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Collaborative Optimisation of High-Speed Rail Express Line Planning and Freight Flow Allocation Considering Multiple Transportation Modes and Products

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ABSTRACT

With the development of high-speed railway (HSR) systems, high-speed rail express delivery (HSReD) is currently the growing trend in railway cargo transport. The decisions on line planning and freight flow allocation are two of the main problems for the practical operation of HSReD. This paper focuses on integrating the above issues, considering differentiated transportation modes and products. A collaborative optimisation model is developed to maximise the benefits of freight transport. Numerical experiments are conducted based on the Beijing-Shanghai HSR. The results show that the collaborative optimisation model gets a 7.96% higher freight-demand fulfilment rate and an 18.64% increase in the profit rate, compared with the two-stage model under the same network conditions and parameter settings. Some operational implications are also obtained based on the sensitivity analysis, which is potentially useful for optimising the daily operation management of HSReD.

KEYWORDS

high-speed rail express delivery; line planning; freight flow distribution; collaborative optimisation model.

1. INTRODUCTION

In recent years, with the rapid development of e-commerce, the inter-city demand for transportation cargo has been increasing significantly. According to the latest statistics, by 2022, the volume of cargo transport has achieved 110.58 billion pieces [1]. With the expansion of the HSR network and growth in demand for inter-city transportation of cargo in the form of large-scale, high-punctuality, fast-speed and low-cost, it is feasible to use the HSR system for cargo transport [3, 18]. Compared to other kinds of carriers, the HSReD has a number of advantages, such as low environmental impact, less susceptibility to weather, large capacity and fast speed [2]. Combined with China's market demand and the characteristics of the HSR system, it has many benefits to use the HSR for fast freight transportation.

However, the HSR is often in a state of idle capacity and defective in operation. How to efficiently utilise the capacity of the HSR network to provide high-speed rail express service is the focus of attention of the operation department and relevant scholars. To operate express delivery in a large-scale network with complex traffic flow and freight flow, it is necessary to solve the two key problems:

1) It is necessary to consider how to make an operation plan (i.e. determining the frequency and the routing of trains) for future freight transportation. This issue is generally referred to as line planning (LP).
2) Based on the LP and the freight demand, it is important to allocate cargo to freight trains or passenger

trains with limited capacity (i.e. matching trains with different transportation modes to cargo items). This issue is generally referred to as freight flow allocation (FFA).

Therefore, in the pattern of mixed transportation of passengers and freights, formulating the line planning and realising the matching between freight flow and train flow are the main issues in the transportation organisation of HSR. Both issues interact and merge into a collaborated optimisation problem. Therefore, we need to build an optimisation model based on the problem of LP and FFA to give some proposals for operators.

The rapid extension of the China railway promotes the large-scale development of HSReD. Some scholars have proved that HSReD can not only meet the requirements of shippers for timeliness but also create economic benefits for railway enterprises [2-4]. At present, there are four types of transportation products for small quantity, high value-added and high timeliness: arriving today (AT), arriving next morning (ANM), arriving the next day (AND) and arriving the day after tomorrow (ADAT). To better complete the delivery demand and make full use of transportation resources, there are four types of transportation modes: dedicated freight train (DFT), confirmation train (CT), reserved carriage train (RCT) and reserved space train (RST). The four transportation modes have different characteristics and the detailed interpretation is set in Section 3.

This paper focuses on integrating line planning and freight flow allocation, considering multiple transportation modes and products. A co-optimisation model is built to optimise the line planning and freight flow allocation. To verify the rationality of the model, a two-stage optimisation model is formulated.

The remaining sections of the paper are set up as follows. The related literature is presented in Section 2. The problem background is described in Section 3. A collaborative optimisation model and a two-stage model (designing the train operation plan, and then allocating the freight flow) are formulated in Section 4. The numerical experiments and the sensitivity analysis are shown in Section 5. The conclusion and future work are set in Section 6.

2. LITERATURE REVIEW

In this paper, the problems in HSReD are distilled into two issues: the LP problem and the FFA problem. Therefore, we have reviewed the previous study on the following two main issues.

The research on the LP problem mainly focused on passenger train optimisation including origin and destination, stop planning, routing and train operation frequency [5–7]. With the development of HSReD, the problem of optimising the mixed transportation of HSR has attracted widespread scholarly concern. Liu and Dessouky [8] made a great contribution to the problem of passenger and freight train scheduling, which formulated a mixed integer programming model to minimise the tardiness of passenger trains and the delay of freight trains. Ozturk and Patrick [9] aimed at the problem of train schedule in line planning, minimising stockpile and delay of freight and passenger trains sharing the same infrastructure. In the HSReD, the multiple transportation modes should be also considered while transporting cargo with the excess capacity of passenger trains or dedicated freight trains [10]. Yao et al. [11] optimised the same-day cargo delivery scheme by selecting the Reserved Space mode. Chao et al. [12] constructed an optimisation model for demand assignment based on the scheduled (passenger) trains, adding the specialised express trains and optimising the train plan to serve the remaining demand when the total capacity of passenger trains cannot satisfy the express demand. It is clear from the above studies that many scholars have studied optimising operational planning but failed to consider matching between multiple types of products and multiple transportation modes. Unlike traditional railway cargo transport, the HSReD can use both dedicated freight trains and passenger trains to meet transportation demand. Moreover, cargo transport by HSR has the feature of small volume and high value-added, which could be transported with the flexible selection of passenger train carriages [3]. In general, the HSReD is very distinctive from traditional rail freight transportation, multiple modes of transportation and multiple types of products make the decision of the LP problem more complex, which promotes the research in this paper.

The second part handles the optimisation problem of freight flow allocation. It is crucial to optimise the FFA problem in mixed transportation. There are many studies focusing on the FFA problem of transportation means [13, 14], including air express [15], metros and trams [16, 17] and other kinds of shared transportation. The HSReD of FFA, as an emerging mode of inter-city cargo transport, has a number of similarities and differences with the transport systems mentioned above. They should consider whether using the same carriage or the same route with different carriages is preferable. For example, Xu et al. [18] focused on the train capacity allocation problem in the HSR system for mixed transportation patterns. However, in order to ensure the safety and comfort of passenger service, passengers and freights will not share the same carriage. However, it is interesting in which way Li et al. [19] dealt with the issue of designing urban rail trains and freight allocation plans. Given the passenger train schedule, freight could be transported by being picked up in the extra space inside the passenger train carriages or by operating dedicated freight trains. However, the previous studies only considered a single mode of transportation, unable to satisfy the transport demand. On this basis, Chen et al. [20] investigated an MIP model for cargo flow allocation, which considered the mode of passenger train piggyback transport, reserved carriage and HSR freight train under uncertain transportation demands. Then, a significant difference between the HSReD and other transport systems of the FFA problem lies in that there are four types of transportation modes in HSReD, which would make the FFA decisions more difficult. So Jin et al. [21] developed a two-stage mixed integer programming model, considering four transportation modes and four transportation products with fixed transportation demand, as well as addressing the problem of the lack of effective decision-making support for the organisation of the HSR cargo transport scheme. Compared with the two-stage model, the co-optimisation model can avoid the local optima resulting from deciding on the first stage before deciding on the second stage. For example, Di et al. [22] investigated a joint optimisation problem of carriage arrangement and flow control in a metro-based underground logistics system, in which passengers and freights are allowable to share each service train. Li et al. [23] implemented mixed passenger and freight transportation on the airport express, two freight transportation modes, i.e. inserting dedicated freight trains and using the surplus capacity of existing passenger trains, are considered. An optimisation model on freight train service planning is developed to determine the train stopping plans, train formation, timetables and shipment allocation.

