Optimization of Passenger and Freight Collaborative Transportation for Urban Rail Transit under Virtual Coupling Condition

Zunzun Hou, Ruichun He, Chenning Liu, Shixiang Wan, Keqiang Yang, and Cunjie Dai

***Abstract*—Urban rail transit has the potential to utilize surplus capacity to carry out urban freight transportation during off-peak periods. Based on the characteristics of virtual coupling operation and organization mode, this paper comprehensively considers the competition between passenger flow and freight flow, takes the train stopping plan and train carriage allocation as the main decision variables, and takes the minimization of passenger waiting time and the maximization of average full load rate as dual objectives to construct a multi-objective optimization model of passenger-freight collaborative transport scheme of urban rail transit under virtual coupling conditions. The multi-objective optimization model is developed to obtain the system optimization of the train stopping plan, running plan, carriage allocation plan, and passenger-freight collaborative transport plan. Numerical experiments are designed to verify the model's validity, using Wuxi Metro Line 3 as an example, and the NSGA-II algorithm solves all experiments. The results of the algorithm show that, compared to the traditional single passenger transport with a fixed large coupling, the scheme in this paper can simultaneously improve the average full capacity of the whole line by about 38.5% during the study period with only 0.65 minutes increase in the average passenger waiting time for the same number of rolling stocks, which can effectively shorten passenger travel time and improve the quality of passenger service in urban rail transit while ensuring transport efficiency.**

***Index Terms*—Urban rail transit, Virtual coupling trains, Multi-objective optimization model, NSGA-II algorithm**

I. Introduction

With the continuous increase of urban population and motor vehicle ownership, road traffic congestion and environmental problems are becoming increasingly serious. In addition, the rapid development of the express delivery industry has led to growing demand for urban logistics and distribution. At the same time, the cost of car travel and road freight remains high with the exacerbation of urban environmental pollution. In order to alleviate road traffic pressure, it has become a feasible solution to develop urban rail logistics networks and collaborative transportation by fully utilizing the redundant capacity of urban rail transit lines during off-peak hours. Utilizing the surplus capacity of urban rail transit during off-peak periods to provide freight services can improve the operational efficiency of rail transit lines and alleviate problems such as road congestion and environmental pollution.

The design of urban public transport freight services has been a hot research topic in recent years, both domestically and abroad. [1] pointed out that the biggest opportunity for future urban logistics lies in the integrated design of public transportation and urban freight services. [2] further demonstrated the feasibility and advantages of freight distribution based on metro lines from the perspectives of event-based simulation models and practical experience in a section of the subway line in Newcastle metro. [3] In order to make full use of the surplus capacity of passenger transport in some periods, [4] studied the freight transport schedule based on the subway network for the form of freight transport using the surplus space of passenger carriages. [5] respectively proposed a model with a fixed train timetable as the input parameter and a model with train number and timetable as the optimization object for the subway freight distribution problem under the passenger-cargo separation mode. [6] optimized the train stopping plan and schedule by considering the two forms of passenger-freight co-loading and a specific freight train. [7] studied the problem of passenger-freight carriage coupling and passenger-freight flow collaborative optimization of urban rail based on a given train stopping scheme and schedule. [8] started from two aspects of operation supply and demand management, aiming at the passenger flow oversaturation and large passenger flow in some stations of some lines, and proposed a collaborative optimization model of train operation diagram and passenger flow control to reduce passenger waiting time. [9] studied the insertion of freight train operating lines into fixed passenger train schedules, with the aim of optimizing freight train schedules and stopping plans. Due to the time-varying nature of urban rail passenger flow and the unbalanced spatial distribution, numerous scholars have investigated the optimization of urban rail transit operation organization from various perspectives to achieve a good match between passenger flow and rolling stock flow. [10] proposed technical requirements and policy recommendations for utilizing the

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metro for logistics distribution during off-peak hours in Beijing. [11] explored the combined passenger and metro logistics transport mode for freight, established a logistics model through Flexsim software, and utilized experimental data to demonstrate the significant economic and energy efficiency benefits of the metro logistics system. [12] introduced a time cost penalty function for the accumulation of goods at the ground transfer point, thoroughly considered the issues of waiting for distribution rolling stocks and the accumulation of goods caused by different arrival times between the ground and underground. They proposed a logistics path optimization model for the metro with time windows based on minimizing the total cost as the objective function and utilized genetic algorithms to solve for the optimal path scheme. [13] considered the synergistic optimization of train schedules and passenger and freight transport schemes in small and large couplings to obtain systematically optimized train coupling schemes, train operating charts, and passenger and freight collaborative transport schemes. Under the passenger and freight collaborative transport mode, [14] integrated the optimization of passenger and freight carriages allocation and passenger and freight flow control on metro lines and proposed an optimization model considering the hard time window for passenger transport and the soft time window for freight transport. [15] addressed the problem of passenger and freight co-transportation on the airport line, based on two forms of freight transportation, namely passenger and freight co-loading and specific freight trains, to maximize net freight revenue considering storage, loading, and unloading, and train operation costs, and constructed a collaborative optimization model of train operation plan and freight allocation scheme to make integrated decisions on the formation and stopping plan, timetable, and cargo list allocation of specific freight trains. [16] constructed an optimization model for mixed passenger and freight transport in urban rail transit, with the arrangement of carriages and the number of passenger and freight demand as the main decision variables and minimization of passenger and freight waiting time and train energy consumption as the objective. The research on urban rail logistics systems is still in the initial stage. Some scholars mainly focus on the feasibility of metro logistics systems, transportation modes, and system arrangements [17]. Only some studies are related to optimizing passenger and freight collaborative transportation and organization for urban rail transit.

