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Multicriteria Intermodal Freight Network Optimal Problem with Heterogeneous Preferences under Belt and Road Initiative

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Abstract: In this study, we demonstrate the importance of incorporating shippers' preference heterogeneity into the optimization of the China Railway express network. In particular, a bilevel programming model is established to minimize the total construction cost for the government in the upper level and maximize the shippers' satisfaction in the lower level. The proposed model considers price, time, reliability, frequency, safety, flexibility, traceability, and emission. Two designs are obtained by applying the model to two scenarios, in which one is of the aggregate shipper group and the other is of the three distinct clusters. Results show that explicitly including heterogeneity in network optimization pays off in terms of the dramatic increase in shippers' satisfaction and the share of the sustainable railway without generating extra cost for the system. The results of this study could lead to insightful implication for proper network planning for the China Railway express and some useful suggestions on the subsidies of the government.

Keywords: sustainable freight network design; heterogeneous preferences; multicriteria decision-making

Highlights:

1. A bilevel network optimization model, which includes choice path behavior with multiple criteria, is built.
2. The sustainability and service level of the network is improved by recognizing the heterogeneous preferences of shippers.
3. The transport requirements of hub cities will not be assigned to the best options to fulfill the needs of cites that are not selected as hub cities for ensuring that the total satisfaction of all shippers could be raised.

1. Introduction

The Belt and Road Initiative (BRI), announced in 2013, together with the "Vision and Actions on Jointly Building the Silk Road Economic Belt and 21st-Century Maritime Silk Road" has provided many opportunities for the trade between China and Europe along with huge benefits for China Railway Express (CRexpress). Since then, China has faced many severe environmental issues because freight transportation is the main contributor of emission.

Over the past 8 years, the number of CRexpress lines experienced a rapid growth from 17 lines in 2011 to 6363 lines in 2018. To date, 56 cities operate CRexpress lines, reaching 49 cities in 15 countries in Europe. In 2015, the Leading Group Office on the Construction of the Belt and Road issued the Development Plan of China–Europe Freight Train Construction (2016–2020), which confirms the significance of the development of the CRexpress given that it serves as an important carrier and gripper to promote the construction of the "Belt and Road". Apart from the thrilling progress, the development of CRexpress has diverse challenges. One key bottleneck that has to be eased is how to establish an environmental sustainability-oriented coordination mechanism and optimize the overall layout of the CRexpress system logistics service network.

The BRI service network has three decision makers: the shippers, the railway companies, and the central government. The shippers aim to get their cargo shipped with abundant benefits. The central government, the logistics service integrator (LSI), will distribute the orders from the clients to the logistics service providers (LSPs), which are the local railway companies. The LSPs will fulfill the demand by providing the corresponding customized services. At present, LSPs operating the lines only aim to be at an advantage in the competition with other LSPs; therefore, services with quite low price are supplied to attract shippers. At the beginning, this approach helped expand the volume, but it also brings bad results as the lines increased. First, many lines covering the same area leads to a huge waste of resources. Second, the cargo supply is insufficient due to the vicious competition. Finally, as a result of the above two scenarios, the LSI has to give a large amount of subsidies to LSPs. Under such a circumstance, the LSI of the CRexpress system guides the development of the LSPs from the overall level and improves the operational quality.

To solve the problem faced by the CRexpress system, a well-researched concept is that of service network design problem (SNDP). The SNDP is a key typical tactical problem in multimodal transportation, which mainly focuses on how to provide proper logistics services. Luathep et al. [1] proposed a global optimization algorithm to solve the transportation network design problem, which is expressed as a mathematical programming with an equilibrium constraint. Alumur et al. [2] addressed a hub location problem with different traveling modes and service time promises. Ambrosino and Sciomachen [3] proposed a mixed integer linear programming (MILP) model in which the containerized demand flow can be split into different services to evaluate suitable sites for dry-ports in northwestern Italian regions. Munim and Haralambides [4] analyzed the cross-border competition and cooperation between ports with a mixed integer linear programming. Their work shows that port users would greatly benefit from the cooperation, although some port authorities would suffer a revenue loss, which could be somehow compensated. Yang et al. [5] dealt with the reconstruction problem of the shipping service network between Asia and Europe. In particular, the authors tested the proposed bilevel model under different scenarios to obtain the new optimal networks. Some researchers investigated the CRexpress problems. Jiang et al. [6] were one of the first researchers that stressed the benefit of setting up consolidation centers for CRexpress. They built a mixed integer programming model, which selected Urimqi to be the only hub for 34 cities all over China.

The above contributions to SNDP are made to achieve a system-optimal solution. However, modeling for freight transport demand has significant wields on SNDP with the expanding commercial competitiveness over the past decade [7]. During a demand analysis, many sophisticated disaggregated models based on individual data have been used. Travel time cost was considered the sole objective in early transportation planning, however, people realized that a transportation network is a large system confronted with varied needs from different aspects [8]. Vinod and Baumol [9] first developed a model with shippers' choice to describe the mode choice with attributes of cost, time, reliability, and safety. Since then, different attributes have been investigated to explain the problem related to freight transport choice. Researchers realized that simply allowing for factors such as cost and time is not enough [10,11]. Cullinane and Toy [12] found out that "cost", "time", and "reliability" are the three commonly used attributes. Shinghal and Fowkes [13] conducted a stated preference survey on the Delhi to Bombay corridor. Their results show that frequency is of great importance to the mode choice. Yu et al. [14] claimed that flexibility could have distinct effects on logistics services under different environmental conditions. Tuzkaya and Önüt [15] evaluated the modes between Turkey and

Germany in which traceability is also selected. Transport has great responsibility for environmental impacts, thus, emission has gained great attention—many articles are concerned about emission [16]. Diverse literature with multiple criteria could be found in Table 1. On the basis of the analysis above, we selected eight attributes to reflect the shippers' demand preference: cost, time, reliability, frequency, flexibility, traceability, emission, and safety.

Methods, such as multicriteria decision-making (MCDM), can be used to unify more than two indices, and approaches of different types of MCDM are employed. Liu et al. [17] used the technique for order preference by similarity to ideal solution (TOPSIS) model combined with entropy weight to evaluate the nodes' importance and features of Shanxi water network and Beijing subway network. Long and Grasman [18] provided a multicriteria decision framework to evaluate the location of inland freight hubs, in which the relevant criteria needed were selected from subject matter experts. Zhao et al. [19] proposed a relative-entropy rank evaluation method for multiple-attribute decision-making. Hui et al. [20] also used multicriteria decision-making in synthesizing the multiple indices to evaluate a complex network. Wang and Yeo [21] built an evaluation structure for intermodal routing from Korea to Central Asia by adopting the Fuzzy Delphi and Fuzzy (Elimination and Choice Translating Reality I) methods. Their cases include five principle factors, among which total cost turns out to be the most important factor that affects the companies when they are selecting a route. We also summarize some applications of integrated attributes and shipper preferences under BRI. Jiang et al. [22] examined the choice probability of two types of goods between CRexpress and shipping among five typical CRexpress routes with a binary logit model. They conclude that government subsidies greatly contribute to decreasing the cost of CRexpress operators, and logistics service producers are more willing to choose CRexpress than others. As an extension of this work, Zhao et al. [23] evaluated cities from the perspective of government policy and CRexpress operation experience with TOPSIS and used mixed integer programming to select the key sites for consolidation. Studies that considered multicriteria decision-making are summarized in Table 1.

During multicriteria decision-making, especially when it is applied in the service network design, shippers' preferences are of great importance. Zeng et al. [24] considered the customer preferences and spatial interaction and provided a bidimensional evaluation method to help people understand the influences of Carat Canal. With many studies adopting shippers' preference in freight transportation network optimization, some have noticed the heterogeneity among freight service preferences [25,26]. One study proved that the service level of the network could be improved by considering the shipper heterogeneity [26]. Zeybek [27] highlighted the meaning of designing differentiated segment strategies for rail transport and used a multimethod to distinguish six behavioral customer segments. Liu et al. [28] pointed out the influence of mass customization on the key decisions made by LSPs and integrators in a logistics supply chain. Given that the level of expectations might vary from segment to segment of the customers, models with disaggregated data integrating different factors into decision-making are badly needed.

To the authors' knowledge, few disaggregated models have been applied to the rail transport, especially to the freight network under BRI, even though they are well-researched. Interaction between service network and mass customization could be found because individually designed services require a higher cost [29]. If the LSI could find cooperation with the LSPs, then the service quality would be improved by reducing transportation with low efficiency. Thus, the carbon emission of the network could be reduced.

Table 1. Literature using multicriteria decision-making and criteria included.

	Price	Time	Reliability	Frequency	Flexibility	Traceability	Emission	Safety
Yu et al. [14]					✓			
García-Menéndez and Feo-Valero [30]	✓	✓						
Jiang et al. [22]	✓	✓						
Arencibia et al. [10]	✓	✓	✓					
Duan et al. [26]	✓	✓	✓					
Moschovou and Giannopoulos [31]			✓	✓		✓		
Shinghal and Fowkes [13]		✓	✓	✓				
Tsamboulas and Moraitis [32]	✓	✓	✓					
Brooks and Trifts [33]	✓	✓		✓				
Bergantino and Bolis [34]	✓	✓	✓	✓				
Reis [35]	✓	✓	✓		✓			
Zotti and Danielis [36]	✓	✓	✓					✓
Wang and Yeo [21]	✓	✓	✓					✓
Zeybek [27]	✓	✓			✓			✓
Zamparini et al. [37]	✓	✓	✓		✓			✓
Norojono and Young [38]	✓	✓	✓		✓			✓
Punakivi and Hinkka [39]	✓	✓	✓	✓				✓
Wen et al. [40]	✓	✓	✓				✓	✓
Zotti and Danielis [36]	✓	✓	✓	✓	✓			
Beuthe and Bouffioux [41]	✓	✓	✓	✓		✓		✓
Witlox and Vandaele [42]	✓	✓	✓	✓	✓			✓
Jain et al. [43]	✓	✓	✓	✓	✓			✓
Tuzkaya and Önüt [15]	✓	✓	✓		✓	✓		✓
Witlox and Vandaele [42]	✓	✓	✓	✓	✓			✓

This study aims to explore the decisions regarding achieving an efficient network of CRexpress with mass customization service. When designing the CRexpress service network, the LSI determines an optimal configuration in terms of terminal locations and allocates the shipper demand to different LSPs. This study aims to answer the following three questions:

(1) Considering the satisfaction of shippers, what layout plan will the LSI come up with to improve the performance of the LSPs and the overall service network of CRexpress?
(2) What type of logistics characteristics should be taken into consideration to capture preferences of shippers?
(3) How will the heterogeneous preferences of shippers influence the selection of the consolidation centers, the market share of the logistics services provided by the LSPs, and the decision of the LSI?