There is a difference in the problem of LP and FFA between the HSReD and the traditional railway cargo transport or urban rail. As can be seen from previous research, we can find that the optimisation problems of LP and FFA are the two main problems that are currently lacking in integrated research. Therefore, this paper concentrated on the uniqueness of actual operations, formulating a co-optimisation model by considering four transportation modes and products, which can offer some contributions to current research.

3. PROBLEM DESCRIPTION

Before constructing the co-optimisation model of LP and FFA problem, we will describe the problem background of HSReD. In Section 3.1, the line planning problem is analysed and the four transportation modes are explained in more detail. Section 3.2 introduces the FFA problem, as well as the four transportation products. The relationship between the LP problem and the FFA problem is accounted for in Section 3.3.

3.1 Line planning problem

The most consideration of optimisation of the LP problem is given to passenger trains, and few studies are focused on mixed transportation. However, with the development of the logistics system, mixed transportation has become greatly universal. So we need to solve the problem of LP in mixed transportation. In China, HSReD has been developed for nearly ten years [24]. Currently, there are four transportation modes (shown in *Figure 1*) in China Railway Express Co., Ltd. The feature of the four modes is shown below.

Dedicated Freight Train: This mode uses dedicated freight trains and the entire train for cargo transport, which has the largest cargo capacity among the four transportation modes and the most flexible design of line planning. The services are designed based on the passenger train diagram. However, the train operation has to consider whether the passing capacity of the section is satisfied and it requires high fixed and variable costs.

Figure 1 – The four modes of transportation

Confirmation Train: This mode refers to the first non-passenger train that runs in the early hours of the day after the maintenance window. It can make full use of its non-passenger characteristics to complete the cargo transport while avoiding conflicts with passengers' travel and creating considerable economic benefits. The confirmation train's operation relies on the train schedules and is fixed to operate one line every day.

Reserved Carriage Train: This mode is launched based on a passenger train set in service. It is usually used during the off-peak hours of passenger demand. In this mode, passengers are concentrated in a few carriages, the other carriages are not ticketed and used for cargo transport. This kind of transportation mode can utilise the idle capacity fully and decrease the conflict between passengers and freights.

Reserved Space Train: This mode refers to the use of the remaining space in the passenger carriages, such as luggage cabinets and crews' working rooms to place freights, which is the most common transportation mode of HSReD at present. The capacity and cost of this mode are the lowest among the four modes.

Table 1 – The optimisation of four transportation modes

Optimisation	**Transportation Mode**			
	Dedicated freight train	**Confirmation train**	**Reserved carriage train**	**Reserved space train**
Operation frequency	√		√	√
Routing	√			
Stop planning	√	√		
Origin and destination	√			

Among the four transportation modes, the mode of DFT needs additional operating trains based on the operation plan of the passenger train. Therefore, it is feasible to optimise operation frequency, routing, stop planning, origin and destination, etc. As for the other three modes, their operation is based on the passenger trains. We cannot change the passenger train schedule because of cargo transportation. However, freight can choose its routing and frequency by choosing which train to transport it.

In summary, the decisions on the LP problem with four types of transportation modes are beneficial to utilising the excess capacity and meeting the demand for passenger and cargo transport. Furthermore, this study constructs a mathematics model for line planning.

3.2 Freight flow allocation problem

As the LP problem has been designed, we need to meet cargo demand through FFA design. The problem of traditional FFA mainly consists of those contents: (a) which train is selected for the cargo transport; (b) which carriage is selected to place the cargo; (c) which route is selected for the cargo transport to the destination, etc. However, the HSReD is different from the traditional problem because it has four types of products. Different products have different timeliness requirements. The characteristics are shown in *Table 2*.

Table 2 – Characteristics of four types of transportation products

Transportation product	Fee (yuan per kg)			
	Cut-off time	Delivery time	First weight	Additional weight
AT	10:00	22:00 today	130	25
ANM	18:00	10:00 next day	30	15
AND	18:00	18:00 next day	20	10-14
ADAT	18:00	18:00 the day after tomorrow	20	6-10

The relationship between transportation modes and transportation products is shown in *Table 3*.

Table 3 – The match between transportation modes and transportation products

Transportation product	Transportation Mode			
	Dedicated freight train	Confirmation train	Reserved carriage train	Reserved space train
AT	√		√	√
ANM	√	√	√	√
AND	√	√	√	√
ADAT	√	√	√	√

There are 15 matches between the four transportation modes and the four transportation products. Confirmation trains are operated after the maintenance window at 4:00 a.m. each day and the cargo has not yet been delivered to the station, so the freight of AT cannot be delivered in CT.

To further illustrate the problem of FFA more intuitively, a small case study is presented in *Figure 2*, which shows an HSR containing three stations. Below the line diagram, there are four line plannings named k_1,k_2, k_3 and k_4. The distance between station A and station B is 100 km, B and C is 150 km.

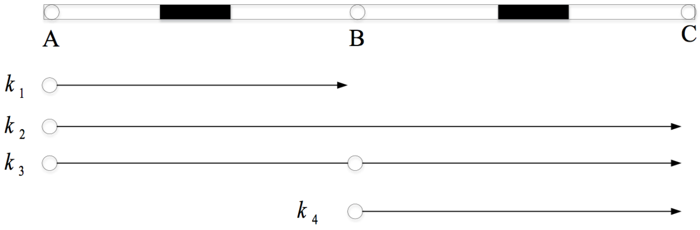


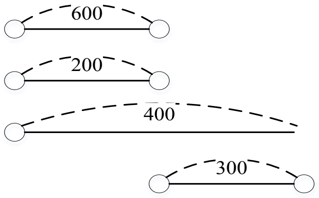
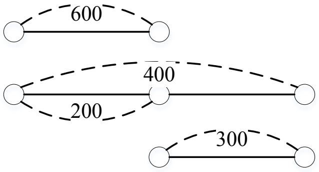
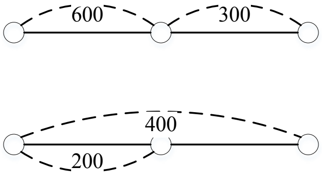
Figure 2 – The line planning

The transportation demand from station A to station B is 800, station A to station C is 400 and station B to station C is 300. To simplify the issue, we choose only one transportation mode (DFT) and assume the train has a capacity of 600. The fixed operation cost per train is yuan and the variable cost is v=10 yuan per km. *Table 4* shows three different feasible plans for freight flow allocation.

