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Optimal subsidies for rail containers: A bi-level programming solution

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Abstract

High demand for containerized cargo and the low share of rail containers in China is causing heavy container truck traffic and pollution. Due to its social benefits, many provinces/municipalities provide subsidies for rail containers. These subsidies, aimed at reducing road traffic and emissions, may, however, have unexpected results if they are uncoordinated. Our objective is to illustrate the problem with uncoordinated subsidies and propose an optimal subsidy scheme. This study applies the minimum cost flow model to analyze three scenarios: no subsidy, the internalization of external costs, and uncoordinated subsidies. A bi-level programming model is developed to study the scenario of coordinated subsidies, where a hypothetical network planner minimizes the total subsidies for a given externality reduction target in the upper level and the cargo owners minimize total transportation cost in the lower level. A novel method is designed to transform the model into a simple four-step linear programming process. The model and solution method are then applied to containerized trade of Northeast Asia with Europe and that with northern Chinese inland cities. The coordinated subsidy scheme is found to use less in total subsidies, achieve better results than the uncoordinated one, and better total social welfare.

Keywords: Optimal subsidy, multimodal container, bi-level programming, novel solution method, transportation network

1. Introduction

The rail transport of containerized cargo has been a hot topic among both transportation economists and policymakers because of its advantages in hauling a large number of high-value containers over a long land route without incurring a high trucking cost and external costs, such as road congestion and air pollution (Luo and Grigalunas, 2003, Wu et al., 2012). As an important mode in multimodal transportation, it has also attracted attention in maritime studies due to its potential to improve efficiency and reduce pollution (Fan et al., 2012, Woodburn, 2007). In developed countries, around 20% of the container port throughput uses rail for land haul (Yin and Zhou, 2016). This number is even higher at the major ports in these countries. For example, about 42% of throughput at the Port of Hamburg comes in and out by rail[1] and 29% at the port of Rotterdam (Yin and Zhou, 2016). In 2017, rail containers represented about 25% of the throughput at the Port of Long Beach and this was expected to reach 35% after a new "on-dock" facility was added.[2] In comparison, the share of rail containers in China was not even 2% of the port throughput (Huang, 2018).

The high demand for imported/exported containerized cargo and the very low share of rail containers in China are causing a heavy flow of container truck traffic, a major culprit of the dire air pollution problems in North China. In addition, this is

[1] https://www.hafen-hamburg.de/en/statistics/modalsplit, accessed Feb 2, 2018

[2] http://labusinessjournal.com/news/2018/jan/23/port-long-beach-approves-dock-rail-facility/, accessed Feb 2, 2018.

creating other serious impacts, such as road congestion, noise pollution, and traffic accidents, especially in the highly populated eastern regions.

In addition to its own trade, China is also trying to boost the volume of transit containers between Far East countries (Japan and Korea) and Europe. In the 1990s, the New Eurasian Land Bridge began to connect the Chinese rail system with Europe via Kazakhstan railways at Alashankou and Khorgos (Figure 1). This has been designated as the second rail corridor between Asia and Europe after the Trans-Siberian Railway (through Manzhouli and Erenhot). However, its demand has grown relatively slowly due to inadequate infrastructure, complicated custom clearance procedures, and few backhauls (Shu, 1997).

Insert Figure 1 here.

The Belt and Road Initiative (BRI) in China revived the development of the new bridge, as the Silk Road Economic Belt, one of the major components in the BRI, is located just along the Eurasian Land Bridge. Many municipalities with coastal ports and inland rail hubs, such as Lianyungang, Qingdao, Tianjin, Yingkou, Xi'an, and Gansu, actively promote the Eurasian Land Bridge by providing subsidies for transit rail containers. At the end of June 2016, a total of 1,881 container rail trips, including 502 backhauls, carried US $17 billion worth of cargo between 16 Chinese departure points and 12 foreign destinations. The number of rail services amounted to 39, with 23 direct services and 10 one-way only services (Table 1). The lack of backhauls has limited the economic efficiency of the freight rail services. Consequently, China’s central and local governments have assigned high priority to enhancing the development and application of container rail transportation to improve connectivity between the West Pacific Coast and East Atlantic Coast.

Insert Table 1

The current subsidies to rail containers are determined independently by each local government without coordination. Although the original purpose of the subsidy was to increase rail use, local governments have been using it to lure more rail cargo from other regions. Therefore, such uncoordinated subsidies may be generating more trucking activities due to the cost saving behavior of individual shippers in arranging the shipments. For example, if two ports both have rail services and only one offers a subsidy for rail containers, shippers will have an incentive to use trucks to haul containers from the port that offers no subsidy to the port that does, causing the subsidy scheme to generate additional trucking activities. Overall, this may result in social welfare losses from both unnecessary subsidies and the externalities from increased trucking activities.

This study analyses the transport route and mode selection problem for transit containers between Northeast Asia (Japan and Korea) and Europe and for direct containers between Northeast Asia and the main inland rail container hubs in northern China. Our objective is to illustrate the problem with uncoordinated subsidies and propose an optimal subsidy scheme that considers both the required subsidies and the externalities from road traffic. Minimum cost flow (MCF) models are designed to highlight the problem with uncoordinated subsidies under different assumptions. A bi-level programming (BLP) model is applied to study the equilibrium between a hypothetical network planner with the objective to minimize total subsidies and container shippers who minimize total shipping costs. A four-step solution is developed to solve the BLP problem.

This study illustrates the importance of coordinating the design of economic incentives that promote multimodal transportation. We show how uncoordinated subsidies, which reflect the current subsidy policy in China, may be creating further problems in terms of heavier road traffic, higher external costs, and wasted public funds, offering a new perspective for policymakers. In addition to these practical contributions, the efficient solution method for the BLP problem, based on economic intuition, adds to the existing toolbox in solving similar problems. Our solution method can solve the problem in four steps, each with a linear programming model, using any optimization software such as Excel Solver, while traditional methods often require non-linear algorithms to find the local optimal and heuristic algorithm for global optimal solutions with many iterations.

