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# Cargo Carrying Model of High-Speed Railway Express Considering Transportation Capacity Sharing and Carbon Trading

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## ABSTRACT

In order to maximise the utilisation of high-speed railway (HSR) transportation capacity and facilitate the low-carbon development in transportation infrastructure, this paper examines the cargo carrying method in the context of transportation capacity sharing of HSR. With carbon trading incorporated into the profit of HSR express, a cargo carrying decision-making model is formulated with consideration of carbon trading. The model incorporates key constraints, including loading capacity of HSR and work ability of stations. A multi-loading rules genetic algorithm is developed within a genetic algorithm framework to solve the model, addressing the influences of cargo service types, origin-destination (OD) pairs and loading priority of HSR trains. The numerical case of Xi'an-Chengdu HSR line is implemented to validate the proposed model by the Gurobi solver, and the performance of different algorithms is compared. Results demonstrate the rationality of the three proposed loading rules and the superior performance of the multi-loading rules genetic algorithm. Sensitivity analysis indicates that improving station work ability and incorporating train transfer can improve overall profitability. However, when station work ability reaches 400 kg/min, further increases yield negligible benefits to total profit. Moreover, considering train transfer does not significantly enhance overall profitability but substantially increases computation time.

## KEYWORDS

high-speed railway express; transportation capacity sharing; carbon trading; cargo carrying; genetic algorithm.

## 1. INTRODUCTION

By the end of 2022, China's high-speed railway (HSR) has reached 42,000 kilometres, and the total mileage and line density of HSR rank first in the world, linking more than 300 cities [1]. Areas along HSR lines feature a prosperous economy, characterized by frequent population mobility, active commercial transactions, and intensive logistics activities [2]. For example, the total express business of cities along the Beijing-Shanghai HSR, which connects the Beijing-Tianjin-Hebei and Yangtze River Delta urban agglomerations, accounts for 1/6 of the national total [3]. Compared with road transportation, HSR has the advantages of fast transportation speed, high punctuality, environmental friendliness, low-carbon and environmental protection [4, 5]. Currently, HSR is primarily used for passenger transportation. However, with increasing logistics demands along HSR lines and available spare transportation capacity, HSR has potential to transport cargoes. These cargoes, such as electronic products and express deliveries, are currently transported predominantly by road. In recent years, with the expanding demand of the express market, it has become the norm to utilise HSR to carry cargoes. At present, a total of 980 HSR lines in China have introduced diversified HSR express services such as "arriving today" (AT), "arriving on the next morning" (ANM), "arriving on the next day" (AND) and "arriving on the day after tomorrow" (ADAT). The freight capacity of HSR express transportation has reached 44,000 tons/year [6, 7]. China Railway has opened 293 HSR express handling stations, covering 31 provinces, autonomous regions and municipalities across the country. Additionally, 3,500 trains are available for transportation of express demand every day, providing sufficient transportation capacity for HSR express services [8].

China has a vast demand for cargo services and the transportation industry is one of the major sources of carbon emissions. Currently, the highway is still the dominant mode of freight transportation in China. In 2022, the total volume of national cargo transportation reached 51.5 billion tons, with road transport accounting for 72% of this total [9]. Carbon emissions from road transport accounted for more than 70 percent of total carbon emissions from the transportation industry [10]. HSR trains, powered by electricity, are widely considered to be a highly efficient, eco-friendly transportation mode [11]. Currently, China has an annual reduction of 11.83 million tons of $CO_2$ equivalent, as HSR shares part of passenger and freight transport tasks of highway [12]. In 2020, the initial HSR express train was officially inaugurated. Since then, the railway departments and express delivery companies have actively explored the feasibility of the "high-speed railway + logistics" freight approach [13].

At the 75th United Nations General Assembly, China announced its intention to implement comprehensive policies and measures to achieve peak $CO_2$ emissions by 2030 and carbon neutrality by 2060 [14]. The country has also established a carbon trading system to aid in the reduction of carbon emissions. Within this system, the government distributes Chinese Emission Allowances (CEAs) and Chinese Certified Emission Reductions (CCERs) to enterprises. These serve as the core commodities in the carbon trading market. Related literature has examined and verified the advantageous impact of the carbon trading protocol on carbon emission control in China, from both macro [15-17] and micro [18, 19] perspectives. The transportation industry plays a crucial role in the carbon trading market owing to its substantial carbon emissions.

This paper introduces the carbon trading into HSR express transportation. HSR utilises the spare capacity to carry cargoes from transportation and logistics enterprises using road transportation vehicles. The reduction in carbon emission costs achieved by substituting road transportation is accounted as the carbon trading revenue of HSR transportation. It promotes the transfer of road freight such as electric commerce goods and express cargoes to HSR transport. This approach alleviates highway congestion, reduces carbon emissions and maximises the utilisation of HSR capacity.

This paper develops a cargo loading decision model for HSR express, incorporating carbon trading within the context of transportation capacity sharing. The study analyses the application characteristics and suitable scenarios of the HSR express model. It offers theoretical and methodological support to maximise HSR transportation capacity utilisation and advance the development of HSR express. Firstly, a cargo carrying decision-model is formulated, considering constraints such as loading capacity of HSR, time window requirements of express service products and work ability of stations. The model aims to maximise the profit of HSR express. The revenue components include transportation revenues and carbon trading revenues. The cost components consist of fixed costs per train usage, variable costs related to transportation distance and the weight of cargoes, and transfer costs for loading and unloading during cargo transfer. Subsequently, a multi-loading rules genetic algorithm is designed to address the influences of cargo service types, OD pairs and HSR trains. Finally, the Xi'an-Chengdu HSR line is used to validate the proposed model and algorithm, with evaluations of performance and sensitivity.

The remainder of this paper is organised as follows. Section 2 introduces the existing research on HSR express. In Section 3, the description and assumptions of the problem are given, and the decision-making of the cargo carrying model in HSR express is established. Section 4 designs the multi-loading rule genetic algorithm. Section 5 evaluates the accuracy and superiority of the model using the Xi'an-Chengdu HSR as a case study. Finally, Section 6 concludes the paper and summarises the key findings of this study.

## 2. REVIEW

The existing works of literature on HSR express can be divided into two main categories: macro-operational analysis and decision-making of cargo carrying scheme.

### 2.1 Macro-operational analysis of HSR express

Some scholars have analysed the social and economic benefits of HSR express. Boehm et al. [20] conducted a comparison of the impact of highway and HSR on low-frequency and high-value commodity transportation, and discovered that the price of HSR was roughly 70% more than that of conventional highway transportation, but carbon emissions could be decreased by 80%. Cai et al. [21] compared the economic benefits of three scenarios, and found that social welfare will always be improved if HSR enters not only the passenger sector but also the cargo sector.

The existing research divides the organisation mode of HSR express into confirmed train, passenger train piggyback, reserved passenger train and specialised HSR express train. Confirmed train and specialised HSR express train are forms of passenger and freight separation, while passenger train piggyback and reserved passenger train operate through transportation capacity sharing. Although the benefits of HSR express have been proved and the transportation organisation model has been studied, the market share of HSR express is still low, and the residual capacity utilisation of passenger trains is below 10% [22]. Boehm et al. [20] found that the market share of HSR express is primarily influenced by transportation management policies, the implementation of HSR express solution and decision-makers' prioritisation of the ecological environment. Gao et al. [23] discovered that economic development of cities and the number of HSR trains impact the increase in HSR express volume. Duan et al. [24] discovered that employing an advance deposit payment method can increase the willingness of HSR express carriers to cooperate, while sharing freight demand information among express demanders can enable carriers to reserve freight space more accurately, thereby improving overall profits.

