	3,490.3	-45%
Food	9,763.4	6,901.3	-29%

(b) July 2019

Commodity category	Average generalized transportation cost without any subsidy ($/TEU)	Average generalized transportation cost with subsidies ($/TEU)	Percentage of cost change due to subsidies (%)
Apparel	5,880.6	3,278.5	-44%
Textiles	4,480.7	1,724.5	-62%
Electronics	11,139.4	8,723.1	-22%
Household	6,505.4	3,625.7	-44%

Iron & steel	5,291.5	2,421.3	-54%
Machinery	6,327.3	3,441.3	-46%
Plastics	4,096.1	1,761.2	-57%
Toys & sports	6,445.2	3,586.3	-44%
Food	9,691.2	6,947.8	-28%

As shown in Table 3, the generalized transportation cost for textiles decreases the most (56% and 62% in February and July 2019, respectively) due to the imposition of subsidies, while the cost for electronics decreases the least (25% and 22% in February and July 2019, respectively). The distinct results of the two types of commodities are due to their different values of time: Textiles have the lowest value of time among all commodity types in our study, while electronics have the highest. The reduction in generalized transportation costs from subsidies is more pronounced for goods with a lower value of time. This conclusion is also analytically justified in Appendix A.

4.5. Policy insights and recommendations

For the sake of policymakers in understanding and leveraging the above results, we present a summary of policy recommendations and insights derived from the analysis of the current CRE subsidy scheme.

Effectiveness of the current subsidy scheme. Our analysis demonstrates the effectiveness of the *current subsidy* scheme, which successfully shifted a weekly average of 2,823 TEUs from liner shipping to CRE, resulting in an annual increase of 78.7% in total CRE freight volume. This shift raised CRE's market share from 1.72% to 3.08%. The subsidy scheme's impact is especially pronounced on specific CRE lines and regions. First, it is highly effective for partially loaded lines. In July 2019, there were 32 partially loaded CRE lines in the China-Europe freight transportation market, carrying a combined volume of 1,744 TEU/week without subsidies. Under the *current subsidy* scheme, this volume increased to 4,547 TEU/week, marking a significant growth of 261%. Second, the scheme is particularly effective for CRE lines originating from inland Chinese regions. For example, lines from Chengdu, Chongqing, Xi'an, Zhengzhou, and Changsha carried 1,369 TEU per week without subsidies, rising to 3,848 TEU/week with subsidies—a 2.8 fold increase.

Limitations of the current subsidy scheme. Our analysis also reveals a few limitations of the *current subsidy* scheme. First, the scheme has little impact on the freight volume of saturated lines. For example, in July 2019, the freight volume for 23 pre-subsidy fully utilized CRE lines was 2,173 TEU/week under both the *no subsidy* and *current subsidy* scenarios. This limited impact is due to capacity constraints that prevent growth on these saturated lines. Similar findings were reported in studies by Lim and Lee (2013) and Pittman et al. (2020). Second, the scheme has limited influence on the freight volume of lines originating from coastal regions like Yiwu, Xiamen, and Tianjin. This geographic limitation is linked to both capacity constraints and shippers' preferences for convenience. Due to distance considerations, inland shippers are more inclined toward CRE services than those in coastal areas, a factor affecting the subsidy's effectiveness. This finding aligns with Qu et al.'s (2020) analysis on European railway subsidies. Third, the reduction in total congestion surcharge comes at the cost of disproportionate dominance of goods with the lowest value of time (i.e., textiles) on a large number of saturated CRE lines. Specifically, textile shippers dominate CRE lines of low freight rates to save their monetary expenditures, thereby forcing shippers of other commodities to either choose CRE lines starting from more distant cities or resort to liner shipping.

Differential impacts on different commodity categories. Our analysis of the generalized transportation cost for nine commodity categories shows that subsidies have different impacts on different categories due to their different values of time. Specifically, goods with a low value of time experience a more substantial reduction in generalized transportation costs compared to those with a high value of time. For example, in July 2019, subsidies reduce the generalized transportation cost of textiles (with a low value of time) by 62% on Line 71 (from Xi'an, China to Duisburg, Germany), whereas the cost for electronics (with a high value of time) decreases by only 22%. Further calculations demonstrate that subsidies and extended transit times benefit goods of a low value of time, while increased freight rates and reduced transit times favor goods of a high value of time. Similar findings in prior studies have led researchers to advocate for differentiated subsidies in terms of commodity categories (e.g., Shi and Du, 2017; Kundu and Sheu, 2019; Yin et al., 2020b; Feng et al., 2020; Chen et al., 2023).

5. Subsidy reallocation

In view of the strengths and limitations of the *current subsidy* scheme, this section develops and implements a subsidy optimization model to improve its overall operational efficacy of the CRE system. The model is of a two-level structure: The aforementioned freight transportation network equilibrium model serves as the lower-level problem and a subsidy optimization objective in the upper-level problem is so set as to simultaneously maximize the capacity utilization and minimize the excessive congestion of CRE lines. The *optimized subsidy* scheme characterized by the model is then analyzed and compared with the *current subsidy* scheme as well as the no subsidy case, with a focus on its economic benefits, practical implications, and recommendations for policymakers.

5.1. Subsidy optimization model

Similar to many decision-making problems involving interactions between government agencies and business or individual stakeholders, the subsidy optimization problem must consider various stakeholders' interests and concerns. From a game theory perspective, an essential feature is that the outcome of decisions made by a higher-level authority (the leader), aimed at achieving specific goals, depends on the reactions of numerous lower-level entities (the followers) who are motivated to optimize their own interests. This leader-follower relationship forms a Stackelberg game. In our study, the Chinese government acts as the subsidy provider in the leader position, setting the subsidy amounts of all CRE lines so as to optimize the CRE system's performance. Individual shippers, acting as followers, select freight transportation modes and services based on their perceived generalized transportation costs, resulting in a sufficiently competitive, equilibrium state of freight flows across the China-Europe freight transportation network. Below, we present the subsidy optimization model within this leader-follower framework, outlining its assumptions and model structure.

A few key assumptions or settings must be clarified prior to the modeling work, which imply a number of essential features of the subsidy allocation problem:

Subsidy provider. We presume that a central government, as the sole subsidy provider and decision maker, subsidizes all CRE lines if needed. This reflects the real subsidy allocation mechanism in China, where most CRE subsidies come from or are controlled by the central government rather than by provincial or local governments. The latter is usually concerned only about CRE lines originating within their regions. Subsidies for CRE lines are structured as a fixed amount per unit of freight while allowing for variation across different lines.