The rest of the paper is organized as follows. Next, we present a literature review on the concept of subsidies as a government policy, general transportation problems arising from the promotion of multimodal transportation, and solution methods for BLP models. This is followed by the introduction of the method, which includes four scenarios for different policy environments, and the BLP model and solution method. Then, we explain the application of the model in assessing different real-world problems in northern China, including model simplification, parameters, explanation, and a comparison of optimal results in different scenarios. Finally, we provide a summary and conclusions.

2. Literature review

Subsidy is one of the most important policy instruments (Myles, 1995, Gruber, 2011), and is often used by governments to promote industries that affect significant public interests or to achieve specific social objectives (Jones and Steenblik, 2010, Clarke, 2015, Cisneros-Montemayor et al., 2016, Ganesan et al., 2014). Most existing literature addresses the theoretical mechanism of subsidy (Jeon et al., 2015) and evaluates the effect of such policies (Yao et al., 2014) from the perspective of economics or international trade. Studies on the optimization of subsidies are rare.

In the transportation sector, subsidies are often used to reduce congestion or control environmental impacts (Button and Verhoef, 1998, Button, 2010) such as subsidies that promote public transportation system use and reduce personal car usage. In recent years, the increase in road traffic has caused congestion, accidents, and air pollution, becoming a key issue in the development of various transport sectors in many countries. To shift long-distance road traffic to more environmentally friendly modes of transportation, many countries have introduced policies that support the development of multimodal transport that mainly uses rail and short-sea and coastwise shipping (Newman and Kenworthy, 1999, Mobility and Transport, 2011, MOT, 2015).

The importance of sustainable development, global supply chain management, and international logistics have made multimodal transportation a hot topic in recent years (Trip and Bontekoning, 2002, Bontekoning et al., 2004, Woxenius, 2007, Melo et al., 2009, Caris et al., 2013, SteadieSeifi et al., 2014, Sugawara, 2017). With respect to multimodal operation planning, many scholars use transportation network modeling with integer and non-linear programming techniques to study the location of transshipment hubs (Arnold et al., 2004), pricing strategies (Li and Tayur, 2005), traffic flow estimation (Bhattacharya et al., 2014), network design and planning, and comparison of different cooperating partners (Odchimar and Hanaoka, 2017). Some have studied the advantages of multimodal transportation from the perspective of carbon emission (Qu et al., 2016, Agbo et al., 2017, Rudi et al., 2017). Others have used simulation methods to study network planning problems for multimodal transportation (Meinert et al., 1998, Dotoli et al., 2014). For model shift, most have studied the impact of different incentive schemes on the selection of transportation methods (Cullinane and Toy, 2000, Blauwens et al., 2006, Tsamboulas et al., 2007, Feo-Valero et al., 2011, Meers and Macharis, 2015). However, there is no research on the optimal policy in multimodal transport.

Most policy research uses geographical information system for road, rail, and sea routes to construct a multimodal transportation network and simulate the impacts of new ports, fuel prices, taxes, and subsidies, together with foreign investment, on the development and operation of such transportation systems (Macharis and Pekin, 2009, Macharis et al., 2011, Iannone, 2012, Zhang et al., 2008, Luo and Grigalunas, 2003). Such research focuses on evaluating the impacts of policy instruments for given costs (times) of different modes of transportation. The policies are usually considered exogenous.

BLP has been frequently used for developing new or expanded public transport networks (Laporte et al., 2000, Mesbah et al., 2011), road transport networks (Ben-Ayed et al., 1992), communication networks (Camacho-Vallejo et al., 2015) managing traffic signals (Ceylan and Bell, 2004), and toll charges (Brotcorne et al., 2000). An overview of the BLP models, application areas, existing methods of solving problems, and the properties of such problems are provided in recent surveys (Colson et al., 2007, Sinha et al., 2017). Here, we present a linear solution method based on economic reasoning. We solve the BLP problem through a four-step progressive method. Compared with general mathematical programming methods, our solution is both more efficient and easier to understand by policymakers.

3. Methodology

We study the mode and route choice of direct and transit containers in a transport network composed of a set of nodes ($\mathbb{N}$) with four components: maritime cargo origins ($\boldsymbol{S}$), coastal ports ($\boldsymbol{V}$), inland cities ($\boldsymbol{U}$), and border crossing points ($\boldsymbol{T}$). A set of indices, o, i, j, and k, are used to denote the elements in maritime cargo origins, coastal ports, inland cities, and border crossing points, respectively. Since the differences among ocean shipping to various northern Chinese coastal ports are negligible, the cost of shipping and its environmental impacts are not considered here. Thus, the set of transportation links among ***V***, ***U,*** and ***T*** can be defined as $\mathbb{L}=\{ij, jk, ik\}$. Figure 2 depicts this transportation network $\{\mathbb{N}, \mathbb{L}\}$.

Insert Figure 2

The transportation demand comprises both transit (d_k) and direct (d_j) containers in international trade, and includes imports and exports. The former refers to containers that pass through Chinese territory, while the latter refers to containers that begin or end at Chinese inland cities. The transportation cost per TEU for rail and road between each pair of nodes is denoted as c_n and c'_n ($\forall n \in \mathbb{L}$), respectively, the capacities for rail and road are u_n and u'_n TEUs, respectively, and the external trucking cost is ex'_n per TEU.

We design the following four scenarios to compare results both with/without the externalities and coordination of subsidies. Scenarios ***a*** to ***c*** are MCF models where shippers are the decision makers and the decision variables are the container traffic flow on each route and mode. Scenario ***d*** requires the use of the BLP method where the network planner is the decision maker in the upper lever and the shippers are those in the lower level.

Scenario *a*: The MCF model where the shippers allocate the container traffic flow on each link and mode to minimize total transportation cost for a given demand at each OD pair.

Scenario *b*: The MCF model considering the external costs. In this model, when allocating the container traffic flow, shippers have to cover external costs. The purpose of this scenario is to show the optimal results if the policy is to internalize the external costs.

Scenario *c*. This MCF model includes subsidies. In this scenario, shippers minimize the overall transportation cost, knowing that the government will give a subsidy for rail containers. The results from this scenario can be used to show the impact of uncoordinated subsidies.

Scenario *d*: This scenario assumes that the hypothetical network planner in the upper level decides the optimal subsidies at each section of the rail to minimize the total subsidy and reduce the external cost of trucking. At the same time, shippers in the lower level follow the same behavior as in scenario ***c***. The subsidies are the equilibrium between shippers and the planner.