## 2.2 Cargo carrying decision-making method of HSR express

Yu et al. [25] formulated a two-stage operation plan for specialised HSR express trains. In the first stage, aiming at the lowest total cost, the operation plan of the optional express train is determined. In the second stage, the specific loading and unloading scheme is decided to maximise the total revenue. On this basis, Yu et al. [26] decided the operation plan for specialised HSR express trains and cargo carrying scheme by applying time-space network theory, which did not disrupt the existing passenger train schedule. Li et al. [27] determined the timetable, passenger and cargo carrying scheme, considering fundamental operation factors such as transportation demand and capacity of trains. Jia et al. [28] developed a strategy to optimise the number of specialised HSR express trains and determine the most effective cargo loading plan based on the periodic fluctuations in freight transport demand. In the context of capacity sharing, Zhen et al. [29] developed a two-stage planning model for the HSR express system. Firstly, the loading and unloading station was decided, and then the passenger train was assigned to the transportation demand of each cargo OD pair. Xu et al. [30] studied the specific carrying scheme for the reserved passenger train mode, which assigned every carriage responsible for transporting either passengers or cargo and assigned OD demand to designated seats. As for mixed organisation mode, Yu et al. [31] established a two-stage model considering the value and time sensitivity of different cargo types. The operation plan of specialised HSR express trains was decided, and a cargo carrying scheme was organised in the context of four organisation modes. Yang et al. [32] constructed a decision-making model of cargo carrying in HSR express based on transportation capacity sharing, and designed a multi-load rules genetic algorithm to solve it.

In conclusion, research on HSR express remains limited, particularly regarding cargo carrying schemes. Existing research primarily concentrates on the operation plan and cargo carrying decision of specialised HSR express trains. Furthermore, the costs or revenues related to carbon emissions in the cargo carrying of HSR express have not been studied at present. Additionally, train transfer combinations and working capacity of stations significantly influence overall transportation efficiency. However, current studies have not comprehensively considered these two factors, which prevents the maximum utilisation of cargo loading capacity and deviates from practical operations. Finally, most studies rely directly on commercial solvers to address the proposed models. Commercial solvers, particularly for large-scale optimisation tasks such as integer and mixed-integer programming, often face challenges like excessive computation times and high memory demands. As the problem scale and constraints increase, the computational efficiency of solvers may decrease, making the solving process unacceptable in practical applications.

In view of the above research deficiencies, this paper selects passenger train piggyback and reserved passenger train as optional organisation modes, to enhance research on cargo carrying decision under transportation capacity sharing. This paper introduces the following innovations. (1) The carbon emissions saved by HSR trains instead of highway are used to calculate the carbon trading income of HSR express, which provides an operation idea of the carbon trading in transportation industry. (2) By utilising the genetic algorithm, which offers greater flexibility and global optimisation capabilities, a multi-loading rules genetic algorithm is designed to solve the model, effectively handling large-scale problems. (3) Cargoes are allowed to make one transfer according to the combination of HSR trains to make full use of the loading capacity. (4)

Taking the working capability of stations into account, the proposed model becomes more practically applicable.

## 3. ESTABLISHMENT OF THE MODEL

Firstly, we elaborate on the characteristics of two organisation models of HSR express, while establishing time window requirements and fee standards for various service products. Then we provide a detailed explanation of the parameters and variables used in the mathematical model. Finally, by specifying the handling of paths and train scheme, we construct a cargo carrying decision-making model of HSR that incorporates constraints such as transportation demand, service product time window, available load capacity of HSR and work capacity of stations.

### 3.1 Problem description

The distribution and demand of OD of HSR express cargo, operation information of HSR trains, as well as the limitation of work capacity of each station are known, and selecting passenger train piggyback and reserved passenger train as the optional organisation modes. On this basis, the served train and carried volume of four service types, as well as the organisation mode of each HSR express train, is decided. The characteristics of the organisation modes of HSR express are shown in *Table 1*. The time window requirements and fee standards of the four HSR express service products are shown in *Table 2*.

*Table 1 – Characteristics of the organisation mode of high-speed railway express*

| **The organisation mode of the HSR express** | **Meanings** | **Carrying capacity** | **Costs** |
|---|---|---|---|
| Passenger train piggyback | Using the large baggage racks, passenger shelves, seat gaps and other spare space to carry express cargoes | Small | Loading cost<br>Escort cost |
| Reserved passenger train | Reserving or converting one or more carriages for freight on HSR passenger trains | Large | Retrofit cost<br>Loading cost |

*Table 2 – Time window requirements and fee standards of high-speed railway express service products*

| **Service product** | **Time window** | **Fee (CNY/kg)** | | |
|---|---|---|---|---|
| | | **Transportation distance $d$ (km)** | | |
| | | **$d \leq 200$** | **$200 < d \leq 500$** | **$500 < d$** |
| AT | 22:00 today | 25 | 30 | 35 |
| ANM | 12:00 the next morning | 18 | 23 | 28 |
| AND | 18:00 the next afternoon | 17 | 22 | 27 |
| ADAT | 18:00 the afternoon of the day after tomorrow | 12 | 17 | 22 |

### 3.2 Parameter definition

Based on the aforementioned problem description, a mixed integer linear programming (MILP) model is constructed to maximise the operational revenue of HSR express. The symbols and meanings in the model are shown in *Table 3*. The model includes two decision variables: determining whether train $k$ adopts the type $m$ HSR express organisation mode for transportation, and the weight of type $n$ service products transported on path $j$.

*Table 3 – Symbols and meanings*

| | **Variables** | **Meanings** |
|---|---|---|
| Set | $m \in M$ | The organisation modes of HSR express, $m = (1,2)$ respectively represent passenger train piggyback and reserved passenger train |
| | $n \in N$ | The type of service products, $n = (1,2,3,4)$ respectively represent same-day delivery, next-morning delivery, next-day delivery and 2-day delivery |
| | $j \in J$ | The set of all feasible paths, the path refers to all possible trains or combinations of trains between the OD of HSR express cargo |
| | $k \in K$ | The set of the trains |
| | $s \in S$ | The set of the stations |
| Parameter | $Q_{od}^{n}$ | Demand for service products of category $n$ between the $od$ $(kg)$, $\forall o, d \in S$ |
| | $\delta_j^k$ | Relation between path $j$ and train $k$, if train $k$ serves path $j$, then $\delta_j^k = 1$, otherwise $\delta_j^k = 0$ |
| | $\varphi_j^s$ | Relation between path $j$ and station $s$, if path $j$ passes through station $s$ (excluding OD station), then $\varphi_j^s = 1$, otherwise $\varphi_j^s = 0$ |
| | $c_j^n$ | Unit fee for category $n$ service products on path $j$ (CNY/$km$) |
| | $c_m^v$ | Transportation cost of type $m$ HSR express organisational mode (CNY) |
| | $c_m^f$ | Fixed cost of type $m$ HSR express organisational mode (CNY) |
| | $c_{trans}$ | Cost of express cargo transfer (CNY/one transfer) |
| | $d_j^k$ | Transportation distance by train $k$ on path $j$ $(km)$ |
| | $G_m$ | The maximum cargo carrying capacity of the type $m$ HSR express organisation mode $(kg)$ |
| | $c_e$ | Unit carbon trading price (CNY/$kg$) |
| | $e$ | Carbon emission factor ($kg$/L) |
| | $\rho^*$ | Fuel consumption of per unit distance by road transport vehicles in fully loaded condition (L/$km$) |
| | $Q_{max}$ | Rated load of road transport vehicles $(kg)$ |
| | $v_{work}$ | Average operating efficiency of HSR station $(kg/min)$ |
| | $t_{wait}^{k,s}$ | Dwell time of train $k$ at station $s$ $(min)$ |
| | $T_j^D$ | Time for the train arriving at the end of the path $j$ |
| | $t_n$ | Expected delivery time for service products of type $n$ |
| | $\alpha_j^s$ | Relation between station $s$ and the origin station of path $j$, if $s$ is the origin station of path $j$, then $\alpha_j^s = 1$, otherwise $\alpha_j^s = 0$ |
| | $\beta_j^s$ | Relation between station $s$ and the destination station of path $j$, if $s$ is the destination station of path $j$, then $\beta_j^s = 1$, otherwise $\beta_j^s = 0$ |
| | $\omega_j^{k,s}$ | If train $k$ on path $j$ is used as a former train to transfer at station $s$, then $\omega_j^{k,s} = 1$, otherwise $\omega_j^{k,s} = 0$ |
| | $u_j^{k,s}$ | If train $k$ on path $j$ is used as a subsequent train to transfer at station $s$, then $u_j^{k,s} = 1$, otherwise $u_j^{k,s} = 0$ |
| | $U$ | Positive number of infinities, $U \gg 0$ |
| Variant | $x_k^m$ | 0-1 variable, if train $k$ transports cargoes using the type $m$ HSR express organisation mode, then $x_k^m = 1$, otherwise, $x_k^m = 0$ |
| | $y_j^n$ | Weight of type $n$ service products transported by path $j$ $(kg)$ |