Obviously, different programs of FFA can make different line planning and require different operating costs. It is important to generate an FFA plan that has lower operating costs while meeting cargo demand as much as possible. Plan 1 only considers meeting cargo demand, with a large deficit of trains, resulting in the highest train operating costs. Plan 2 makes full use of the train capacity by rationalising the train-stopping strategy but still requires running three trains. With the high fixed cost of running one train, plan 3 gives a further optimisation strategy, where the total cargo demand can be satisfied by running only two trains. Plan 3 is therefore the best choice.

Based on the above analysis, we can find that the HSReD problem requires the optimal allocation of freight flow with varying OD pairs, volume and timeliness under operated dedicated freight trains or passenger trains. In general, we observe the rule of 'first-come-first-shipped'. However, this kind of FFA decision may cause the waste of the train capacity or be unable to meet the freight demand with the train capacity insufficient. Therefore, the purpose of this research is to develop a mathematical model that will assist managers in FFA efficiently in a certain condition to optimise the profit.

Table 4 – An illustration of different FFA and their operating costs

Plan	Freight flow allocation	Cost
1		$4f + 3vd_{AB} + 2vd_{BC} = 46000$
2		$3f + 2vd_{AB} + 2vd_{BC} = 35000$
3		$2f + 2vd_{AB} + 2vd_{BC} = 25000$

3.3 The relationship between the problem of LP and FFA

By introducing the problem of LP and FFA, it is clear that the two problems are connected. The LP problem will constrain the decisions of the FFA problem due to the limited transportation capacity and the fixed operation time for freights with different OD pairs and service types. Meanwhile, the FFA decisions will decide the net operation profit of a certain LP under a variety of situations, influencing the evaluation of the LP problem's performance. The linked relationship between the LP problem and the FFA problem highlights a property of the above problem's integrated optimisation.

Therefore, the main issues to be addressed in this paper are as follows:

1) Aiming to the problem of LP and FFA in mixed transportation of passenger and cargo, four modes of transportation and four types of transportation products are considered at the same time. According to the transport demand with different timeliness and OD pairs, the train frequency, the train mode and the cargo flow distribution are determined, and the matching between the four transportation modes and the four transportation products is realised. The optimisation of the problem of CT, RST and RCT is based on the passenger train scheme. The DFT mode is added based on the alternative train set while taking into account the passing capacity of the section and other conditions.
2) To avoid a locally optimal solution while designing the LP first, and then designing the FFA based on the LP, a collaborative optimisation model of the LP and FFA problems is constructed.

4. MODEL

In this chapter, we make the assumptions in Section 4.1 and symbol descriptions in Section 4.2. In Section 4.3, the model is formulated. It contains a collaborative optimisation model and a two-stage model. The linearisation of the model is set in Section 4.4.

4.1 Modelling assumptions

Based on the above analysis, a collaborative optimisation model is formulated to optimise the operation of the HSReD, and the specific form of the model is elaborated in the next section. Before addressing the model, some underlying assumptions need to be clarified:

Assumption 1. No conflict between the DFT and the existing high-speed passenger trains.

Assumption 2. Different types of trains have the same capacity and operate with the same fixed and variable costs.

Assumption 3. The paper only focuses on the weight of the cargo, regardless of the size and volume.

Assumption 4. When the train arrives at the station, the loading and unloading of cargo can be carried out simultaneously without interference.

4.2 Symbol descriptions

In this section, based on the previous problem description, a collaborative optimisation model is constructed to maximise the total transport revenue, taking into account the constraints of train capacity, section passing capacity and so on. The model can optimise the LP and the FFA simultaneously. The symbols and meanings in the model are shown in *Table 5*.

Table 5 – Symbols and meanings

	Symbol	Meaning
Set	$G(S,E)$	The network of railway
	S	Set of stations of railway network G; i, s, j is one of the stations, respectively
	E	Set of section railway network G; e represents each segment of the network, $e \in E$
	M	Set of transportation modes, $M=\{1,2,3,4\}$
	N	Set of transportation products, $N=\{1,2,3,4\}$
	Ω	Set of OD pairs of cargo demand, $(i,j) \in \Omega$
	L	Set of trains, $l \in L$
	$\Omega(l)$	Set of OD pairs that the train l covers
	$E(l)$	Set of sections that the train l passes
	$P(l)$	Set of stations where the train l stops, $P(l) \subset S$
	$F(l)$	Excluding the first and last stations, the set of stations where the train l stops, $F(l) \subset S$
Parameter	m	Indicates four transportation modes (m=1 represents DFT mode, m=2 represents CT mode, m=3 represents RCT mode, m=4 represents RST mode)
	n	Indicates four types of transportation products (n=1 represents AT, n=2 represents ANM, n=3 represents AND, n=4 represents ADAT)
	m_l	The transportation mode selected by the train l, only one transportation mode can be selected for each train, m_l=1,2,3,4
	$C^n_{i,j}$	The costs per unit weight for transporting the product n in OD pair (i,j)
	C^1_m	Fixed cost of train operating in mode m, unit: yuan
	C^2_m	Variable cost of train operating in mode m, unit: yuan
	d_{ij}	Distance between station i and station j, unit: km
	T_{m_l}	The maximum capacity of train l in mode m, unit: ton
	S_e	The maximum passing capacity of section e
	$Q^n_{i,j}$	The volume of transportation product n in OD pair (i,j)
	W^l_s	The maximum capacity of loading and unloading at station s of train l in mode m, unit: ton
	F^l_{ij}	The frequency of the train l operating in OD pair (i,j)
	$\alpha_{l,e}$	If train l passes section e, then the value is 1, otherwise, the value is 0
	$\beta^{l,e}_{i,j}$	The freight demand of OD pair (i,j), if train l passes through the section e, the value is 1, otherwise, the value is 0
	γ^{ml}_n	If train l in mode m and transports product n, the value is 1, otherwise, the value is 0
	y^l_s	If train l has a passenger service at the station s, the value is 1, otherwise, the value is 0
Variant	f_l	Frequency of train l operation
	$q^{l,n}_{i,j}$	The freight demand of OD pair (i,j), the volume of product n expressed by train l, unit: ton per train

4.3 Model formulation

In this part, we formulate a collaborative optimisation model for optimising the problem of LP and FFA. To justify the rationality of the model, a two-stage model is designed.