There are two optimization processes used in these scenarios: MCF and optimal subsidies. Scenarios ***a-c*** only require the former, while scenario ***d*** requires both.

3.1 Minimum cost flow model

Let $\mathrm{l_n}$ be the number of containers on rail link *n* ($n \in \mathbb{L}$) and l'_n the trucking containers at that section, then the MCF model can be written as:

$$\min_{l_n, l'_n} z = \sum_{n \in \mathbb{L}} [c_n l_n + c'_n l'_n] \tag{1}$$

$$s.t.\ \sum_{i\in\boldsymbol{V}}(l_{ik}+l'_{ik})+\sum_{j\in\boldsymbol{U}}(l_{jk}+l'_{jk})=d_k,\forall k\in\boldsymbol{T} \quad (2)$$

$$\sum_{i\in\boldsymbol{V}}(l_{ij}+l'_{ij})-\sum_{k\in\boldsymbol{T}}(l_{jk}+l'_{jk})=d_j,\forall j\in\boldsymbol{U} \quad (3)$$

$$\sum_{j\in\boldsymbol{U}}(l_{ij}+l'_{ij})+\sum_{k\in\boldsymbol{T}}(l_{ik}+l'_{ik})=\sum_{k\in\boldsymbol{T}}d_k+\sum_{j\in\boldsymbol{U}}d_j\,,\forall i\in\boldsymbol{V} \quad (4)$$

$$0\le l_n\le u_n,\forall n\in\mathbb{L} \quad (5)$$

$$0\le l'_n\le u'_n,\forall n\in\mathbb{L} \quad (6)$$

where z denotes the objective value (the total cost to meet the transport demand). The constraints (2-4) are the flow conservation conditions. Constraint (2) specifies the total transit containers at each border crossing point; (3) is for the direct containers at each inland city; and (4) means no containers at the coastal container ports. All containers at the ports should either have started/ended at inland cities or passed border-crossing points. The constraints (5-6) are the capacity constraints at each section of rail and road.

Based on eq. (1), scenario ***b*** can be modeled by changing the objective function to eq. (7), with the same set of constraints:

$$\min_{l_n,l'_n} z=\sum_{n\in\mathbb{L}}[c_nl_n+(c'_n+ex'_n)l'_n] \quad (7)$$

Since the external cost ex'_n is added to the trucking unit cost, the model simulates the effect of internalizing the external cost on the road traffic. For scenario ***c***, the unit rail cost in eq. (1) only needs to subtract subsidy S_n; all else remains unchanged:

$$\min_{l_n,l'_n} z=\sum_{n\in\mathbb{L}}[(c_n-s_n)l_n+c'_nl'_n] \quad (8)$$

3.2 BLP considering government subsidies

The purpose of a coordinated subsidy is to achieve the social objective—limiting the external road costs while minimizing total subsidies. It assumes that the hypothetical social planner coordinates the subsidy across all involved regions rather than each region determining its own subsidy. Scenario ***c*** describes the least-cost traffic flow when subsidies are not coordinated; however, such subsidies may not be optimal from the perspective of the whole region. To enable a comparison, scenario ***d*** models the problem in a bi-level structure. Shippers still determine the least-cost traffic flow based on scenario ***c***; however, a hypothetical network planner determines the subsidies (s_n) considering the objective to reduce externalities to a predetermined level ($SocialL$) through minimal overall subsidies. Therefore, the decision variables for scenario ***d*** are (s_n, l_n, l'_n). Since demand for international freight transportation is derived demand, which is inelastic to freight rate changes, to limit the scope of this study, we assume that there is no induced demand due to subsidy.

This problem is solved using a BLP model where the upper level models the behavior of the social planner in deciding subsidy policy, while the lower level is the MCF model:

$$\min_{s_n} \omega = \sum_{n \in \mathbb{L}} s_n l_n \tag{9}$$

$$s.t. \sum_{n \in \mathbb{L}} ex'_n l'_n \leq SocialL \tag{10}$$

$$\min_{l_n, l'_n} z = \sum_{n \in \mathbb{L}} [(c_n - s_n) l_n + c'_n l'_n] \tag{11}$$

$$s.t. \sum_{i \in \boldsymbol{V}} (l_{ik} + l'_{ik}) + \sum_{j \in \boldsymbol{U}} (l_{jk} + l'_{jk}) = d_k, \forall k \in \boldsymbol{T} \tag{12}$$

$$\sum_{i \in \boldsymbol{V}} (l_{ij} + l'_{ij}) - \sum_{k \in \boldsymbol{T}} (l_{jk} + l'_{jk}) = d_j, \forall j \in \boldsymbol{U} \tag{13}$$

$$\sum_{j \in \boldsymbol{U}} (l_{ij} + l'_{ij}) + \sum_{k \in \boldsymbol{T}} (l_{ik} + l'_{ik}) = \sum_{k \in \boldsymbol{T}} d_k + \sum_{j \in \boldsymbol{U}} d_j, \forall i \in \boldsymbol{V} \tag{14}$$

$$0 \le l_n \le u_n, \forall n \in \mathbb{L} \tag{15}$$

$$0 \le l'_n \le u'_n, \forall n \in \mathbb{L} \tag{16}$$

The constraint (10) in the upper level specifies the social constraint, namely, the externality from trucking should be within an acceptable level ($SocialL$). The objective (eq. 9) is to minimize the overall subsidy. Many studies maximize social welfare for given subsidies (Hong and Ke, 2011, Qu et al., 2017). As the induced effect of subsidies is not considered, the welfare increase is mainly from the externality reduction due to reduced trucking activity. Therefore, minimizing the overall subsidies for a given externality level will have the same result as social welfare maximization.

3.3 Model solution algorithm

BLP is inherently difficult to solve, because the objective value of the upper level depends on the optimal solutions of the lower level. It is non-convex and non-differentiable, even the "simplest" linear-linear model is NP-hard (Colson et al., 2007). All the algorithms used to solve BLP include tedious iterations, and often can only find the local optimal solution instead. Such algorithms includes the descent direction approach, iterative linear programming (Candler and Townsley, 1982, Júdice and Faustino, 1992), and branch-and-cut algorithms. In our study, the upper level model is non-linear and non-concave. Often, such problems require the use of evolution algorithms (Brotcorne et al., 2000). Here, we present three linear programming models to perform the function of the BLP model. These linear programming models can be solved through any optimization software, even Excel Solver. The solution process is as follows.