The virtual coupling train can realize a more flexible transportation mode because there is no hook connection between rolling stocks to cope with the problem of uneven distribution of passenger flow in time and space. In the peak period, the virtual coupling technology can realize multiple rolling stocks quickly linked together to form a long formation of trains into the station to carry passengers to meet the transport demand. In 1999, [18] were the first to propose the virtual coupling (VC) "between train rolling stocks without relying on mechanical hooks, but through rolling stock-to-rolling stock (V2V) wireless communication technology to realize the linkage. In 2015, the European Shift2Rail program proposed virtual coupling technology as an important research direction for European railroads, which formally set off the research boom of virtual coupling [19][20]. At present, domestic and foreign research on virtual coupling technology mainly focuses on the analysis of the application prospect of virtual coupling technology and train operation control in order to shorten the train tracking interval and improve line utilization [21][22][23][24]. The basic application scenarios and related conditions of virtual coupling in recent years have been explored to some extent [25][26][27]. [28] introduced the concept of virtual coupling in detail, performed line throughput analysis, and proposed a train tracking model to capture the train operation status, proving that virtual coupling can improve line throughput. [29] compared the transport efficiency of Super Highspeed Rail with two signal systems, mobile block section, and virtual coupling, and concluded that virtual coupling technology can provide higher capacity with safety and comfort, provided the technical condition is feasible. [30] proposed a dynamic coupling-based spatiotemporal scheduling model based on virtual coupling technology, which can effectively allocate transport capacity according to the uneven spatiotemporal distribution of passenger flows, considering real-time passenger flows. [31] suggested that the application of virtual coupling technology can effectively reduce travel time in the case of spatially uneven distribution of passenger demand. [32] proposed an algorithm for generating virtual coupling train operation schemes, in which each train operates according to a fixed periodic stopping scheme without considering the effect of differences in passenger flow at different stations. [33] proposed an optimization model based on virtual coupling trains to optimize the number of trains on a one-way loop to avoid wasting train capacity. On this basis, [34] also used a complex Y-shaped line to optimize the train operation route to meet passenger travel demand and reduce passenger detention. [35] conducted a study on the application of virtual coupling technology for a Y-type subway line with two parts of suburban and urban stations, and the results proved that the optimized scheme of virtual coupling effectively improved the line passing capacity and reduced passenger travel time during the morning peak period. [36] analyzed the effectiveness of the train operation scheme based on virtual coupling technology to improve the service level and reduce the operation cost. [37] proposed a dynamic train coupling and scheduling scheme based on virtual coupling under major epidemics to improve the transportation efficiency of urban rail transit. [38] analyzed the technical advantages of virtual coupling trains in fast and slow train transportation organization modes with and without crossing lines, respectively, and verified the superiority of virtual coupling technology under different crossing conditions through cases. [39] proposed the optimization method of the virtual train formation operation scheme to shorten passenger travel time and improve train transportation efficiency, considering the station with avoidance conditions, and gave the optimization design results based on the OD data of the morning peak passenger flow of actual urban rail transit lines. [40] proposed a new train operation organization scheme based on virtual coupling technology, taking a typical urban railroad line with "one trunk and many branches" as an example, and proved the obvious advantages of virtual coupling in reducing passenger travel time and rolling stock kilometers traveled.

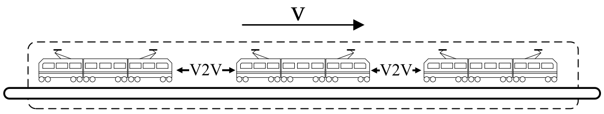

Fig.1. Schematic of virtually coupling trains

Existing research on the application of virtual coupling technology in the optimization of transportation and organization is still in the initial stage, and more of them focus on the optimization of urban rail transit passenger transport, with almost no application research on passenger and freight collaborative transportation.

Based on virtual coupling technology, based on fully ensuring the quality of passenger transportation service, considering the competitive relationship between passenger flow and freight flow, this paper researches the optimization of urban rail transit passenger-freight collaborative transport organization. It constructs the optimization model based on virtual coupling and successfully ensures the bi-directional interests of urban passenger service quality and enterprise operation efficiency.

II. Problem Description

This paper uses a rail line with unsaturated passenger traffic as the research object, and it is assumed that wireless communication is available along the whole line. Both passenger and freight demand exist along the line, where any station can handle passenger operations. However, only some stations can handle freight operations, and passenger demand stays the same due to freight service.

Minimum transportation units can deploy capacity more precisely and flexibly according to the passenger demand and meet the direct passenger demand to the maximum extent. Therefore, in this paper, the minimum transport unit is a small group of trains under the virtual coupling condition to study the cooperative transportation scheme for urban rail transit passengers and freight.

