# Optimization of Urban Rail Passenger and Freight Collaborative Transport Scheme under The Dual-Carbon Objective

Zunzun Hou, Ruichun He, Chengning Liu, Cunjie Dai

*Abstract*—**Regarding alleviating urban traffic pressure and conserving environmental energy, it is essential to utilize the redundant capacity of urban rail transit during non-peak hours for passenger-freight collaborative transportation. In order to achieve the "dual carbon" goals in urban rail transit, a study has been conducted on the coordinated transportation of passengers and goods, which can adapt to the evolving carbon emission policies. A method for calculating the waiting time that allows passengers to queue for a second time has been proposed by studying the queue of passengers. A multi-objective optimization model for urban rail transit passenger-freight collaborative transportation has been constructed, with the objectives of minimizing carbon emissions and passenger waiting time, considering constraints such as carbon emission policy, train operation safety, passenger and freight loading balance, and train formation scheme. An improved non-dominated sorting genetic algorithm (NSGA-II) has been designed to deal with the complexity of solving the multi-objective model. The algorithm utilizes the filtering function of the constraint conditions during the initial population generation process, effectively balancing the relationship between the filtering and time consumption of the NSGA-II algorithm. Taking the Wuxi Metro Line 3 as an example for analysis, the results show that: ① Although the average passenger waiting time increases by about 0.53 minutes in this method, the carbon emissions of the trains decrease by approximately 21.3%. Meanwhile, the average seating rate of the optimized solution is 5%~15% higher than the traditional transportation scheme used by Wuxi Metro Line 3. The superiority of urban rail transportation for passenger-freight collaborative transportation has been verified. ② With the mandatory control of carbon emission control, the passenger-freight collaborative optimization scheme is not affected by different carbon emission limits. Under the carbon tax policy, transportation schemes are less affected by different carbon tax levels. Transportation schemes remain consistent under the different limits of carbon trading policies. The proposed model and algorithm provide decision-making support for urban rail transit operators to optimize transportation plans under different carbon emission policies.**

Manuscript received February 5, 2024; revised May 24, 2024.

This work was supported in part by Young-Doctor Found Project of Gansu Province Higher Education (No. 2022QB-065) and Natural Science Foundation of Gansu Province(23JRRA858).

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*Index Terms* — **Urban rail transit, coordination transportation, Mixed-integer model, Carbon emission policy, NSGA-II**

## I. Introduction

Urban rail transport has the characteristics of large capacity, low emission, and low transport cost, which has a good effect on alleviating the pressure of ground transport and responding to the appeal of "carbon emission reduction." [1] pointed out that it is feasible to make full use of the redundant capacity of metro lines during off-peak hours to develop an underground logistics network with coordinated metro transport. [2] demonstrated the feasibility and advantages of underground logistics distribution based on the simulation model of events and the practice of the Newcastle Metro section. [3] Moreover, [4] respectively studied based on the determination of the demand of the established passenger mixed freight train sets and high-speed rail express train form of the optimization of the operation scheme for rail transport freight research provides a reference. [5] studied the train schedule optimization of increasing the number of specialized trains for freight transport. [6] studied the train schedule optimization problem using the remaining space of passenger cars. [7] studied the train stop program and train timetable based on two forms of passenger and freight trains and specialized freight trains. [8] analyzed the co-optimization problem of passenger and freight car layout and flow management in the metro by taking the minimum weighted sum of operating costs and total delay penalties as the objective. [9] the co-optimization of train formation and passenger and freight transport under flexible formation conditions was considered to obtain the operating map, train formation scheme, and passenger and freight co-optimization scheme for achieving system optimization. [10] studied the problem of inserting freight trains under fixed passenger trains to optimize the train timetable and stopping scheme. [11] studied the optimization model of passenger and freight co-transportation on airport express with two freight forms, passenger and freight co-transportation, and special freight train, to maximize the net freight surplus. [12] developed a co-transportation model combining passenger and freight by setting up freight cars at both ends of passenger trains as the research object, and quantitatively analyzed the actual performance of the logistics function in the metro system while making assumptions on the uncertainties. None of the above studies considered the train carbon emission target, [13] assessed the carbon emissions in the operation phase of the urban rail transit system, and the study showed that the carbon emissions generated in the operation phase accounted for 82% of the system. The train and station carbon emissions accounted for 50% and 42%, respectively. [14] established a calculation model with the VB program for carbon emissions from vehicles and stations during the operation phase of urban rail transport. [15] Constructed the optimization scheme for large and small interchanges to reduce passenger travel costs, train carbon emissions, and corporate operating costs. [16] proposed the minimum waiting time for passengers and goods and the minimum energy consumption of train operation as the dual objectives and constructed an optimization model of mixed passenger and freight operation to optimize the energy consumption of urban rail transit.

The main contributions of this study are as follows: under the "dual-carbon" objective, to adapt to the differences in carbon emission policies, this paper investigates the passenger and freight co-transportation optimization of urban rail transit dominated by the low-carbon objective and adapts to different carbon emission policies. The comparison of the research problems and models constructed in this paper with those in the related literature is shown in Table I.

TABLE I
DEFINITION OF SYMBOLS AND PARAMETERS

| Symbols & Parameters | Definition |
|---|---|
| $S=\{1,2,...,i,...,j,...,S^n\}$ | The set of stations, $S^n$ is the total number of stations, and $i, j$ are the station indices. |
| $K=\{1,2,...,i,...,j,...,K^n\}$ | The set of trains, $K^n$ is the total number of trains and $k$ is the index of trains. |
| $S^{(F)}$ | Alternative collection of stations that can handle freight services |
| $T=\{1,2,...,t,...,T^n\}$ | The set of discrete time slots $t$ is the time slot identifier and $T^n$ is the total number of discrete time slots. |
| $\sigma$ | Length of discrete time intervals |
| $R_k^i$ | Running time of train $k$ between stations $i$ and $i+1$ |
| $h_k^{(\max)}, h_k^{(\min)}$ | Maximum and Minimum of safe departure intervals between train $k$ and $k+1$ |
| $E_p, E_q$ | Carbon Emission Factors for rail passenger transportation and freight transportation |
| $F^P, F^q$ | Rated passenger capacity per unit of passenger carriage and rated freight capacity per unit of freight carriage |
| $p_{i,j}^{(d)}(t), q_{i,j}^{(d)}(t)$ | Passenger and freight flow demand from station $i$ to station $j$ arriving in time $t$ |