Subsidy recipient. We recognize that shippers are the recipients of subsidies, which directly reduce their out-of-pocket monetary costs for CRE services. This is also the current practice of the CRE subsidy allocation in China. In contrast, freight subsidies in some other countries were distributed to various recipients. For example, subsidies were directed exclusively to shippers (e.g., Kundu and Sheu, 2019), exclusively to freight service operators (e.g., Santos et al., 2015), or to both shippers and operators (e.g., Yang et al., 2019).

Subsidy range and values. We limit the subsidy amount for each CRE line to range from zero to its freight rate, ensuring the actual freight rate remains positive after subsidy deduction. To align with publicly announced subsidy schedules, we assume that feasible subsidy values for a CRE line are constrained to only integer multiples of $500 between $0 and the freight rate. In other words, the set of possible subsidy amounts for a service line is $\{0, 500, 1000, ..., \lfloor r/500 \rfloor \times 500\}$, where r denotes the freight rate.

Time-varying subsidy. A separate subsidy optimization model is applied for each month with the month's specific freight demand pattern to generate a month-specific subsidy schedule. In other words, the *optimized subsidy* scheme includes 12 subsidy schedules, where each month has a unique schedule. Such a time-varying subsidy scheme is expected to produce greater efficacy than a uniform subsidy scheme for the whole year.

Demand inelasticity. For modeling simplicity, we assume that subsidy adjustments do not significantly alter the total freight demand amount and pattern in the China-Europe freight transportation market. After all, the production of freight demand is due to many factors, such as supply, market, trading policies, tariffs, and so on, in which subsidy is just a minor factor. However, individual shippers may switch between different transportation modes and service lines in response to subsidy reallocation.

Then the formulation of the subsidy optimization problem can be sketched as the following form, which mathematically presents a mixed integer nonlinear nonconvex programming problem:

$$\text{minimize} \quad Z = \theta L(\mathbf{f}, \bar{\mathbf{c}}, \bar{\mathbf{u}}) + (1-\theta) S(\mathbf{f}, \boldsymbol{\mu}) \tag{8}$$

$$\text{subject to} \quad \mathbf{s}\boldsymbol{\Lambda}\mathbf{f} \leq B \tag{9}$$

$$\mathbf{s} \in \mathbf{S} \tag{10}$$

$$\Phi(\bar{\mathbf{t}}_a, \mathbf{t}_b(\mathbf{f}), \boldsymbol{\mu}, \mathbf{s}, \bar{\mathbf{c}}) = \mathbf{f} \tag{11}$$

$$\Theta(\mathbf{f}, \boldsymbol{\mu}, \bar{\mathbf{u}}) \geq \mathbf{0} \tag{12}$$

where $\mathbf{s}$ is the vector of line-specific subsidy variables, $\mathbf{\Lambda}$ is the line-path incidence matrix, B represents the budget on the sum of subsidies, and $\mathbf{S}$ is set of all feasible values of $\mathbf{s}$, each of which under our setting is a vector of integer multiples of 500 and less than its corresponding freight rate. The notation and definition of other variables and parameters can be found in Section 4.

The objective function in (8) is to maximize the capacity utilization of CRE lines while minimizing the excessive congestion of shippers. The capacity utilization of a CRE line is measured by the *revenue loss* of the line, which is of interest to the CRE operator and is defined as the product of freight rate and unused capacity of the line. The congestion level of a CRE line arises when the freight demand exceeds the transportation capacity of this line and can be quantified by the congestion-induced waiting delay, or its monetarized term, *congestion surcharge*, of individual shippers who choose the line. It should be noted that the evaluation of congestion surcharge must consider the different values of time of different freight categories. As a freight economics term, congestion surcharge represents the additional cost shippers incur to secure immediate access to their targeted service line, on top of the regular freight rate (Wang, 2020; Bliemer et al., 2014). In overall, the objective function of the subsidy optimization problem presents a weighted sum of the total revenue loss $L(\cdot)$ and total congestion surcharge $S(\cdot)$. The weighting coefficient, θ, is used to adjust the tradeoff between the two terms, or the two stakeholders, the CRE operator and shippers. In this study, we simply set $\theta = 1 - \theta = 0.5$.

It is readily known that if the freight demand for a service line is just equal to the capacity of this line, its transported freight volume reaches the maximal level or the residual capacity is minimized; if its congestion surcharge is equal to 0, it means that all the potential demand is serviced on time without any delay. Such a case represents the most ideal condition of this service line, in terms of the objective function defined above. In most cases, because complex competition exists between different service lines and between CRE and China-Europe liner shipping, such an ideal condition cannot be perfectly achieved for most lines.

Furthermore, the proposed subsidy optimization problem includes 4 sets of constraints. The constraint in (9) is the budget constraint, setting the maximum expenditure for subsidies. For modeling simplicity and fairness, we use the total subsidy expenditure of each month under the *current subsidy* scheme as the budget value of the subsidy optimization problem for the same month. The monthly subsidy expenditures in the 12 months of 2019 can be found from Figure 4. The constraint in (10) simply specifies the feasible values of each service line-based subsidy, which are a set of discrete values between zero and the freight rate. The complementarity constraints in (11) and (12) are from the aforementioned complementarity model that characterizes the freight transportation network flow pattern, as detailed in Section 4.

Obviously, the constraints in (11) and (12), on one hand, present a set of nonlinear constraints for the subsidy optimization problem, and on the other hand, pose a complementarity model for the underlying freight transportation network equilibrium problem. Due to this reason, we say that the freight transportation network equilibrium problem is embedded in the subsidy optimization problem or stands as a subproblem of the subsidy optimization problem. Given the solution complexity caused by the non-convexity nature of this discrete optimization model, we developed a tabu search metaheuristic to approximate its global optimum. The algorithmic details of the metaheuristic procedure are given in Appendix B.