The remaining part of this paper is organized as follows: Section 2 describes the system and the problem and then introduces the notation and the bilevel programming formulation. The solution approach to the bilevel model is also introduced. Section 3 includes the application and results. The conclusions and implications can be found in Section 4.

2. Materials and Methods

2.1. Background of the CRexpress Service Network

The CRexpress service network in our paper is denoted by $G(N, A)$, where N represents the set of nodes (including shippers and gateways), while A stands for the set of arcs in the network. We use the selected 27 cities for the 27 provinces in China in Zhao et al. [23] as the shippers for the CRexpress service network. According to the authors, the cities could be classified into two groups: (i) one group of 17 cities that will not be chosen as consolidation center candidates after evaluation, denoted by I (indexed by i); and (ii) one group of 10 cities as candidates for consolidation centers, represented by J. We further divide the second group into two sets depending on whether it is chosen after optimization. Specifically, city $j \in J$ is the optimized consolidation center, and city $n \in J$ is excluded from the result. City $n \in J$, which is not chosen as the consolidation center among the candidate cities (set J), will be treated as origin cities in the further analysis. All shippers above have the demand to be exported through the CRexpress network. The railway and road are considered in the CRexpress network, represented by M (indexed by m).

Figure 1 is an illustration of the routes and modes of all shippers, which could be summarized as follows:

1. In every $i \in I$, the cargo is delivered to $j \in J$ by railway or road transportation and consolidated into one single CRexpress train with other cargos received at $j \in J$ and then continuing to gateway $k \in K$;
2. In every $n \in J$ that is not chosen as the consolidation center, the cargo is delivered to $j \in J$ by railway or road transportation and consolidated into one single CRexpress train with other cargo received at $j \in J$ and then continuing to gateway $k \in K$;
3. The transport demand of every $j \in J$ will be consolidated with other cargos received at $j \in J$; then, the cargos continue to gateway $k \in K$;
4. All cargos are assumed to be transported to the single destination in this study.

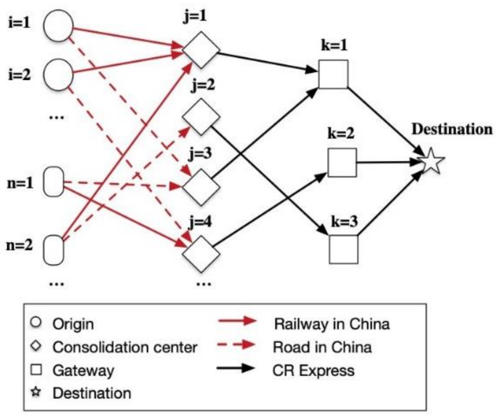

Figure 1. Illustration of the process in the CRexpress network. Node j also has its own transport demand.

The shippers' aim from route and mode selection is to identify the optimal alternatives with the highest utility from all feasible alternatives in the network. The utility function is the weighted sum of eight logistics characteristics to evaluate the route and mode alternatives in the CRexpress network. The details of the utilities will be described in the next section.

2.2. Utility Function

In this section we introduce the utility function as a foundation for the optimization model. The utility function is the weighted sum of logistic factors to evaluate the alternatives [10]. With the assumptions we build the utility function with integrated indicators in order to improve the decision-making process.

2.2.1. Assumptions

The utility function we build is based on the following assumptions:

- All decision makers are economists, who choose the alternative that maximizes their own utility.
- Only road and railway transportation are included in this system.
- The decisions made in this system are considered for a specified time period.
- The indicators in the models are considered constant parameters rather than stochastic variables for the given time period;
- This system has no congestion, and the loading and unloading times are not considered.

2.2.2. Formulating the Utility Function

We first explain the formulation of city $i \in I$, and the utility function for city $n \in J$ could be obtained following the same principle. In each city $i \in I$, the transportation distance consists of two arcs, namely, from the $i \in I$ to $j \in J$ and from $j \in J$ to the destination through $k \in K$. The railway and road are considered, represented by M (indexed by m). The factors cost, time, and emission, which are distance- and mode-dependent, also have two parts. The cost, time, and emission for $i \in I$ exporting the cargo equal the sum of the costs incurred by the arcs contained (Equations (1)–(3)).

$$c_{ijk}^{m} = c_{ij}^{m} + c_{jk} \tag{1}$$

$$t_{ijk}^{m} = t_{ij}^{m} + t_{jk} \tag{2}$$

$$e_{ijk}^{m} = e_{ij}^{m} + e_{jk} \tag{3}$$

The factors, such as frequency, reliability, safety, flexibility, and traceability, are only mode-dependent in our case, which means that the second arc has no influence on it. In each city $j \in J$ that is selected as the consolidation center, the shippers shall choose from three gateways, and the corresponding factors are listed in Table 2.

Table 2. Definitions and notations.

Factor	Definition	Notation	Unit
Cost	Monetary expenditure	$c_{ijk}^{m}, c_{njk}^{m} c_{jk}$	Yuan
Time	Transportation time needed	$t_{ijk}^{m}, t_{njk}^{m}, t_{jk}$	Hour
Emission	CO_2 emitted	$e_{ijk}^{m}, e_{njk}^{m}, e_{jk}$	$g(CO_2)$
Frequency	Times of the service	$f_{ijk}^{m}, f_{njk}^{m}, f_{jk}$	Times/day
Reliability	Probability of goods delivered in time	$r_{ijk}^{m}, r_{ink}^{m}, r_{jk}$	Probability
Safety	Probability of goods not being damaged	$s_{ijk}^{m}, s_{njk}^{m}, s_{jk}$	Probability
Flexibility	Probability of executing a nonprogrammed shipment without delay	$p_{ijk}^{m}, p_{njk}^{m}, p_{jk}$	Probability
Traceability	Probability of tracing the goods	$v_{ijk}^{m}, v_{njk}^{m}, v_{jk}$	Probability

The measurement scales of the above factors are different, which causes infeasibility to simply add them together. We normalize these attributes for a fair comparison. $c_{ijk}^{\hat{m}}$, $t_{ijk}^{\hat{m}}$, $e_{ijk}^{\hat{m}}$, $r_{ijk}^{\hat{m}}$, $f_{ijk}^{\hat{m}}$, $s_{ijk}^{\hat{m}}$, $p_{ijk}^{\hat{m}}$, and $v_{ijk}^{\hat{m}}$ are the normalized cost, time, emission, reliability, frequency, safety, flexibility, and traceability of the alternative, respectively. Equation (4) is the min–max normalized function [43], in which we utilize the notation with a line on the top representing the maximum value of the attributes, while the one with a line in the bottom refers to the minimum. All factors are valued in [0, 1] after normalization.

$$\hat{\Omega} = \frac{\Omega - \underline{\Omega}}{\overline{\Omega} - \underline{\Omega}},\ \Omega = c_{ijk}^{m}, t_{ijk}^{m},\ e_{ijk}^{m},\ r_{ijk}^{m},\ f_{ijk}^{m},\ s_{ijk}^{m},\ p_{ijk}^{m} \text{ and } v_{ijk}^{m} \tag{4}$$

The unit utility function is formulated in Equation (5), where w_c, w_t, w_e, w_r, w_f, w_s, w_p, and w_v are the non-negative weight parameters for cost, time, emission, reliability, frequency, safety, flexibility, and traceability, respectively. The unit utility function is generally composed of two parts: (i) the negative component of the weighted sum of cost, time, and emission; and (ii) the positive component of the weighted sum of the reliability, frequency, safety, flexibility, and traceability. The weights are the preferences of the shippers toward various attributes when choosing the alternative.

$$U_{ijk}^{m} = -w_c * c_{ijk}^{\hat{m}} - w_t * t_{ijk}^{\hat{m}} - w_e * e_{ijk}^{\hat{m}} + w_f * f_{ijk}^{\hat{m}} + w_r * s_{ijk}^{\hat{m}} + w_s * r_{ijk}^{\hat{m}} + w_v * p_{ijk}^{\hat{m}} + w_p * v_{ijk}^{\hat{m}} \tag{5}$$

Considering that the total demand could be split into several alternatives, the overall utility of the city $i \in I$ is the sum of utility (U_{ijk}^{m}) multiplied by the volume (x_{ijk}^{m}) (Equation (6)). The utility of cities $n \in J$ and $j \in J$ could also be obtained following the same principle (Equations (7) and (8)).

$$U_i = \sum_{j \in J} \sum_{k \in K} \sum_{m \in M} U_{ijk}^{m} * x_{ijk}^{m}, \ \forall i \in I \tag{6}$$

$$U_n = \sum_{j \in J} \sum_{k \in K} \sum_{m \in M} U_{njk}^{m} * x_{njk}^{m}, \ \forall n \in J \tag{7}$$

$$U_j = \sum_{k \in K} U_{jk} * x_{jk}, \ \forall j \in J \tag{8}$$

2.3. Mathematical Formulation of the Bilevel Model

This model deals with the contradiction among the LSI, LSP, and shippers using the CRexpress network. The leader–follower problem can be mathematically expressed as a bilevel program. The decision-maker in the upper level, the LSI, makes their decision about how to assign the demand flow to different LSPs for minimizing the construction cost. Shippers in the lower level will determine the flows on the network that maximize travel utility.