Collaborative optimisation model

The collaborative optimisation model has the objective of maximising the total revenue and the objective function consists of two parts, the first part is the revenue of express cargo, specifically as follows:

$$Z_1 = \sum_{l \in L} \sum_{(i,j) \in \Omega} \sum_{n \in N} C_{i,j}^{n} q_{i,j}^{l,n} f_l d_{ij} \tag{1}$$

where Z_1 denotes the total revenue, the value of which is related to the fare of the four transportation products, the volume, the frequency and the distance of train operation;

$$Z_2 = \sum_{l \in L} \sum_{n \in N} \sum_{m \in M} C_m^1 \gamma_n^{m_l} f_l + \sum_{l \in L} \sum_{n \in N} \sum_{m \in M} \sum_{(i,j) \in \Omega} C_m^2 d_{ij} q_{i,j}^{l,n} f_l \tag{2}$$

where Z_2 represents the cost of express cargo, consisting of fixed cost and variable cost. To simplify the problem, labour costs, mechanical handling costs and train starting and stopping costs are consolidated into variable costs.

The objective function is equal to the total revenue Z_1 minus the total cost Z_2:

$$\max Z = Z_1 - Z_2 \tag{3}$$

Constraint on OD pair's demand satisfaction. *Equation 4* ensures that the actual volume of cargo is less than or equal to the transportation demand.

$$\sum_{l \in L} f_l \cdot q_{i,j}^{l,n} \leq Q_{i,j}^{n} \quad \forall (i,j) \in \Omega, n \tag{4}$$

Constraint on train capacity. The capacities of trains vary by the modes of transportation. *Equation 5* ensures that the train l in the mode m cannot loaded beyond the maximum capacity in section *e*.

$$\sum_{(i,j) \in \Omega(l)} \sum_{n \in N} q_{i,j}^{l,n} \cdot \beta_{i,j}^{l,e} \leq T_{m_l} \quad \forall l, e \in E(l) \tag{5}$$

Constraint on section passing capacity. These modes of CT, RCT and RST rely on passenger train schedules to complete cargo transport, so it is not necessary to consider the section passing capacity. However, as DFT is an additional train, it is necessary to consider whether the section passing capacity meets the condition for the additional train. Therefore, *Equation 6* ensures that the number of additional DFTs does not exceed the remaining passing capacity of the section.

$$\sum_{l \in L} f_l \alpha_{l,e} \leq S_e \quad \forall e \in E, m_l = 1 \tag{6}$$

Constraint on express revenue. It is expensive with a fixed cost to operate the DFT. In order to ensure profitability, a dedicated freight train is launched when the loading rate is above a certain level. In this paper, the minimum loading rate is taken to be 80%. This constraint ensures that the ratio of the actual load to the maximum load of train *l* is above 80% in the entire journey (*Equation 7*).

$$\frac{\sum_{(i,j) \in \Omega} \sum_{n \in N} q_{i,j}^{l,n} \beta_{i,j}^{l,e}}{Tm_l} \cdot 100\% \geq 80\% \quad \forall l \in \{ l \in L | m_l = 1 \}, f_l \in N \tag{7}$$

Constraint on the matching of transportation modes and transportation products. The mode of confirmation train cannot match with the product of arrived today. In *Equation 8*, if $\gamma_n^{m_l}$ values as $\gamma_1^{2l} = 0$, in order to ensure *Equation 8* is equal to 0, $q_{i,j}^{l,n} = 0$, the volume of arrived today in confirmation train l is zero. *Equation 9* ensures that the operation frequency of the confirmation train is one line every day.

$$(1 - \gamma_n^{m_l}) q_{i,j}^{l,n} = 0 \quad \forall (i,j) \in \Omega, l, n \tag{8}$$

$$f_l \leq 1, \quad \forall l \in \{ l \in L | m_l = 2 \} \tag{9}$$

Constraint on the train loading and unloading time in the station. The reserved space mode's operation is based on the passenger train schedule. In order to reduce the impact on passengers, the operation of freight is subject to strict control in the number of stations and hours. For the number of operating stations, freight operations can only be carried out at stations based on passenger operations. For the operating hours, the total time spent loading and unloading cargo at each station is lower than the stopping time of the train.

$$\sum_{i\in S\setminus\{s\}} q_{i,s}^{l,n} \sum_{j\in S\setminus\{s\}} q_{s,j}^{l,n} \le W_s^{m_l} \quad \forall l\in\{l\in L|m_l=4\}, s\in P(l) \tag{10}$$

Constraint on train operation. In the mode of reserved carriage, the freight can only be handled from its origin to its destination straightly by trains and no loading or unloading of cargo is allowed in the process of transportation.

$$\begin{cases} \sum\limits_{i\in S\setminus\{s\}} q_{i,s}^{l,n}=0 \\ \sum\limits_{j\in S\setminus\{s\}} q_{s,j}^{l,n}=0 \end{cases} \quad \forall l\in\{l\in L|m_l=3\}, s\in F(l) \tag{11}$$

Constraint on frequency of train. The reserved carriage train and reserved space train are launched based on scheduled passenger train sets in service. Therefore, the sum of their frequency is below the passenger train frequency.

$$\sum_{l\in L\{L|m_l=3 \text{ or } m_l=4\}} f_l \le F_{i,j}^l \quad \forall (i,j)\in\Omega \tag{12}$$

Construction of a two-stage model

To further evaluate the advantages and disadvantages of the collaborative optimisation model, a two-stage model is designed in this paper. Based on the same network conditions and parameter settings, every OD pair's large-volume shipments in the first stage are transported by DFT. In the second stage, the remaining cargo is matched with the three modes of CT, RCT and RST to complete the freight demand.

Design of the line planning of DFT. This part investigates the transportation mode of the Dedicated Special Train, to maximise the volume of express cargo:

$$\max Z_1=\sum_{l\in L}\sum_{n\in N}\sum_{(i,j)\in\Omega} q_{i,j}^{l,n} \tag{13}$$

Then, the operation frequency of the train is determined.

$$\begin{cases} 0.8T_{m_l}f_l \ge \sum\limits_{j\in S\setminus\{i\}}\sum\limits_{(i,j)\in\Omega} q_{i,j}^{l,n} \\ f_l T_{m_l} \le \sum\limits_{j\in S\setminus\{i\}}\sum\limits_{(i,j)\in\Omega} q_{i,j}^{l,n} \end{cases} \quad l\in\{l\in L|m(l)=1\}, f_l\in N \tag{14}$$

This paper considers the OD pair's demand and *Equation 6* of section passing capacity. *Equation 14* ensures that the actual quantity for loading is higher than the minimum loading ratio and lower than the OD pair's demand.