Compute the MCF (scenario ***a***); obtain the container flow on each section of the rail and road ($l_n^{*0}, l_n'^{*0}$) and minimum transportation cost (Y^{*0}) when there is no subsidy:

$$X^{*0} = (l_n^{*0}, l_n'^{*0}),\ \ Y^{*0} \tag{17}$$

Step1. Put the externality condition (eq. 10) as a constraint on the MCF model, and compute the new optimal solution ($l_n^{*1}, l_n'^{*1}$) and the minimum cost (Y^{*1}) again:

$$X^{*1} = (l_n^{*1}, l_n'^{*1}), \qquad Y^{*1} \tag{18}$$

The difference between Y^{*1} and Y^{*0} represents the increase in the transportation cost to satisfy the externality condition. Such an increase is due to the shifting of containers from road to rail. If the rail cost is lower than trucking, it will be used without the externality condition, which is reflected in step 1. If the externality condition has to be satisfied, more rail sections with higher costs have to be used, and the transportation cost will increase. From this, we identify the minimum total subsidies necessary to satisfy the social objective of reducing the externality. Note that during this process it is possible that road containers may be partially shifted to rail. Create a vector I to indicate whether there are any containers in rail section n, i.e., $I_n = \{1\ if\ l_n^* > 0, else\ 0\}$.

Step2. Using the l_n^{*1} obtained above, find the subsidies s_n that minimize total subsidies, and that can cover the incremental cost $(Y^{*1} - Y^{*0})$, namely:

$$\min_{s_n} \omega = \sum_{n \in \boldsymbol{L}} s_n l_n^{*1} \quad (19)$$

$$\sum_{n \in \boldsymbol{L}} s_n l_n^{*1} \geq Y^{*1} - Y^{*0} \quad (20)$$

$$s_n \geq \max[(c_n - c_n')I_n, 0], \quad \forall n \in \mathbb{L} \quad (21)$$

Eq. (19) is the objective. The first constraint requires that the overall subsidies be at least the same as the additional cost incurred by the shippers due to the requirement of the externality constraint in step 2. The second constraint requires that the subsidies on each rail link be at least equal to the cost differences between rail transportation and trucking. If the rail cost is already cheaper than the road cost at any link, then the subsidy is not necessary.

Step3. The MCF $(l_n^{*1}, l_n'^{*1})$ obtained in step 2 only has to satisfy the acceptable externality level. This may result in partial shifts from road to rail at a link. However, at the lower level of scenario ***d***, for a given s_n^*, if $c_n - s_n^* < c_n'$, all the containers on section *n* will be shifted to rail. Therefore, although s_n^* is the minimum subsidy to satisfy the externality condition, the total subsidies should be larger, and the externality should be lower. Hence, we need to compute the MCF $(l_n^*, l_n'^*)$ using the model in scenario ***c***. Then, the overall subsidies ω^* and externality E^* can be calculated:

$$\omega^* = \sum_{n \in \boldsymbol{L}} s_n^* l_n^* \tag{22}$$

$$E^* = \sum_{n \in L} ex_n l_n'^* \tag{23}$$

This new total subsidy is $\omega^* \geq \omega$, where ω is the total of subsidies obtained in step 3; and the new total externality is $E^* \leq socialL$, where equal signs only happen when the $socialL$ in step 2 causes no partial shifts in any link.

To illustrate the four scenarios and the application of the four progressive steps in solving the BLP model, the models developed in Section 3 are applied to the optimal subsidy problem in northern China. We present this next.

4. Case study: Optimal subsidy for direct and transit rail containers in northern China

In northern China, four container ports, namely Qingdao, Tianjin, Yingkou and Dalian, are competing for transit containers from Japan and Korea to Europe and the Middle East through the continental bridge, as well as serving the direct containerized trade between these two countries and Chinese inland cities. For such cargo, Tianjin port has the most attractive position (Xu, 2007, Xia, 2013), as it is located at the most inland part of Bohai Bay and has the shortest land distance to Russia, Mongolia, and Central and West Asia. In the 1990s, Tianjin port started rail services to Manzhouli, Erenhot, and Alashankou, gaining preference among users for the Eurasian

Continental Bridge. Although the rail service to Khorgos accounted for 23.8% market share of the total border crossing containers in 2015, about 73.5% of its containers were from the East China region. Less than 3% actually came from Tianjin, Dalian, Zhengzhou, and Xi'an (CAOP, 2016). Therefore, Khorgos was not included in this study.

In 2010, the Tianjin government announced its subsidy for transit rail containers from Tianjin port to three border-crossing points. This policy was terminated after one year but multimodal containers kept increasing throughout 2011 and 2012. After 2011, all other potential ports and major cities hosting inland container freight terminals along the Eurasian Continental Bridge started to subsidize rail containers (Zhang, 2017).

To understand the current subsidies for transit rail containers, a series of on-site interviews and questionnaire surveys were conducted with 17 multimodal container shipping companies in Tianjin from May to September 2015. During these interviews, we found that the subsidies determined by each provincial government had increased the usage of trucking on some routes. For cargo between Tianjin and Manzhouli, the subsidy offered by the Yingkou and Dalian ports lured some shippers to truck their containers to these ports and put them on freight rail there, rather than use the rail services at Tianjin port directly. For transit containers to Alashankou and Khorgos, the subsidies at Zhengzhou, Xi’an, and Lanzhou also increased the road traffic of transit containers between Tianjin and these cities. These subsidies, therefore, caused an increase both in emissions from trucking activities and in road congestion.

4.1 Multimodal transportation networks in northern China

Based on the description of the subsidies for rail containers in northern China, and to enable an analysis of the optimal subsidy, the multimodal transportation network in this region is illustrated in Figure 3.