The decision variables corresponding to the decisions made in the model are listed below. We let binary variable O_j represent which city to be chosen as the consolidation center, in which $O_j = 1$ if $j \in J$ is selected, and 0 otherwise. We denote x_{ijk}^{m} as the volume transported city $i \in I$ to consolidation center $j \in J$ to destination through gateway $k \in K$ by mode $m \in M$. x_{njk}^{m} is denoted as the volume transported city $n \in J$ to consolidation center $j \in J$ to destination through gateway $k \in K$ by mode $m \in M$, when $n \in J$ is not chosen to be the consolidation center. x_{jk} is the ictal demand volume at city $j \in J$ that will be transported to the destination through gateway $k \in K$.

Every city in the network has its demand to the destination. In each $n \in J$ that is not selected as the consolidation center, it will also serve as a city. Therefore, in each $i \in I$, $n \in J$, and $j \in J$, we let D_i, D_n, and D_j represent the demand of nodes i, n, and j that has to be served by the CRexpress network, respectively. Ca is the maximum operating capacity of a consolidation center. The capacity for each CRexpress train leaving $j \in J$ for $k \in K$ is denoted by B. c_0 is the fixed construction. The reference of notations can be found in Table A1.

The bilevel problem can be written as follows:

Upper level:

$$\min_{O} P_{Total} = \sum_{j \in J} O_j c_0 \tag{9}$$

subject to

$$O_j \in \{0, 1\}, \ \forall j \in J; \tag{10}$$

Lower level:

$$\max_{x_{ijk}^{m}, x_{njk}^{m}, x_{jk}} \mathrm{U}_{Total} = \sum_{i \in i} U_i + \sum_{n \in J} U_n + \sum_{j \in J} U_j \tag{11}$$

subject to

$$w_c + w_t + w_e + w_f + w_r + w_s + w_p + w_v = 1, \tag{12}$$

$$\sum_{m \in M} \sum_{j \in J} \sum_{k \in K} x_{ijk}^{m} = D_i, \forall i \in I, \tag{13}$$

$$\sum_{k \in K} x_{jk} = D_j O_j, \forall j \in J, \tag{14}$$

$$\sum_{m\in M}\sum_{j\in J}\sum_{k\in K} x_{njk}^{m} = D_n(1-O_n), \forall n \in J, n \neq j, \tag{15}$$

$$x_{ijk}^{m} \leq O_j D_i, \forall i \in I, \forall j \in J, \forall m \in M, \forall k \in K, \tag{16}$$

$$x_{njk}^{m} \leq O_j D_n, \forall j \in J, \forall m \in M, \forall n \in J, n \neq j, \forall k \in K, \tag{17}$$

$$D_j + \sum_{m\in M}\sum_{i\in I}\sum_{k\in K} x_{ijk}^{m} + \sum_{m\in M}\sum_{n\in J}\sum_{k\in K} x_{njk}^{m} \leq Ca \ \ , \forall j \in J, \tag{18}$$

$$\sum_{m\in M}\sum_{i\in I} x_{ijk}^{m} + \sum_{m\in M}\sum_{n\in J} x_{njk}^{m} + x_{jk} \leq B,\ \forall k \in K, \forall j \in J, \tag{19}$$

$$x_{ijk}^{m} \geq 0, \forall i \in I, \forall j \in J, \forall k \in K, \forall m \in M, \tag{20}$$

$$x_{njk}^{m} \geq 0, \forall j \in J, \forall m \in M, \forall k \in K, \forall n \in J, n \neq j, \tag{21}$$

$$x_{jk} \geq 0, \forall k \in K, \forall j \in J. \tag{22}$$

In the upper level, the objective function (9) is to minimize the construction cost for setting up a consolidation center. Constraint (10) shows that a consolidation center has to be chosen to be in the network.

In the lower level, the objective function (11) is to maximize the total satisfaction of all shippers when certain consolidation centers are selected by the decision-maker in the upper level (i.e., central LSP). Constraint (12) ensures that all weights add up to one. Constraints (13)–(15) ensure that the demands of all cities are satisfied. Constraints (16)–(17) imply that the flow will not enter any nodes that are not chosen as consolidation centers. Constraint (18) guarantees that the volume received at each consolidation center is under its maximum capacity. Constraint (19) restricts that all cargo leaving each consolidation center are transported by CRexpress. Constraints (20)–(22) define the non-negativity of the decision variables.

In summary, the CRexpress network optimization problem is mathematically expressed as a bilevel program. The upper level objective involves the decision variables in the lower level. We show how to solve this problem in the next section.

2.4. Solution Approach and Reformulation

In a given O_j from the upper level, the lower level problem (i.e., Equations (11)–(22) is a linear programming formulation. Therefore, the bilevel program we proposed could be reformulated into a single-level MILP formulation by replacing the lower level optimization program with the Karush–Kuhn–Tucker (KKT) conditions [44]. First, we replace the lower level problem with KKT conditions, then, we transform the nonlinearities of the complementarity constraints, finally, we strengthen them to improve the computational performance of solving the program.

2.4.1. KKT Conditions for the Lower Level

To obtain the KKT conditions for the lower level program, first, we describe the primal feasibility together with the dual feasibility. The primal feasibility includes the following, and the dual variables for each constraint in the lower level are parenthetically indicated:

$$\sum_{m\in M}\sum_{j\in J}\sum_{k\in K} x_{ijk}^{m} = D_i,\ \forall i \in I,\ (\beta_i), \tag{23}$$

$$\sum_{m\in M}\sum_{j\in J}\sum_{k\in K} x_{njk}^{m} = D_n(1-O_n),\ \forall n \in J, n \neq j,\ (\alpha_n), \tag{24}$$

$$\sum_{k\in K} x_{jk} = D_j O_j,\ \forall j \in J\ ,\ \left(\rho_j\right), \tag{25}$$

$$x^m_{ijk} \le O_j D_i,\ \forall i \in I, \forall j \in J, \forall m \in M, \forall k \in K,\ \left(\pi^m_{ijk}\right), \tag{26}$$

$$x^m_{njk} \le O_j D_n, \forall j \in J, \forall m \in M, \forall n \in J, n \ne j, \forall k \in K \left(\lambda^m_{njk}\right), \tag{27}$$

$$\sum_{m\in M}\sum_{i\in I}\sum_{k\in K} x^m_{ijk} + \sum_{m\in M}\sum_{n\in J}\sum_{k\in K} x^m_{njk} + \sum_{k\in K} x_{jk} \le Ca\ ,\ \forall j \in J,\ \left(\delta_j\right), \tag{28}$$

$$\sum_{m\in M}\sum_{i\in I} x^m_{ijk} + \sum_{m\in M}\sum_{n\in J} x^m_{njk} + x_{jk} \le B,\ \forall k \in K, \forall j \in J,\ \left(\eta_{jk}\right), \tag{29}$$

$$-x^m_{ijk} \le 0, \forall i \in I, \forall j \in J, \forall k \in K, \forall m \in M,\ \left(\tau^m_{ijk}\right), \tag{30}$$

$$-x^m_{njk} \le 0, \forall j \in J, \forall k \in K, \forall m \in M, \forall n \in J, n \ne j\ ,\ \left(\omega^m_{njk}\right), \tag{31}$$

$$-x_{jk} \le 0, \forall k \in K, \forall j \in J,\ \left(\mu_{jk}\right). \tag{32}$$

Dual feasibility implies the following:

$$\pi^m_{ijk}, \tau^m_{ijk} \ge 0, \forall i \in I, \forall j \in J, \forall k \in K, \forall m \in M, \tag{33}$$

$$\lambda^m_{njk}, \omega^m_{njk} \ge 0, \forall j \in J, \forall k \in K, \forall m \in M, \forall n \in J, n \ne j, \tag{34}$$

$$\delta_j \ge 0, \forall j \in J, \tag{35}$$

$$\eta_{jk}, \mu_{jk}, \eta_{jk} \ge 0, \forall k \in K, \forall j \in J. \tag{36}$$

Then, we can derive the stationarity equations:

$$U^m_{ijk} + \beta_i + \delta_j + \pi^m_{ijk} - \tau^m_{ijk} + \eta_{jk} = 0, \forall i \in I, \forall j \in J, \forall k \in K, \forall m \in M, \tag{37}$$

$$U^m_{ijk} + \alpha_n + \delta_j + \lambda^m_{njk} - \omega^m_{njk} + \eta_{jk} = 0, \forall j \in J, \forall k \in K, \forall m \in M, \forall n \in J, n \ne j, \tag{38}$$

$$U_{jk} + \rho_j + \delta_j - \mu_{jk} + \eta_{jk} = 0, \forall k \in K, \forall j \in J. \tag{39}$$