Design of freight flow distribution. In the second stage, the remaining demand for cargo express is used as the sample data. To maximise operational revenue, this part considers the constraint of OD pair's demand satisfaction, train capacity, section passing capacity and so on, which determines the frequency of trains and the planning of freight flow distribution.

Aiming to maximise profitability, the objectives and constraints are as follows:

$$\max Z_1=\sum_{l\in L}\sum_{(i,j)\in\Omega}\sum_{n\in N} C_{i,j}^n q_{i,j}^{l,n} f_l d_{ij} - \sum_{l\in L}\sum_{n\in N}\sum_{m=M} C_m^1 \gamma_n^{m_l} f_l - \sum_{l\in L}\sum_{n\in N}\sum_{m\in M}\sum_{(i,j)\in\Omega} C_m^2 d_{ij} q_{i,j}^{l,n} f_l \tag{15}$$

subject to: *Equations 4, 5 and 8–12*.

Linearisation of the model

The left half of *Equation 4*, which is obtained from the multiplication of two variables, is a nonlinear constraint. In this paper, it is linearised by introducing the variable p with $p_{i,j}^{l,n}=f_l q_{i,j}^{l,n}$, so that *Equation 1* transforms into $\sum\limits_{l\in L}\sum\limits_{n\in N} p_{i,j}^{l,n} \le Q_{i,j}^n, \ \forall (i,j)\in\Omega$. For *Equation 5*, through multiplying both sides of the equation by f_l, the equation transforms into $\sum\limits_{(i,j)\in\Omega}\sum\limits_{n\in N} p_{i,j}^{l,n}\beta_{i,j}^{l,e} \le T_{m_l}f_l, \ \forall l,e\in E(l)$. For *Equation 7*, through multiplying both sides of the equation by f_l and equation transformation, the equation transforms into $\sum_{(i,j)\in\Omega}\sum_{n\in N} p_{i,j}^{l,n}\beta_{i,j}^{l,e} \geq 0.8T_l,\ \forall l \in \{l \in L(l) | m(l) = 1\},\ f_l \in N$. Finally, the novel model is as follows:

$$\max Z = \sum_{l\in L}\sum_{(i,j)\in\Omega}\sum_{n\in N} C_{i,j}^{n}\cdot p_{i,j}^{l,n}\cdot d_{ij} - \left(\sum_{l\in L}\sum_{n\in N}\sum_{m=M} C_m^1\cdot\gamma_n^{m_l}\cdot f_l - \sum_{l\in L}\sum_{n\in N}\sum_{m\in M}\sum_{(i,j)\in\Omega} C_m^2\cdot d_{ij}\cdot p_{i,j}^{l,n}\right) \tag{16}$$

$$\begin{cases}
\sum_{l\in L} p_{i,j}^{l,n} \leq Q_{i,j}^{n}, & \forall(i,j)\in\Omega, n\\
\sum_{(i,j)\in\Omega}\sum_{n\in N} p_{i,j}^{l,n}\beta_{i,j}^{l,e} \leq T_{m_l} f_l & \forall l, e\in E(l)\\
\sum_{l\in L} f_l\alpha_{l,e} \leq s_e, & \forall e\in E, m_l = 1\\
\sum_{(i,j)\in\Omega}\sum_{n\in N} p_{i,j}^{l,n}\beta_{i,j}^{l,e} \geq 0.8Tm_l f_l, & \forall l, \{l\in L | m_l = 1\}\\
\left(1-\gamma_n^{m(l)}\right)p_{i,j}^{l,n} = 0, & \forall(i,j)\in\Omega, l, n\\
f_l \leq 1, & \forall l\in\{l\in L | m_l = 4\}\\
\sum_{i\in S\setminus\{s\}} p_{i,s}^{l,n} + \sum_{j\in S\setminus\{s\}} p_{s,j}^{l,n} \leq W_s^{m_l} f_l, & \forall l\in\{l\in L | m_l = 4\} s\in P(l)\\
\sum_{i\in S\setminus\{s\}} p_{i,s}^{l,n} = 0 \sum_{j\in S\setminus\{s\}} p_{s,j}^{l,n} 0 = {}_l, & \forall l\in\{l\in L | m_l = 4\} s\in F(l)\\
\sum_{l\in\{L | m_l = 3 \text{ or } m_l = 4\}} f_l \leq F_{i,j}^{l}, & \forall(i,j)\in\Omega\\
f_l \in N
\end{cases} \tag{17}$$

5. NUMERICAL EXPERIMENTS

As an essential line connecting Beijing and Shanghai, the Beijing-Shanghai HSR, with a total length of 1,318 km, connects the two economic regions of Beijing-Tianjin-Hebei and the Yangtze River Delta. It is one of the busiest passenger and freight transport lines in China. Especially after the completion of the Beijing-Shanghai "second line", its capacity will be fully released, providing great potential for the development of freight transportation, with high research value.

So this paper takes the Beijing-Shanghai HSR as a research background, selecting five stations, Beijing, Tianjin, Jinan, Nanjing and Shanghai. Then we use the collaborative optimisation model constructed in the previous section to design the line planning and freight flow distribution. Finally, the results of the two-stage model are calculated to verify the superiority of the collaborative optimisation model while keeping the line and all the parameters unchanged.

5.1 Parameter settings

Different types of trains have the same speed level and different stop planning, which is divided into through train, every-station stop train and multi-station stop train. According to the forecast of express demand of Beijing-Shanghai HSR [21] and the research on the freight flow sharing rate of the four products in 2025, the transportation demand of the four products between different OD pairs is shown in *Figure 3*.

Their respective capacities of the four modes, as well as fixed and variable costs, are shown in *Table 6*.

The existing passenger train operation schemes and the alternative set of dedicated freight trains in the downward direction are shown in *Figure 4* and *Figure 5*, in which Lines 1-7 stipulate that it is an existing passenger train set, and its optional transportation modes are Reserved Space Train, Reserved Carriage Train and Confirmation Train, and Lines 8-11 stipulate that it is an alternative set of Dedicated Freight Train, and its optional transportation modes are Dedicated Freight Train or Confirmation Train.

5.2 Performance analysis

With the above parameter settings, the model solution is implemented on a personal computer (Intel Core CPU2.50GHz, RAM 8.00 G) by programming in Python3.8 and mixed-integer linear programming (MILP).