5.2. Comparative analysis of the optimized subsidy scheme

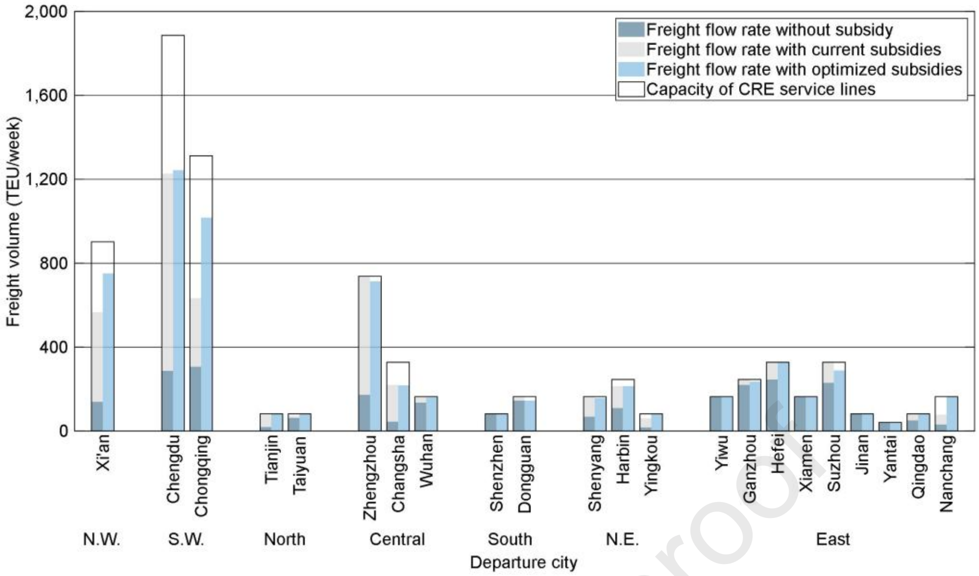
Solving the subsidy optimization problem for all 12 months in 2019 results in the following findings and insights. We first take a look at how the China-Europe freight flow pattern may be updated with the *optimized subsidy* scheme. Table 4 displays the monthly freight volume of the CRE system under the *no subsidy* and *optimized subsidy* schemes. It is evident that the *optimized subsidy* scheme results in a significant increase in the total freight volume for each month. If comparing the results from Table 4 and Table 2, we can find that the *optimized subsidy* scheme almost always outperforms the *current subsidy* scheme in terms of freight volume increase, demonstrating its efficacy of attracting more demand for the CRE system. The only exception occurred in September 2019, where the resulting total freight volume under the *optimized subsidy* scheme is 0.9% lower than that from the *current subsidy* scenario. This result, however, should not be very surprising since the subsidy optimization model given in (8)-(12) does not fully comply with maximizing the total freight volume carried by the CRE system.

Table 4 Monthly total freight volume changes due to the optimized subsidy scheme

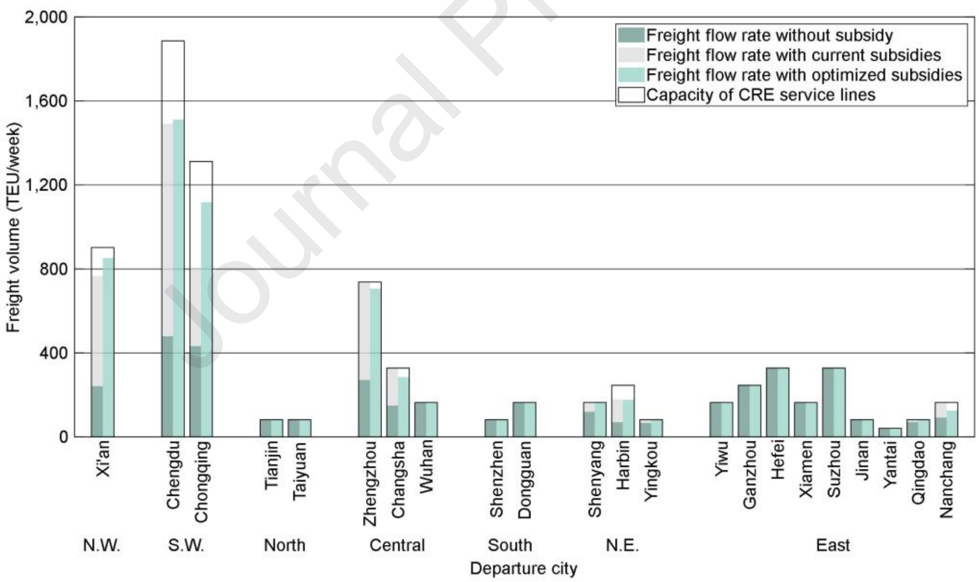
Month of the year of 2019	Total freight volume without subsidy (TEU/week)	Total freight volume with the optimized subsidy scheme (TEU/week)	Freight volume change
January	3,663.47	6,972.65	+90%

February	2,815.39	6,493.93	+131%
March	2,988.73	6,418.80	+115%
April	3,343.31	6,507.85	+95%
May	3,528.99	6,045.53	+71%
June	3,773.75	6,333.93	+68%
July	3,917.51	7,024.85	+79%
August	3,871.88	7,172.69	+85%
September	4,084.98	7,053.66	+73%
October	3,856.71	7,025.07	+82%
November	3,593.00	6,969.58	+94%
December	3,595.14	7,034.62	+96%

The impact of the *optimized subsidy* scheme on the freight volumes from the departure cities of CRE service lines is governed by a complex mechanism and show a network effect. Figure 12 shows that, compared to the *current subsidy* scheme, although, for instance, the *optimized subsidy* scheme diverts 599 TEUs and 304 TEUs per week from liner shipping to CRE in February and July 2019, respectively, not all departure cities experience increasing freight volumes. For example, in July 2019, the freight volume carried by CRE lines departing from Chongqing and Xi'an, both located in the west part of China, increase significantly, while some cities in the middle part of China, like Zhengzhou, Changsha and Nanchang, show a slight decline in freight volume.



(a) February 2019



(b) July 2019

Figure 12 Comparison of the *optimized subsidy* and *current subsidy* schemes in stimulating freight demand from the departure cities of CRE service lines

In terms of total revenue loss and total congestion surcharge, which are directly impacted by subsidies and the main concerns of CRE operator and individual shippers, the economic advantage of the *optimized subsidy* scheme is also evident, as shown in Figure 13. It clearly shows that a significantly lower level of the two performance measures is realized by the *optimized subsidy* scheme than that under either the *no subsidy* scenario or the *current subsidy* scenario for all months of the year 2019, indicating that it benefits both the CRE operator and shippers as expected and performs overwhelmingly better than the *current subsidy* scenario. Specifically, the total revenue loss under the *optimized subsidy* scheme is reduced by 27.7% on average over the 12 months, equivalent to $1.78 million per week, from that under the *current subsidy* scheme, alongside a 63.9% decrease in the total congestion surcharge. In contrast, the *current subsidy* scheme is much less effective and reliable in reducing revenue loss and congestion surcharge. For instance, while the *current subsidy* scheme successfully results in an average 12.7% decline of total congestion surcharge in most months, it unexpectedly makes a climb of this measure in February and March 2019. In summary, we can conclude that the *optimized subsidy* scheme contributes to the reduction of total revenue loss and total congestion surcharge all the time, but the *current subsidy* scheme seems to be designed for reducing the revenue loss of the CRE operator only.