## II. PROBLEM DESCRIPTION

Th research object of this paper is an urban rail transit line, which is not saturated with passengers; considering the time-varying demand of passenger flow, there are both passenger and freight demands along the line. Any station can handle passenger operation, but only some stations can handle freight business; train cars can provide services for passengers and goods, taking the transition period from off-peak hour to peak hour as the time domain, carrying out collaborative passenger and freight transport, and giving priority to meeting passenger demand. The primary considerations are the train coupling scheme and train departure interval decision, the distribution of passengers and goods in train carriages, with the optimization objective of minimum passenger waiting time and carbon emission, and consideration of passenger queuing in the actual operation process to reduce the waste of transport capacity.

## III. MODEL COSTRUCTION

### A. Model Assumption

To construct a rigorous mathematical optimization model, the following basic assumptions are given in this paper for the cooperative passenger and freight transportation optimization problem: To construct a rigorous mathematical model, this paper needle to make the following basic assumptions.

Assumption 1: The quantity of passenger and freight demand is known, the total demand for passenger and cargo flow will not change.

Assumption 2: All the carriages have the exact specifications, with the same load capacity and power-consuming equipment and facilities.

Assumption 3: Passenger carriages and freight carriages are independent of each other. No goods are transported in passenger carriages in the entire journey, and no passengers are transported in freight carriages.

The symbols and parameters involved in this paper and their related definitions are shown in Table 2.

The decision variables and intermediate variables required to construct the model are as follows:

$h_k$ —decision variable, train departure interval, denotes the departure interval between the front train $k$ and the rear train $k+1$, min;

$\alpha_k^i(t)$ —0-1 variable, indicates whether train $k$ has departed from station $i$ at moment $t$, 1 if yes and 0 otherwise;

$A_k^i$ —train arrival moment, indicates the moment when train $k$ arrives at station $i$;

$D_k^i$ —train departure moment, indicates the moment when train $k$ leaves station $i$;

$\xi_i$ —0-1 decision variable, indicates carbon emission policy selection, $i=1,2,3$, respectively representing mandatory carbon emission limitation policy, carbon tax policy, and carbon trading policy;

$n_k^i$ —0-1 decision variable, indicates the type of train group, with 1 being the large group type and 0 being the small group type;

$\alpha,\beta$ —percentage of passengers and freight in transportation programs;

$L_k$ —total length of intersections for trains $k$;

$\theta$ —brightness of lamps and air-conditioning intensity in freight cars;

$t_n$ —total length of study period;

$t_y$ —operating hours;

$E_t$ —percentage of carbon emissions from train operations;

$U_t$ —corporate carbon allowance;

$\phi$ —carbon tax collected by the government for each unit of carbon emissions produced by a company;

$U_s$ —carbon credits for enterprises under the carbon trading policy;

$\vartheta$ —carbon credits for enterprises under the carbon trading policy;

$Q_s$ —carbon emission credits to be purchased by enterprises under the carbon trading policy;

$n_k^{(p)}, n_k^{(q)}$ —decision variables, the total number of passenger carriages and the total number of freight cars assigned to train $k$;

$T_k^{\mathrm{i}}$ —critical boarding moment for passengers boarding train $k$ at station $i$;

$m_k$ —the total number of carriages in the coupling of train $k$;

$\alpha_k^i(t)$ —0-1 decision variable, indicates whether train $k$ has departed from station $i$ at time $t$. 1 if yes and 0 otherwise;

$p_i^{(w)}(t)$ , $q_i^{(w)}(t)$ —the number of passengers and freight arrived in station $i$ at moment $t$, people or boxes;

$C_{k,i}^{(p)}, C_{k,i}^{(q)}$ —maximum passenger transport capacity and freight transport capacity after passengers are disembarked and freight is unloaded when train $k$ arrives at station $i$;

$U_{k,i}^{(p)}, U_{k,i}^{(q)}$ —the number of passengers boarded and freight loaded when train $k$ is at station $i$, people or boxes;

$P_{k,i}^{(p)}, P_{k,i}^{(q)}$ —the number of passengers boarded and freight loaded when train $k$ is leaving station $i$, people or boxes;

$X_{k,i}^{(p)}, X_{k,i}^{(q)}$ —The number of passengers disembarked and unloaded train $k$ arrives at station $i$, people or boxes;

$P_{k,i,j}^{(q)}$ —The loading quantity of train $k$ when leaving station $i$ for station $j$, boxes;

$PC_{sub}$ —The power consumption of train operation during urban rail operation, including the power consumption of train traction and the power consumption of ventilation and air-conditioning, lighting, and signal systems.

*B. Objective Function*

The line with no saturated passenger flow is usually unable to send trains with high frequency, and passengers generally must wait for the train.

After the train arrives at the station and the passengers get off, the remaining passenger capacity of the train determines the critical time when the passengers can board the train. If the passenger arrives at the station earlier than or equal to the critical time, the train can board the train. As shown in (1).

$$\begin{cases} T_k^{\mathrm{i}} = D_k^{\mathrm{i}}, & \sum_{i<j} \sum_{t \in \left[T_{k-1}^i, D_k^i\right]} p_{i,j}^{(d)}(t) \le C_{k,i}^{(p)} \\ T_{\mathrm{k}}^i = \max\left\{ h \middle| \sum_{i<j} \sum_{t \in \left[T_{k-1}^i, h\right]} p_{i,j}^{(d)}(t) \le C_{k,i}^{(p)} \right\}, & \sum_{i<j} \sum_{t \in \left[T_{k-1}^i, D_k^i\right]} p_{i,j}^{(d)}(t) > C_{k,i}^{(p)} \end{cases}, \forall k \in K \setminus \{|1|\} \tag{1}$$