The set of complementary conditions is as follows:

$$\pi^m_{ijk}\left(x^m_{ijk} - O_j D_i\right) = 0,\ \forall i \in I, \forall j \in J, \forall k \in K, \forall m \in M, \tag{40}$$

$$\lambda^m_{njk}\left(x^m_{njk} - O_j D_n\right) = 0,\ \forall j \in J, \forall k \in K, \forall m \in M, \forall n \in J, n \ne j, \tag{41}$$

$$\delta_j\left(\sum_{m\in M}\sum_{i\in I}\sum_{k\in K} x^m_{ijk} + \sum_{m\in M}\sum_{n\in J}\sum_{k\in K} x^m_{njk} + \sum_{k\in K} x_{jk} - Ca\right) = 0,\ \forall j \in J, \tag{42}$$

$$\eta_{jk}\left(\sum_{m\in M}\sum_{i\in I} x^m_{ijk} + \sum_{m\in M}\sum_{n\in J} x^m_{njk} + x_{jk} - B\right) = 0,\ \forall k \in K, \forall j \in J, \tag{43}$$

$$\tau^m_{ijk} x^m_{ijk} = 0,\ \forall i \in I, \forall j \in J, \forall k \in K, \forall m \in M, \tag{44}$$

$$\omega^m_{njk} x^m_{njk} = 0,\ \forall j \in J, \forall k \in K, \forall m \in M, \forall n \in K, n \ne j, \tag{45}$$

$$\mu_{jk} x_{jk} = 0,\ \forall k \in K, \forall j \in J. \tag{46}$$

2.4.2. Reformulating Complementarity Conditions

The above KKT conditions for the lower level are all linear except for the complementarity set, which can be linearized with a binary variable and a large constant [45]. On the basis of the methods proposed in the literature, we introduce binary variables for constraints (40)–(46), which are the ones with a star on the right top corner (i.e., $\pi_{ijk}^{m\,*}$ is the binary variable for π_{ijk}^{m}) and M as the arbitrarily large number. Then, we obtain the equivalent linear constraints:

$$\pi_{ijk}^{m} \le M\pi_{ijk}^{m\,*},\ \forall i \in I, \forall j \in J, \forall k \in K, \forall m \in M, \tag{47}$$

$$x_{ijk}^{m} - O_j D_i \le M\left(1 - \pi_{ijk}^{m\,*}\right),\ \forall i \in I, \forall j \in J, \forall k \in K, \forall m \in M, \tag{48}$$

$$\lambda_{njk}^{m} \le M\lambda_{njk}^{m\,*},\ \forall j \in J, \forall k \in K, \forall m \in M, \forall n \in J, n \ne j, \tag{49}$$

$$x_{njk}^{m} - O_j D_n \le M\left(1 - \lambda_{njk}^{m\,*}\right),\ \forall j \in J, \forall k \in K, \forall m \in M, \forall n \in J, n \ne j, \tag{50}$$

$$\delta_j \le M\delta_j^{*},\ \forall j \in J, \tag{51}$$

$$\sum_{m\in M}\sum_{i\in I}\sum_{k\in K} x_{ijk}^{m} + \sum_{m\in M}\sum_{k\in K}\sum_{i\in I} x_{njk}^{m} + \sum_{k\in K} x_{jk} - Ca \ \le M\left(1 - \delta_j^{*}\right),\ \forall j \in J, \tag{52}$$

$$\eta_{jk} \le M\eta_{jk}^{*},\ \forall k \in K, \forall j \in J, \tag{53}$$

$$\sum_{m\in M}\sum_{i\in I} x_{ijk}^{m} + \sum_{m\in M}\sum_{n\in J} x_{njk}^{m} + x_{jk} - B \le M\left(1 - \ \eta_{jk}^{*}\right),\ \ \forall k \in K, \forall j \in J, \tag{54}$$

$$\tau_{ijk}^{m} \le M\tau_{ijk}^{m\,*},\ \ \forall i \in I, \forall j \in J, \forall k \in K, \forall m \in M, \tag{55}$$

$$x_{ijk}^{m} \le M\left(1 - \ \tau_{ijk}^{m\,*}\right),\ \ \forall i \in I, \forall j \in J, \forall k \in K, \forall m \in M, \tag{56}$$

$$\omega_{njk}^{m} \le M\omega_{njk}^{m\,*},\ \ \forall j \in J, \forall k \in K, \forall m \in M, \forall n \in J, n \ne j, \tag{57}$$

$$x_{njk}^{m} \le M\left(1 - \ \omega_{njk}^{m\,*}\right),\ \ \forall j \in J, \forall k \in K, \forall m \in M, \forall n \in J, n \ne j, \tag{58}$$

$$\mu_{jk} \le M\mu_{jk}^{*},\ \ \forall k \in K, \forall j \in J, \tag{59}$$

$$x_{jk} \le M\left(1 - \mu_{jk}^{*}\right),\ \ \forall k \in K, \forall j \in J. \tag{60}$$

2.4.3. Strengthen the Constraints

The large value for M might lead to poor bounds from linear relaxation. In this step, we strengthen some constraints by replacing each big M with a relatively small number, which does not cut off the optimal solution. For instance, in constraint (48), D_i is always greater than $x_{ijk}^{m} - O_j D_i$; thus, we can tighten constraint (48) with D_i. The rest follows the same principle.

$$x_{ijk}^{m} - O_j D_i \le D_i\left(1 - \pi_{ijk}^{m\,*}\right),\ \forall i \in I, \forall j \in J, \forall k \in K, \forall m \in M \tag{61}$$

$$x_{njk}^{m} - O_j D_n \le D_n\left(1 - \lambda_{njk}^{m\ *}\right),\ \forall j \in J, \forall k \in K, \forall m \in M, \forall n \in J, n \neq j \tag{62}$$

$$\sum_{m \in M}\sum_{i \in I}\sum_{k \in K} x_{ijk}^{m} + \sum_{m \in M}\sum_{k \in K}\sum_{i \in I} x_{njk}^{m} + \sum_{k \in K} x_{jk} - Ca \le Ca\left(1 - \delta_j^{\ *}\right),\ \forall j \in J \tag{63}$$

$$\sum_{m \in M}\sum_{i \in I} x_{ijk}^{m} + \sum_{m \in M}\sum_{n \in J} x_{njk}^{m} + x_{jk} - B \le B\left(1 - \eta_{jk}^{\ *}\right),\ \forall k \in K, \forall j \in J \tag{64}$$

$$x_{ijk}^{m} \le D_i\left(1 - \tau_{ijk}^{m\ *}\right),\ \forall i \in I, \forall j \in J, \forall k \in K, \forall m \in M \tag{65}$$

$$x_{njk}^{m} \le D_n\left(1 - \omega_{njk}^{m\ *}\right),\ \forall j \in J, \forall k \in K, \forall m \in M, \forall n \in J, n \neq j \tag{66}$$

$$x_{jk} \le D_j\left(1 - \mu_{jk}^{\ *}\right),\ \forall k \in K, \forall j \in J \tag{67}$$

Our proposed bilevel programming model can be finally reformulated as an MILP formulation as follows through the above steps:

$$\min_{\substack{O, x, y, \beta, \alpha, \pi, \\ \lambda, \delta, \rho, \eta, \tau, \omega, \mu, \\ \pi^*, \lambda^*, \delta^*, \eta^*, \tau^*, \omega^*, \mu^*}} \quad P_{Total} = \sum_{j \in J} O_j c_0 \tag{68}$$

subject to

$$\pi^*, \lambda^*, \delta^*, \eta^*, \tau^*, \omega^*, \mu^* \in \{0, 1\}. \tag{69}$$

(10),(12)–(22),(33)–(46),(47),(49),(51),(53),(55),(57),(59),(61)–(67).

The final formulation can be accurately solved by existing optimization solvers. We adopt CPLEX 12.9 [46] to implement this model and perform other scenario analysis, which is discussed in the next section.

3. Results

In this section, we perform the proposed model in Section 2 by using realistic data as input and analyzing some results for insightful findings. We first describe the data obtained from existing literature. Then, we provide the definitions of all the attributes included and their values. Furthermore, we introduce two problem scenarios to understand the effects of incorporating shippers' heterogeneous preferences into the CRexpress network. Finally, we adopt CPLEX 12.9 as our optimization solver to solve the above model.

3.1. Input Parameters

In this case, we utilize the network as used in Zhao et al. [23]. Twenty-seven cities are present in the network, among which 10 are chosen as alternative consolidation centers. Considering all the three possible corridor routes, we have Manzhouli, Ernhot, and Altwa as gateways. We assume Hamburg to be the only destination. The annual volume between each city and Hamburg in 2020 is calculated on the basis of Zhao et al. [23]. The maximum capacities of the consolidation center and CRexpress trains are 10,000 and 2200 t, respectively. The fixed cost for setting up a consolidation center is 6.8×10^8 .

Now, we describe the data for all the logistic attributes, namely, price, time, frequency, reliability, flexibility, traceability, safety, and emission.

According to the China Railway Customer Service Center website (https://www.12306.cn), three types of services are offered, namely, full truck load, less than truck load, and container transportation. We follow the method in Zhao et al. [23] to obtain the average price. First, we define the maximum container load of the common international standards for containers as 22 and 27 t for 20- and 40-foot containers, respectively. On this basis, the average freight train cargo equals

0.15 RMB/ton/km. With regard to the road freight rate, we use 0.45 RMB/ton/km, which is calculated as the price estimated from a Chinese road freight website (https://www.jctrans.com).

The traffic safety regulations in China set the maximum and minimum speeds for trucks on highways to be 100 and 60 km/h, respectively, considering different situations in China, the speed of 60 km/h is applied for road transportation. The average speed of freight trains in China has been estimated to be 40 km/h, and the speed of CRexpress is defined as 60 km/h because the speed within China is slower than those overseas. Distance data are obtained from the China Railway Customer Service Center website (http://www.12306.cn) and the China highway website (http://www.china-highway.com). The transportation time for road and railway inside China could then be calculated (Tables A4–A6).

We use the average frequency of two trains/day for railway inside China. In real life, road trucks can leave at any time. However, a large value may introduce numerical stability issues, thus, we suppose that road trucks leave every hour. Based on the data released on https://www.yidaiyilu.gov.cn/xwzx/gnxw/76434.htm, 6300 CRexpress trains operated in 2018. Considering the diversity in different parts of China and three corridors, we utilize three trains per day as the average frequency of CRexpress.

The attribute reliability is regarded as the percentage of cargos transported to the destination within a given time [35]. Safety refers to the percentage of the commercial value of the total freight shipped that is not lost or damaged; while transportation flexibility represents the percentage of executed nonprogrammed shipment without undue delay [41]. Railway is the more reliable than road transportation [35]. For example, road trucks can be easily disturbed by traffic conditions or bad weather, while freight trains are less affected. With regard to transportation security, railway could provide more security than road transport. By contrast, road transportation has a good flexibility performance in responding to unexpected demands because rigid timetables are not that necessary and the ease of freight loading and unloading in road transportation [15].