## 3.3 Paths and treatments

A complex relationship exists between OD pairs and trains: the demand of one OD pair can be fulfilled by different trains, and one train can serve the transportation needs of different OD pairs. In order to clearly represent the service relationship between trains and OD pairs, a feasible service train plan for an OD pair is referred to as a "path", denoted by $j$. To improve the demand completion rate and maximise the utilisation of HSR transportation capacity, this study considers various path options. These paths not only include the direct path served by one train, but also include the transfer path with two trains combined transport.

*Figure 1* shows the relationship of OD, path and train. The transportation demand of $\mathrm{OD}_{23}$ can be fulfilled independently by either train $k_1$ or train $k_2$; the feasible paths of $\mathrm{OD}_{23}$ are path $j_1$ and path $j_4$, which are both direct paths. Although train $k_1$ and train $k_2$ cannot independently transport cargo from station 4 to station 7, they can work together to complete transportation needs if the cargo makes a transfer at station 5. Thus, path $j_3$ is a feasible path for $\mathrm{OD}_{47}$ which belongs to the transfer path. Path $j_{3_{(1)}}$ denotes the initial segment of the transportation completed by train $k_1$. Path $j_{3_{(2)}}$ denotes the subsequent portion of the transportation completed by train $k_2$.

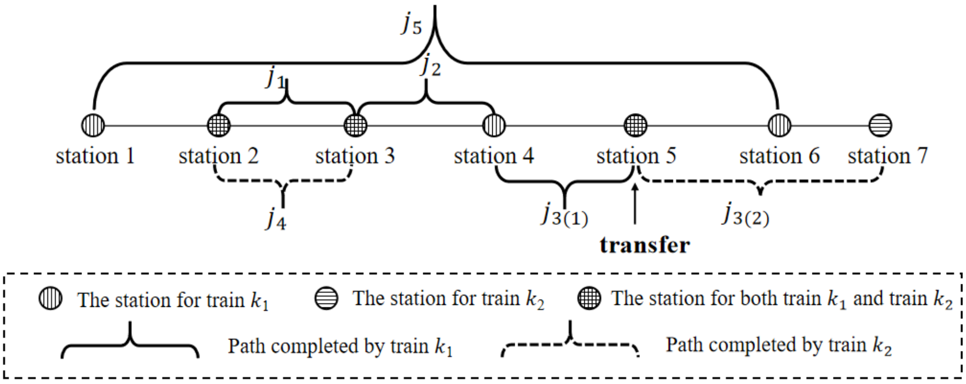

*Figure 1 – Example of the relationship of OD, path and train*

All feasible paths between OD pairs can be obtained based on the information of train schedules. The specific processing steps are as follows.

First, path $J_{od}$ is the set of feasible paths between the origin station O and the destination station D. All trains that stop at both stations O and D are added to $J_{od}$, which is the direct path.

Then, the trains that stop at station O and do not stop at station D are the former trains. The trains that stop at station D and do not stop at station O are the subsequent candidate trains. Add to $J_{od}$ (transfer paths) if the combination of the former train and the subsequent train meets the following two conditions. 1) The former train and the subsequent train have at least one common station between station O and station D. 2) The arrival time of the subsequent train is later than that of the former train.

Finally, repeat this procedure for all OD pairs.

## 3.4 Model formulation

This paper comprehensively considers the revenues and costs in the operation process of HSR express transportation, and the maximisation of the total profit is taken as the optimisation objective. Specifically, the revenues include transportation revenues and carbon trading revenues, and the costs include fixed costs, variable costs and transfer costs.

### *Transportation revenues*

Transportation revenues refer to the direct income generated by delivering cargoes to their destination, which are related to the weight of the cargoes and the transportation distance. The method of calculating the transportation revenues of HSR express is shown in *Equation 1*.

$$I_1 = \sum_{j \in J} \sum_{n \in N} c_j^n \cdot y_j^n \tag{1}$$

### *Carbon trading revenues*

We use the carbon emissions from road transportation as the basis for determining the carbon trading volume. The carbon trading revenues of HSR express are calculated by multiplying the carbon emissions from road transportation by the unit carbon trading price. The carbon emissions from road transportation are determined by the unit fuel consumption per kilometre $\rho^*$, the rated load of road transport vehicles $Q_{max}$, the transportation distance and the cargo weight. Additionally, it is assumed that the cargo weight and transportation distance for road transportation are identical to those for HSR express. Therefore, the carbon trading revenues generated by adopting HSR express can be calculated as shown in *Equation 2*.

$$I_2 = c_e \cdot \sum_{j \in J} \sum_{n \in N} \sum_{k \in K} e \cdot \frac{\rho^*}{Q_{max}} \cdot y_j^n \cdot d_j^k \tag{2}$$

### *Fixed costs*

Fixed costs are the cost per use of the HSR train. Fixed costs vary for trains with different organisational modes of express transportation. The calculation of the fixed costs $C_1$ is shown in *Equation 3*.

$$C_1 = \sum_{m \in M} \sum_{k \in K} c_m^f \cdot x_k^m \tag{3}$$

### *Variable costs*

Variable costs, also known as transportation costs, are the cost of power consumption and equipment loss during the transportation of HSR train, which are related to the weight of cargoes and the transportation distance $d_j^k$. Meanwhile, transportation costs vary across different HSR express organisational modes. The calculation method for variable costs $C_2$ is shown in *Equation 4*.

$$C_2 = \sum_{j \in J} \sum_{m \in M} c_m^v \sum_{k \in K} \sum_{n \in N} y_j^n \cdot x_k^m \cdot d_j^k \tag{4}$$

### *Transfer costs*

When utilising a transfer path with combined transport by two trains, manual handling is required at transfer stations, which results in transfer costs. The transfer costs account for the weight of cargoes to be transferred and the cost of express cargo transfer, denoted as $c_{trans}$. The calculation of the transit costs $C_3$ is shown in *Equation 5*.

$$C_3 = c_{\mathrm{trans}} \sum_{j \in J} \sum_{n \in N} y_j^n \sum_{s \in S} \omega_j^s \tag{5}$$