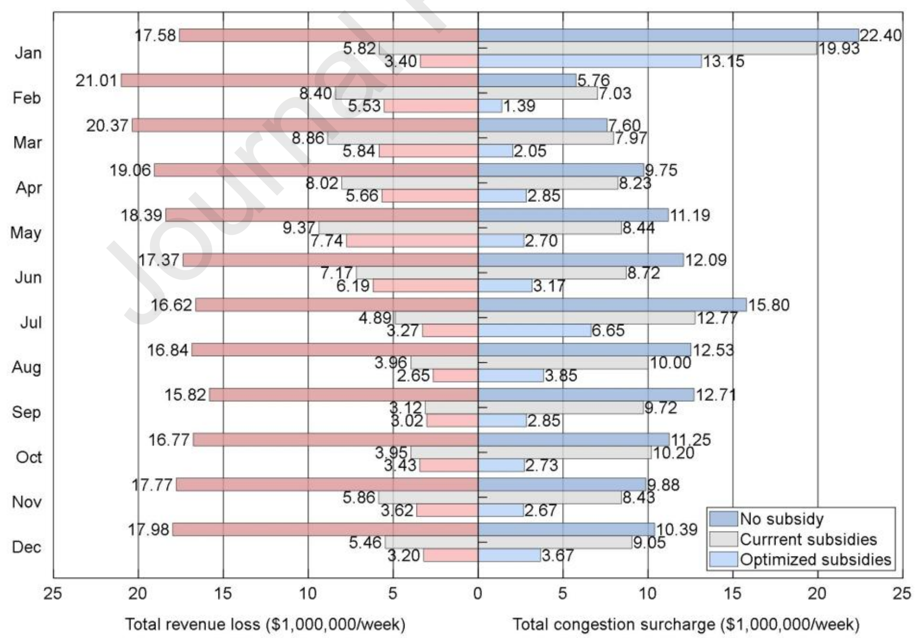
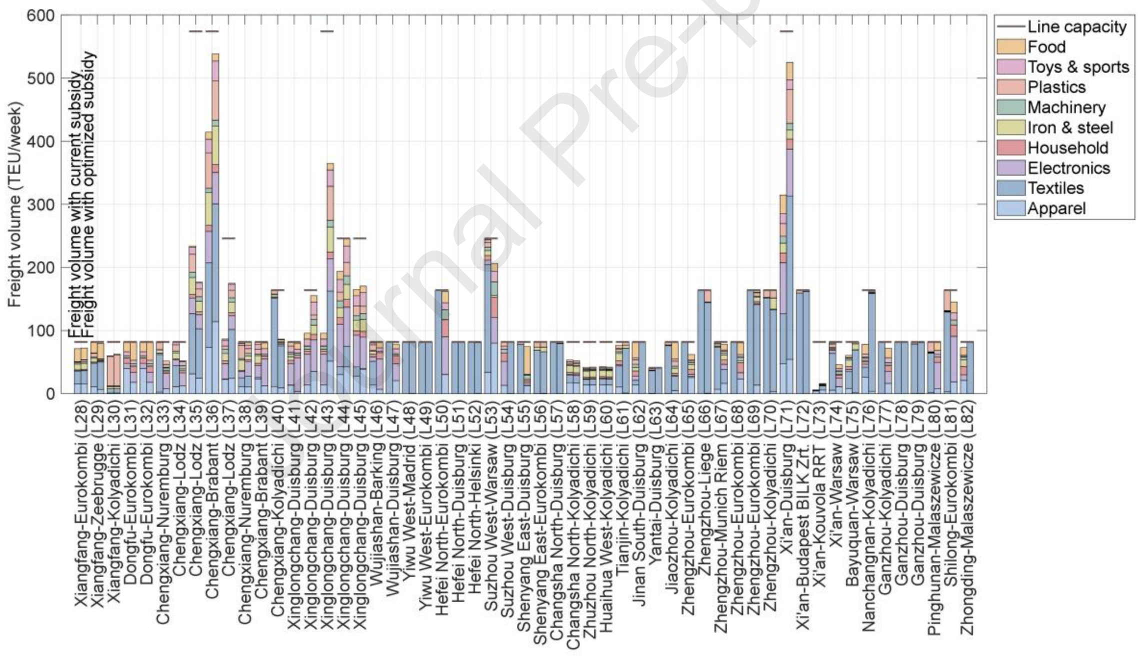
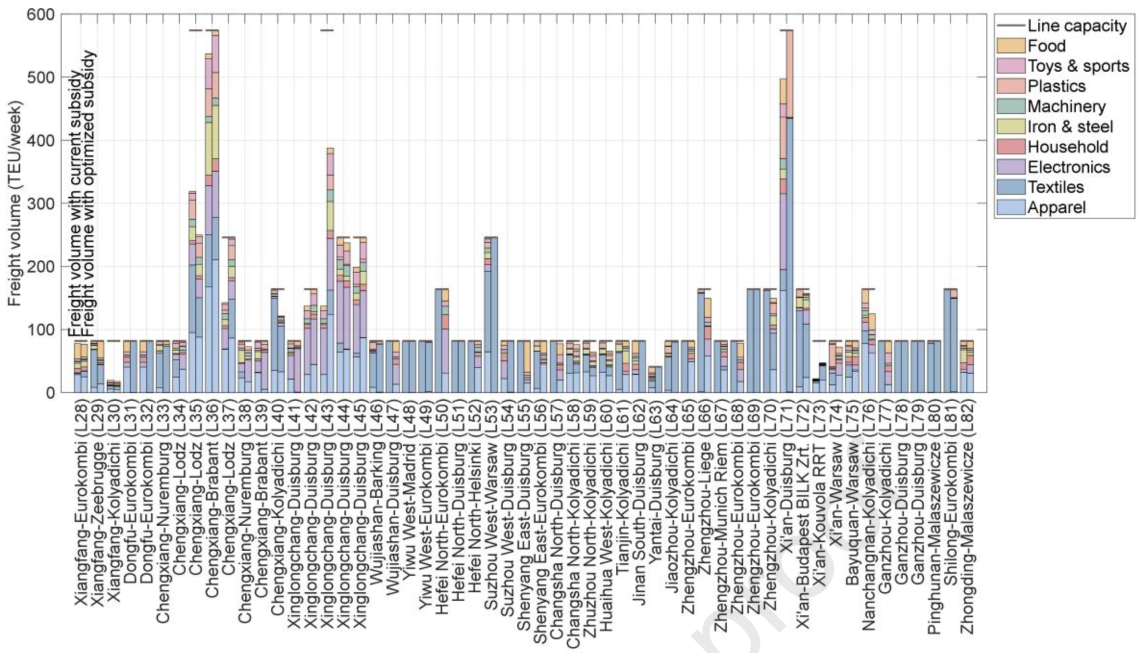