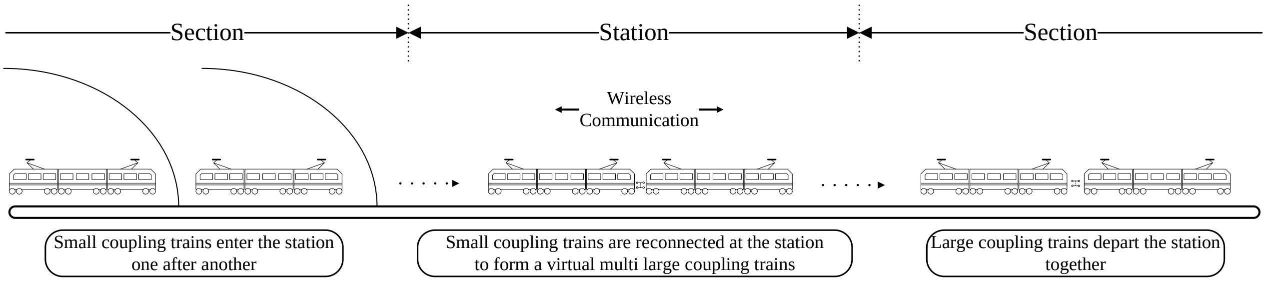

Fig.2. Station reconnection

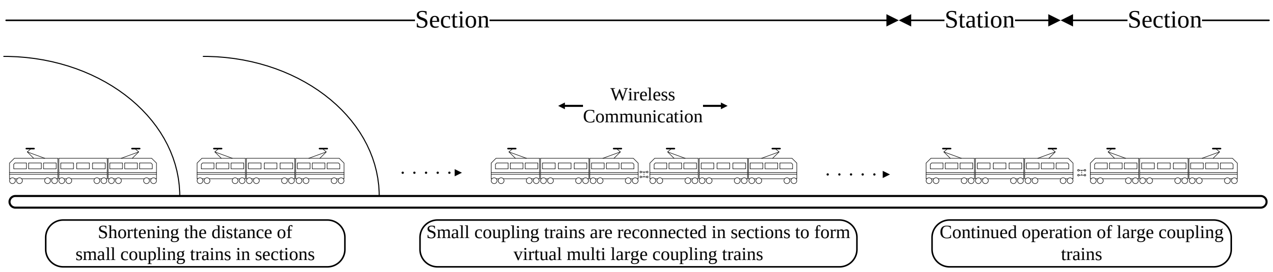

Fig.3. Section reconnection

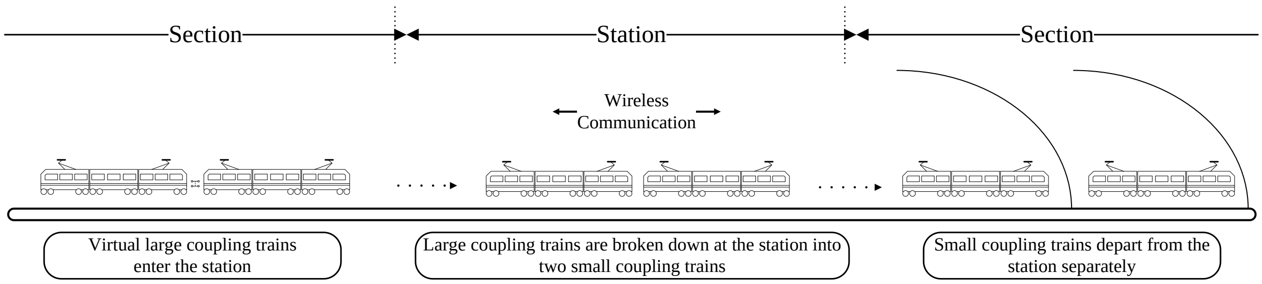

Fig.4. Station Decomposition

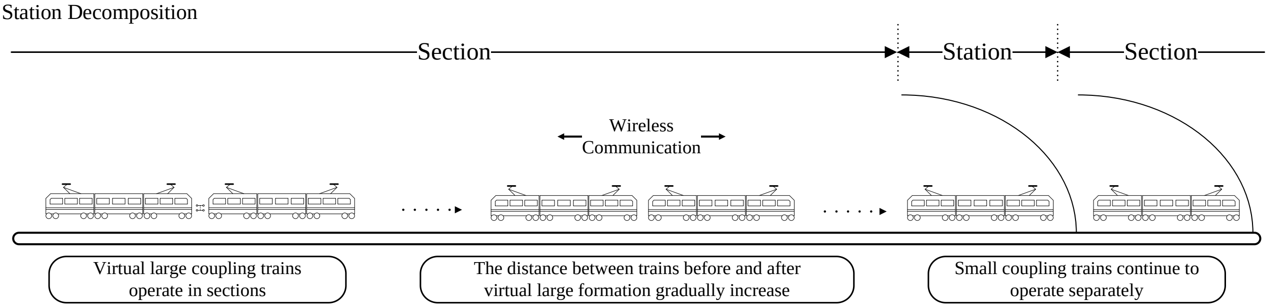

Fig.5. Section Decomposition

The virtual reconnection operation under the virtual coupling condition can be divided into station reconnection and inter-district reconnection.

(1) Station reconnection. The front train waits for the rear train to enter the station when it stops at the station and departs in a virtual reconnection state after the station reconnection (Fig.2). If station reconnection is adopted, the station tracking interval of trains should be considered, and the stopping time of the front train should be extended appropriately with measures such as increasing the interval running speed of the rear train to ensure that the rear train catches up with the front train.