For the passengers who arrive at station $i$ on the time $t$ when their arrival moment is between the critical moment of boarding the previous train $T_{k-1}^i$ and the critical moment of boarding of the current arriving train $T_k^i$. The passengers will take the current arriving train $k$ when their arrival moment is later than the critical moment $T_k^i$, they will continue to wait for the train $k+1$. Since this paper introduces the integer discrete time lengths, the total passenger waiting time is the product of the number of waiting passengers in the set of all discrete time intervals and the length of the unit discrete intervals. As shown in (2).

$$F_1 = \sum_{t \in \left[T_{k-1}^i, T_k^i\right]} \sum_{i<j} \sum_{k \in K} p_{i,j}^{(d)}(t) \cdot \sigma \tag{2}$$

Train carbon emission during the operation of urban rail transit system is included in the optimization objectives, the carbon emissions during the operation of the train, which can be optimized are mainly concentrated in the subway train traction, ventilation and air conditioning, lighting, signaling system and other impacts, in the coordinated transportation of passengers and freight under the conditions of the freight in the premise that does not affect its transportation and counting operations, through the reduction of the number of train lighting equipment used in the way to reduce the freight carriages of the carbon emissions generated by [15], can effectively promote the construction of the Green Traffic, so the train carbon emissions can be expressed as a sum of the carbon emissions of the passenger compartment and the freight carriages. As shown in (3).

$$Ce = PC_{sub} \cdot \alpha \cdot E_p + PC_{sub} \cdot \beta \cdot E_q \tag{3}$$

The passenger ratio $\alpha$ can be expressed as the ratio of the total number of passenger carriages to the total number of carriages in the transport scheme, and the same applies to the freight ratio $\beta$.

$$\alpha = \frac{\sum_{k \in K} n_k^{(p)}}{\sum_{k \in K} m_k} \tag{4}$$

$$\beta = \frac{\sum_{k \in K} n_k^{(q)}}{\sum_{k \in K} m_k} \tag{5}$$

The power consumption of a train during operation can be expressed as the product of the work done by the train during operation and the sum of the electrical power of the train's air-conditioning, lighting, and signal systems and the running time.

$$PC_{sub} = (P_F + P_{de}) \cdot \sum_{k \in K} \sum_{i \in S} (R_k^i + S_k^i) \tag{6}$$

The work done by the train during operation is calculated by (9) [18], and the electric power of train air-conditioning, lighting, and signal systems is calculated by (10).

$$F_\mu = P_\mu \cdot g \cdot (0.24 + \frac{12}{100 + 8v}) \tag{7}$$

$$\omega_0 = \rho_1 + \rho_2 \cdot v + \rho_3 \cdot v^2 \tag{8}$$

$$P_F = \left(F_\mu + \omega_0 \cdot P_\mu \cdot g\right) \times \sum_{k \in K} m_k \cdot L_k \Big/ 3\,600 \tag{9}$$

$$P_{de}=\frac{(\sum_{k\in K}n_k^{(p)}+\theta\cdot\sum_{k\in K}n_k^{(q)})(40\cdot\rho_{air}+6\cdot S_{ve}\cdot Te+2\cdot 230)}{3600} \quad (10)$$

Carbon emission policies vary across time and regions. Under the policy of mandatory limitation of carbon emissions, the government requires enterprises to emit carbon within a certain limit $U_t$, and the cost of carbon emissions within the quota is a fixed value $Ce_1$; under the policy of carbon tax, the government levies a carbon tax $\phi$ at a fixed rate on the unit of carbon emissions generated by enterprises; under the policy of carbon trading, if carbon emissions exceed the limit, it is necessary to purchase emission credits separately, and the saved carbon credits can be sold to the outside world. The paper introduces the 0-1 decision variable. The 0-1 decision variable $\xi_i$ is introduced to ensure a single carbon emission policy context so that cost of carbon emission can be expressed as

$$F_2=Ce_1\cdot\xi_1+Ce\cdot\xi_2\cdot\phi+Ce\cdot\xi_3\cdot\left[(-\vartheta\cdot\varpi)+(1-\varpi)\cdot\vartheta\right] \quad (11)$$

*C. Model Constraints*

(1) Train travel-related constraints

(12) constructs the correlation constraints between the remaining passenger loading capacity after the train arrives at the station and completes the passenger boarding and unloading and the passenger flow on and off the train. (13) ensures that the number of boarding passengers at the station is less than the remaining passenger loading capacity of the train. (14) and (15) construct the loading constraints for boarding and alighting passenger flows, where the train has no passenger boarding or alighting at the originating station, the number of boarding passengers at other stations is the total number of arriving passengers between the passengers boarding the preceding train and the train's critical boarding moments, and the number of alighting passengers is the total number of passengers boarding the train's preceding train at the stations with the destination of that station.

$$C_{k,i}^{(p)}=\begin{cases}F^p\cdot n_k^{(p)}, i=1,S^{(n)}\\ C_{k,i-1}^{(p)}-U_{k,i-1}^{(p)}+X_{k,i}^{(p)},\ \ others\end{cases} \quad (12)$$

$$U_{k,i}^{(p)}\le C_{k,i}^{(p)},\forall k\in K,\forall \mathrm{i}\in S \quad (13)$$

$$U_{k,i}^{(p)}=\begin{cases}0, i=S^{(n)}\\ \sum_{\mathrm{i<j}}\sum_{T_{k-1}^{\mathrm{i}}}^{T_k^i}p_{i,j}^{(d)}(t), others\end{cases} \quad (14)$$

$$X_{k,i}^{(p)}=\begin{cases}0, i=1\\ \sum_{\mathrm{i<j}}\sum_{T_{k-1}^{i}}^{T_k^i}p_{j,i}^{(d)}(t), others\end{cases} \quad (15)$$

$$\alpha_k^i(t)=\begin{cases}1, \mathrm{t}\ge D_k^i\\ 0, others\end{cases},\forall k\in K,\forall i\in S \quad (16)$$

$$\alpha_k^i(t)\ge\alpha_k^i(t-1) \quad (17)$$

(16) and (17) construct the train departure 0-1 variable and its non-decreasing properties. (18) constructs the correlation constraint on the number of passengers waiting at a station, where the number of passengers waiting at the station $i$ at the moment $t$ is equal to the sum of the number of passengers waiting at moment $t-1$ and the number of arriving passengers at the moment $t$ minus the number of boarding and departing passengers. As with the passenger loading process, (19) ensures the need to complete all cargo transport.