Insert Figure 3

In this figure, the maritime container cargo (***S***) represents foreign countries, such as Japan and Korea, that have containers to be shipped to a set of inland cities ***U*** ={Zhengzhou, Xi'an, Lanzhou}, and a set of border crossing points ***T***={Erenhot, Alashankou, Manzhouli}, through a set of coastal ports ***V***={Tianjin, Qingdao, Dalian, Yingkou}. From each port to each border crossing point, there are both direct links by road and freight rail services, and indirect ones through the inland cities. It is also possible to change the mode of transportation at inland cities. Figure 3 shows only the rail and road connections from Tianjin Ports. For clarity, the connections from other ports are not plotted.

4.2 Model parameters

The demand by transit containers at each border crossing point (d_k), as well as direct containers at the inland cities (d_j), are annual container flow estimates from the 2011-2015 container freight data from Tianjin Freight Station, Beijing Railway Administration, together with import/export data from these three cities.

The rail freight rate per TEU can be found on the official website of the rail services (www.12306.cn). The capacity of each freight rail is obtained from many freight agencies. The upper bound of the rail capacity is much higher than the transportation demand in this problem. Its lower bound is not a problem, as the rail company is State owned and already profitable on these routes. For the capacity limit of the road, the lower bound is just nonnegative, and the upper bound is not considered, as the container traffic is just a small fraction of the total traffic. Of course, it may have some impact on road congestion.

The external cost of trucking, including the impact of air pollution, congestion, noise, and traffic accidents, is 0.0535 euro per km for a 40-ton truck (Janic and Vleugel, 2012). It is converted to \$0.0448 per TEU·KM by dividing the value by 1.5, reflecting that the external cost per TEU should be less than trucking 40 tons and taking into account the exchange rate ($1\ euro \approx 1.23\ US\$$). Based on the trucking distances from 'Baidu', the externalities for each section of the link can be calculated. Table 2 lists the externality and rail freight rate per TEU on each route, Table 3 the container traffic flow at border crossing points and the import and export containers at the inland cities, and Table 4 lists all the current subsidies from each border crossing point to inland cities and ports.

Insert Table 2

Insert Table 3

Insert Table 4

Based on the above data, we apply the models developed in Section 3 to analyze the traffic flow problem described in the four scenarios. For scenario ***d***, we apply the four-step progressive model. As a comparison, we also compute the results using the traditional method by transferring the lower level problem into the KTT conditions of the upper level. Although the KTT method can solve the problem using Lingo, it requires 380 iterations. However, using our method, we only need to go through four steps, with one step equivalent to one iteration. Thus, our method is more efficient than the traditional method. The results are presented in next section.

4.3 Optimization of traffic flows in different scenarios

Figure 4 presents the modes and routes selection results in the four scenarios. Scenarios ***a***, ***b***, and ***c*** are the MCF when shippers only consider freight cost, internalize the externality, and have subsidies from each province for rail containers. In ***d***, the minimal coordinated subsidies are given for all the rail containers to eliminate trucking. In all the scenarios, Qingdao and Dalian are never selected for both the direct and transit containers from Japan or Korea due to their location disadvantage. Yingkou port is always selected for the transit cargo to Manzhouli using rail due to their proximity.

Insert Figure 4

In scenario ***a***, only transit containers to Alashankou use rail from Tianjin; all others are transported by trucks. If external costs have to be internalized (scenario ***b***), only direct containers from Tianjin to Zhengzhou will be trucked—all others will go by rail. In scenario ***c***, the current subsidy scheme specified in Table 4, the 5210 TEU rail containers to Alashankou in scenario ***a*** will be trucked to Lanzhou first, then go by rail to Alashankou. This is because Tianjin does not provide a subsidy for rail containers, whereas Lanzhou does. Therefore, the current uncoordinated subsidy scheme results in more trucking.

In scenario ***d***, the coordinated subsidies to eliminate all road traffic on each route are given in parentheses. The direct containers to three inland cities, as well as the transit containers to Erenhot, require subsidy to go by rail. No subsidies are required for transit containers to Alashankou and Manzhouli. The minimal subsidy to achieve this result is $3.32 million yuan.

The optimal result (the minimum required subsidy) for certain level of acceptable externality is a constant. This is because there is no constraint on total subsidies and, for a given subsidy on each rail section, the containers on the corresponding road will either remain on the road if the subsidy is not enough, or will shift to rail. Figure 5 shows the model result of scenario ***d***, with horizontal axis as the $SocialL$ and vertical one as the total subsidy. As a sensitivity analysis, we provided the required subsidies (the horizontal lines) for four levels of $SocialL$: level 1 $[0, 0.77)$, level 2 $[0.77, 1.77)$, level 3 $[1.77, 2.88)$, and level 4 $[2.88, 3.56)$. The decimal numbers above each stepped line, namely 3.32, 1.04, 0.48, 0.09, are the required subsidies to reduce the externality to any point within each level. The slopped lines are the intermediate results from step 3 for each $SocialL$.

Insert Figure 5

For any predetermined externality within each level, such as at point A in the figure, the minimum overall subsidy from step 3 of the solution method is $1.5

million. However, this allows a partial shift from road to rail. If all containers in this section have to be transferred to rail, then the total subsidy will be at the level of the top horizontal line (i.e., $3.32 million); and the total externality will be the left end of this line (the red dot in each section; 0 in this case), which satisfies the externality constraint (eq. 10). If the allowable maximum externality is B, which is higher than A, then the total required subsidy is less ($1.04 million), and the effective externality level is 0.77.

This graph indicates that the total externality in the MCF model is about $3.56 million. If the required reduction in externality is small, the section with the lowest required subsidies will shift first. For example, if the acceptable externality level is within level 4, the minimum total subsidy is $0.09 million, which is just enough to subsidize the containers from Tianjin to Lanzhou to use rail transport, as the required subsidy for each container is only $9.44 (Figure 4, **d**), and the total externality is about $2.88 million. For $socialL$ between 1.77 and 2.88, the containers from Tianjin to Erenhot will shift to rail, as the unit subsidy is $12.96. After that, rail will be preferred from Tianjin to Xi'an, and the last section to shift is then from Tianjin to Zhengzhou.

To compare economic efficiency in these four scenarios, Table 5 summarizes the results in terms of rail percentage, freight cost, externality, total subsidy, and total social cost (the sum of freight cost, externality, and subsidy).