### *Cargo carrying model for HSR express transportation*

The mathematical model of the HSR express cargo carrying problem based on capacity sharing is specified as follows:

$$MaxZ = I_1 + I_2 - C_1 - C_2 - C_3 \tag{6}$$

$$\sum_{j \in J} y_j^n \alpha_j^o \beta_j^d \le Q_{od}^n, \forall o, d \in S, n \in N \tag{7}$$

$$\sum_{j \in J} \sum_{n \in N} y_j^n \delta_j^k x_k^m \left(\alpha_j^s + u_j^{k,s} + \varphi_j^s\right) \le G_m, \forall k \in K, m \in M, s \in S \tag{8}$$

$$\sum_{j\in J}\sum_{n\in N}\delta_j^k y_j^n\left(\alpha_j^s+\beta_j^s+\omega_j^{k,s}+u_j^{k,s}\right)\le v_{\mathrm{work}}t_{\mathrm{wait}}^{k,s},\forall k\in K,s\in S \tag{9}$$

$$\left(T_j^D-t_n\right)y_j^n\le 0,\forall j\in J,n\in N \tag{10}$$

$$\sum_{m\in M}x_k^m\le 1,\forall k\in K \tag{11}$$

$$\sum_{n\in N}y_j^n\delta_j^k\le\sum_{m\in M}G_m x_k^m,\forall j\in J,k\in K \tag{12}$$

$$x_k^m=\begin{cases}1, train\ k\ transports\ cargoes\ using\ the\ type\ m\ organisation\ mode\\ 0, else\end{cases} \tag{13}$$

$$y_j^n\ge 0 \tag{14}$$

*Equation 6* is the objective function, maximising HSR express profits, which is the HSR express transportation revenues and carbon trading revenues minus the HSR express fixed costs, variable costs and transit costs. *Constraint 7* limits the demand for the service products. *Constraint 8* restricts the load capacity of the train. *Constraint 9* sets the working capacity of the station. *Constraint 10* meets the delivery time of service products. *Constraint 11* ensures that only one organisation mode of express transport can be used for a train. *Constraint 12* shows the correlation between decision variables $y_j^n$ and $x_k^m$. *Equations 13 and 14* are decision variables constraints.

*Equation 8* contains the product of decision variables $y_j^n$ and $x_k^m$, which is a nonlinear constraint. Finding the optimal solution for a nonlinear model is difficult due to the large number of poles. Therefore, in this paper, the large $M$ method is used to linearise the nonlinear programming model into a linear programming model which is easier to solve. Set $Z_{j,k}^{n,m}=y_j^n x_k^m$, then *Equation 8* can be transformed as follows. The decision variable $x_k^m$ is binary variable, and $U$ is a positive infinite number. *Constraint 16* ensures that when $x_k^m=0$, $Z_{j,k}^{n,m}=0$. *Constraint 17* ensures that when $x_k^m=1$, $Z_{j,k}^{n,m}=y_j^n x_k^m=y_j^n$. *Constraint 18* guarantees that when $x_k^m=1$, $Z_{j,k}^{n,m}=y_j^n x_k^m=y_j^n$, and when $x_k^m=0$, $Z_{j,k}^{n,m}=0$. *Constraint 19* makes sure that $Z_{j,k}^{n,m}$ cannot be negative.

$$\sum_{j\in J}\sum_{n\in N}\delta_j^k Z_{j,k}^{n,m}\left(\alpha_j^s+u_j^{k,s}+\varphi_j^s\right)\le G_m,\forall k\in K,m\in M,s\in S \tag{15}$$

$$Z_{j,k}^{n,m}\le Ux_k^m,\forall j\in J,n\in N,k\in K,m\in M \tag{16}$$

$$Z_{j,k}^{n,m}\le y_j^n,\forall j\in J,n\in N,k\in K,m\in M \tag{17}$$

$$Z_{j,k}^{n,m}\ge y_j^n-U\left(1-x_k^m\right),\forall j\in J,n\in N,k\in K,m\in M \tag{18}$$

$$Z_{j,k}^{n,m}\ge 0,\forall j\in J,n\in N,k\in K,m\in M \tag{19}$$

## 4. METHODOLOGY

The above model is a mixed integer linear programming model with complex constraints, and it belongs to the NP-hard problem. Genetic algorithms offer advantages such as superior search capabilities, parallelism and robustness, making them more widely applicable than intelligent algorithms like the ant colony algorithm and simulated annealing algorithm [33, 34]. In addition, the decision variable of the model, the loaded weight of the service product, is a continuous variable, which makes it difficult to solve. It is closely related to the fee of the actual loaded service product, the load capacity and arrival time of the train, and the working capacity of the station. Therefore, we propose a multi-loading rules genetic algorithm, and *Figure 2* depicts the specific process of the designed algorithm. The main operations of the algorithm (genetic algorithm operations and multi-loading rules) are respectively described in Section 4.1 and 4.2.

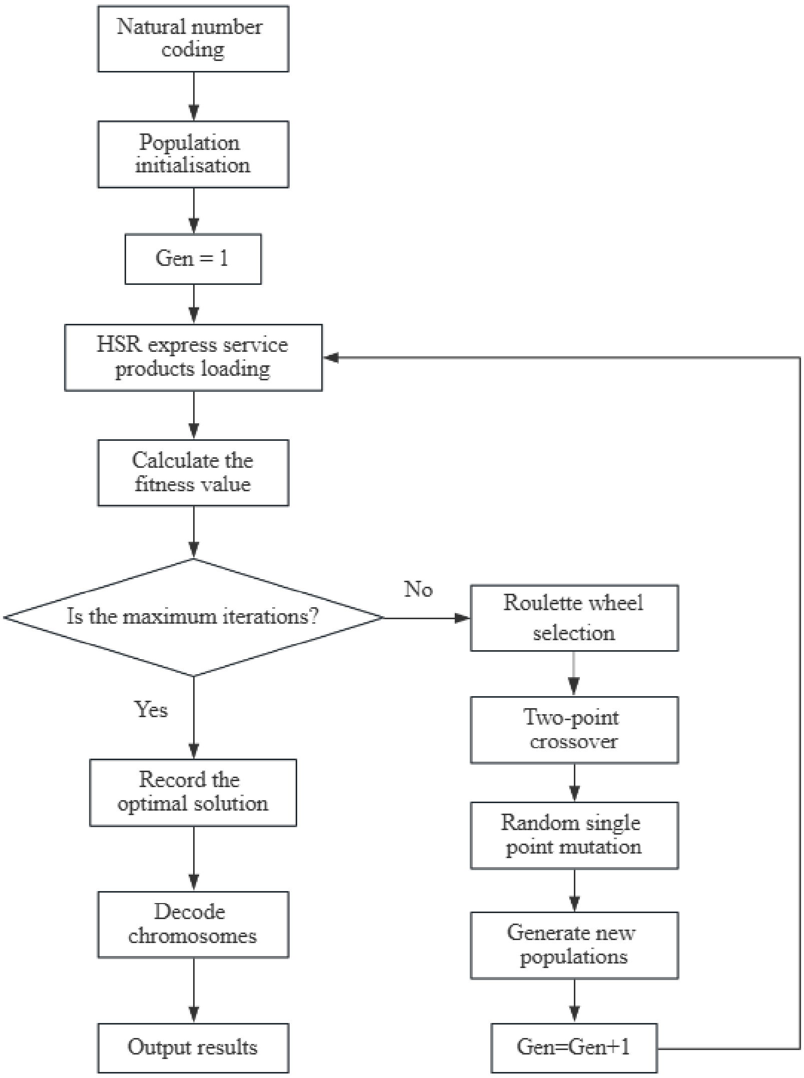

*Figure 2 – Framework of multi-loading rules genetic algorithm*

## 4.1 Genetic algorithm operations

The genetic algorithm is a global optimisation, adaptive probabilistic search algorithm that simulates the processes of gene replication, crossover and mutation in natural selection and inheritance. It determines the optimal or suboptimal solution through random search and has the advantages of simplicity, speed and strong robustness. In this section, we explain the specific steps of the genetic algorithm.

### *Coding*

When solving the problem using genetic algorithms, it is necessary to express the actual solution of the problem as a chromosome through coding. According to the characteristics of the problem, we adopt the natural number coding, and set the chromosome as the organisation mode of a train. The length of the chromosome corresponds to the total number of trains. Each chromosome gene can be assigned as {1,2}, which respectively represents the two organisation modes of passenger train piggyback and reserved passenger train. Taking the chromosome shown in *Figure 3* as an example, the first gene of this chromosome is 2, which indicates that train 1 adopts organisation mode 2 (reserved passenger train), and so on.