Figure 13 Comparison of total revenue loss and total congestion surcharge under the *no subsidy*, *current subsidy* and *optimized subsidy* scenarios

Figure 14 compares the containerized freight flow rates and compositions of all CRE service lines under the *current subsidy* and *optimized subsidy* scenarios. Not surprisingly, similar conclusions can be drawn to the result in Figure 9: The volume of high-value goods carried by a line remains stable unless the line reaches saturation under the *optimized subsidy* scheme. On the other hand, those saturated lines under the *current subsidy* scheme observed the *optimized subsidy* scheme's success in enabling a larger proportion of high-value goods to use these lines (e.g., Line 50, Line 67 and Line 77 in February and July 2019), except for a few cases where lines remain dominated by textiles under the *optimized subsidy* scheme due to their relatively low subsidy values under the *current subsidy* scheme (e.g., Line 54 and Line 62 in February and July 2019). Moreover, a small number of saturated lines under the *current subsidy* scheme are now carrying cargoes below their capacity under the *optimized subsidy* scheme (e.g., Line 40 and Line 74 in February and July 2019). This outcome corroborates the findings in Figure 12.

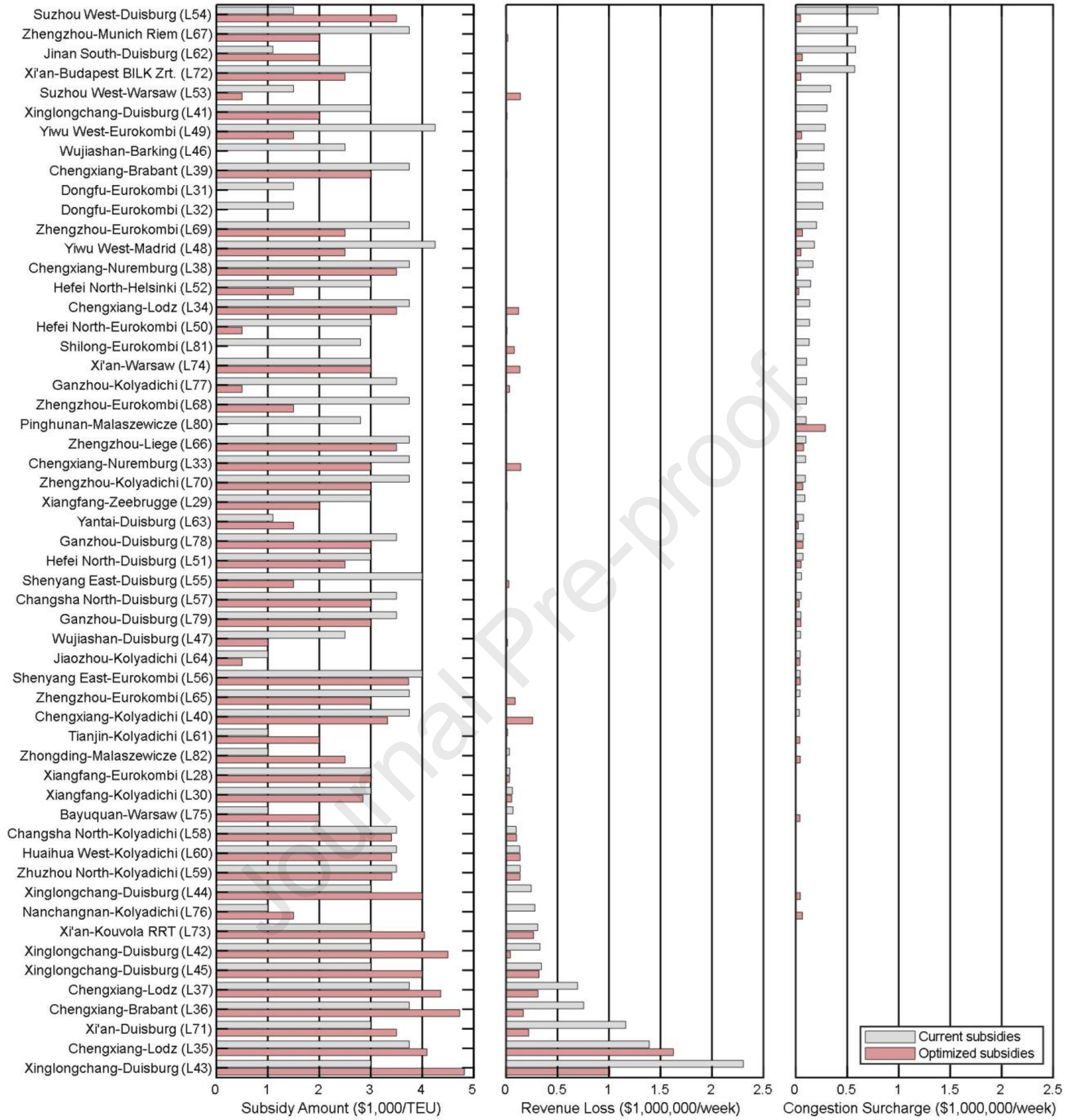


(a) February 2019

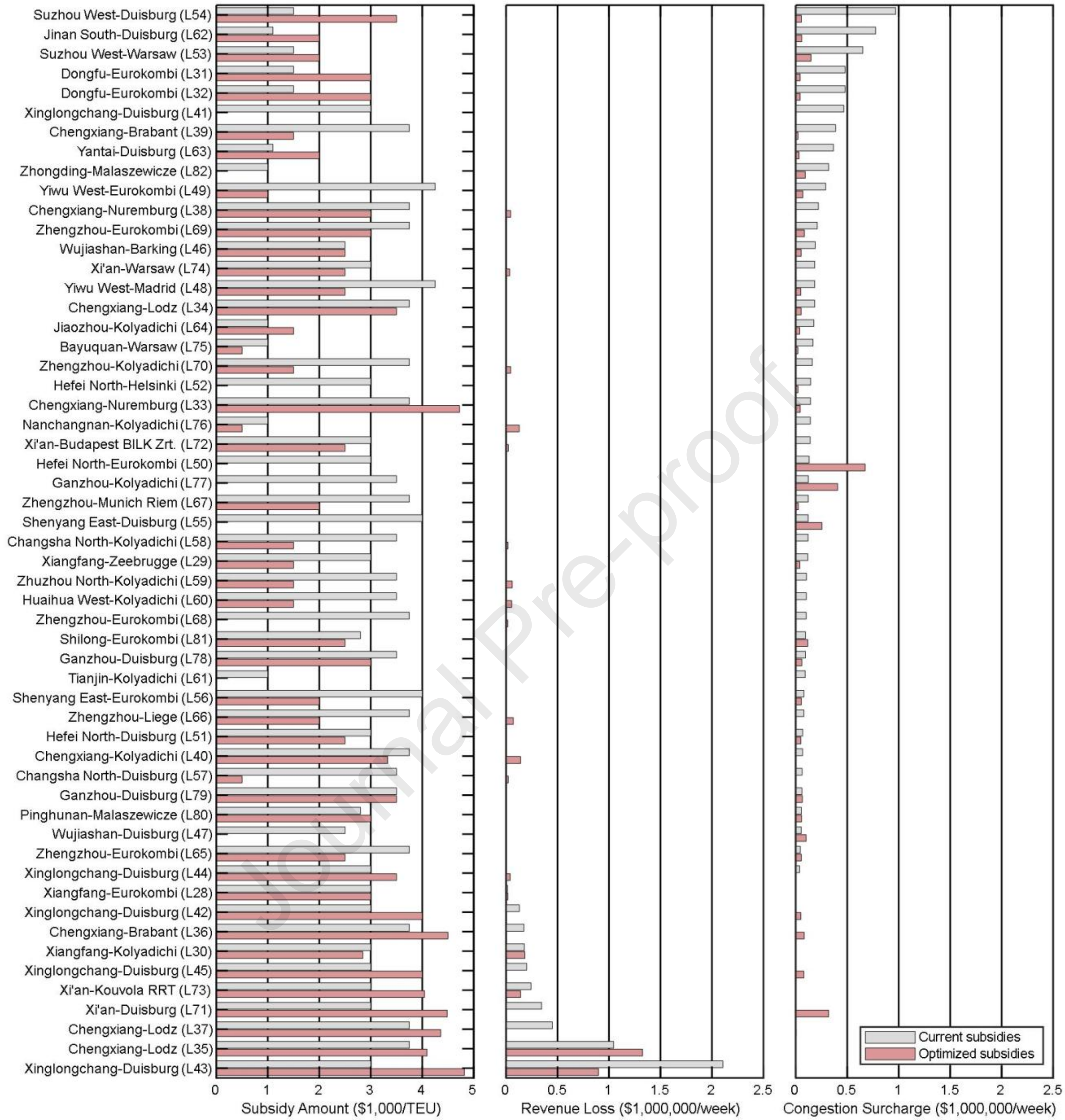


(b) July 2019

Figure 14 Comparison of freight flow redistribution under the *current subsidy* and *optimized subsidy* scenarios



(a) February 2019



(b) July 2019

Figure 15 Revenue loss and congestion surcharge of individual CRE lines under the *current subsidy* and *optimized subsidy* scenarios

We then make an in-depth comparison of the subsidy amount, revenue loss and congestion surcharge on the line level between the *current subsidy* and *optimized subsidy* scheme, as shown in Figure 15. Overall, the *optimized subsidy* scheme greatly reduces both the revenue loss and congestion surcharge for most of the CRE lines, exhibiting its good equity performance in enhancing individual lines' efficiency. All CRE lines may be grouped into three subsets: 1) lines with zero/low revenue loss and high congestion surcharge; 2) lines with zero/low revenue loss and zero/low congestion surcharge; 3) lines with high revenue loss and zero/low congestion surcharge. The high congestion surcharge or revenue loss phenomena with the lines in the first and third subsets are typically due to demand shortage/surplus and geographical locations of those lines. It is interesting to find that the subsidy level of most unsaturated CRE lines under the *optimized subsidy* scheme is not lower than that under the *current subsidy* scheme. Specifically, 14 of 18 unsaturated lines in February 2019 and 9 of 10 unsaturated lines in July 2019 receive a higher or comparable subsidy compared to that under