$$p_i^{(w)}(t)=\begin{cases}\sum_{i<j}p_{i,j}^{(d)}(t), t=0\\ p_i^{(w)}(t-1)+\sum_{i<j}p_{i,j}^{(d)}(t)-\sum_{k\in K}U_{k,i}^{(p)}\cdot\alpha_{k,i}(t), t\ne 0\end{cases} \quad (18)$$

$$\sum_{k\in K}P_{k,i,j}^{(q)}=\sum_{i<j}\sum_{T_{k-1}^{i}}^{T_k^i}q_{i,j}^{(d)}(t) \quad (19)$$

(20) and (21) construct the constraints on the amount of freight loaded and freight unloaded after the train arrives at the station, and (22) is the freight on-board transport constraints. (23) describes the constraints between the train's cargo capacity and the formation type. (24) ensures that the amount of cargo loaded on the train at the station cannot exceed the remaining cargo transport capacity of the train.

$$U_{k,i}^{(q)}=\begin{cases}0, i=|S|\\ \sum_{\mathrm{i<j}}\sum_{T_{k-1}^{i}}^{T_k^i}q_{i,j}^{(d)}(t), others\end{cases} \quad (20)$$

$$X_{k,i}^{(q)}=\begin{cases}0, i=1\\ \sum_{\mathrm{i<j}}\sum_{T_{k-1}^{i}}^{T_k^i}q_{i,j}^{(d)}(t), others\end{cases} \quad (21)$$

$$P_{k,i}^{(q)}=\begin{cases}P_{k,i}^{(q)}, i=1\\ P_{k,i-1}^{(q)}-X_{k,i}^{(q)}+U_{k,i}^{(q)}, others\\ 0, i=|S|\end{cases} \quad (22)$$

$$C_{k,i}^{(q)}=\begin{cases}F^q\cdot n_k^{(q)}, i=1,S^{(n)}\\ C_{k,i-1}^{(q)}-U_{k,i-1}^{(q)}+X_{k,i}^{(q)},\ \ others\end{cases} \quad (23)$$

$$U_{k,i}^{(q)}\le C_{k,i}^{(q)},\forall k\in K,\forall \mathrm{i}\in S \quad (24)$$

As with the passenger loading process, (25) ensures the need to complete all cargo transport. (26) and (27) construct the constraints on the amount of freight loaded and freight unloaded after the train arrives at the station, and (28) is the freight on-board transport constraints. (29) describes the constraints between the train's cargo capacity and the formation type. (30) ensures that the amount of cargo loaded on the train at the station cannot exceed the remaining cargo transport capacity of the train.

$$h_k^{(\min)}\le h_k\le h_k^{(\max)},\forall k\in K \quad (25)$$

$$h_k=D_{k+1}^1-D_k^1 \quad (26)$$

$$A_k^i=A_k^1+\sum_{u=1}^{i-1}R_k^u+\sum_{u=1}^{i-1}S_k^u \quad (27)$$

$$D_k^i=A_k^i+S_k^i,\forall k\in K,\forall i\in S \quad (28)$$

$$m_k=6\cdot n_k+3\cdot(1-n_k^i),\forall k\in K \quad (29)$$

$$0\le n_k^{(\mathrm{q})}\le m_k,\ \ \forall k\in K \quad (30)$$

(31) ensures that only one carbon emission policy can be selected in the model. (32) is the carbon emission limit

constraint under the mandatory carbon emission limitation policy and $M$ is a maximal constant. (33) is a set of mutually exclusive constraints that constructs the sell and buy quota constraints under the carbon trading policy. (34) constructs an indicator variable for whether a firm is over-exceeding its quota under the carbon trading policy.

$$\sum_{i=1}^{4}\xi_i = 1 \tag{31}$$

$$F_2 \le U_t \cdot E_t \cdot \frac{t_n}{t_y} \cdot \frac{1}{2} \cdot \xi_1 + (1-\xi_1) \cdot M \tag{32}$$

$$\begin{cases} (Ce - Q_s) \cdot \xi_3 \cdot \varpi = U_s \cdot \xi_3 \cdot \varpi \\ (Q_s - Ce) \cdot \xi_3 \cdot (1-\varpi) = U_s \cdot \xi_3 \cdot (1-\varpi) \end{cases} \tag{33}$$

$$\varpi = \begin{cases} 1, Ce \le Q_s \\ 0, Ce > Q_s \end{cases} \tag{34}$$

### *D. Algorithm Design*

The model constructed in this paper is a multi-objective planning model with conflicting objectives, so the improved NSGA-II algorithm is applied to solve the model. Because the model constructed in this paper is a mixed integer planning model, the traditional NSGA-II algorithm cannot adapt to this model well, so the algorithm is partially improved, mainly for the design of chromosome coding and initial population generation. The improved algorithm can save about 1276s of computation time.

The algorithm is designed with a chromosome length of $3*K^{(n)}$, and each 3-bit code represents the design of the relevant parameters of a train. The first bit is a binary code, indicating the type of train formation; the second and third bit is a decimal code, respectively, indicating that the train and the previous sequence of car departure intervals in the number of freight cars allocated to the train. As shown in Fig. 1.

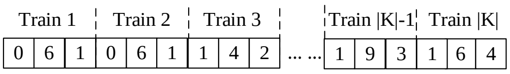


Fig.1. Chromosome coding design

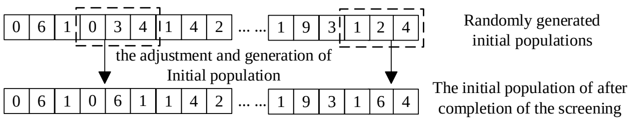


Fig.2. Initial population screening

The first round of screening of individuals is performed at the time $o(t)$ generating the initial population, and some of the constraints are incorporated into the process to improve the algorithm's efficiency. First of all, randomly generate the initial population of size $npop$, will not meet the constraints of the population individuals screened out of the population, again randomly generating the same number of individuals, assuming that the number of individuals sifted for $m$ times is $nc_m(nc_m \le npop)$, then the $m$ times screening randomly generate $nc_m$ individuals different from the population that has been generated from the initial population. Repeat the above steps until the number of populations after screening is completed, then the initial population generation is complete. As shown in Fig. 2.