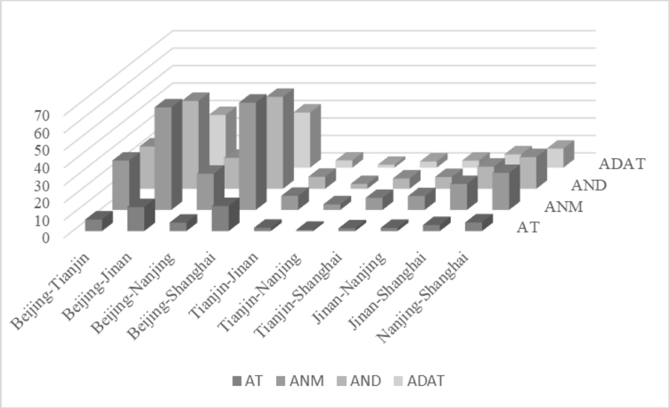


Figure 3 – Transportation demand of the four products between different OD pairs

Table 3 – The match between transportation modes and transportation products

Transportation product	**Transportation Mode**			
	Dedicated freight train	**Confirmation train**	**Reserved carriage train**	**Reserved space train**
AT	√		√	√
ANM	√	√	√	√
AND	√	√	√	√
ADAT	√	√	√	√

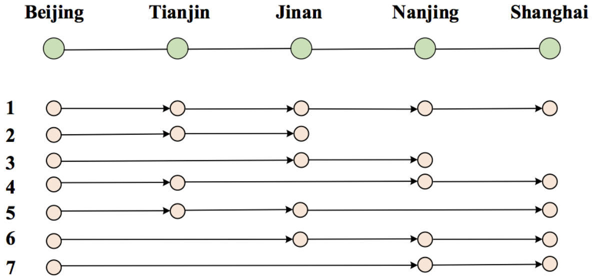


Figure 4 – The existing passenger train number

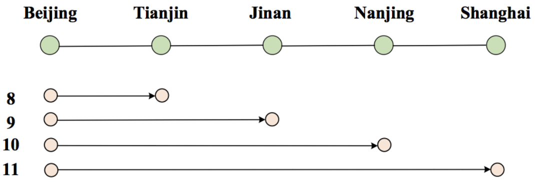


Figure 5 – The special freight train number

The results of the solution are shown in *Table 7*, where only a part of the decisions are presented due to the large number of combinations of OD pair's demand and transportation products.

As can be seen from *Table 7*, there is a match between the four transportation modes and the four transportation products, realising the accurate match of freight flow and train flow. From the selection of the transportation mode, most OD pair's demand is transported by two or more combined modes, which is determined by the quantity of cargo and requirements for timeliness. From the perspective of transportation mode sharing, 54.11% of the cargo is transported by DFT. Due to the high demand for freight transportation, the operation section is mainly for the cargo from Beijing to other stations. As is depicted from the freight demand of each OD pair for four kinds of transportation products in *Figure 4*, the mode of RST takes full advantage of the characteristics of small quantities and multiple batches. In the case of small freight volume between OD pairs, it plays an important role. Confirmation Trains and Reserved Carriage Trains bear the main transportation tasks in meeting the needs of medium and long-distance transportation, effectively utilising the excess capacity of the train to create certain benefits. To further analyse the operation of trains and the utilisation of the section, the transportation modes and frequency of trains are shown in *Table 8*.

Table 8 – Transportation mode and frequency of trains

Table 7 – The decision-making options for transportation modes

OD	Transportation product	Transportation mode sharing			
		Dedicated Freight Train	**Confirmation Train**	**Reserved Carriage Train**	**Reserved Space Train**
Beijing-Tianjin	AT	6.618	0.000	0.000	0.000
	ANM	21.140	0.000	3.153	4.000
	AND	24.24	0.000	0.000	0.000
	ADAT	8.849	3.194	0.000	2.505
Beijing-Jinan	AT	9.985	0.000	0.000	0.695
	ANM	26.969	15.097	0.000	4.000
	AND	39.468	0.000	0.000	0.000
	ADAT	0.000	16.488	0.000	7.200
Beijing-Nanjing	AT	0.000	0.000	0.000	1.594
	ANM	0.000	3.421	3.412	0.000
	AND	0.000	3.449	0.000	2.405
Tianjin- Jinan	ANM	0.000	7.564	0.000	0.498
Tianjin- Nanjing	ANM	0.000	1.474	0.000	1.751
Jinan - Nanjing	ANM	0.000	5.758	0.000	2.15
	ADAT	0.000	0.332	0.000	3.734
Nanjing -Shanghai	ANM	0.000	19.756	0.000	1.435

Train number	**Transportation mode**	**Frequency in the collaborative optimisation model**	**Frequency in the two-stage model**
1	Reserved Space Train	3	4
	Confirmation Train	1	1
	Reserved Carriage Train	1	0
2	Reserved Space Train	0	5
	Confirmation Train	1	0
3	Reserved Space Train	4	2
	Reserved Carriage Train	1	3
4	Reserved Space Train	2	2
	Confirmation Train	1	1
5	Reserved Space Train	3	3
6	Reserved Space Train	9	9
	Confirmation Train	1	1
7	Reserved Space Train	5	5
8	Dedicated Freight Train	1	1
9	Dedicated Freight Train	1	1
	Confirmation Train	1	0
10	Confirmation Train	1	0
11	Dedicated Freight Train	2	2
Summary		38	40

It can be seen from *Table 8* that the train operation frequency of the two-stage model is two more trains than that of the collaborative optimisation model, which leads to more operation costs. In terms of the selection of train transportation mode, 74% of trains adopted the reserved space mode under the condition of limited section passing capacity, which is consistent with the actual operating situation of the network.

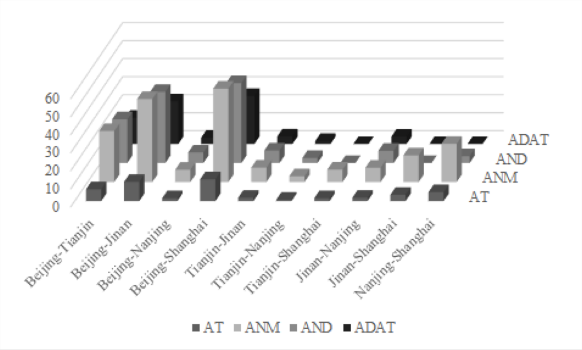


Figure 6 – Freight demand fulfilment in the co-optimisation model

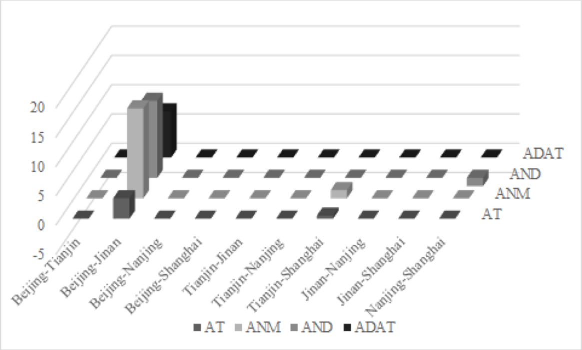


Figure 7 – Differences of results between the co-optimisation model and the two-stage model

However, due to the small cargo capacity of this mode, it is necessary to select additional dedicated freight trains to complete the transportation of large quantities of cargo. Train mode selection suggests that in the OD pair with a small volume of cargo, they can be completely transported by reserved space mode. The mode of reserved space, reserved carriage and confirmation train can be adopted in the section with medium freight demand. With the large freight demand of OD pairs, three transportation modes are adopted to complete the cargo with high timeliness requirements. Then, according to the volume of the remaining cargo flow and the passing capacity of the section, additional dedicated freight trains are considered to meet the freight demand.