(2) Section reconnection. The rear train follows the front train in the interval. It enters the station in a reconnection state (Fig.3). If the interval reconnection is adopted, the relative distance of the rear train becomes smaller, and the relative speed becomes larger compared with the front train, which is more likely to produce danger and requires higher requirements for safe train operation. At the same time, since both the front and rear trains are in operation during the reconnection process, it is necessary to consider the tracking interval of trains, the interval operation speed, and whether the line length meets the requirements of section reconnection.

(3) Station deconfiguration (Fig.4). At the same time as the station is carrying out passenger pick-up and drop-off operations, the large group of trains is virtually reconfigured into a small group of trains, using measures such as adjusting the stopping time to keep the front and rear trains at a sufficiently safe distance to continue running within a certain time frame.

(4) Section decoding (Fig.5). Since the two trains in a virtual reconnection state are running at a certain speed in the section, virtual decoding in the section needs to create a speed difference by accelerating the front train or decelerating the rear train, which can produce sufficient safety distance after maintaining a certain time. However, this method has certain requirements on section length, train performance, and needs to be decided according to specific line conditions.

In this paper, under the virtual coupling condition, for the dynamic passenger and freight transportation demand, the train transportation efficiency and the train capacity of different car allocation schemes are fully considered to determine the specific car allocation scheme of each train and the stopping scheme of each train as the main decision, and the allocation of corresponding passenger and freight flow on each train as the auxiliary decision, to carry out the synergistic optimization of rail traffic passenger and cargo transportation in both time and space and realize the good matching of rail traffic passenger flow, freight flow and train flow.

III. Model Costruction

A. Model Assumption

In order 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:

Assumption 1: Rolling stock travel at the same speed between line sectors and will be synchronized by virtual coupling technology when meeting at station sectors;

Assumption 2: All stations have avoidance conditions, and rolling stocks can be coupled and uncoupled as they enter or leave the station;

Assumption 3: The operating time of rolling stock linking and unlinking and the change in speed of rolling stocks during this process are ignored;

Assumption 4: All rolling stocks have the same stopping time at each station and stop at both the origin and destination stations;

Assumption 5: A study of passenger and freight transport is carried out under conditions of sufficient train capacity, where all transport needs are guaranteed to be met, and no secondary waiting and interchanges are allowed for passenger transport, but waiting and early delivery of goods are allowed;

Assumption 6: That only train operations in one direction are considered.

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
σ	Length of discrete time intervals
R_k^i	Running time of train k between stations i and $i+1$
m_k	Total number of rolling stocks in formation for train k
F^P,F^q	Rated passenger capacity per unit of passenger carriage and rated freight capacity per unit of freight carriage
C_k^p,C_k^q	Maximum capacity of train k for passengers and maximum capacity for
h_k	Departure interval between the front train k and the rea train $k+1$ at the departure station of the virtual coupling
$p_{i,j}^{(d)}(t),q_{i,j}^{(d)}(t)$	Passenger and freight flow demand from station i to station j arriving in time slot t

Assumption 7: Assumes that both passenger and freight demand are known and do not shift during operation, i.e., that the total passenger and freight demand does not change;

Assumption 8: It is assumed that all goods are loaded in advance into standard freight containers by origin and destination and that only some of the alternative stations allow for freight movements.

For the sake of description, the symbols and parameters involved in the model of this paper and their related definitions are shown in Table I.

The decision variables used to construct the model in this paper include:

(1) Decision variables and intermediate variables related to train movements

S_k^i —the stopping time of train k when it is stopping at station i ;

A_k^i —the moment of arrival of a train, indicating the moment when train k arrives at station i ;

D_k^i —the moment of departure of the train, indicating the moment when train k leaves station i ;

$h_{i,j}^{x,y}$ —the interval between the departure of train x from station i to j and the departure of the last train y from station i to destination j ;

θ_k^i —a stop indicator variable indicating whether train k stops at station i , 1 for yes, 0 for no;

ω_k — number of stops of train k on the whole line;

$\alpha_k^i(t)$ —a departure indicator variable, indicating whether train k has left station i at time t , 1 for yes, 0 for no;

$\lambda_{i,j}(t)$ —indicates the index of preceding trains which have been issued at time t and which have stopped at both stations i and j ;

(2) Decision variables and intermediate variables related to train coupling

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

$\varepsilon_{\min}^{(p)}, \varepsilon_{\max}^{(p)}$ —minimum and maximum occupancy rates for passenger carriages;

$\varepsilon_{\min}^{(q)}, \varepsilon_{\max}^{(q)}$ —minimum and maximum occupancy rates for freight carriages;

(3) Passenger and freight flow loading related decision variables and intermediate variables

$P_{k,i}^{(p)}, P_{k,i}^{(q)}$ —the passenger and cargo capacity of train k when it leaves station i ;

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

$P_{k,i,j}^{(q)}$ —loading of train k to station j when it leaves station i ;

$X_{k,i}^{(p)}, X_{k,i}^{(q)}$ —the amount of passengers discharged and the amount of goods unloaded when train k arrives at station i ;

$p_i^{(w)}(t)$ —the number of passengers arriving at station i at time t ;

$q_i^{(w)}(t)$ —the number of freights arriving at station i at time t ;

$w_{i,j}^{(p)}(t)$ —the number of passengers waiting at station i to go to station j at time t ;

B. Objective Function

In this paper, we propose to carry out freight transport services based on passenger transport services on unsaturated lines to fully use rail transport capacity while ensuring a high frequency of train departures (reducing passenger waiting time). In order to ensure the quality of passenger transport services, the optimization objectives of this model are to minimize the total passenger waiting time and maximize the average full train load ratio.