The flowchart of the improved NSGA-II algorithm is shown in Fig.3 and the parameter settings are shown in Table II.

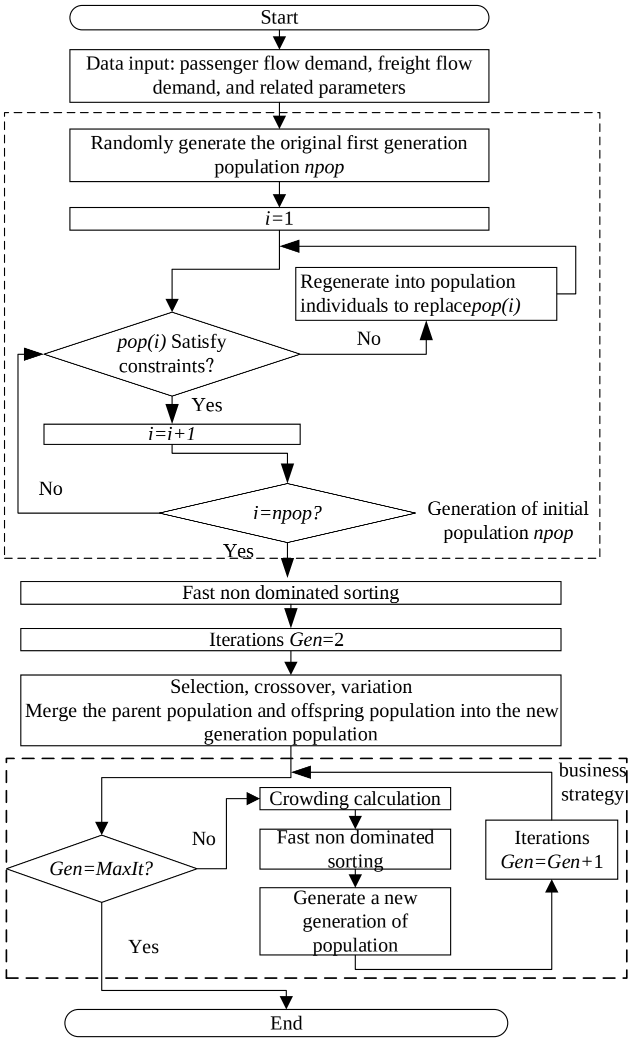


Fig.3. NSGA-II flowchart

TABLE II
VALUES OF ALGORITHM PARAMETERS

| Parameter | Meaning | Value |
|---|---|---|
| $MaxIt$ | Maximum population evolution algebra | 200 |
| $pop(i)$ | Population size $i$ | $[1, npop]$ |
| $Pc$ | Proportion of cross | 0.7 |
| $Pm$ | Proportion of variation | 0.4 |
| $npop$ | Population size | 200 |

## IV. CASE STUDY

### *A. Case Background*

The research object is Wuxi Metro Line 3 (referred to as Line 3), the line is schematically shown in Fig. 4, and eight stations are considered as passenger and freight handling stations at Shuofang Airport, Changjiang South Road, WuxiXinqu, Xinguang Road, Dongfeng, Wuxi Railway Station, Shimen Road, and Sumiao. An ordinary weekday from 14:00 to 17:00 is selected as the study period, covering both off-peak and peak periods of passenger flow, and the discrete length of time is set to be 1minute, and the demand distribution of 180 periods is input.


Fig.4. Wuxi Metro Line 3

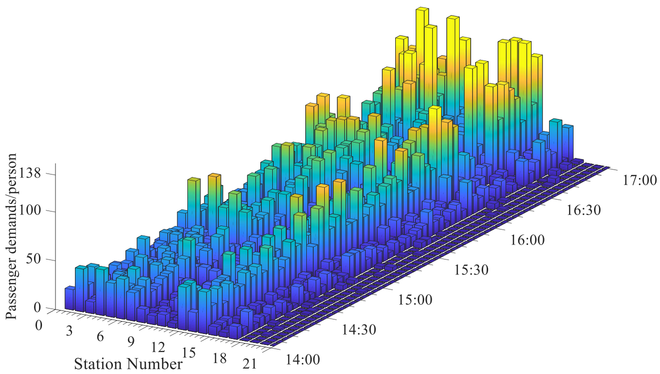


Fig.5 Distribution of passenger demands

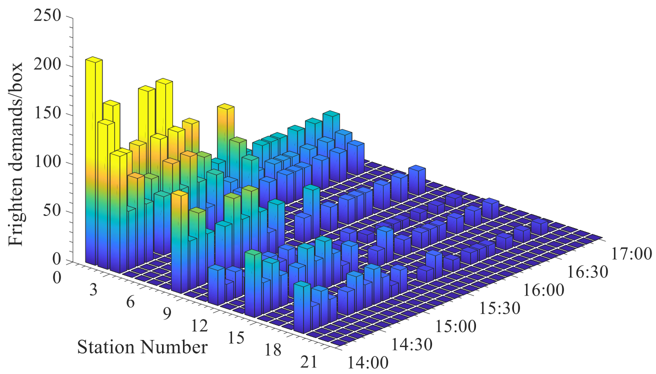


Fig.6. Distribution of frighten demands

Fig. 5 and Fig. 6 illustrate the distribution of passenger and freight flow demand. The passenger flow data is the historical data exported from the automatic fare collection system (AFC) of Line 3, and the data is the value given based on experience combined with the regular pattern of freight transportation in Wuxi due to the freight flow data is not available in the current operation. The train type of the Line 3 is a B1. The basic length of the train is 19 meters, the basic width is 2.8 meters, and the height is 3.8 meters. The stopping time after arrival is 1min, and the set of interval running time is {2,2,3,2,2,3,2,2,2,2,2,2,2,2,2,3,2,3,2,2}. The parameters of the model are shown in Table III.