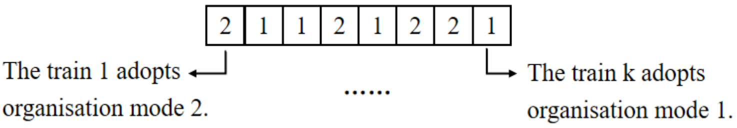

*Figure 3 – Coding*

### *Calculation of fitness*

In accordance with the principle of survival of the fittest, evolutionary algorithms must assess the fitness of individuals to ensure their survival in complex environments. Fitness is the measure of chromosome quality. According to the objective function of the model, we use total profit as the fitness, and consider the chromosome with high fitness to be of better quality. In order to calculate the fitness, it is necessary to know both the organisation mode of the train and the loading weight of service products on the path. The former is provided by the chromosomal genes and the latter is given through the loading rules of Section 4.2.

### *Selection operator*

The selection operation is carried out based on a comprehensive evaluation of the fitness values. Within a population, there is a certain degree of diversity among individuals. Therefore, the selection operation effectively promotes gene exchange and integration within the population. The primary objective of the selection operation is to pass on individuals with greater adaptability to the environment to the next generation, thus enhancing global convergence and computational efficiency, ultimately leading to better genetic results.

We utilise the roulette wheel strategy to perform the selection operation, input the fitness, and calculate the probability that it will be selected as the parent according to *Equation 20*. The more fit an individual is, the greater the probability of being selected.

$$P(x_i) = \frac{f(x_i)}{\sum_{j=1}^{N} f(x_j)} \tag{20}$$

In the above equation: $p(x_i)$ is the selection probability of individual for chromosome $x_i$ ( $i = 1,2,\ldots,N, N$) is the population size, $f(x_i)$ is the fitness of chromosome $x_i$.

### *Crossover operator*

Crossover operation refers to the exchange of genes between two matched chromosomes, resulting in the formation of two new individuals. This paper uses the two-point crossover operator. In the two-point crossover, genes between two randomly selected pairing points from the previous generation chromosome are exchanged, as shown in *Figure 4*, which illustrates the process of gene exchange between the selected points.

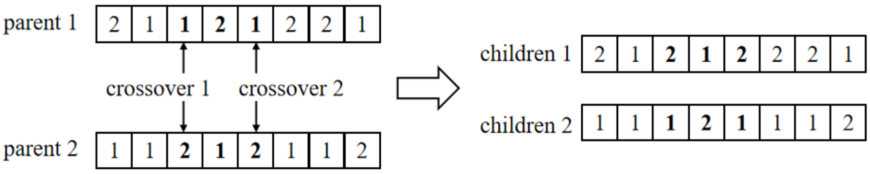

*Figure 4 – Two-point crossover operator*

### *Mutation operator*

To enhance the local search capability of the genetic algorithm, maintain population diversity and prevent premature convergence, a mutation operator needs to be employed. We use random single-point mutation. Random single-point mutation refers to the replacement of a gene at a certain position on a chromosome with a certain probability. In *Figure 5*, the seventh position of the parent chromosome is selected as the mutation point. The organisation mode 2 at this position is mutated to mode 1 and then passed on to the children.

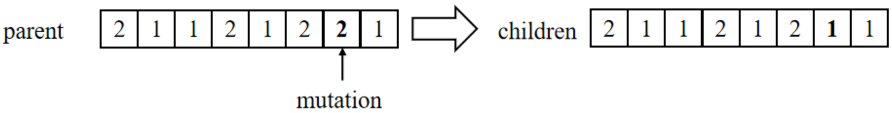

*Figure 5 – Single-point mutation operator*

*Termination condition*

The common termination conditions have iteration time, number of iterations and fitness value conditions, et al. This paper chooses the number of iterations as the termination condition, when the number of population generations reaches the maximum number of iterations, outputs the current optimal solution.

## 4.2 Cargo loading rules

The cargo loading rule aims to get the feasible loading scheme by taking the information of the organisation mode, the customer's delivery demand and HSR trains expressed by the genetic algorithm chromosome as inputs. The specific process is shown in *Figure 6*. Firstly, the information of the organisation mode, the customer's delivery demand and HSR trains expressed by the genetic algorithm chromosome is inputted. After that, the current service products, OD pairs and trains are selected to be loaded once according to the three loading rules. The feasibility of each selection is judged according to the three constraints, and the feasible loading scheme is then selected. This process continues until all the customer's delivery demands are met or trains are fully loaded.

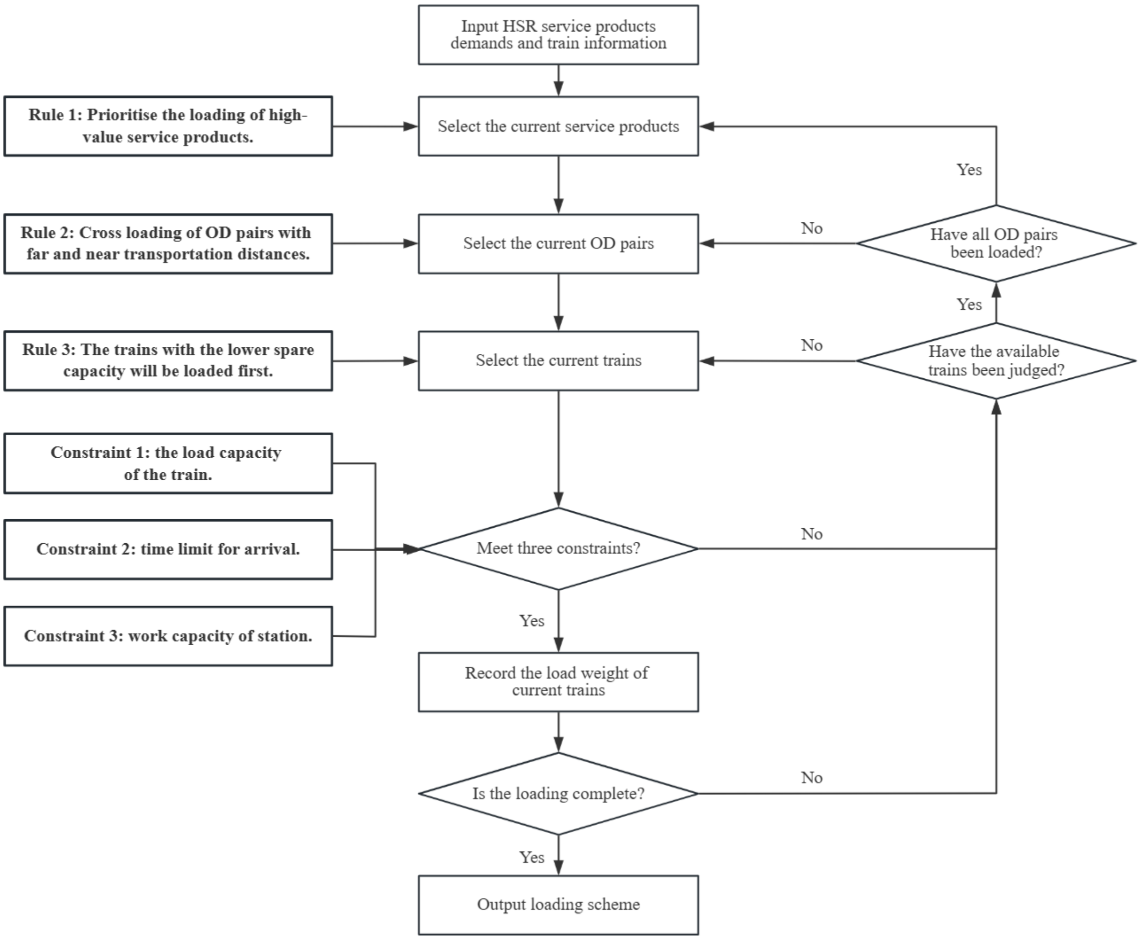

*Figure 6 – Loading process of service products*

The three service products loading rules used in this paper are as follows.