These last years, transportation traceability has become the focus of interest for many researchers and decision-makers because it contributes to the control of flows and allows the optimization of the supply chain in its totality. Many investigations on the system have been conducted to support a real-time access to information for supply chain stakeholders [47,48]. Different shippers may vary in the satisfaction toward the traceability they received from different supply chain suppliers. Therefore, we use percentage in our study to represent shipper satisfaction toward traceability. The Global Positioning System (GPS) and Radio Frequency Identification (RFID) can help provide the shippers additional information about their cargos, however, it comes at a compromise cost. The level of application of GPS and RFID and tracking of cargos is higher in road than in railway/CRexpress. Therefore, shippers will have higher satisfaction toward road than railway/CRexpress.

Safety, flexibility, and traceability for road and railway transportation are randomly generated corresponding to the discussion above. Further details about the conversion into percentage can be found in [40].

Greenhouse gas emission is the main environmental criterion for the CRexpress' performance. Carbon dioxide, methane, nitrous oxide, and ozone are the primary transportation-related, man-made greenhouse gases. The impact of these gases can be calculated together as carbon dioxide equivalents (CO_2e). The model in this study focuses on the comparison between road and railway, and all parameters can be normalized into values in [0, 1]. Accordingly, we use the emission of carbon dioxide (CO_2) to represent the emission criteria.

Similar to the method proposed in Wiegmans and Janic [49], we calculate the environmental performance of road and railway transportation with data collected from Jong and Riet [50]. Road transportation generates a higher level of carbon dioxide than freight trains. Table 3 summarizes the values of eight criteria for road and railway inside China.

3.2. Scenarios Description

In the application of the proposed bilevel model, two scenarios are included in which we have two representatives of shipper population. In scenario A, all shippers hold homogeneous weights, whereas in scenario B, shippers distinguish with heterogeneous preferences. Unlike in scenario A, where all shippers share the same preference, each demand flow in scenario B is divided into three clusters from that in scenario A on the basis of the membership size. The different preferences and sizes of three clusters are obtained from Li et al. [51].In the aforementioned study, a stated preference survey was conducted from 29th March 2019 to 18th April 2019 via face-to-face personal interviews at Chengdu International Railway Service Co., Ltd. in China. This company is one of the important platforms where CRexpress' customers from all over the country gather. Therefore, the result of their study could represent the preferences of all CRexpress' customers in China. Table 4 lists the different preferences and cluster sizes. The visualized weighted, directed graph is shown in Figure 2.

Table 3. Values used for some parameters.

Criteria	Units	Values	
		Road	Railway
Price	¥/t-km	0.45	0.15
Time (speed)	km/h	60	40
Reliability	-	70%	85%
Frequency	times/day	24	2
Safety	-	85%	95%
Flexibility	-	80%	70%
Traceability	-	80%	60%
Emission	gCO_2/t-km	77	13

Table 4. Shipper preferences in two scenarios.

Criteria	Scenario A	Scenario B		
		Cluster1 (38.1%)	Cluster2 (50.8%)	Cluster3 (11.1%)
Price	0.241	0.382	0.334	0.198
Time	0.155	0.143	0.13	0.123
Reliability	0.190	0.142	0.204	0.322
Frequency	0.100	0.089	0.079	0.067
Safety	0.124	0.088	0.102	0.132
Flexibility	0.062	0.056	0.054	0.049
Traceability	0.080	0.064	0.068	0.079
Emission	0.048	0.037	0.03	0.031

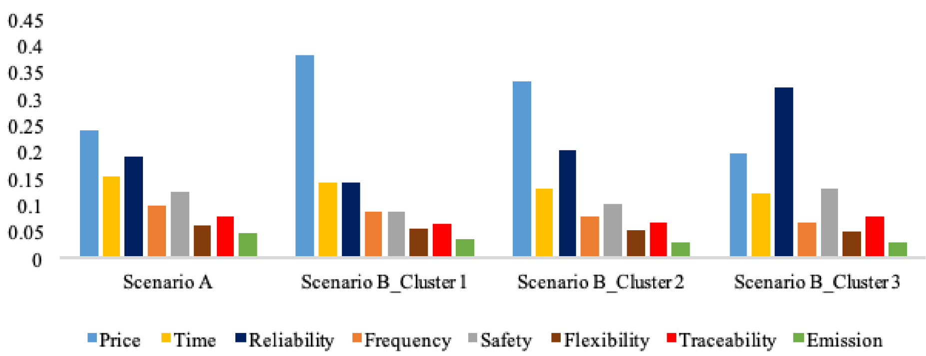

Figure 2. Visualized weighted, directed graph of shippers' preferences in two scenarios.

Scenario A simulates the baseline where we have the aggregated weights of the attributes. This scenario could be concluded from that in the baseline scenario, and the weights for all criteria are relatively equal, which is quite different from that in scenario B. Cluster 1 (38.1% of shippers) consists of shippers who are highly sensitive to price, followed by time and reliability, and the weights of rest criteria are rather small. The shippers in cluster 2 (50.8%) are also easily affected by price, however, reliability also means much to them. With regard to the shippers in cluster 3 (11.1%), the important indicator is reliability, and their preferences for price are not as strong as the former two clusters.

If we compare the weights of three clusters in scenario B with the aggregated weights in scenario A, cluster 2 is the most similar one, while clusters 3 and 1 are quite different. This finding shows that the traditional way of modeling ignored the type of shippers in clusters 1 and 2, which are observed in our study.

3.3. Designs and Analysis

We obtain the optimal layout of flows and the selection of construction centers in two scenarios, namely, designs (A) and (B), by applying the proposed model to the above inputs. Taiyuan, Zhengzhou, Wuhan, Chengdu, and Suzhou are chosen in design A, while design B identifies Xian, Lanzhou, Taiyuan, Wuhan, and Suzhou. The details of the flows, including the transportation mode from cities to consolidation centers in two designs, can be found in Table A2. Details of flow are in design A and Table A3. Most cities generally change their choices either for transportation mode or consolidation centers. We then investigate the adjustment from two aspects, namely, (1) the whole shippers and (2) difference among three clusters.

The comparison from the perspective of the whole network is based on the fair calculation by using the heterogeneous preference in scenario B, given that the three types of shippers exist in real life. Table 5 illustrates the utilities of all cites in both designs. The comparison result of the utilities between the two designs indicated that 15 out of 27 cites increased in utilities (indicated with up arrows) after segmentation, with a volume of 31,991 t, which is 78% of the total demand volume. Cities with an underline are the potential consolidation centers. Given that the utility of cost, time, and emission are negative, the total utility of some cities might be negative (Table 5).

Table 5. Utilities of all cities in both designs.

City	Design A	Design B		Volume	City	Design A	Design B		Volume	City	Design A	Design B		Volume
Harbin	3.52	4.79	↑	46	Chongqing	42.48	82.19	↑	523	Lanzhou	1.77	0.64	↓	84
Changchun	6.78	13.68	↑	96	Nanchang	3.41	5.22	↑	61	Taiyuan	165.81	−103.77	↓	565
Shenyang	78.15	100.83	↑	1128	Changsha	42.41	37.53	↓	285	Zhengzhou	265.30	114.28	↓	904
Tianjin	24.08	32.61	↑	833	Hohhot	8.89	1.67	↓	154	Shanghai	283.63	448.49	↑	3318
Shijiazhuang	37.01	12.10	↓	352	Liuzhou	10.65	46.30	↑	326	Wuhan	144.98	−98.64	↓	494
Yinchuan	4.11	7.56	↑	84	Ningbo	539.74	765.38	↑	6280	Chengdu	153.49	69.09	↓	523
Hefei	8.03	2.73	↓	58	Xiamen	106.89	132.25	↑	1376	Guangzhou	1183.81	2115.53	↑	14,720
Kunming	21.58	5.68	↓	176	Urumqi	14.89	17.42	↑	175	Suzhou	475.56	24.68	↓	5456
Guiyang	6.82	6.68	↓	79	<u>Xian</u>	10.27	165.87	↑	565	Qingdao	86.93	107.61	↑	2460

↑ and ↓ represent the increase or decrease of utilities, respectively.

To achieve a highly visualized impression of the key performances in two designs, we introduce the term of performance for the eight indicators involved. The performance of each indicator is measured with the sum of flow volume multiplied by its corresponding utility. The total performance is the sum of the eight indicators. Figure 3 presents all the performances, including the total performance and eight indicators. Given that the weight of emission, time, and cost are negative, their unit performances are also negative. The negative indicators that are closer to zero represent the better performance level. Meanwhile, the positive ones with higher values are highly preferred.

The total performance level is improved because the total performance in design B is higher than that of design A by 10.4%. More than half of the shippers have their service quality improved, and the number of consolidation centers are the same in two designs, hence, including shippers' heterogeneous preferences will not bring any extra construction cost. Accordingly, the model with shippers' heterogeneous preferences greatly improves in providing services that could satisfy many shippers.

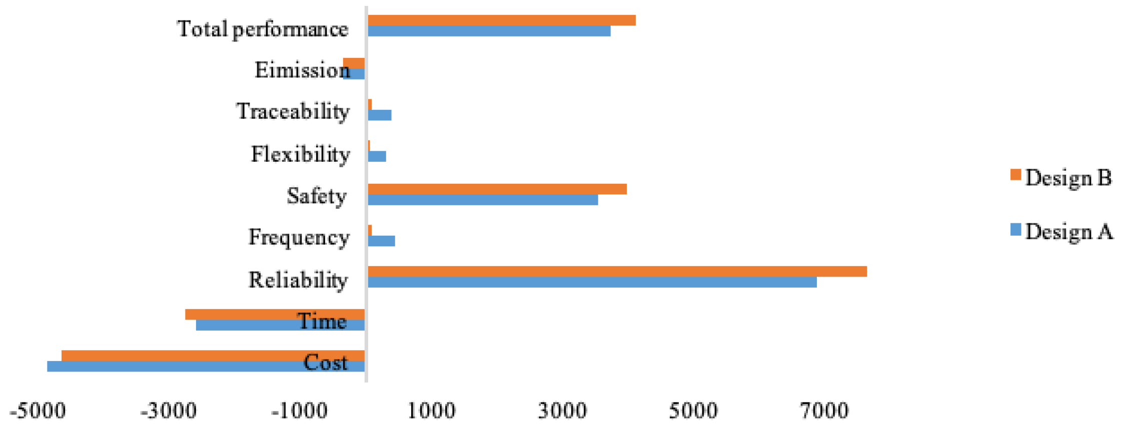

Figure 3. Performance of eight indicators in two designs.