the *current subsidy* scheme. In contrast, 33 of 37 saturated lines in February 2019 and 34 of 45 oversaturated lines in July 2019 receive a lower subsidy, wherein 5 of these lines in February 2019 and 9 of these lines in July 2019 receive no subsidy under the *optimized subsidy* scheme. This subsidy reduction alleviates greatly the congestion surcharge with most of these oversaturated lines, where some lines even become unsaturated with a minor revenue loss. This finding justifies that the *optimized subsidy* scheme improves the system performance on two aspects simultaneously: Increasing the subsidy level for unsaturated lines and reducing the financial support from oversaturated ones. Under the implementation of such an intentionally *optimized subsidy* scheme, over 90% of the CRE lines are now either saturated with a short waiting delay or unsaturated with a small unused capacity.

We finally make a comparative evaluation on the economic effectiveness of the *optimized subsidy* scenario against the *no subsidy* and *current subsidy* scenarios, as shown in Table 5. In July 2019, for example, with a total subsidy expenditure of $19,710,206, the *optimized subsidy* scheme reduces the CRE operator's total revenue loss and shippers' total congestion surcharge by 33% and 48%, respectively, compared to the *current subsidy* scenario, respectively, though the subsidy expenditure paid by the government is only 97% of that under the *current subsidy* scheme. We define the *benefit-cost ratio* (BCR) as total cost reduction divided by total subsidy expenditure, where the total cost reduction is the sum of total revenue loss reduction and total congestion surcharge reduction made by subsidies. A higher BCR indicates greater efficiency in producing system benefits by subsidies. Again, by using February and July 2019 as two example months, we found that the BCR is only 0.63 in February and 0.72 in July under the *current subsidy* scheme; however, the BCR reaches 1.08 and 1.14 in the two months under the *optimized subsidy* scheme. Findings from other months in 2019 demonstrate that the government's subsidy expenditure is reduced by 7.7% on average under the *optimized subsidy* scheme. A subsidy expenditure of $1 would reduce the system loss by $1.08 to $1.39, with an average of $1.20, compared to $0.63 to $0.73 under the *current subsidy* scheme, which averages $0.69. As we know, a BCR value greater than 1 indicates that the produced benefit outweighs the invested cost. The above result shows that the *current subsidy* scheme is unfortunately not a financially worthy option in that it produces a net social loss, but the *optimized subsidy* scheme successfully overcomes the deficiency. In summary, the *optimized subsidy* scheme achieves a desirable tripartite situation, in which the government, CRE operator, and individual shippers all benefit from it.