B.1. Passenger Waiting Time

Under the virtual train operation scenario, the passenger waiting time may increase due to the reduction of the number of train stops, significantly reducing passenger travel time. For this reason, a passenger waiting time model is established to reflect the scheme's passenger service advantages and disadvantages. Since this paper assumes that no passenger is waiting twice, the passenger waiting time can be expressed as the sum of the product of the number of waiting passengers and the length of the discrete period in all discrete time intervals, as shown in (1).

$$F_1 = \sum_{i\in S}\sum_{t\in T} p_i^{(w)}(t)\cdot\sigma \tag{1}$$

B.2. Average Full Load Rate of Trains

The real-time passenger load factor $\varepsilon_{k,i}^{(p)}$ of the train under the virtual coupling condition can be expressed as the ratio between the real-time passenger load and the number of rolling stock crew, as shown in (2), and the average passenger load factor $\varepsilon^{(p)}$ of the whole line can be expressed as the ratio $\varepsilon_{k,i}^{(q)}$ between the passenger load and the number of rolling stock crew of the whole line, as shown in (3)(5), sum the number of train stops to obtain the number of presidential stops for this scenario as shown in (4) and the real-time cargo load factor $\varepsilon^{(q)}$ of the freight car and the average cargo load factor of the whole line can be obtained similarly, as shown in (6). The carbon emissions targets constructed in this paper is shown in (7).

$$\varepsilon_{k,i}^{(p)} = \frac{P_{k,i}^{(p)}}{C_k^p}, \forall k\in K, \forall j\in S \tag{2}$$

$$\varepsilon^{(p)} = \frac{\sum_{i\in S}(\theta_k^i\cdot P_{k,i}^{(p)})}{C_k^p\cdot\omega_k}, \forall k\in K \tag{3}$$

$$\omega_k = \sum_{i\in S}\theta_k^i, \forall k\in K \tag{4}$$

$$\varepsilon_{k,i}^{(q)} = \frac{P_{k,i}^{(q)}}{C_k^q}, \forall k\in K, \forall j\in S \tag{5}$$

$$\varepsilon^{(q)} = \frac{\sum_{i\in S}(\theta_k^i\cdot P_{k,i}^{(q)})}{C_k^q\cdot\omega_k}, \forall k\in K \tag{6}$$

$$F_2 = \rho_P\cdot\omega_1 + \rho_q\cdot\omega_2 \tag{7}$$

In summary, this paper constructs as shown in (8).

$$\min F = \left[F_1, -F_2\right]^T \tag{8}$$

C. Model Constraints

(1) Train travel-related constraints

In order to ensure the necessary service level, it is necessary to ensure that trains are running between any two stations to meet the real-time passenger flow demand and, at the same time, have trains running between any freight organization stations to meet the real-time freight flow demand. Any train must stop at the development and terminal stations, as shown in (9)(10).

$$\sum_{i<j}\sum_{k\in K}\theta_k^i \cdot \theta_k^j \geq 1, \forall i, j \in S \tag{9}$$

$$\theta_k^1 \cdot \theta_k^{S^{(n)}} = 1, \forall k \in K \tag{10}$$

In this paper, we assume that the interval running time and stopping time of the train are fixed values, and the arrival and departure time of the train at each station can be introduced according to the departure time of the train at the originating station in the reverse direction, the arrival time of the train k at the station i is the sum of the departure time of the train k at the originating station 1 and the stopping time of the en route station $2,3,...,i-1$ and the interval running time before the station The departure time of the train k at station i is the sum of the arrival time of train k at the station and i the stopping time of the train k at station i . The departure interval between the rolling stock x departing from station i to destination j and the previous rolling stock y departing from station i to destination j can be expressed as the difference between the departure times of the two rolling stocks; therefore, the correlation constraint, as shown in (11)(12)(13).

$$A_k^i = A_k^1 + \sum_{u=1}^{i-1} R_k^u + \sum_{u=1}^{i-1} W_k^u, \forall k \in K, \forall i \in S \tag{11}$$

$$D_k^i = A_k^i + W_k^i, \forall k \in K, \forall i \in S \tag{12}$$

$$h_{i,j}^{x,y} = D_y^i - D_x^i, \forall i, j \in S, \forall x, y \in K, x < y \tag{13}$$

(2) Constraints on train capacity

In order to ensure the efficiency of train transportation, this paper constraints that the passenger load factor and the cargo load factor of the train shall not be lower than a minimum passenger load factor constant and a minimum cargo load factor constant and that the passenger load factor of the passenger compartment shall not be higher than a maximum load factor constant and the cargo load factor of the cargo compartment shall not be higher than a maximum load factor constant in order to ensure a better riding environment for passengers, as shown in (14)(15).