Insert Table 5

Comparing scenarios ***a*** and ***b****:* if shippers are required to pay the external cost from trucking (scenario ***b***), around 76% of the containers will use rail services, and the social cost will be the lowest. However, under the current uncoordinated subsidy scheme (scenario ***c***), rail containers only account for around 14.63%, which is even lower than ***a***. In scenario ***c***, externality is the highest, together with the total social cost, which clearly shows the inefficiency in the current subsidy scheme. For scenario ***d***, the total freight cost is the same as that in ***a***, but the total subsidy is less than the total externality in scenario ***a***. Therefore, the total social cost of ***d*** is the lowest compared with ***a*** and ***c***. This indicates that a coordinated subsidy is better than both no subsidy and an uncoordinated subsidy. Of course, scenario ***b***, internalizing the externality, is the best. However, there is no existing mechanism to make this happen.

5. Summary and conclusion

The rail transportation of containers is efficient for long-distance high value cargo. It can also reduce trucking activity and congestion on the roads, which is beneficial for improving air quality around populated cities and large container ports. Due to its social benefits, many provinces/municipalities provide subsidies for rail containers. However, uncoordinated subsidies in different regions may not result in the expected reduction in the externalities caused by road traffic.

This paper presents a BLP model and a solution method and analyzes the optimal subsidies for rail containers for both the transit and direct containerized trade of North East Asia (Japan and Korea) with Europe and northern China. Four scenarios are designed to illustrate the differing results for no subsidies, internalizing the external cost, for uncoordinated subsidies, and for coordinated subsidies. The solution method for the BLP problem is creative and efficient, and it converts an equilibrium problem that may require many iterations between the two levels to a simple four-step linear programming problem.

The model results demonstrate that uncoordinated subsidies can result in the highest total social cost due to high total subsidies and the external cost. In the coordinated subsidies scenario, total subsidies to eliminate the external cost are less than the external cost when there are no subsidies. This implies that providing subsidies is a good choice. It also demonstrates the superiority of the internalizing externality approach, as this can attain the lowest total social cost. However, this approach shows the highest increase in private transport costs, as shippers not only have to bear the freight cost but also the external cost.

The academic contribution of this study is its novel solution method to the BLP model. It demonstrates a new way of solving the BLP problem based on economic reasoning. In practice, it also contributes to the formulation of subsidies for rail containers. It points out that uncoordinated subsidies may not achieve their intended goal. Rather, this can create unnecessary competition among the regions involved, resulting in social welfare reduction.

One limitation of this study is that it only considers the case in northern China, due to data availability. It would be much useful to expand to the national level, as many other regions are also giving subsidies to rail containers.

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Table 1: Direct rail services between China and the European Union

No.	City in China	Border crossing	Foreign city	Direction
1	Chongqing	Alashankou (Khorgos)	Duisburg	Round trip
2	Chongqing	Manzhouli	Cherkessk	One way
3	Zhengzhou	Alashankou (Khorgos)	Hamburg	Round trip
4	Zhengzhou	Erenhot	Hamburg	Round trip
5	Chengdu	Alashankou (Khorgos)	Łódź	Round trip
6	Wuhan	Alashankou (Khorgos)	Pardubice	Round trip
7	Wuhan	Alashankou (Khorgos)	Hamburg	Round trip
8	Wuhan	Manzhouli	Tomsk	One way
9	Suzhou	Manzhouli	Warsaw	One way
10	Suzhou	Manzhouli	Brest	One way
11	Yiwu	Alashankou (Khorgos)	Madrid	Round trip
12	Shenyang	Manzhouli	Hamburg	Round trip
13	Changsha	Manzhouli	Hamburg	One way
14	Lanzhou	Alashankou (Khorgos)	Hamburg	Round trip
15	Beijing Tianjin	Erenhot	Ulaanbaatar	Round trip
16	Lianyungang	Alashankou (Khorgos)	Almaty	Round trip
17	Yingkou	Manzhouli	Oblast Transbaikal	Round trip
18	Qingdao	Alashankou (Khorgos)	Almaty	One way
19	Urumqi	Alashankou (Khorgos)	Almaty	One way
20	Xi'an	Alashankou (Khorgos)	Almaty	Round trip
21	Hefei	Alashankou (Khorgos)	Almaty	One way
22	Jinan	Alashankou (Khorgos)	Almaty	One way
23	Dongguan	Alashankou (Khorgos)	Almaty	One way

Source: *National Development & Reform Committee* (NDRC, 2015)

Table 2. Rail freight and trucking externality ($/TEU)

From	To	Rail freight	External cost	From	To	Rail freight	External cost	From	To	Rail freight	External cost
TJ	ZZ	528	31.94	QD	③	1556	112.57	DL	②	1103	68.99
TJ	XA	735	50.17	YK	ZZ	993	60.92	DL	③	1130	79.74
TJ	LZ	1015	67.87	YK	XA	1198	78.26	ZZ	①	2091	157.06
TJ	①	1927	165.75	YK	LZ	1439	96.76	ZZ	②	1048	52.86
TJ	②	650	36.73	YK	①	2287	192.63	ZZ	③	1616	122.30
TJ	③	1173	90.94	YK	②	992	61.37	XA	①	1837	136.41
QD	ZZ	529	32.51	YK	③	1109	70.78	XA	②	1126	60.48
QD	XA	793	52.94	DL	ZZ	1106	68.09	XA	③	1818	139.77
QD	LZ	1170	79.00	DL	XA	1309	85.56	LZ	①	1542	107.51
QD	①	2303	176.91	DL	LZ	1549	104.38	LZ	②	1128	71.23
QD	②	1021	60.63	DL	①	2394	201.59	LZ	③	1922	159.03

Notes: TJ (Tianjin), QD (Qingdao), YK (Yingkou), DL (Dalian), ZZ (Zhengzhou), XA (Xi'an), LZ (Lanzhou). Border crossing points: ① Alashankou, ② Erenhot, ③ Manzhouli. *Trucking costs cannot be published due to the non-disclosure agreement with the trucking companies in the survey.*

Table 3. Container transportation demand (TEUs/year)

Node	Demand	Node	Demand
Zhengzhou	24000	Alashankou	5210
Xi’an	20000	Erenhot	30184
Lanzhou	10000	Manzhouli	12270