To visually demonstrate the advantages of the co-optimisation model formulated in this paper, the result of the co-optimisation model is compared with the two-stage model, as shown in *Figure 6* (co-optimisation model) and *Figure 7* (two-stage model).

As is depicted in *Figure 6* and *Figure 7*, in the OD pairs with small freight demand, the fulfilment rate of the four transportation products of the two models is the same, such as Tianjin-Nanjing, Tianjin-Shanghai, etc. In the OD pairs with large freight demand, the fulfilment of the transportation products in the co-optimisation model is better than the two-stage model, such as Tianjin-Jinan. The two-stage model solves the local problem at the beginning and then optimises the remaining problem, which will produce the local optimal solution but cannot reach the global optimal. *Figure 7* shows the differences in results between the co-optimisation model and the two-stage model. It is obtained by subtracting the results of the two-stage model from the results of the co-optimisation model. From *Figure 7*, it is obvious that the difference between the two models is small for the four transportation products of most OD pairs. But in the OD pair of Beijing-Jinan, there is a large gap in the fulfilment of freight demand, especially for the product arriving the next morning and arriving the next day.

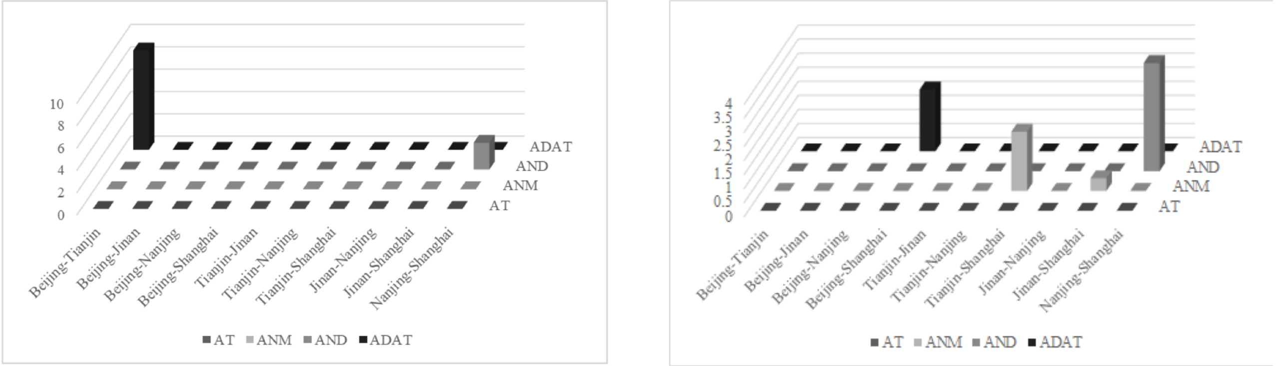
Table 9 – Revenue and freight demand fulfilment

	Revenue (yuan)	**Freight demand fulfilment**
Collaborative optimisation model	7,935,866.206(+1,246,650.697)	89.18% (+7.96%)
Two-stage model	6,689,215.509	81.22%

Table 9 shows the revenue and freight demand fulfilment rate obtained under the two models. It can be seen that the freight demand fulfilment rate of the co-optimisation model is 7.96% higher than that of the two-stage model. Compared with the revenue of the two-stage model, the revenue of the co-optimisation model is 18.64% higher, which further verifies the advantages of the model.

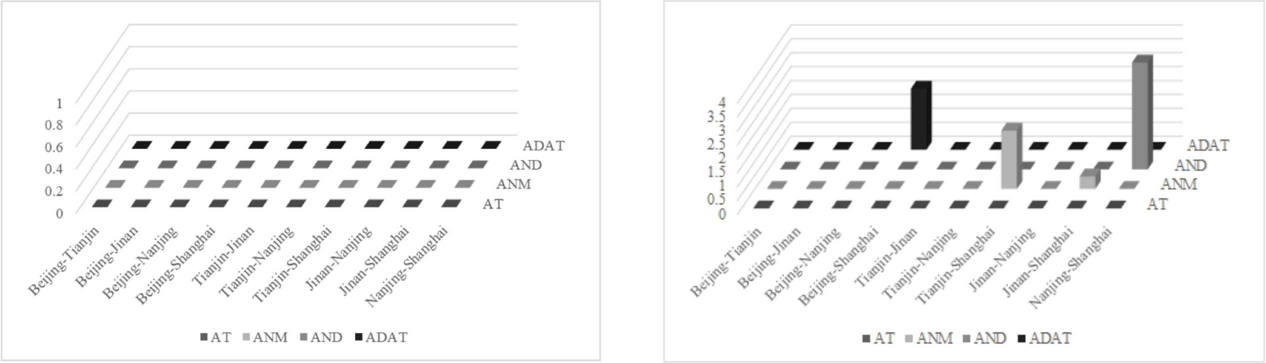
5.3 Sensitivity analyses of section passing capacity

To further analyse the relationship between the revenue and demand fulfilment rate of HSReD and the line passing capacity of the section, the sensitivity analysis is carried out for the section passing capacity. We decreased the number of lines passing capacity and 4 experiments were carried out. The specific steps are as follows: (1) decreasing the passing capacity of each section by 1 respectively, for example, to keep the passing capacity of Section Tianjin-Jinan, Jinan-Nanjing, Nanjing-Shanghai unchanged, and to reduce the passing capacity of Section Beijing-Tianjin by 1; (2) calculating its freight demand result, revenue and freight demand fulfilment rate. The impact of changing the passing capacity of the section on the revenue, fulfilment rate and freight flow distribution is analysed. The results are shown in *Figure 8* and *Table 10*.



a) Decreasing the line passing capacity by 1 of Beijing-Tianjin

b) Decreasing the line passing capacity by 1 of Tianjin-Jinan



c) Decreasing the line passing capacity by 1 of Jinan-Nanjing

d) Decreasing the line passing capacity by 1 of Nanjing-Shanghai

Figure 8 – Difference in freight demand fulfilment compared to the original results with four cases