$$\varepsilon_{\min}^{(p)} \leq \varepsilon_{k,i}^{(p)} \leq \varepsilon_{\max}^{(p)}, \forall k \in K, \forall i \in S \tag{14}$$

$$\varepsilon_{\min}^{(q)} \leq \varepsilon_{k,i}^{(q)} \leq \varepsilon_{\max}^{(q)}, \forall k \in K, \forall i \in S \tag{15}$$

In order to achieve a good match between train capacity and passenger and cargo flows, the allocation of train cars should ensure that neither passenger nor freight cars exceed the total number of cars in the train formation, as shown in (16)(17).

$$n_k^{(q)} \leq m_k \tag{16}$$

$$n_k^{(p)} \leq m_k \tag{17}$$

(3) Constraints related to passenger loading

As this paper intends to make full use of the residual capacity of rail transport to carry out cargo transport, in order to ensure that all passenger demand can get the necessary transport services, the train will generate passengers getting on and off during the stopping time after arriving at the urban rail transport station, this paper assumes that there is no secondary waiting, so the passenger flow demand related constraint is given as shown

$$\alpha_k^i(t) = \begin{cases} 1, t \geq D_k^i \\ 0, others \end{cases}, \forall k \in K, \forall i \in S \tag{18}$$

$$\alpha_k^i(t) \geq \alpha_k^i(t-1) \tag{19}$$

$$\lambda_{i,j}(t) = \begin{cases} M, t = 0 \\ k, t \in T \setminus \{1\}, \theta_k^i = \theta_k^i = \alpha_k^i(t) = 1, \forall k \in K \\ \lambda_{i,j}(t-1), t \in T \setminus \{1\}, others \end{cases} \tag{20}$$

$$U_{k,i}^{(p)} = \begin{cases} 0, \text{i} = |S| \\ \sum_{\text{i}<\text{j}} \sum_{D^i_{\lambda_{i,j}(D_k^i)}}^{D_k^i} p_{i,j}^{(d)}(t) \cdot \theta_k^i \cdot \theta_k^i, others \end{cases} \tag{21}$$

$$X_{k,i}^{(p)} = \begin{cases} 0, \text{i=1} \\ \sum_{\text{i}<\text{j}} \sum_{D^i_{\lambda_{i,j}(D_k^i)}}^{D_k^i} p_{j,i}^{(d)}(t) \cdot \theta_k^i \cdot \theta_k^i, others \end{cases}, \forall k \in K \tag{22}$$

$$P_{k,i}^{(p)} = \begin{cases} P_{k,i}^{(p)}, \text{i} = 1 \\ P_{k,i-1}^{(p)} - X_{k,i}^{(p)} + U_{k,i}^{(p)}, others \\ 0, i = |S| \end{cases}, \forall k \in K \tag{23}$$

$$C_k^p = F^p \cdot n_k^{(p)} \tag{24}$$

$$p_i^{(w)}(t) = \begin{cases} \sum_{i<j} p_{i,j}^{(d)}(t), t = 0 \\ p_i^{(w)}(t-1) + \sum_{i<j} p_{i,j}^{(d)}(t) - \sum_{k\in K} U_{k,i}^{(p)} \cdot \alpha_{k,i}(t), t \neq 0 \end{cases} \tag{25}$$

(18) constructs the departure indicator variable, (19) the non-decreasing characteristic of the departure indicator variable， (20) constructs the relationship between the rolling stock departing from the station and arriving at a destination, and the last rolling stock departing from the station and arriving at the destination, (21) and (22) construct the correlation constraint between the number of boarding and alighting passengers, Eq. The association constraint between the number of passengers carried. The number of boarding and alighting passengers at the station is constructed in(23), and the association constraint between the capacity of the train and the carriage allocation is constructed in (24);(25) is the association constraint between the number of passengers waiting at discrete times and the number of arriving passengers and the number of boarding passengers, indicating that the number of passengers waiting at station at time is equal to the sum of the number of passengers waiting at time and the number of arriving passengers at time t minus the number of boarding and departing passengers The number of passengers waiting at station at time t is equal to the sum of the number of passengers waiting at time and the number of passengers arriving at time minus the number of passengers leaving the station.

(4) Freight flow loading-related constraints

In this paper, under virtual coupling conditions, passenger and cargo transport is carried out to make full use of rail transport capacity and increase the efficiency of train transport due to carrying out freight transport without affecting the quality of passenger transport services. Due to the competitive relationship between passenger and freight traffic, this paper allows for some delay in freight transport and for freight to be transported earlier. At the same time, in order to ensure the necessary quality of service for freight transport, it is assumed that all freight transport needs to be satisfied and the demand constraint for freight flows is constructed as

$$\sum_{k\in K} P_{k,i,j}^{(q)} = \sum_{i<j} \sum_{D^i_{\lambda_{i,j}(D_k^i)}}^{D_k^i} q_{i,j}^{(d)}(t), \forall i, j \in S^{(F)} \tag{26}$$

$$U_{k,i}^{(q)} = \begin{cases} 0, \mathrm{i} = |S| \\ \sum_{\mathrm{i}<\mathrm{j}} \sum_{D^i_{\lambda_{i,j}(D_k^i)}}^{D_k^i} q_{i,j}^{(d)}(t)\cdot\theta_k^i\cdot\theta_k^i, others \end{cases} \tag{27}$$