- Rule 1: Prioritise the loading of high-value service products. The higher the value of the service product, the higher the total revenue for the same amount of load.
- Rule 2: Cross-loading of OD pairs with far and near transportation distances. In the case of transporting service products of the same value and weight, the longer the transportation distance between OD pairs, the higher the total profit. However, prioritising the loading of OD pairs with long distances will result in the problems of lower overall loading capacity and difficulty in meeting the time requirements for transporting high-value products. Therefore, the service products are cross-loaded with long-distance and short-distance products.

— Rule 3: The trains with the lower spare capacity will be loaded first. By prioritising the loading of trains with lower spare capacity, it is possible to complete the loading task with fewer trains, increase the loading rate of trains, and thus increase the total profit.

Three constraints need to be met when deciding on the cargo carrying scheme of the HSR express.

First, time constraint. Different service products have different time windows. The arrival time of the train cannot be later than the required time of the service products.

Second, load constraints. The organisation mode of the train determines the maximum load capacity, and the load capacity constraints of the train should be met throughout the transportation process.

Finally, station loading capacity constraints. Since the cargo carrying of HSR express by capacity sharing mode is based on passenger trains, the staff need to finish cargo loading and unloading within the short dwell time of the trains on the station (usually 3~13 minutes). Therefore, the working capacity of the station determines the maximum loading and unloading capacity of the train during the dwell time.

## 5. ANALYSIS AND RESULT

In this paper, 22 stations of Xi'an-Chengdu HSR are used as the origin and destination stations for service products transportation, constituting a large-scale case. Five cities (Xi'an, Hanzhong, Guangyuan, Mianyang and Chengdu) are selected as a small-scale case to validate the feasibility of the model and algorithm, and conduct sensitivity analysis. The algorithmic programs for solving the cases in this paper were all run on a computer configured with an Intel(R) Core(TM) i5-8265U CPU @ 1.60GHz 1.80 GHz.

### 5.1 Model verification

Using the small-scale case as an example, the demand for HSR service products from the five cities of Xi'an, Hanzhong, Guangyuan, Mianyang and Chengdu is shown in *Table 4*. *Table 5* presents the timetables of the 54 trains from Xi'an to Chengdu [32]. In the table, blank space indicates that the train does not stop at the station of that city. Other parameters and values are shown in *Table 6* [35, 36].

*Table 4 – Demand of high-speed railway express service products (unit: kg)*

| **Origin station** | **Service product** | **Destination station** | | | |
|---|---|---|---|---|---|
| | | **Hanzhong** | **Guangyuan** | **Mianyang** | **Chengdu** |
| Xi'an | AT | 4,318 | 2,024 | 2,776 | 6,280 |
| | ANM | 10,630 | 4,984 | 6,836 | 15,460 |
| | AND | 9,302 | 4,362 | 5,982 | 13,526 |
| | ADAT | 8,970 | 4,206 | 5,768 | 13,044 |
| Hanzhong | AT | - | 414 | 408 | 854 |
| | ANM | | 1,018 | 1,004 | 2,102 |
| | AND | | 890 | 878 | 1,840 |
| | ADAT | | 858 | 848 | 1,774 |
| Guangyuan | AT | - | - | 444 | 744 |
| | ANM | | | 1,094 | 1,832 |
| | AND | | | 958 | 1,602 |
| | ADAT | | | 924 | 1,546 |
| Mianyang | AT | - | - | - | 2,048 |
| | ANM | | | | 5,042 |
| | AND | | | | 4,412 |
| | ADAT | | | | 4,254 |

*Table 5 – Part of Xi'an-Chengdu high-speed railway timetable*

| City | Xi'an | Hanzhong | | Guangyuan | | Mianyang | | Chengdu |
|---|---|---|---|---|---|---|---|---|
| **Train & timetable** | **departure** | **arrival** | **departure** | **arrival** | **departure** | **arrival** | **departure** | **arrival** |
| D1901 | 11:01 | 12:17 | 12:20 | 13:17 | 13:24 | | | 14:58 |
| D1903 | 18:21 | 19:37 | 19:39 | 20:34 | 20:38 | 21:30 | 21:32 | 22:15 |
| D1905 | 19:40 | 20:50 | 20:52 | 21:33 | 21:44 | 22:37 | 22:41 | 23:18 |
| D1917 | 09:00 | | | 10:48 | 10:52 | | | 12:17 |
| D1919 | 09:25 | 10:47 | 10:49 | 11:31 | 11:35 | 12:37 | 12:40 | 13:30 |
| D1931 | 12:32 | 13:54 | 13:57 | 14:40 | 14:45 | | | 16:28 |
| D1937 | 14:10 | 15:20 | 15:22 | 16:04 | 16:08 | 17:00 | 17:02 | 17:40 |
| D1939 | 14:30 | 15:47 | 15:49 | 16:43 | 16:50 | 17:57 | 17:59 | 18:37 |
| D1947 | 17:37 | 18:54 | 18:56 | 19:39 | 19:48 | 20:54 | 20:56 | 21:41 |
| D1971 | 07:43 | 12:17 | 09:01 | 09:42 | 09:46 | 10:39 | 10:41 | 11:24 |
| … | … | … | … | … | … | … | … | … |

*Table 6 – Related parameters and values*

| Parameters | | Values | Parameters | | Values |
|---|---|---|---|---|---|
| Maximum load capacity (kg) | Passenger train piggyback | 2,430 | Fixed cost (CNY) | Passenger train piggyback | 0 |
| | Reserved passenger train | 12,660 | | Reserved passenger train | 2,346.34 |
| Transfer cost (CNY/kg) | | 0.1 | Working capacity of the station (kg/min) | | 800 |
| Road vehicle load capacity (kg) | | 10,000 | Unit fuel consumption of fully loaded road vehicle (L/km) | | 0.390 |
| Carbon emission factor (kg/L) | | 2.61 | Unit carbon trading price (CNY/kg) | | 2 |

The maximum solution time is set as 2,000 s, and the Gurobi solver is called by Matlab R2023b to solve the case. *Table 7* presents the obtained HSR express cargo carrying scheme. According to the trains, the loading and unloading weight at the station and the adopted organisation mode, it can be seen that the cargo carrying scheme meets the constraints of the train load capacity. Furthermore, the loading and unloading weight is less than the station's working capacity, indicating that the model correctly expresses the realistic constraints.