Table 5 Economic performance results of CRE under different subsidy schemes

(a) February 2019

Performance measure	No subsidy	Current subsidy scheme	Optimized subsidy scheme
Total freight flow rate (TEU/week)	2,815.39	5,894.80	6,493.93
Total revenue loss ($/week)	21,012,709	8,399,960	5,525,508
Total congestion surcharge ($/week)	5,758,169	7,030,585	1,389,188
Total cost reduction ($/week)	0	11,340,334	19,856,183
Total subsidy expenditure ($/week)	0	17,915,269	17,915,269
Benefit-cost ratio	—	0.63	1.08

(b) July 2019

Performance measure	No subsidy	Current subsidy scheme	Optimized subsidy scheme
Total freight flow rate (TEU/week)	3,917.51	6,721.00	7,024.85
Total revenue loss ($/week)	16,623,766	4,885,089	3,268,242
Total congestion surcharge ($/week)	15,797,573	12,769,490	6,651,558
Total cost reduction ($/week)	0	14,766,759	22,501,539

Total subsidy expenditure ($/week)	0	20,403,471	19,710,206
Benefit-cost ratio	—	0.72	1.14

5.4. Policy insights and recommendations

In terms of the updated freight flow results from the subsidy optimization, we may draw a set of policy insights and recommendations as follows.

Subsidy allocation objective. One of the most important modeling issues in this study is how to set up the objective of the subsidy optimization model so as to properly address the efficiency and equity issues we encounter. In our case, the model is set to consider the benefits of both the CRE operator and individual shippers and accordingly includes both revenue loss and congestion surcharge into the objective function. Such a bi-term setting of revenue loss and congestion surcharge is rarely seen in previous studies, but merely similar to a multi-objective subsidy optimization model presented by Hu et al. (2022). As we can see from Figure 13, the comparison results in terms of these two economic measures show that the *optimized subsidy* scheme outperforms the *current subsidy* scheme in all months of the year of 2019, where the latter was proposed for increasing the capacity utilization of CRE lines only. This finding strongly suggests that revenue loss and congestion surcharge should be included in enacting a subsidy scheme for a massive freight transportation system like the CRE system.

Subsidy coordination mechanism. The *optimized subsidy* scheme naturally coordinates subsidies across different CRE lines within a fixed budget. The basic mechanism of improving the economic efficiency of individual CRE lines can be simply described as: Injecting sufficient subsidies to unsaturated CRE lines that truly need support to prevent the operator from bearing a significant revenue loss and withholding support from other lines encountering inherently heavy congestion, so as to reset the relative attractiveness of all CRE lines among themselves and to liner shipping lines. In its implementation, it is important to properly allocate the subsidy budget and avoid unnecessary interference with the effectiveness of subsidies on those nearly saturated lines. Compared to the *current subsidy* scheme, the *optimized subsidy* scheme allocates subsidies more selectively and strategically across CRE lines over different time-of-year periods, achieving a much more effective trade-off between capacity utilization and congestion reduction. This result confirms the necessity of implementing a structurally sophisticated, behaviorally sounding, computationally feasible model if a well-coordinated subsidy scheme is required.

Line-specific subsidies. The *optimized subsidy* scheme sets a tailored subsidy amount for each CRE line, offering a more powerful tool compared to prior studies. Previous research, including Shi and Du (2017), Kundu and Sheu (2019), Yin et al. (2020b), Feng et al. (2020), Gong and Li (2020), and Chen et al. (2023), often recommended a single, uniform subsidy amount as the optimal solution, which, while straightforward to implement, tends to be overly simplistic and less effective. On the other hand, Zhang et al. (2018) proposed subsidies for individual segments within a freight transportation network, a theoretically precise but impractically complex solution, as implementing differentiated subsidies for each network segment is not feasible for any government. Only Yang et al. (2019) did suggest varying subsidies for different originating cities and border crossings, a structure that aligns closely with our approach. The service line-specific subsidies strike a good balance between subsidy allocation feasibility and flexibility, enhancing both policy implementation and the economic impact.

Period-specific subsidies. The *optimized subsidy* scheme outperforms the *current subsidy* scheme not only due to its spatial coordination strategy for individual service lines, but also benefiting from its time-dependent adjustment. Both the system-wide and line-based revenue loss and congestion surcharge results clearly show the superior performance of the optimized line-specific, month-specific subsidy scheme. In some cases, however, adopting a month-to-month subsidy schedule might be overly frequent and responsive, possibly creating information processing and comprehension difficulty or even confusion for individual shippers. Considering the periodical change of freight demand patterns, perhaps it is more appropriate to divide a year not by calendar month, but by different seasons or periods. For instance, the weeks before Christmas Day and New Year's Day can be categorized into a single period and a summer peak period could span from late April to early September. Dividing the year into 3 to 5 periods and producing a separate subsidy table for each period would yield a more practical and easier-to-accept subsidy schedule.

6. Conclusion

This study examines the role and impact of subsidies in enhancing the competitiveness of CRE in the China-Europe freight transportation market. For this purpose, we collected, processed and consolidated the China-Europe freight transportation services, China-Europe freight demand, and CRE subsidy data for the year of 2019 to form a complete set of research data. As part of the methodological efforts, we applied a multimodal multicommodity freight transportation network equilibrium model to assess the existing subsidy scheme and constructed an equilibrium-embedded subsidy optimization model for line-specific, month-specific subsidy allocation. On one hand, we examined the impact of the *current subsidy* scheme on the CRE network, service lines, and transportation paths, covering the effects of subsidies on the spatial distribution of containerized freight flows, congestion levels, and transportation costs; on the other hand, we demonstrated that the *optimized subsidy* scheme obtained by a tailored tabu search procedure stands as a subsidy solution that is economically much more appealing than the *current subsidy* scheme and can simultaneously benefit all the participating stakeholders, including the government, CRE operator, and shippers.

In terms of our evaluation results, the *current subsidy* scheme has increased the CRE freight volume and reduced CRE's total revenue loss and congestion surcharge. However, its effectiveness varies greatly across different CRE lines and different months, and its overall efficacy may not reach our expected level in that the resulting benefit-cost ratio is less than 1, i.e., the sum of the total revenue loss reduction and congestion surcharge reduction is lower than the total subsidy expenditure. Through subsidy optimization, we showed that a subsidy scheme for CRE lines could be fine-tuned by considering not only service lines but also commodity types and demand patterns, since different commodities own different time sensitivity and responsiveness attributes to freight rate adjustment. Given the seasonality of freight demand, resetting subsidies for each season is often desirable and potentially increases the attractiveness of the CRE system. In the long term, designing and implementing an adaptive subsidy allocation mechanism is critical for enhancing the competitiveness and economic sustainability of the CRE system in the China-Europe freight transportation market. Finally, we must acknowledge that subsidies are not a panacea for promoting and managing the CRE system. As the China-Europe freight transportation market grows increasingly complex with the integration of new management technologies and business models, subsidies should be redesigned and combined with other financial instruments for enhancing CRE's market competitiveness.