$$X_{k,i}^{(q)} = \begin{cases} 0, \mathrm{i} = 1 \\ \sum_{\mathrm{i}<\mathrm{j}} \sum_{D^i_{\lambda_{i,j}(D_k^i)}}^{D_k^i} q_{j,i}^{(d)}(t)\cdot\theta_k^i\cdot\theta_k^i, others \end{cases} \tag{28}$$

$$P_{k,i}^{(q)} = \begin{cases} P_{k,i}^{(q)}, \mathrm{i} = 1 \\ P_{k,i-1}^{(q)} - X_{k,i}^{(q)} + U_{k,i}^{(q)}, others \\ 0, i = |S| \end{cases} \tag{29}$$

$$C_k^q = F^q \cdot n_k^{(q)} \tag{30}$$

(26) ensures that all cargo demands are met; equation (27) indicates that the number of goods loaded at a station is equal to the sum of the number of goods loaded corresponding to the departure from that station to the remaining stations; (28) indicates that the number of goods unloaded at a station is the sum of the number of goods loaded with that station as the destination; equations (29) construct the relationship between the number of goods on board and the number of goods loaded and unloaded and ensure that the number of goods carried by train does not exceed the cargo capacity of the flexibly grouped train; (30) constructs the correlation constraint between the cargo capacity of the train and the carriage allocation.

In summary, (31) is used to construct a multi-objective planning model for collaborative passenger and freight transport in rail transport based on virtual coupling in this paper.

$$\min F = \left[F_1, -F_2\right]^T \tag{31}$$

D. Algorithm Design

Since the only two states of each rolling stock of the virtual group train at each station are stopping and passing, the stopping scheme can be represented by 1 and 0, respectively. Thus, the operation scheme of each rolling stock can be represented by a binary number whose digits are the number of stations. However, the train operation scheme has an obvious tendency for combinatorial explosion with the increase of the number of rolling stocks and passing stations, which is difficult to solve by traditional optimization methods. Meanwhile, there are multiple optimization objectives in this paper, so NSGA-II, a fast, non-dominated ranking genetic algorithm with low computational complexity and good population diversity, is used for solving, and the flow chart of the NSGA-II algorithm is shown in Fig.6.

Firstly, a combined population is formed with a limited number of populations. Then, the populations are ranked according to non-dominance. Elitism is guaranteed since the current population contains all the population members of the parent and current offspring. [42] For the minimization multi-objective optimization problem, for n objective components $f_i(x), i = 1,2,...,n$,any two decision variables X_a , X_b are said to dominate X_a if (32) and (33) are made to hold.

$$f_i(X_a) \le f_i(X_b), \forall i \in 1,2,...,n \tag{32}$$

$$f_i(X_a) < f_i(X_b), \exists i \in 1,2,...,n \tag{33}$$

If, for a decision variable, there is no other decision variable that can dominate it, then the decision variable is said to be a non-dominated solution. In a set of solutions, the Pareto rank of the non-dominated solution is defined as 1. By removing the non-dominated solution from the set of solutions, the Pareto rank of the remaining solutions is defined as 2. So on, the Pareto ranks of all solutions in the set of solutions can be obtained. The schematic diagram is shown in Fig.7.

The solution belonging to the best non-dominated set is the best in the combined total and must be closer to the goal than any other solution in the combined total. If the size is less than, we will definitely select all members of the set as the new overall. The remaining population members are selected from the subsequent non-dominated fronts according to their ranking. Thus, the solution is next selected from the set, then from the set, and so on. This process continues until there are only so many sets to accommodate. Assume that this set is the last non-dominated set, which cannot accommodate other sets. Generally, the number of solutions from all sets will be larger than the overall size.