Table 10 – Revenue and freight demand fulfilment at different section passing capacities

Classification	OD	The line passing capacity (train per day)	Revenue (yuan)	Freight demand fulfilment rate
Case 1	Beijing-Tianjin	Decrease by 1	7868457	86.95%
Case 2	Tianjin-Jinan	Decrease by 1	7843516	87.48%
Case 3	Jinan-Nanjing	Decrease by 1	7935849	89.18%
Case 4	Nanjing-Shanghai	Decrease by 1	7843516	87.48%

In combination with *Figure 8* and *Table 10*, it can be seen that by changing the line passing capacity, the income and fulfilment rates of different OD pairs are also different. From *Figure 8*, it is apparent that by decreasing the number of line passing capacity, the freight demand fulfilment of the four scenarios is different from that of the co-optimisation model. The main difference in case 1 is the product of ADAT in the Beijing-Tianjin, which is caused by decreasing the number of line passing capacity, and with the limited through capacity of the section, it can only be ensured that cargo with higher tariff can be met first, so it results in more cargo of ADAT being stranded. The results of case 2 and case 4 are the same when changing the zone passing capacity, indicating that the route conditions are similar in both zones and that changing the passing capacity in either zone will have a large impact on the freight demand fulfilment rates and revenues. Case 3 shows that the passing capacity of the Jinan-Nanjing section decreases by 1 line per day, which has no impact on the revenue and freight demand fulfilment rate. Compared with the collaborative optimisation model results, it is found that the line 11 of the dedicated freight mode running in the alternative concentration, the passing capacity of the Jinan-Nanjing section is occupied by 2 trains per day, while the passing capacity of the Jinan-Nanjing section is 2 trains per day after the decrease of 1. The prevailing demand is still satisfied, so the result of case 3 is the same as that of the collaborative optimisation model. In case 1, compared with case 2 and case 4, the fulfilment rate of freight demand is lower, but the income is higher. The comparative analysis of the three freight flow distribution results shows that in case 1, more freight capacity is allocated to transport products with higher freight prices, thus obtaining higher income.

Table 11 – Transportation mode and freight demand fulfilment under four cases

Train number	**Transportation mode**	**Case 1**	**Case 2**	**Case 3**	**Case 4**
1	Reserved Space Train	4	4	4	4
	Confirmation Train	1	1	1	1
	Reserved Carriage Train	0	0	0	0
2	Reserved Space Train	8	0	0	0
	Confirmation Train	1	1	1	1
	Reserved Carriage Train	1	0	0	0
3	Reserved Space Train	5	4	5	4
	Reserved Carriage Train	0	1	0	1
4	Reserved Space Train	2	2	2	0
	Confirmation Train	1	1	1	1
	Reserved Carriage Train	0	0	0	2
5	Reserved Space Train	3	2	3	3
	Reserved Carriage Train	0	1	0	0
6	Reserved Space Train	9	7	9	8
	Confirmation Train	1	1	1	1
	Reserved Carriage Train	0	2	0	1
7	Reserved Space Train	5	0	5	0
	Reserved Carriage Train	0	5	0	1
8	Confirmation Train	1	0	0	0
	Dedicated Freight Train	0	1	1	1
9	Confirmation Train	1	1	1	1
	Dedicated Freight Train	1	1	1	1
10	Confirmation Train	1	1	1	1
11	Dedicated Freight Train	2	1	2	1
	Confirmation Train	0	0	0	1
Summary		47	37	38	34

As can be seen from *Table 11*, under the same volume of transport demand, the transportation mode and operation frequency will change when the line passing capacity of different sections is changed. The passing capacity of Beijing-Tianjin will be reduced by 1, and the total train frequency will be increased by 9.

The conclusion from the sensitivity analysis of the passing capacity of the section above is that for small quantities of cargo, the combination of reserved space, reserved carriage and confirmation train is used to complete the cargo transportation. For large quantities of cargo, in the case of the passing capacity allowed, it is more beneficial to select additional dedicated freight trains to achieve point-to-point cargo transport. In the case of the passing capacity of the section is not allowed, it is preferential to meet the transportation needs of cargo with high timeliness requirements.

6. CONCLUSION AND FUTURE WORK

In the HSR system, mixed transportation can provide an effective way to utilise the excess transport capacities and meet the demand for fast freight delivery. In this paper, we propose a co-optimisation model, which integrates the consideration of LP and FFA with multiple transportation modes and products. By analysing the results of numerical experiments and the sensitivity of section passing capacity, we can summarise the following conclusions.

1) By comparing the results of the co-optimisation model and the two-stage model, we can find that the freight fulfilment rates and total profits of the co-optimisation model are higher than the two-stage model, which proves the reasonableness and the superiority of the collaborative optimisation model.
2) The sensitivity analysis shows that the freight fulfilment rate and total profit will not change with the passing capacity fluctuation of different sections. If there is an adequate section passing capacity, reducing the passing capacity will have no impact on express delivery. If there is inadequate capacity, lowering the section passing capacity will significantly reduce freight fulfilment rates and profits.
3) For the train capacity, if the train's capacity is insufficient, it is necessary to preferentially transport cargo with high requirements for timeliness (i.e. cargo with high freight fee). Then, based on the freight volume and line conditions, managers should choose to operate DFT. If the train's capacity is sufficient, using the three modes (i.e. CT, RCT, RST) can satisfy the freight demand. There is no need to operate DFT since the operation of DFT requires consideration of several constraints, and the fixed and variable costs of operating them are higher.

HSReD is still in the initial stage, and there are many contents for research in the future. The following are some future research enhancements:

1) Optimising the problem of LP and FFA for multiple modes of transportation and multiple freight products with uncertain freight demand.
2) For dedicated freight trains, considering the LP optimisation problem with the maintenance window in the case of night operation.

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考虑多种运输模式和运输产品的高铁快运列车开行方案与货流分配协同优化

摘要：

随着高速铁路网络的发展，高铁快运被用于满足不断增长的货运需求。列车开行方

案与货流分配是高铁快运运营中需要解决的两大问题。本文基于多种运输模式和运输产品，综合考虑上述的两个问题，以货运总收益最大化为目标，建立了协同优化模型。以京沪高铁为背景，结果分析发现，在相同的路网条件及参数设置下，协同优化模型货运需求兑现率比两阶段模型的兑现率高了7.96%，收益率高了18.64%。最后对区间通过能力进行敏感性分析，得出了一些操作上的启示，对优化高铁快运的日常运营管理提帮助。

关键词：
高铁快运；列车开行方案；货流分配；协同优化模型