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Statements and declarations

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. In particular, none of the authors has any business relation with China Railway Express, China Railway Container Transportation Co., Ltd., China State Railway Group Co. Ltd., or any subsidiary of these commercial entities for this research and the research result presented herein merely reflects the authors' opinion.

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Appendix A. Proof of the analytical relationship between reduction rate of generalized transportation costs and value of time when subsidies are implemented

Suppose that there is a freight transportation path connecting origin o and destination d with transportation time t and freight rate c. For two types of shippers, whose values of time are v_1 and v_2 (where $v_1 > v_2$), the generalized transportation costs they pay for this freight service are $C_1 = v_1 t + c$ and $C_2 = v_2 t + c$, respectively. Since $v_1 > v_2$, there is $C_1 > C_2$. Suppose that the government provides a subsidy b for the service line used by this freight transportation path, which results in a lower freight rate $c - b$, corresponding to a reduction in the generalized transportation costs for the two types of shippers as $C_1' = v_1 t + c - b$ and $C_2' = v_2 t + c - b$, and thus we can calculate the percentage reduction in the generalized transportation cost due to the subsidy using $\alpha = (C - C')/C$. We get $\alpha_1 = b/C_1$ and $\alpha_2 = b/C_2$. Since $C_1 > C_2$, so there is $\alpha_1 < \alpha_2$, i.e., the generalized transportation cost reduction for the shippers with a low value of time is greater than the shippers with a high value of time.

Appendix B. A tabu search procedure for the subsidy optimization problem and its convergence performance

The essential features and algorithmic procedure of the implemented tabu search procedure for this research are briefly described here. Three essential components define the structure of tabu search: Generation of candidate solutions, design of tabu lists, and selection of aspiration criteria.

The generation of candidate solutions involves exploring and screening neighboring solutions in each iteration. The objective is to identify a direction that reduces the value of the objective function by examining neighboring solutions. In this study, the solution corresponds to a subsidy scheme that specifies the subsidy amount for each CRE line. Thus, a candidate solution is a new subsidy scheme obtained by modifying the subsidy amount for any single line from the *current subsidy* scheme, where the subsidy amount can be increased or decreased with a minimum incremental or decremental amount, subject to the preset feasible values. Tabu lists play a critical role by permitting the search process to prevent recent solutions from being chosen again and temporarily accept inferior solutions so as to promote exploration beyond local optima. While tabu list designs are diverse across applications, we constructed short-term tabu lists with a fixed tenure and long-term tabu lists with an unbounded tenure in our implementation. A short-term tabu list records move attributes including subsidy values and changes to prohibit move reversals. A long-term tabu list archives all identified local solutions in all past iterations, preventing the algorithm from retracing the same trajectory. To ensure that high-quality solutions are not excessively restricted, aspiration criteria are also introduced to override the tabu status of a solution if it outperforms the current best solution in terms of the objective function value.

The short-term tabu tenure is a critical algorithmic parameter of any tabu search procedure and requires careful calibration for maximizing the procedure's solution performance. We evaluated the tenure efficacy based on two criteria: Solution quality as the primary criterion and convergence efficiency as the second. The former is measured by the objective function value of each candidate solution, while the latter is typically counted by number of iterations. We conducted a series of computational tests of the tabu search procedure, using the value of a short-term tabu tenure ranging from 7 to 30. The experimental results demonstrated that the tenure value of 25 achieves the best overall performance and hence is recommended for performing all the experiments used for reporting the results in the paper.

The algorithmic procedure of the proposed tabu search metaheuristic for solving the subsidy optimization problem is sketched as follows:

Step 0 (Initialization): Randomly generate an initial solution $\mathbf{s}_0$ and initialize the short-term and long-term tabu lists. Set $\mathbf{s}^* = \mathbf{s}_0$, set $n \coloneqq 1$ and go to Step 1.

Step 1 (Neighborhood search): Search the neighborhood of $\mathbf{s}_{n-1}$ and identify a set of candidate solutions.

Step 2 (Solution evaluation): Evaluate the candidate solutions through parallel computing, where each evaluation is done by solving the multimodal multicommodity freight transportation network equilibrium problem.

Step 3 (Solution selection): Select the current solution from the solution evaluation result subject to the tabu lists and aspiration criteria and denote it as $\mathbf{s}_n$.

Step 4 (Termination check): Set $\mathbf{s}^* = \mathbf{s}_n$ if $Z(\mathbf{s}_n) < Z(\mathbf{s}^*)$. If any of the predefined termination criteria is satisfied, terminate the algorithmic process and report $\mathbf{s}^*$ as the optimal solution; otherwise, set $n \coloneqq \boldsymbol{n} + 1$ and go to Step 1.

Although the tabu search procedure expands the exploration scope through dynamic maintenance of the tabu lists to escape suboptimal solutions, its search efficiency is inevitably affected by the initial solutions. We therefore ran the tabu search procedure for each month multiple times with different initial subsidy solutions generated randomly, and took the best solution obtained from the multiple runs for each month as the optimized subsidy scheme.

Highlights

- Constructing a multimodal, multicommodity freight transportation network connecting China and Europe, which accommodates the full range of China Railway Express (CRE) service lines, China-Europe liner shipping lines, major highway networks in China and Europe, and all types of containerized freight demands in the market;
- Designing and solving a rail freight subsidy optimization model of a bi-term objective and bi-level structure for simultaneously maximizing capacity utilization and minimizing congestion level of all CRE lines, where its lower level features a multimodal, multicommodity freight transportation network equilibrium problem;
- Introducing the revenue loss of the CRE operator and the congestion surcharge of individual shippers as the performance measures of rail freight subsidy design, which are evaluated by using the primal solution and dual solution, respectively, of the subsidy optimization model;
- The optimized subsidy design lowers the government's monthly average subsidy expenditure by 7.7%, decreases the total revenue loss and total congestion surcharge by 27.7% and 63.9%, respectively, and increases the social benefit generated by a subsidy expenditure of $1 to the entire China-Europe freight transportation market from $0.69 to $1.20.