*Table 7 – HSR express cargo carrying scheme (unit: kg)*

| **Train number** | **Xi'an** | **Hanzhong** | | **Guangyuan** | | **Mianyang** | | **Chengdu** | **The organisation mode of the HSR express** |
|---|---|---|---|---|---|---|---|---|---|
| | **loading** | **loading** | **unloading** | **loading** | **unloading** | **loading** | **unloading** | **unloading** | |
| D1901 | 2,430.00 | 1,270.00 | 1,270.00 | 0.00 | 1,576.00 | 0.00 | 0.00 | 854.00 | 1 |
| D1903 | 682.00 | 874.00 | 682.00 | 2,000.00 | 444.00 | 0.00 | 2,000.00 | 430.00 | 1 |
| D1905 | 9,000.00 | 1,000.00 | 0.00 | 3,377.24 | 1,809.64 | 0.00 | 4,000.00 | 7,567.60 | 2 |
| D1917 | 2,430.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2,430.00 | 1 |
| D1919 | 2,430.00 | 744.00 | 893.00 | 744.00 | 744.00 | 1,335.00 | 1,186.00 | 2,430.00 | 1 |
| D1931 | 860.00 | 1,570.00 | 0.00 | 1,000.00 | 1,000.00 | 0.00 | 0.00 | 2,430.00 | 1 |
| D1937 | 1,140.00 | 1,000.00 | 0.00 | 1,430.00 | 1,140.00 | 442.00 | 442.00 | 2,430.00 | 1 |
| D1939 | 616.04 | 2,430.00 | 616.04 | 430.00 | 430.00 | 0.00 | 2,000.00 | 430.00 | 1 |
| D1947 | 1,367.10 | 1,062.86 | 0.00 | 381.36 | 1,367.10 | 1,492.90 | 507.12 | 2,430.00 | 1 |
| D1971 | 7,586.30 | 2,000.04 | 0.00 | 0.00 | 2,586.30 | 0.00 | 2,000.04 | 5,000.00 | 2 |
| D1979 | 1,678.68 | 1,309.32 | 690.68 | 0.00 | 2,297.32 | 0.00 | 0.00 | 0.00 | 1 |
| D1997 | 1,430.00 | 1,000.00 | 0.00 | 0.00 | 0.00 | 1,000.00 | 1,000.00 | 2,430.00 | 1 |
| … | … | … | … | … | … | … | … | … | … |
| G307 | 4,095.80 | 0.00 | 634.40 | 0.00 | 0.00 | 0.00 | 1,622.70 | 1,838.70 | 2 |
| G387 | 2,430.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2,430.00 | 1 |
| G1281 | 2,430.00 | 468.54 | 822.60 | 822.64 | 468.54 | 392.64 | 1,607.40 | 1,215.28 | 1 |
| G685 | 2,430.00 | 0.00 | 2,430.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1 |
| G2851 | 11,750.00 | 773.96 | 1,375.00 | 0.00 | 0.00 | 0.00 | 3,149.00 | 7,999.96 | 2 |
| G2855 | 1,019.00 | 1,411.00 | 0.00 | 0.00 | 2,430.00 | 0.00 | 0.00 | 0.00 | 1 |
| G87 | 2,430.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2,430.00 | 1 |
| G1887 | 2,429.98 | 532.48 | 532.48 | 532.48 | 532.48 | 102.48 | 1,897.50 | 634.96 | 1 |
| G1975 | 2,430.00 | 0.00 | 0.00 | 0.00 | 0.00 | 68.32 | 68.32 | 2,430.00 | 1 |
| G1835 | 2,430.00 | 0.00 | 2,000.00 | 0.00 | 0.00 | 0.00 | 430.00 | 0.00 | 1 |
| G89 | 2,430.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2,430.00 | 1 |
| D1779 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2,430.00 | 0.00 | 2,430.00 | 1 |
| G8783 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 642.52 | 0.00 | 642.52 | 1 |
| D6855 | 2,430.00 | 0.00 | 2,430.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1 |
| D6857 | 2,430.00 | 0.00 | 2,430.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1 |
| D6859 | 2,430.00 | 0.00 | 2,430.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1 |
| D6863 | 1,000.00 | 0.00 | 1,000.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1 |
| D6865 | 2,430.00 | 0.00 | 2,430.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1 |
| D6867 | 2,430.00 | 0.00 | 2,430.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1 |
| D6869 | 2,430.00 | 0.00 | 2,430.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1 |

*Note: Passenger train piggyback is denoted by 1; reserved passenger train is denoted by 2*

## 5.2 Performance analysis of algorithms

An algorithm that uses the basic genetic algorithm framework and randomly determines the cargo loading order is referred to as a traditional genetic algorithm. Based on the traditional genetic algorithm, an algorithm that imposes a single loading rule is called a single-loading rule genetic algorithm. The same case is solved using the multi-loading rules genetic algorithm, single-loading rule genetic algorithm and traditional genetic algorithm, respectively. The parameters for the small-scale case are set as follows: initial population size is 50, crossover probability is 0.75, mutation probability is 0.1 and the maximum iterations are 200. Under the same algorithm parameters and iterations, the performances of different algorithms for small-scale cases are shown in *Figure 7*. It can be observed from the figure that the schemes obtained by the single-loading rule genetic algorithm are better than the traditional genetic algorithm. Meanwhile, the multi-loading rules genetic algorithm is significantly better than the single-loading rule genetic algorithm and the traditional genetic algorithm in terms of the quality of the optimal solution and the convergence speed of the algorithm. The maximum number of iterations is set to 100 for the large-scale case, and the other algorithm parameters are kept the same as the small-scale case. Using the same method to analyse the performances of different algorithms for solving the large-scale case, the results are shown in *Figure 8*, and it is found that the advantage of the genetic algorithm with multi-loading rules also holds.

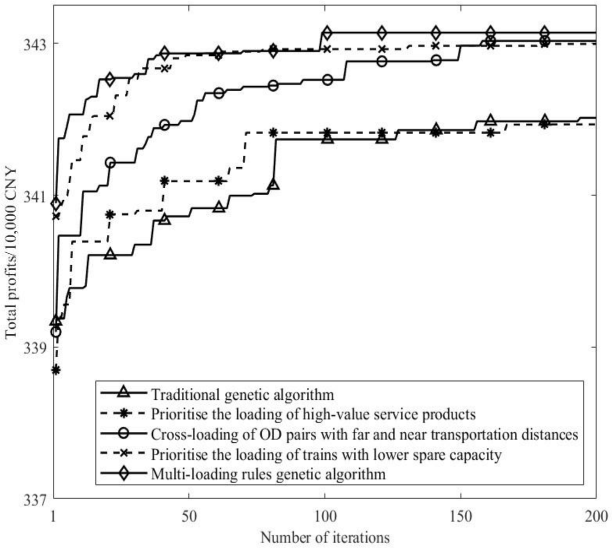

*Figure 7 – Performances of small-scale case*

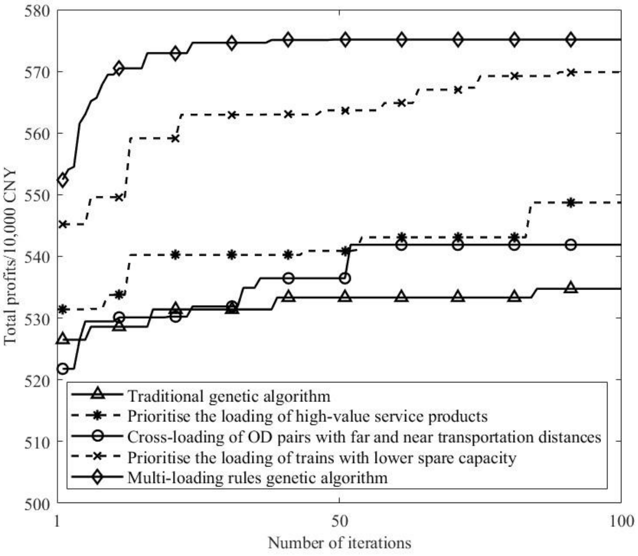

*Figure 8 – Performances of large-scale case*

*Table 8* presents the solution results obtained using the multi-loading rules genetic algorithm and the Gurobi solver. For the small-scale case, the total profit obtained after 100 iterations of the multi-loading rules genetic algorithm is better than that of Gurobi, and the solution time is only about 1/6 of that of Gurobi. The total revenues of both methods are the same. However, the fixed costs and variable costs of the genetic algorithm with multi-loading rules are respectively 61.64% and 2.34% lower than those of Gurobi. This also makes the total profit obtained by the genetic algorithm with multi-loading rules 23,000 RMB higher. When the case size is increased to 22 cities, Gurobi is unable to find an effective solution in 24 h, but the genetic algorithm with multi-loading rules is able to obtain a carrying scheme in 90 min. By comparison, the multi-loading rules genetic algorithm performs better than Gurobi in both the small-scale case and the large-scale case.

In summary, the multi-loading rules genetic algorithm proposed in this paper outperforms both the traditional genetic algorithm and the single-loading rule genetic algorithm. Furthermore, it is more effective than the Gurobi solver in solving the cargo carrying problem of HSR express transportation based on capacity sharing.