Furthermore, the analysis in Figure 4 shows that the share for railway as the transportation mode from origin city to consolidation center increased by 13% in design B than in design A. Railway transportation has the advantage of low emission, which is only 20% of road transportation. Therefore, the model with segmentation not only improved the service level but also provided a sustainable network. Different clusters have varying reactions to the segmentation.

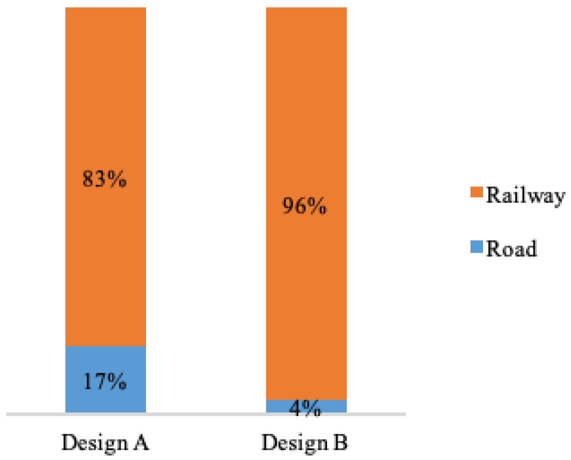

Figure 4. Mode share of all shippers in two designs.

Figure 5 demonstrates the utilities of three clusters in two designs, with utilities of all shippers on the right. The shippers in cluster 1 have huge promotion, those in cluster 3 have decreased utility, and those in cluster 2 suffer most. This phenomenon occurs because in design A, we ignored the type of shippers in cluster 1 (Figure 2). However, the utilities of such shippers are increased by recognizing them in design B. The increase is the compensation made by the shippers in clusters 2 and 3, who share similar preferences in terms of aggregate weights. The shippers in cluster 3 have different priorities in reliability and price with the aggregate weights, which is shared by shippers in cluster 2. Accordingly, sacrifice of these shippers is slighter than those in cluster 2. In conclusion, Figure 5 confirms that the improvement of utilities of all shippers in design B is achieved by recognizing the different types of shippers (cluster 1), which is one of the contributions of our work.

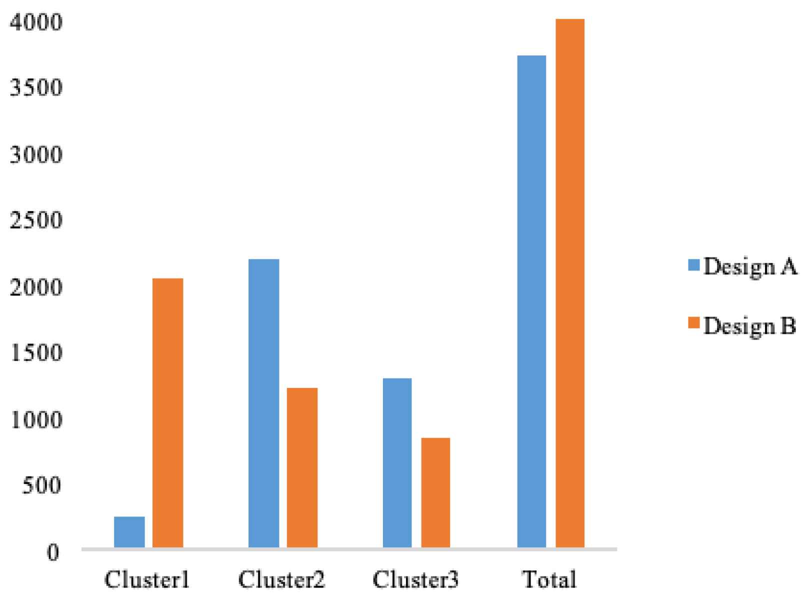

Figure 5. Utilities of three clusters in two designs.

Table 5 and Figure 5 illustrate that shippers with less utility after segmentation are mainly the underlined cities, which are defined as potential consolidation centers in set *J*. Although some cities, such as Shijiazhuang and Hefei, which are not in set *J*, also suffered, their sacrifice are less than those in set *J* such as Taiyuan and Chengdu. This notion means that the decrease observed in Table 5 is the result of the decrease in set *J*.

The details in Table A2. Details of flow in design A provide the explanation of the above findings. The cities in the potential consolidation centers (set *J*) choose farther gateways if they are chosen. If a city in set *J* is not chosen as a consolidation center, then the demand is likely to be transported in the most satisfying way for the shippers. Nevertheless, design B provides the priority of the nearest gateway to the volume from other origin cities if the city is chosen as a consolidation center because of the capacity of CRexpress. The chosen consolidation centers must satisfy the demand of unchosen origin cities to improve the overall level of the whole system.

The following analyses are conducted on two groups, i.e., cities in sets *I* and *J*, for fair calculation. Two reasons have to be stressed for group analysis. First, city *n* in set *J* will be treated as an origin city if it is not chosen as a consolidation center. If we divide the cities on the basis of whether it is an origin city, then the total volume will change. Second, most cities suffered if they are chosen as consolidation centers, which means that the choices are a combination of their real preferences and the purpose of optimizing the network. Accordingly, the impact of shipper real weights on the choice is difficult to investigate.

The analysis of mode share of shippers in set *I* confirms that the different reactions among three clusters are in line with their importance toward each logistics character in Table 4.

We first calculated the mode share of the three clusters in two designs (Figure 6). Shippers in clusters 1 and 2 show more preference for railway in design B than in design A, while those in cluster 3 have the opposite choice. Table 3 illustrates that railway has the advantage of price and emission compared with road. Accordingly, shippers who show strong importance toward price and reliability are likely to choose railway. However, the weight for price in cluster 1 increased by 58% compared with that in design A, while the rate for cluster 2 is only 38%. The weight for reliability increased by 58% for shippers in cluster 3, while that for price decreased by 41%. Based on the discussion above, the different mode shares of shippers in set *I* are quite reasonable. The overall share of railway increased by 13%, and shippers with high weight for price and reliability can get their cargo transported by railway in design B. Therefore, our proposed model makes a great contribution to improving the sustainability of the system because it meets most shippers' demands.

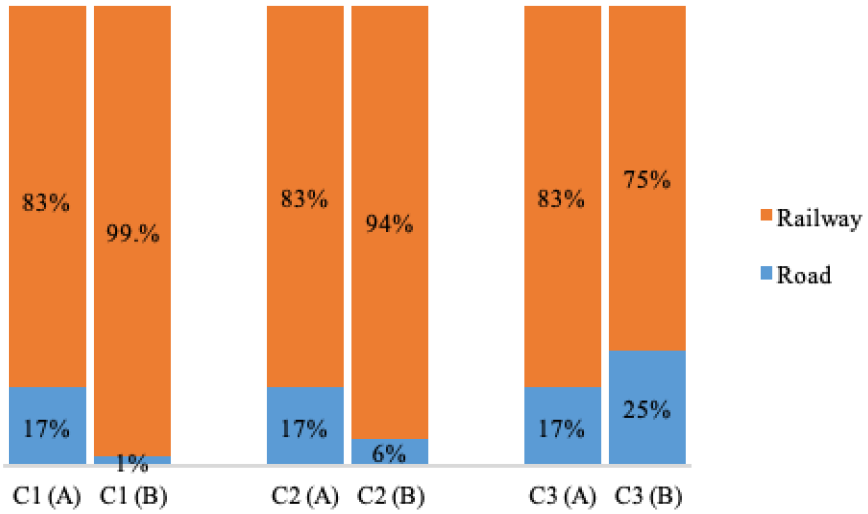

Figure 6. Mode share of shippers in set *I* in two designs.

We summarize the eight indicators among three clusters in two groups of cities. The results of indicators can be divided into two parts, namely, the positive (Figure 7a,b) and the negative (Figure 7c,d). We summarize all the negative indicators among three clusters, also with that from design A as the baseline to the left. The heights of each indicator could tell us how much it has been improved before and after segmentation. The eight indicators are compared to see how the preferences of shippers influence the decision-making process, thus, we focus on the factors that are expected to be improved in design B. Specifically, shippers in cluster 1 expect a lower price, those in cluster 2 desire lower price and high reliability performance, and those in cluster 3 would prefer a high reliability and safety level (Figure 2).

First, we look at the cities in set *I*. Apparently shippers in clusters 1 and 2 get exactly what they want, while those in cluster 3 do not. This situation may happen because the size of cluster 3 is only 11.11% of all the shippers in set *I*, which could be easily made to compensate for optimization of the whole system. With regard to cities in set *J*, shippers in cluster 1 received the lowest price, just as their preferences. Shippers in cluster 2 still have high reliability, but it comes with a high price. This phenomenon occurs because such shippers sacrifice the further gateway for convenience of other origin cities. Shippers in cluster 3 have increased reliability and safety, however, regardless of which gateway the chosen consolidation centers choose, the normalized values of reliability and safety are always one, which is larger than that of the origin cities, which vary in [0, 1]. The increase in cluster 3 does not mean that shippers are more satisfied in design B.

The model built after segmentation on the basis of preference heterogeneity could provide a service network for CRexpress with high service quality and sustainability level for most shippers in three ways. First, although some shippers have decreased utility, the utility of the total system can still be increased, which is exactly the purpose of the LSI. Second, the total share of railway transportation, which is a more sustainable mode compared with road, is promoted by 13%. Finally, the LSI of the CRexpress network could provide the shippers with additional customized services with the integrated indicators, which will make a great contribution to the maintenance of its competitiveness.