*B. Result Analysis*

Based on the above data inputs and parameter settings, (30)-(33) were solved by Matlab a 2021 using the improved NSGA-II with an initial population size of 200, and the Pareto front after 200 iterations is illustrated in Fig. 7.

During the studied period, the optimized transport scheme operates 31 trains (13 in large groups and 18 in small groups) with 132 carriages (90 passenger wagons and 42 freight wagons). The train carbon emissions generated during the study period were approximately 75,401 kg, and the total passenger waiting time was approximately 230,968 min. Compared to the current transportation scheme used on Line 3, the passenger waiting time increased by approximately 22,101 min, and the carbon emissions were reduced by approximately 21.3%, for a total of 20,385 kg.

The distribution of train carriages and the calculation of passenger and freight loads are shown in Table IV. Of the 31 trains in service, there are two freight-only trains, both small coupling and 7 passenger-only trains. A total of 90 passenger carriages and 42 freight carriages were allocated.

TABLE III
VALUES OF PARAMETERS

| Symbols | Values & Units | Symbols | Values & Units |
|---|---|---|---|
| $K^{(n)}$ | 31 | $h_{min}$ | 3min |
| $m_k$ | 3 /6 | $h_{max}$ | 10min |
| $\sigma$ | 1min | $s_{ve}$ | 272.08 $m^2$ |
| $\theta$ | 0.5 | $\rho_{air}$ | 10 |
| $E_p$ | 0.027[19] | $F^{(p)}$ | 230 person |
| $E_q$ | 0.008[19] | $F^{(q)}$ | 120 box |
| $L_k$ | 28.493km | $v$ | 75km/h |
| $Te$ | 15℃ | | |

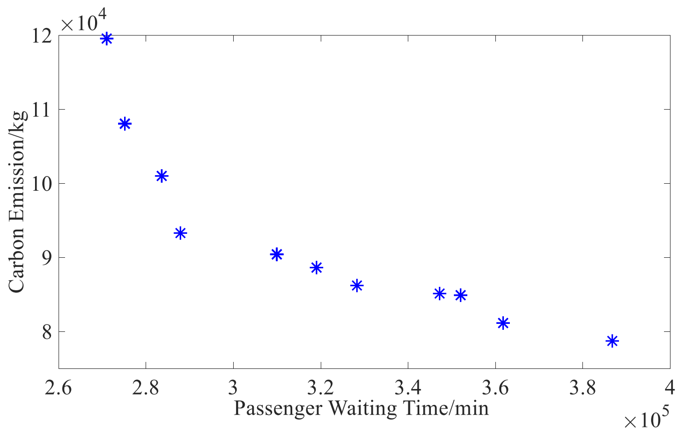


Fig.7. The Pareto front

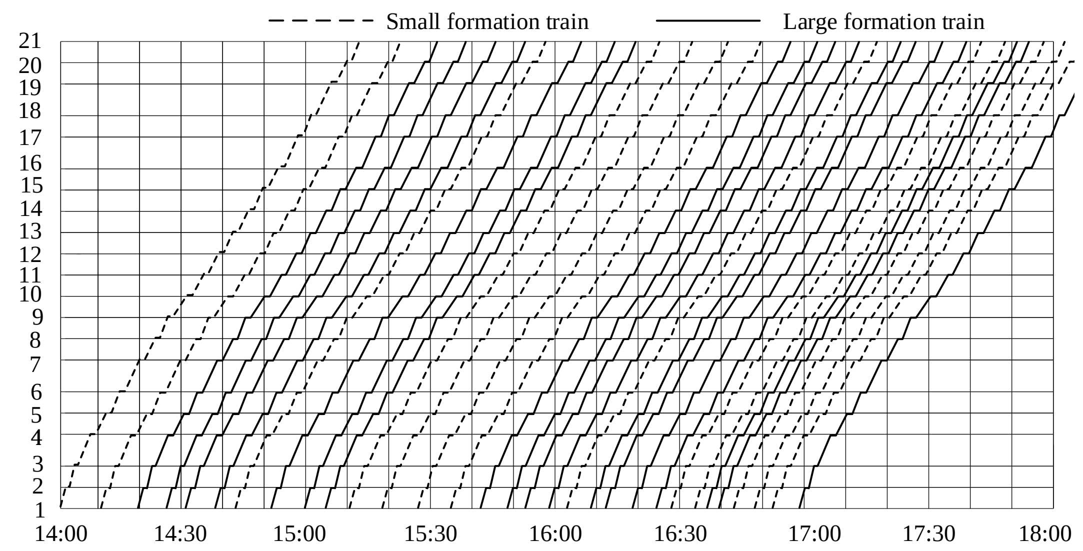

Fig.8. The operation diagram of the optimization scheme

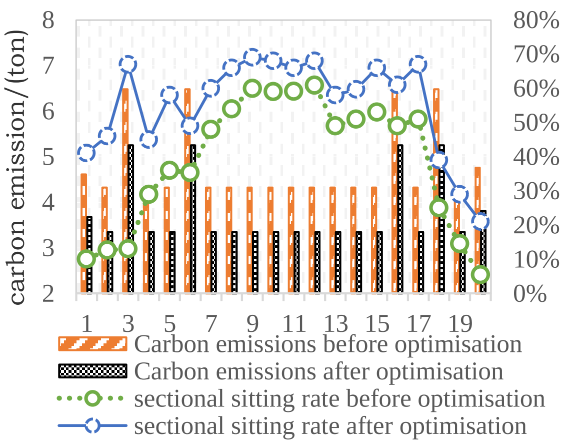

Fig.9. Cross-section carbon emissions and sitting rate

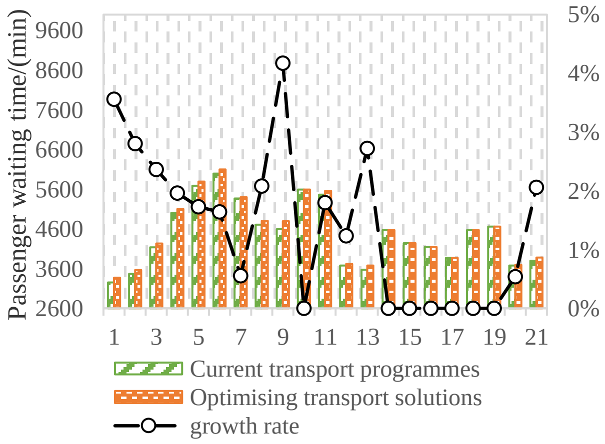

Fig.10. Station passenger waiting time and its increase

During the off-peak hours, more carriages are used to carry freight, and as passenger traffic increase, more carriages are allocated to passengers.