*Table 8 – Results comparison of Gurobi and genetic algorithm with multi-loading rules*

| **Comparison item** | **Small-scale case** | | | **Large-scale case** |
|---|---|---|---|---|
| | **Gurobi** | **Genetic algorithm with multi-loading rules** | **Gap / %** | **Genetic algorithm with multi-loading rules** |
| Total profit (ten thousand CNY) | 340.84 | 343.14 | 0.67 | 575.14 |
| Transportation revenues (ten thousand CNY) | 367.37 | 367.37 | 0.00 | 615.52 |
| Carbon trading revenues (ten thousand CNY) | 1.33 | 1.33 | — | 1.86 |
| Fixed costs (ten thousand CNY) | 3.05 | 1.17 | -61.64 | 6.57 |
| Variable costs (ten thousand CNY) | 24.81 | 24.23 | -2.34 | 35.16 |
| Transfer costs (ten thousand CNY) | 0.00 | 0.15 | — | 0.51 |
| Fulfilment rate of service product demand / % | 100.00 | 100.00 | 0.00 | 83.53 |
| Solving time | 2,000s | 340.13s | -82.99 | 82.5min |

## 5.3 The sensitivity analysis

This section analyses the station working capacity and train transfer, respectively, and studies their impact on HSR revenue. The findings aim to assist HSR express in optimising the cargo carrying decision-making mode.

### *Station working capacity analysis*

This paper studies the effect of station working capacity on the HSR express cargo carrying scheme. By setting different working capacities of stations, the cargoes carrying results of the small-scale case are shown in *Figure 9*. When the working capacity is less than 400 kg/min, the total profit and the fulfilment rate of express demands both increase with the working capacity of the station. This is because the low station working capacity limits the amount of cargo that can be loaded and unloaded during the train's dwell time at the station. As a result, this leads to lower cargo loads on trains and reduces total revenues, which is unable to meet demands for HSR express transportation. When the station working capacity is up to 400 kg/min, the fulfilment rate of HSR express demands reaches 100%. The total profit increases slightly when the station's working capacity is increased to 700 kg/min. This is due to the fact that, with the same cargo transportation demands, a higher station working capacity enables the maximised utilisation of the carrying capacity of the trains. Consequently, fewer trains are required to meet the cargo transportation demands. The total profit is maximum at 700 kg/min of station working capacity, and it does not improve when the working capacity of the station is further increased.

Therefore, the working capacity of the station affects the fulfilment rate of cargo transportation demands and the total profit of HSR. If the cargo carrying demand is not fully met and there is still spare transportation capacity, more demands can be accomplished by increasing the working capacity of the station. When the demand for express transportation is constant, appropriately increasing the working capacity of stations can reduce the number of trains needed and increase the total profit of HSR.

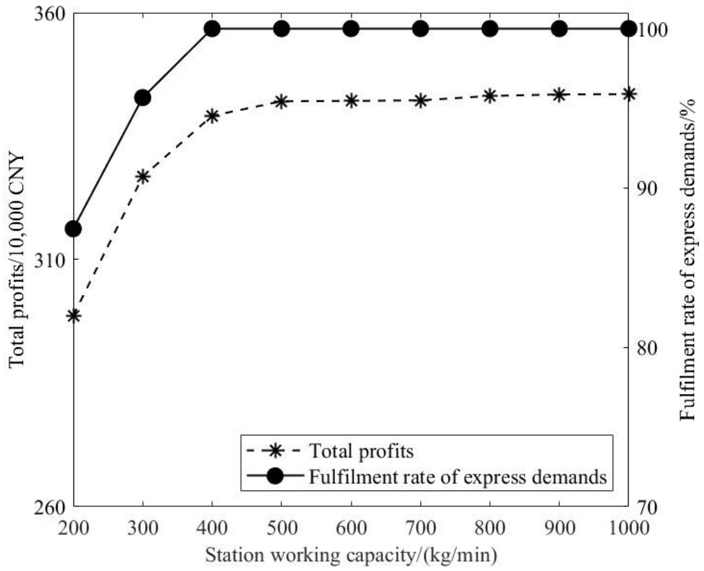

*Figure 9 – Load results for different working capacities of the station*

*Analysis of train transfer*

This section validates the impact of transfer paths on HSR cargoes carrying schemes. To provide a clearer comparison of how the inclusion of transfer paths improves transportation capacity, a large-scale case is used, where express demands are not fully satisfied. The comparison is made between two scenarios under the same parameters and solution methods: one considering only direct paths and the other considering both direct paths and transfer paths. The results of this comparison are shown in *Table 9*, demonstrating the effect of incorporating transfer paths on improving cargo transportation capacity and meeting higher demand. It is observed that the total number of feasible paths increases by 10 times after considering train transfer, making the solution space even larger and requiring longer solving time. Compared to only considering direct paths, the completion rate of express demand increases by 1.11% and a 0.51% increase in total profit when both direct and transfer paths are considered. This proves that considering train transfer can contribute to the maximised utilisation of transport capacity and enhance revenue. However, it substantially increases the number of feasible paths, which in turn prolongs computation time.

*Table 9 – Comparison of considering transfer paths for the large-scale case*

| **Comparison item** | **Direct paths** | **Direct paths and transfer paths** | **Gap / %** |
|---|---|---|---|
| Total number of feasible paths | 1,069 | 11,500 | 975.77 |
| Total profit (ten thousand CNY) | 572.25 | 575.14 | 0.51 |
| Transportation revenues (ten thousand CNY) | 608.62 | 615.52 | 1.13 |
| Carbon trading revenues (ten thousand CNY) | 1.84 | 1.86 | 1.09 |
| Fixed costs (ten thousand CNY) | 3.75 | 6.57 | 75.20 |
| Variable costs (ten thousand CNY) | 34.46 | 35.16 | 2.03 |
| Transfer costs (ten thousand CNY) | 0.00 | 0.51 | — |
| Fulfilment rate of service product demand / % | 82.60 | 83.53 | 1.11 |
| Solving time (min) | 4.28 | 82.50 | 1,827.57 |

## 6. CONCLUSIONS

The purpose of this paper is to utilise the existing HSR capacity to provide a decision-making model for cargo carrying scheme, in which we consider carbon trading and HSR transportation capacity sharing. The main work and findings are as follows.

1) This study incorporates the carbon trading into HSR express transportation under passenger train piggyback and reserved passenger train. A cargo carrying decision-making model is developed, considering constraints such as transportation demand, service product time window, load capacity of HSR and work capacity of stations, to maximise the utilisation of HSR capacity. By including carbon trading revenue in the optimisation objective, the study demonstrates the potential of carbon trading policies to enhance the profitability of transportation enterprises. It also promotes greater adoption of HSR by logistics companies, reducing reliance on high-emission road transport. The research facilitates the green transformation of the transportation structure, achieving mutual benefits for both HSR operators and logistics enterprises.
2) We design a multi-loading rules genetic algorithm by integrating genetic algorithms with loading rules to reduce solution complexity. Comparative experiments compare the multi-loading rules genetic algorithm, traditional genetic algorithm, single loading rule genetic algorithm and Gurobi on cases of varying scales. The results confirm the validity of the three loading rules. The study shows that the proposed algorithm should significantly outperform the single loading rule and traditional genetic algorithms in terms of solution quality and convergence speed. Additionally, it can perform better than Gurobi in both small-scale case and large-scale case, demonstrating strong overall optimisation capability.
3) The proposed cargo carrying decision-making model for HSR express and the multi-loading rules genetic algorithm apply to various scenarios, including capacity sharing modes, freight dedicated modes, single routes, HSR networks, as well as single-direction and bi-directional cargo loading. In the case study of the Xi'an-Chengdu HSR, sensitivity analysis on station working capacity and train transfer validates the model's flexibility and practicality. The study shows that increasing station working capacity alleviates loading constraints, while transfer paths can enhance HSR capacity utilisation and express freight fulfilment rates; however, transfer paths significantly increase computation time. The findings provide support for the design of HSR cargo loading plans and establish a solid foundation for shifting e-commerce and express cargo from road to HSR.

## ACKNOWLEDGEMENTS

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