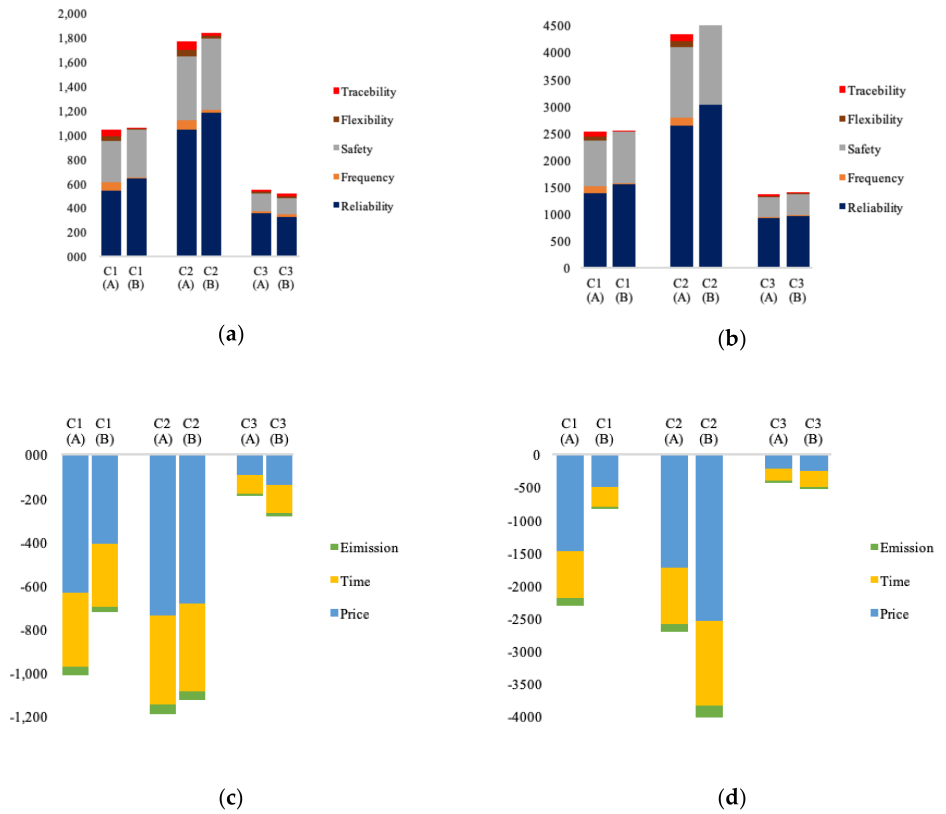

Figure 7. Indicators of shippers in two designs. (**a**) Positive indicators of shippers in set *I*. (**b**) Positive indicators of shippers in set *J*. (**c**) Negative indicators of shippers in set *I*. (**d**) Negative indicators of shippers in set *J*.

4. Discussion and Conclusions

The service network design problem with customization is an important problem, which deals with the contradiction among the LSI, LSPs, and shippers. The traditional way of operating the network classifies the cargo on the basis of its size and appearance, which does not pay great attention to shippers' preferences toward other logistics characteristics, and is no longer suitable at this stage. The establishment of the BRI together with the increasing international trade between China and European countries also places an additional requirement for the CRexpress to maintain its competitiveness. A bilevel programming formulation is established to address the necessity of integrating logistic service-related attributes and shippers' heterogeneity in the CRexpress network.

In the upper level of the model, the construction cost is minimized to reduce unnecessary transportation, while the lower level maximizes the satisfaction of shippers. The model is transferred through the methodology of the KKT conditions into a linear programming formulation and then solved with an advanced commercial optimization solver. We identify eight indicators, namely, price, time, reliability, frequency, safety, flexibility, traceability, and emission, to assess the performance of the network by reviewing the literature with integrated attributes.

Two designs are established in the case study to demonstrate the impact of considering preference heterogeneity, i.e., (A) based on preference homogeneity and (B) divided into three groups with different preferences. The comprehensive analysis between two designs indicated that the utility of more than 78% of the shippers improved while maintaining the same construction cost by considering the variations between shippers in the optimization process. Many shippers choose railway as the transportation mode as a result of segmentation, which is also the desire of the LSI because it is sustainable. Further comparison of eight indicators shows that most shippers could get the most promotion in the criteria that they weighted most highly. The above results imply that shippers' heterogeneity may be allowed to improve shippers' satisfaction to conduct a well-customized service network.

This study could also serve as a reference on how to provide proper subsidies to the cities' operation of CRexpress. The knowledge about the preferences of different user groups and the performance of different designs can further be used by the government to establish how subsidies should be allocated to achieve the desired effects. For example, if the objective of a government subsidy scheme is to achieve a greener transport system, the emission reduction obtained with a design, combined with an assumption about market prices, can be used to evaluate the required subsidy to achieve a unit value of emission reduction in the network. Subsidies could be allocated based on these costs.

In summary, this study contributes to the optimization of the CRexpress network with four aspects. First, the bilevel model builds a good connection among the LSI, LSPs, and shippers. This aspect not only gives the selection of consolidation centers but also the optimal assignment of the flows of all shippers to different LSPs. Second, the proposed model is reformulated by the KKT conditions and solved with the commercial optimization solver, which is of great interest to operators in real life because it is simple and easily accessible. Third, the model contains eight different logistics characteristics, which could provide a comprehensive description of the system. Lastly, shippers' heterogeneity is effectively considered in the model and elicits significant improvement.

The potential directions of the further study of this topic include but are not limited to the following topics. First, further study should be extended to the impact on CRexpress of other transportation modes, such as shipping and airfreight, given that China has become increasingly important in international freight transportation. Second, a game theory model should be taken into consideration to explicitly understand the cooperation and competition among cities, together with that between the shippers and the LSP.

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Appendix A

Table A1. Notations and definitions.

Notation	Definition
Sets	
M	Set of transport modes, indexed by m
I	Set of cities, indexed by i
J	Set of cities that could be chosen as consolidation centers, indexed by j if it is chosen, and n otherwise
K	Set of gateways, indexed by k
Parameters	
D_i	Demand volume from city i
D_n	Demand volume from city n
D_j	Demand volume from city j
U_{ijk}^m	Route utility from city i to consolidation center j to the destination through gateway k by mode m
U_i, U_n, U_j	Total utility of all shippers in city i, n, and j, respectively
c_o	Fixed construction cost for setting up a consolidation center
B	Maximum capacity of a single CRexpress train
Ca	Maximum operation capacity at a consolidation center k
M	A large-enough number set by the user
Decision variables	
x_{ijk}^m	Volume transported from city i to consolidation center j to destination through gateway k by mode m
x_{njk}^m	Volume transported from city n to consolidation center j to destination through gateway k by mode m
x_{jk}	Original demand volume at consolidation center j to the destination through gateway k
O_j	$O_j = 1$ if consolidation center j is selected, and 0 otherwise

Table A2. Details of flow in design A.

Design A									
City	**Consolidation Center**	**Mode**	**Gateway**	**Volume**	**City**	**Consolidation Center**	**Mode**	**Gateway**	**Volume**
Changchun	Chengdu	railway	Manzhouli	41	Nanchang	Taiyuan	railway	Manzhouli	32
	Taiyuan	railway	Erenhot	34		Wuhan	road	Erenhot	29
	Taiyuan	road	Manzhouli	21	Ningbo	Suzhou	railway	Alatwa	3300
Changsha	Taiyuan	railway	Erenhot	285		Zhengzhou	railway	Alatwa	2386
Chongqing	Chengdu	railway	Manzhouli	388		Taiyuan	railway	Alatwa	510
	Wuhan	railway	Erenhot	96		Zhengzhou	railway	Erenhot	84
	Chengdu	road	Erenhot	39	Qingdao	Taiyuan	road	Manzhouli	1792
Guangzhou	Wuhan	railway	Alatwa	3300		Taiyuan	railway	Erenhot	668
	Wuhan	railway	Manzhouli	3300	Shanghai	Chengdu	railway	Manzhouli	1467
	Zhengzhou	railway	Manzhouli	3300		Zhengzhou	railway	Erenhot	863
	Wuhan	railway	Erenhot	2122		Zhengzhou	railway	Alatwa	429
	Chengdu	road	Erenhot	1194		Wuhan	railway	Erenhot	355
	Taiyuan	railway	Alatwa	1169		Chengdu	railway	Erenhot	204
	Chengdu	railway	Erenhot	335	Shenyang	Taiyuan	railway	Manzhouli	492
Guiyang	Chengdu	railway	Manzhouli	71		Chengdu	railway	Alatwa	370
	Wuhan	railway	Erenhot	8		Taiyuan	road	Erenhot	266
Harbin	Chengdu	railway	Manzhouli	21	Shijiazhuang	Taiyuan	railway	Alatwa	352
	Taiyuan	railway	Erenhot	18	Tianjin	Taiyuan	road	Manzhouli	681
Hefei	Chengdu	railway	Erenhot	36		Taiyuan	railway	Erenhot	152
	Taiyuan	railway	Erenhot	22	Urumqi	Chengdu	railway	Manzhouli	133
Hohhot	Chengdu	railway	Erenhot	90		Chengdu	railway	Erenhot	42
	Chengdu	road	Erenhot	64	Xiamen	Zhengzhou	railway	Alatwa	485
Kunming	Chengdu	road	Erenhot	124		Suzhou	road	Erenhot	475
	Taiyuan	railway	Erenhot	52		Taiyuan	railway	Manzhouli	273
Lanzhou	Chengdu	road	Erenhot	84		Wuhan	railway	Erenhot	143
Liuzhou	Zhengzhou	road	Erenhot	254	Xian	Chengdu	road	Erenhot	552
	Wuhan	railway	Erenhot	53		Chengdu	railway	Erenhot	12
	Taiyuan	railway	Alatwa	18		Taiyuan	road	Erenhot	1
	Chengdu	road	Erenhot	1	Yinchuan	Taiyuan	road	Erenhot	46
						Chengdu	railway	Alatwa	38
						Chengdu	railway	Alatwa	38

Table A3. Details of flow in design B.