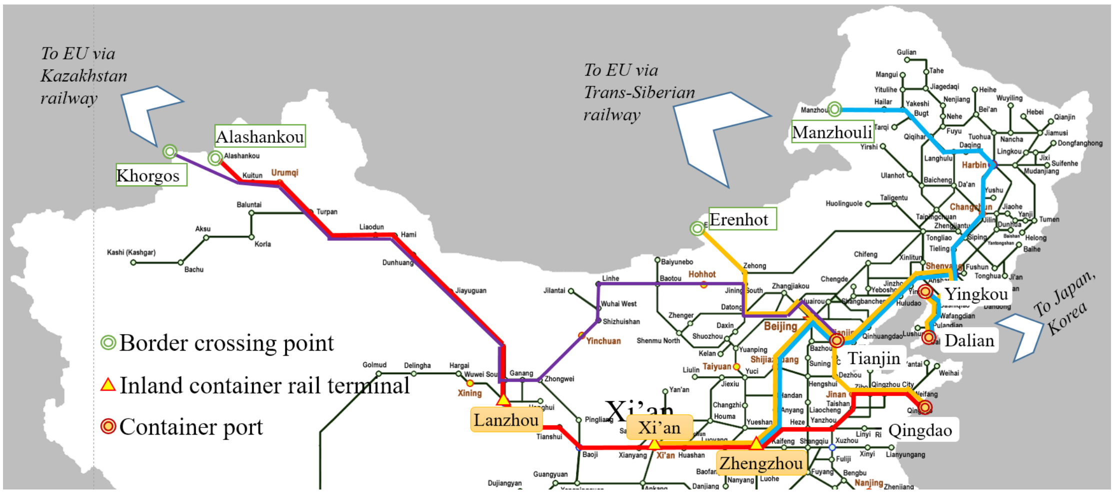
Table 4: Subsidies to rail containers in current scheme

Border crossing	Ports/Cities	Subsidy
Altaw/Erenhot	Xi'an	$720 /TEU
Altaw	Lanzhou	$800 /TEU
Altaw/Manzhouli/Erenhot	Zhengzhou	$560 /TEU
Manzhouli/Erenhot	Yingkou	$160 /TEU, + reduce MFC by 20%, about $19 /TEU
Manzhouli/Erenhot	Dalian	$64 /TEU, + reduce MFC by 30%, about $91 /TEU
Altaw/Erenhot	Qingdao	$240 /TEU + reduce MFC by 50%, about $287 /TEU

Notes: 1. MFC (Multimodal Freight Charge) includes loading/unloading charges at ships or rail trailers, customs, storage, and agent fees. 2. Data source: 'Port Economy'.

Table 5: Model result in different scenarios (million $)

	Scenario			
	a	**b**	**c**	**d**
Rail containers (%)	17.19%	76.39%	14.63%	100%
Freight cost	77.502	79.306	74.374	77.502
Externality	3.557	0.767	3.911	0.000
Total subsidy	——	——	6.361	3.317
Total social cost	81.061	80.072	84.646	80.819



Note：The blue lines are the railways from ports and inland cities to Manzhouli, the yellow ones are those to Erenhot, the red lines to Alashankou, and the purple lines to Khorgos;