The operation diagram of the optimization scheme is shown in Fig. 8. From 14:00 to 14:15, a larger capacity is allocated to meet the demand for goods, and two large-group trains are operated. From 15:16 to 15:40, the passenger flow peak gradually arrives, and four large-group trains are operated. During 14:30-15:10, the demand for passenger and goods flow is relatively low, and small-group trains with a small headway can meet the real-time passenger and goods flow along the line. From 15:45 onwards, the demand for goods flow suddenly decreases, and the demand for passenger flow increases more, so this section is mainly for passenger transport, and running small-group trains with a higher frequency can not only meet the passenger flow efficiently but also increase the passenger flow demand.

During 14:30-15:10, passenger and cargo flow demand are less; only small-group trains with small departure intervals can meet the real-time demand for passenger and cargo flow along the line. From 15:45 onwards, the demand for cargo flow decreases sharply, and the demand for passenger flow increases significantly. Therefore, passenger traffic is mainly transported at this time, and small-group trains with higher departure frequencies can not only transport many passengers efficiently but also reduce the waiting time of the passengers. From 16:20 onwards, the demand for passenger flow surges, so large-group trains are frequently operated to satisfy the peak of the passenger flow input.

In this paper, the section carbon emission and section seating rate, as well as passenger waiting time and its increase at stations under the transport scheme once used in Line 3 and the optimized transport scheme derived from this paper are compared and analyzed, as shown in Fig.9 and 10, the section seating rate of the optimized scheme is about 5% to 15% higher than that of the current train operation scheme, and the increase in passenger waiting time is mainly concentrated in the passenger and freight cooperative stations. In comparison, the scheme can reduce carbon emissions by about 21.3% of carbon emissions.

The optimization results of collaborative passenger and freight transport under different carbon emission limitation policies are shown in Table V. The impact on the choice of collaborative transport scheme of urban rail transit is not significant due to the low carbon emission level in the rail transit system. The impact of different carbon tax prices on transport costs is neglected, and the transport scheme remains the same when the carbon tax price changes because the carbon tax cost accounts for a lower proportion than the total operating cost of urban rail, which has a minor impact on the choice of the transport scheme.

TABLE IV
CALCULATION OF CARRIAGE ALLOCATION AND CARRYING PASSENGERS AND FRIGHT

| NO. | Number of Grouping | Passenger/Freight carriages allocation (rolling stocks) | Passenger/Freight capacity (persons/containers) |
|---|---|---|---|
| 1 | 6 | 3/3 | 765/303 |
| 2 | 6 | 3/3 | 888/346 |
| 3 | 3 | 0/3 | 0/331 |
| 4 | 3 | 2/1 | 621/104 |
| 5 | 3 | 1/2 | 815/219 |
| 6 | 3 | 0/3 | 0/336 |
| 7 | 6 | 4/2 | 1026/208 |
| 8 | 3 | 2/1 | 694/119 |
| 9 | 3 | 1/2 | 451/196 |
| 10 | 3 | 2/1 | 861/106 |
| 11 | 6 | 4/2 | 2185/236 |
| 12 | 6 | 5/1 | 1001/69 |
| 13 | 6 | 3/3 | 2675/165 |
| 14 | 6 | 4/2 | 654/92 |
| 15 | 3 | 2/1 | 1062/0 |
| 16 | 3 | 3/0 | 1291/101 |
| 17 | 3 | 1/2 | 1006/87 |
| 18 | 3 | 2/1 | 2901/0 |
| 19 | 6 | 4/2 | 3499/0 |
| 20 | 3 | 2/1 | 1552/101 |
| 21 | 3 | 3/0 | 1996/0 |
| 22 | 3 | 2/1 | 1001/69 |
| 23 | 3 | 2/1 | 1006/87 |
| 24 | 6 | 6/0 | 2901/0 |
| 25 | 6 | 6/0 | 3499/0 |
| 26 | 3 | 2/1 | 1552/101 |
| 27 | 3 | 3/0 | 1996/0 |
| 28 | 6 | 6/0 | 3593/0 |
| 29 | 6 | 4/2 | 3081/180 |
| 30 | 6 | 5/1 | 3582/121 |
| 31 | 3 | 3/0 | 2269/0 |

## V. CONCLUSION

In order to release the excess capacity of urban rail transit and respond to the call for carbon emission reduction, this paper takes the passenger waiting time as the optimization objective, constructs a multi-objective urban rail transit passenger and freight cooperative optimization model under different carbon emission policies, takes the train carbon emission and passenger waiting time as the optimization objective.

The type of train formation, the carriage allocation scheme, and the train departure interval as the optimization objectives construct an urban rail transit collaborative passenger and freight transport scheme optimization model with low carbon objectives under different carbon emission policies.

The transport scenario is still the same when different emission allowances are set under the carbon trading policy because, at the current stage, the government overestimates the demand for carbon allowances from rail transport companies, which results in an oversupply of allowances. Therefore, the carbon trading policy has a negligible impact on this transport scenario. In summary, the existing carbon emission policy has a negligible impact on the urban rail collaborative passenger and freight scheme.Finally apply the constructed model to the empirical study of Wuxi Metro Line 3, and the results show that:

TABLE V
OPTIMAL TRAIN OPERATION PLANS

| Mandatory Carbon Emission Limitation Policy | Emission limitation $U_c$ / kg | Optimized Transport Scheme | Number of Carriages for Passengers | Number of Carriages for Freight |
|---|---|---|---|---|
| | [0, 60000] | insoluble | — | — |
| | [60001, +∞] | √ | 90 | 42 |
| **Carbon Trading Policy** | **Emission limitation $U_s$ / kg** | **Optimized Transport Scheme** | **Number of Carriages for Passengers** | **Number of Carriages for Freight** |
| | 76000 | √ | 90 | 42 |
| | 81000 | √ | 90 | 42 |
| **Carbon tax policies** | **Carbon tax rate $\phi$ / \$/t** | **Optimized Transport Scheme** | **Number of Carriages for Passengers** | **Number of Carriages for Freight** |
| | 5 | √ | 91 | 41 |
| | 15 | √ | 91 | 41 |
| | 25 | √ | 91 | 41 |
| | 35 | √ | 91 | 41 |
| | 45 | √ | 91 | 41 |