Design B									
City	**Consolidation Center**	**Mode**	**Gateway**	**Volume**	**City**	**Consolidation Center**	**Mode**	**Gateway**	**Volume**
Changchun	Xian	railway	Erenhot	49	Nanchang	Xian	railway	Alatwa	31
	Taiyuan	railway	Manzhouli	37		Xian	railway	Erenhot	23
	Taiyuan	road	Manzhouli	11		Xian	railway	Manzhouli	7
Changsha	Taiyuan	railway	Erenhot	145	Ningbo	Suzhou	railway	Manzhouli	3190
	Lanzhou	railway	Erenhot	108		Lanzhou	railway	Erenhot	1775
	Taiyuan	railway	Manzhouli	32		Taiyuan	railway	Alatwa	697
Chengdu	Xian	railway	Manzhouli	324		Taiyuan	railway	Erenhot	618
	Lanzhou	road	Erenhot	200	Qingdao	Lanzhou	railway	Manzhouli	1245
Chongqing	Xian	road	Erenhot	266		Taiyuan	railway	Alatwa	937
	Lanzhou	railway	Erenhot	199		Taiyuan	road	Alatwa	273
	Lanzhou	railway	Alatwa	58	Shanghai	Xian	railway	Manzhouli	1686
Guangzhou	Wuhan	railway	Erenhot	3300		Suzhou	railway	Erenhot	1201
	Wuhan	railway	Manzhouli	3112		Taiyuan	railway	Manzhouli	368
	Wuhan	railway	Alatwa	2994		Taiyuan	railway	Erenhot	63
	Xian	railway	Erenhot	2011	Shenyang	Taiyuan	railway	Alatwa	573
	Lanzhou	railway	Manzhouli	1634		Taiyuan	railway	Manzhouli	430
	Xian	railway	Alatwa	1372		Taiyuan	road	Manzhouli	125
	Lanzhou	railway	Erenhot	297	Shijiazhuang	Lanzhou	railway	Alatwa	179
Guiyang	Taiyuan	railway	Manzhouli	40		Taiyuan	railway	Manzhouli	134
	Xian	railway	Manzhouli	30		Taiyuan	road	Manzhouli	39
	Xian	railway	Erenhot	9	Tianjin	Lanzhou	railway	Alatwa	423
Harbin	Lanzhou	railway	Alatwa	24		Taiyuan	railway	Manzhouli	317
	Taiyuan	railway	Manzhouli	18		Taiyuan	road	Manzhouli	92
	Xian	railway	Erenhot	5	Urumqi	Taiyuan	railway	Manzhouli	89

Table A3. *Cont.*

Design B									
City	**Consolidation Center**	**Mode**	**Gateway**	**Volume**	**City**	**Consolidation Center**	**Mode**	**Gateway**	**Volume**
Hefei	Lanzhou	railway	Alatwa	29		Lanzhou	railway	Alatwa	67
	Taiyuan	road	Erenhot	22		Xian	road	Erenhot	19
	Xian	railway	Manzhouli	6	Xiamen	Xian	railway	Alatwa	699
Hohhot	Taiyuan	road	Manzhouli	78		Lanzhou	railway	Erenhot	524
	Lanzhou	railway	Alatwa	59		Lanzhou	railway	Manzhouli	153
	Lanzhou	road	Alatwa	17	Yinchuan	Taiyuan	railway	Alatwa	43
Kunming	Taiyuan	railway	Manzhouli	89		Lanzhou	railway	Alatwa	32
	Taiyuan	road	Erenhot	67		Xian	road	Erenhot	9
	Suzhou	road	Erenhot	20	Zhengzhou	Xian	railway	Erenhot	344
Liuzhou	Lanzhou	railway	Erenhot	166		Xian	railway	Manzhouli	396
	Taiyuan	railway	Erenhot	124		Lanzhou	railway	Manzhouli	263
	Taiyuan	railway	Manzhouli	36					

Table A4. Distances between city pairs for road (km).

	Xian	**Zhengzhou**	**Wuhan**	**Chengdu**	**Suzhou**	**Taiyuan**	**Guangzhou**	**Qingdao**	**Shanghai**	**Lanzhou**
Harbin	2304	1916	2350	3051	2217	1725	3383	1743	2342	2849
Changchun	2795	1662	2137	2847	1865	1473	3133	1475	2090	2598
Shenyang	1763	1368	1827	2547	1685	1179	2832	1192	1796	2303
Tianjin	1576	711	1187	1897	1070	539	1865	586	1130	1517
Shijiazhuang	1240	418	955	1593	1046	240	1860	700	1119	1213
Xian	999,999	478	813	798	1297	602	1760	1180	1381	624
Lanzhou	1097	1103	1446	1058	1297	987	2288	2007	1997	99,999,999
Yinchuan	723	1189	1471	1291	1904	705	2396	1457	1957	441
Taiyuan	602	437	997	1392	1873	9,999,999	1948	854	1326	1008
Zhengzhou	478	999,999	569	1278	856	437	1516	722	943	1103
Hefei	1104	622	457	1860	385	1051	1268	714	467	1685
Shanghai	1381	943	908	2181	110	1320	1438	720	9,999,999	2003
Wuhan	813	569	9,999,999	1455	748	940	1021	1114	908	1446
Kunming	3475	2100	1834	917	2315	2085	1561	2580	2516	1672
Guiyang	2885	1544	1278	736	1827	1652	1300	2065	1867	1352
Chengdu	798	1278	1455	9,999,999	1953	1392	2047	1903	2181	1058
Chongqing	847	1326	1078	256	1602	1450	1710	1813	1945	1275
Nanchang	1205	961	434	757	757	1289	850	1123	774	1761
Changsha	1097	853	361	1072	1072	1281	734	1430	1049	1727
Guangzhou	1760	1516	1021	1432	1432	1948	999,999	1904	1438	2288
Hohhot	965	887	1391	1702	1598	456	2318	1143	1686	1104
Liuzhou	1582	1435	976	1157	1653	1852	499	2071	1671	1854
Ningbo	1526	1089	927	2055	238	1478	1448	877	214	2136
Xiamen	1814	1531	1030	2001	1001	1962	646	1641	1019	2433
Suzhou	1297	856	748	1953	9,999,999	1873	1432	679	106	1913
Urumqi	2534	3000	3308	2762	3819	2744	4195	3433	3904	1910
Qingdao	1180	722	1114	1903	679	854	1904	9,999,999	717	1791

Table A5. Distances between city pairs for railway (km).

	Xian	**Zhengzhou**	**Wuhan**	**Chengdu**	**Suzhou**	**Taiyuan**	**Guangzhou**	**Qingdao**	**Shanghai**	**Lanzhou**
Harbin	2628	2146	2197	3466	2517	1861	3568	1908	2553	2857
Changchun	2399	1716	2301	3220	2522	1615	3321	1668	2314	2604
Shenyang	2163	1429	1986	2929	1930	1195	3029	1370	2014	2282
Tianjin	1393	857	1242	2231	750	524	2309	699	1325	1950
Shijiazhuang	919	408	948	1760	669	232	2021	696	1406	1503
Xian	9,999,999	511	972	842	934	571	2116	1631	1509	676
Lanzhou	676	1187	1648	1172	1610	1142	2792	2199	2185	9,999,999
Yinchuan	806	1294	2186	1841	1608	710	2778	1640	2315	468
Taiyuan	767	577	1114	1605	930	9,999,999	2492	930	1513	1142
Zhengzhou	511	9,999,999	590	1627	858	644	1605	1042	998	1187
Hefei	1113	602	362	1600	211	1159	1424	990	468	1831
Shanghai	1509	998	807	2167	140	1630	1790	1300	9,999,999	2077
Wuhan	972	590	9999999	1189	582	1180	1069	1578	827	1648
Kunming	1942	2485	2088	1100	2585	9,999,999	1311	9,999,999	2868	1928
Guiyang	1234	1847	1318	993	1982	9,999,999	857	9,999,999	1789	1234
Chengdu	842	1627	2167	9999999	1880	1229	1500	2688	1976	1172

Table A5. *Cont.*

	Xian	Zhengzhou	Wuhan	Chengdu	Suzhou	Taiyuan	Guangzhou	Qingdao	Shanghai	Lanzhou
Chongqing	861	1372	742	504	1429	1309	1198	2427	1672	862
Nanchang	1486	975	333	1707	919	1600	1049	1555	741	1951
Changsha	1409	898	413	1707	1165	1542	707	1940	1083	2085
Guangzhou	2176	1605	920	2012	1520	2492	9,999,999	2647	1790	2687
Hohhot	1064	9,999,999	9,999,999	9,999,999	9,999,999	732	2947	1612	2346	1144
Liuzhou	1945	1583	9,999,999	1236	9,999,999	9,999,999	610	2593	1758	1915
Ningbo	2333	1102	994	2333	395	9,999,999	1596	9,999,999	332	2280
Xiamen	2113	9,999,999	999,9999	2540	9,999,999	2452	770	2043	1109	2774
Suzhou	934	858	140	1880	9,999,999	1549	1878	1212	84	1610
Urumqi	2603	3114	3630	2781	4028	2654	4719	9,999,999	4112	1927
Qingdao	1631	1042	2688	2688	1212	930	2647	9,999,999	1300	2139

Table A6. Distances between city in set *J* and gateways (km).

	Xian	Zhengzhou	Wuhan	Chengdu	Suzhou	Taiyuan	Guangzhou	Qingdao	Shanghai	Lanzhou
Manzhouli	10,680	10,301	10,712	11,415	10,598	10,114	11,689	10,122	10,665	11,045
Erenhot	7416	7253	7759	8152	7878	6818	8680	7403	7946	7604
Alatwa	9779	10,245	10,555	10,008	11,066	9991	11,441	10,680	11,150	9153

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