Figure 1: Rail connections to Eurasian land bridges in Northern China

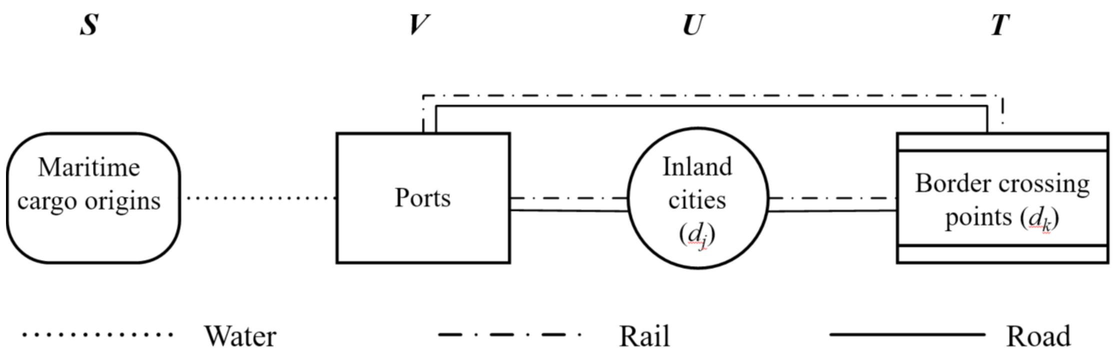


Figure 2: Structure of the multimodal transportation network

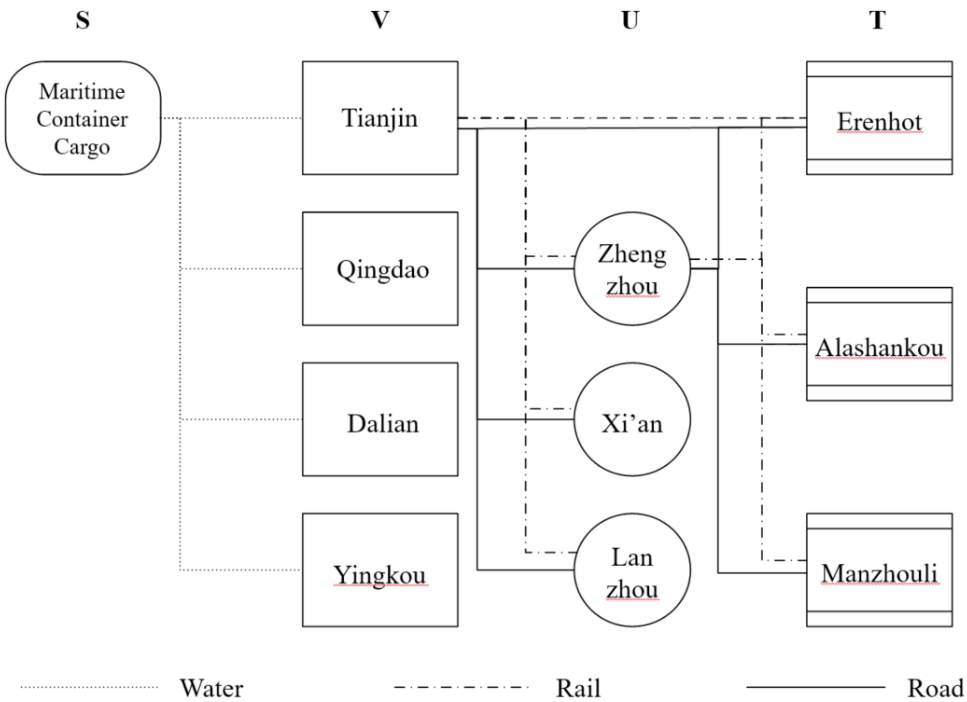


Figure 3: Multimodal container transportation network in north-eastern China

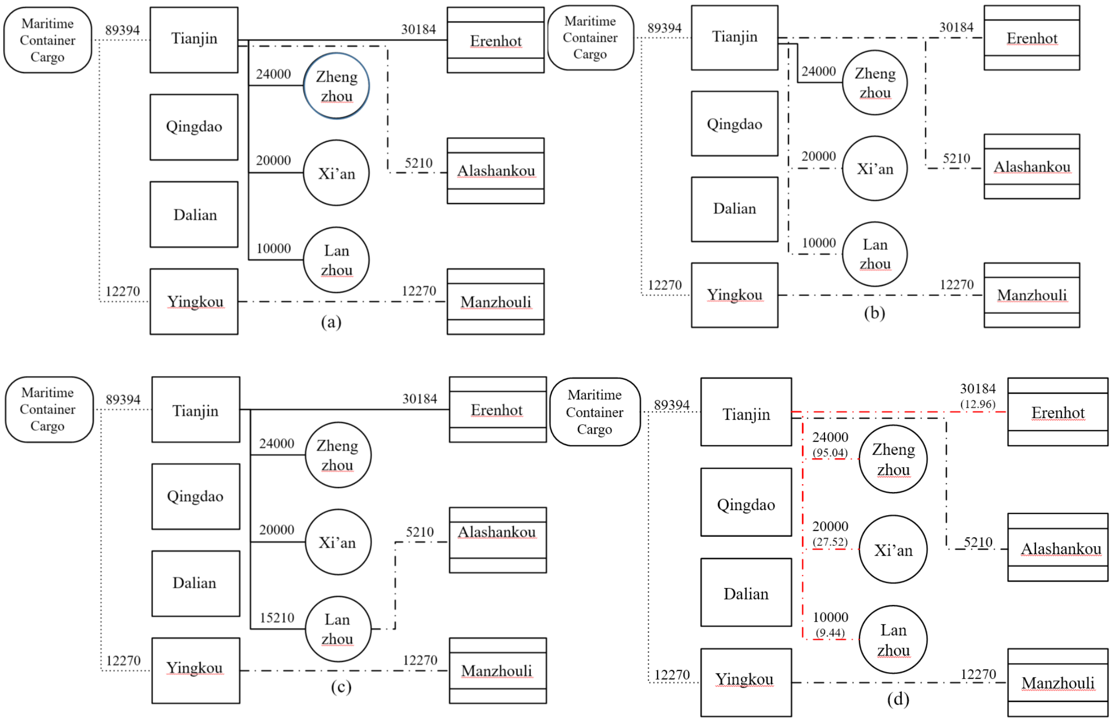


Figure 4: Results from scenarios ***a***, ***b***, ***c***, and ***d***

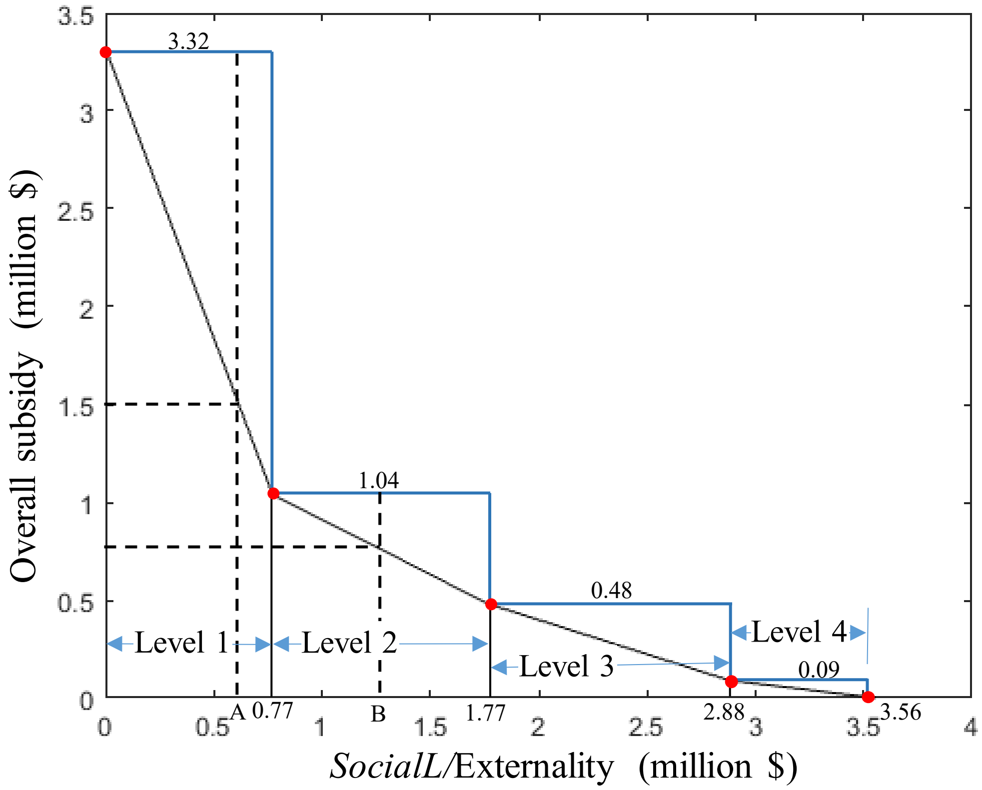


Figure 5. Optimization results for different SocialL

Figure Captions:

Figure 1. Rail connections to Eurasian land bridges in Northern China

Figure 2. Structure of the multimodal transportation network

Figure 3. Multimodal container transportation network in north-eastern China

Figure 4. Results from scenarios ***a, b, c,*** and ***d***

Figure 5. Optimization results for different SocialL