(1) The current government policy on carbon emission limitation has less influence on the urban rail transit collaborative passenger and freight transport scheme. The collaborative passenger and freight transport scheme model constructed in this paper under different policies, including mandatory carbon emission limitation policy, carbon tax policy, and carbon trading policy, is a general multi-objective hybrid planning model, which can be adapted to the changes of the carbon policy in different stages of development by changing the parameter settings of some of the parameters. In the future, when the government formulates reasonable carbon emission policies according to the differences of each industry, this model can still have better optimization performance.

(2) Compared with the single passenger flow organization mode, the combination of flexible coupling conditions and uneven departure interval operation mode for collaborative passenger and freight transport can reduce the carbon emission of the train by about 21.3% under the circumstance that the average waiting time of passengers is almost unaffected. In terms of passenger waiting, the waiting process proposed in this paper is more detailed, fully

considering the possibility of passengers waiting for trains several times, which is in line with the actual operating conditions; in terms of carriage allocation, with the increase in passenger demand, more freight carriages are allocated to passenger transport, which verifies the validity of this model.

(3) Future research direction: Urban rail transit to carry out the process of freight transport, considering the form of freight transport and cargo storage, loading and unloading of the whole process of the link is worthy of further research; in addition, the transport of some of the particular goods of the time window problem is also a collaborative development of the process of passenger and freight transport in the direction of more refined research. The construction of an underground logistics network cannot only rely on the underground transport system, but multimodal transport in combination with other modes of transport in the city can further enhance the potential of underground transport for cargo transport. Therefore, optimizing urban multimodal transport networks with consideration of urban rail transit is also a direction for further research in the future.

## References


[1] SAVELSBERGH M, VAN W T, "50th anniversary invited article-city logistics: challenges and opportunities," *Journal of Transportation Science*, vol. 50, no. 2, pp. 579-590, 2016.

[2] MOTRAGHI A, and MARINOV M V, "Analysis of urban freight by rail using event-based simulation," *Journal of Simulation Modelling Practice and Theory*, vol. 25, no. 3, pp. 73-89, 2012.

[3] Y.Y. YAO, Y.Z. ZHANG, "Study on express freight transport scheme of high-speed rail in piggyback mode of passenger car," *Journal of Railway Science and Engineering,* 2020, 17(1): 31-38.

[4] Y.H. CHAO, R.H. GAO, H.M. NIU, "Optimization of train plan on high-speed railway immediate delivery based on candidate train set," *Journal of Railway Science and Engineering,* 2022, 19(12): 3505-3514.

[5] OZTURK O, and PATRICK J, "An optimization model for freight transport using urban rail transit," *European Journal of Operational Research*, vol. 267, no. 3, pp. 1110-1121, 2018.

[6] BEHIRI W, and BELMOKHTAR B S, CHU C, "Urban freight transport using passenger rail network: scientific issues and quantitative analysis," *Transportation Research Part E: Logistics and Transportation Review,* 2018, 115: 227-245.

[7] Z. Li, SHALABY A, and ROORDA M J, "Urban rail service design for collaborative passenger and freight transport," *Journal of Transportation Research Part E: Logistics and Transportation Review*, vol. 147, no. 4, pp. 102205, 2021.

[8] Z. Di, L. Yang, and J. Shi, "Joint optimization of carriage arrangement and flow control in a metro-based underground logistics system," *Journal of Transportation Research Part B*: *Methodological,* vol. 159, no. 2, pp. 1-23, 2022.

[9] J.G. Qi, H.S. Zhou, and L.X. Yang, "Optimization methods of combined passenger and freight transportation based on flexible train composition mode," *Journal of Transportation Systems Engineering and Information Technology*, vol. 22, no. 2, pp. 197-205, 2022.

[10] CACCHIANI V, CAPRARA A, and TOTH P, "Scheduling extra freight trains on railway networks," *Journal of Transportation Research Part B*, vol. 44, no. 2, pp. 215-231, 2010.

[11] Z.Z. Li, Y. Bai, and Y. Chen, "Integrated optimization of train service planning and shipment allocation for airport expresses under mixed passenger and freight transportation," *Journal of Transportation Systems Engineering and Information Technology*, vol. 22, no. 5, pp. 155-163, 2022.

[12] RICHARD P L, *Carbon footprint report. London: Transport for London,* 2019.

[13] J.Y. LONG, "Evaluation model and optimization method of urban passenger transport system based on carbon emission target,". *Wuhan: Huazhong University of Science & Technology,* 2012.

[14] Y.Z. DAI, S.G. ZHAN. "Analysis of full-length and short-turn routing of urban rail transit considering carbon emission," *Journal of Railway Science and Engineering*,2022, 19(12): 3546-3556.

[15] H.C. Pan, J.B. Lu, H. Hu, Z.G. Liu, and Y. Sha, "Collaborative optimization of urban rail timetable and flow control under mixed passenger and freight transportation," *Journal of Transportation Systems Engineering and Information Technology*, vol. 23, no. 2, pp. 187-196, 2023.

[16] J.J. Ning, "Research on model and algorithm of energy saving operation for urban rail transit," *Beijing: Beijing Jiaotong University,* 2017.

[17] H.M. Niu, M.M. Chen, M.H. Zhang, "Optimization theory and method of train operation scheme for urban rail transit," *China Railway Science,* 2011, 32(4): 128−133.

[18] B.H. MAO. "Train performance calculation and design," *Beijing: China Communications Press,* 2008.

[19] X.Y. Wu, B.H. Mao, Q. Zhou, "Comparative of carbon emission factor levels in different modes of transportation industry," *Journal of East China Jiaotong University,* 2022,39(4):41-47.


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