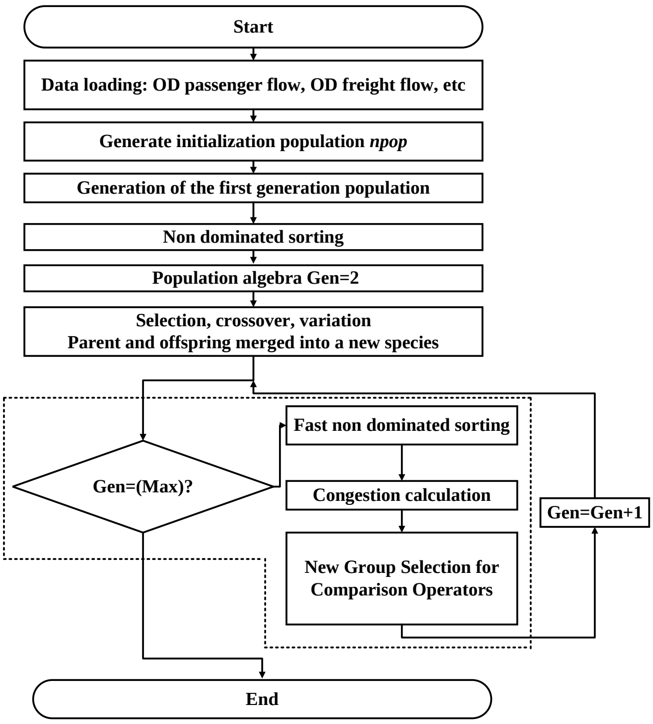

Fig.6. Algorithm Flow

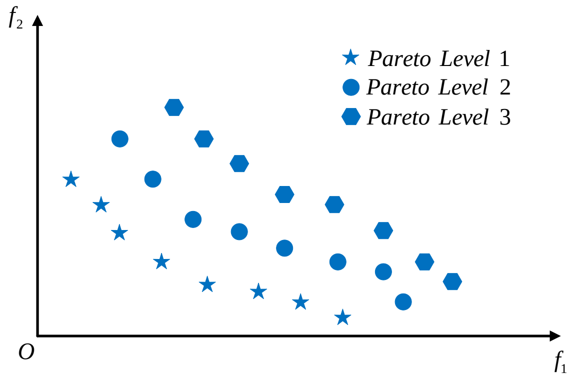

Fig.7. Illustration of Pareto levels

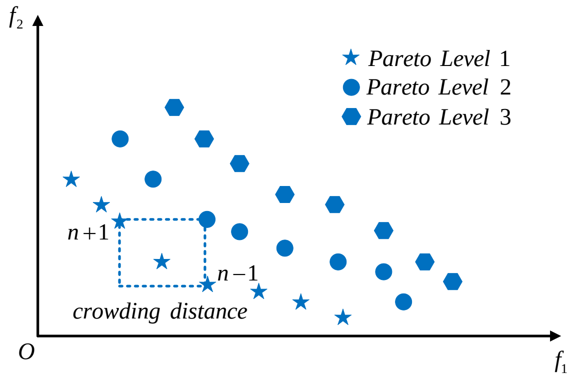

Fig.8. Illustration of congestion

To accurately select the population members, we use the congestion comparison operator to sort the solutions of the last frontier in descending order. The new size population is now used for selection, crossover, and mutation to create a new population. We use the binary tournament selection operator, but the selection criteria are now based on the crowded comparison operator. Since this operator requires the rank and congestion distance of each solution in the population, we calculate these quantities while forming the population [41], noting that $f_m^{\max}$ is the f_m maximum value of the individual objective function value and $f_m^{\min}$ is the f_m minimum value of the individual objective function value, and the congestion degree value for the two boundaries after sorting is a great number M. The congestion degree n_d of the intermediate individuals is calculated as in (34) is shown.

$$n_d = \frac{f_m(i+1) - f_m(i-1)}{f_m^{\max} - f_m^{\min}} \tag{34}$$

$f_m(i-1)$ and $f_m(i+1)$ are the values of the objective function before and after sorting that individual, respectively. In a multi-objective optimization problem, it is like the sum of the side lengths of the largest rectangle (which cannot touch any other point in the target space) that that individual can generate in the target space. A schematic representation of congestion is shown in Fig.8.

The parameter settings for the NSGA-II algorithm used in this paper are shown in Table II.

TABLE II
ALGORITHM PARAMETER SETTINGS

Parameter	Meaning	Value
MaxIt	Maximum population evolution algebra	200
Pc	Crossover probability	0.7
Pm	Mutation probability	0.4
npop	Population size	200

IV. CASE STUDY

A. Case Background

Taking Wuxi Metro Line 3 (Shuofang Airport - Sumiao) as the research object (21 stations), eight stations that can handle freight service are considered, and all stations can handle freight operation. The line diagram is shown in Fig.9.

Combined with the historical card data of the Automatic Fare Collection System (AFC), the research period was selected as 9:00-12:00 am on weekdays, the discrete-time length was set as 1 minute, and the passenger flow demand data of 180 time-sections were collected. The train has three cars, and each freight car and passenger car capacity is 120 boxes of goods and 230 people, respectively; the model parameters are shown in Table III. This paper, 36 trains are considered, all of which are small marshaling types, and the train stop time is 1 minute. Interval elapsed time is {2,3,2,2,3,2,2,2,2,2,2,2,2,2,3,2,3,2,2,2}.

In order to further ensure passengers' riding experience, the average load rate weight coefficients ω_1 and ω_2 are {0.65, 0.35} respectively.

Fig.10 and Fig.11 show the OD distribution diagram of passenger flow and freight flow demand of Wuxi Metro Line 3. Fig. 12 and Figure 13 show the arrival statistics of passenger and freight flow in different periods. The research time is selected as 09:00 to 12:00 of a working day, covering the transition period between the off-peak period and the peak period of passenger flow, and passenger flow shows an upward trend with time growth. Freight flow data is difficult to obtain in actual operation, and the values of the data are given according to the actual law according to experience.

Fig.12 and Fig.13 show that the passenger flow input and freight flow demand have obvious time-varying volatility and unbalanced spatial distribution.

TABLE III Values of parameters

Parameters	Symbols	Values & Units
Number of trains	$K^{(n)}$	36
Number of train couples	m_k	3
Length of discrete interval	σ	1min
Capacity of single passenger carriage	$F^{(p)}$	230
Capacity of single freight carriage	$F^{(q)}$	120 carriages
Maximum full load factor for passenger carriages	$\varepsilon_{\max}^{(p)}$	1
Minimum full load factor for passenger carriages	$\varepsilon_{\min}^{(p)}$	0.85
Maximum full load factor for freight carriages	$\varepsilon_{\max}^{(q)}$	1
Minimum full load factor for freight carriages	$\varepsilon_{\min}^{(q)}$	0.85
Departure interval	h_k	5min

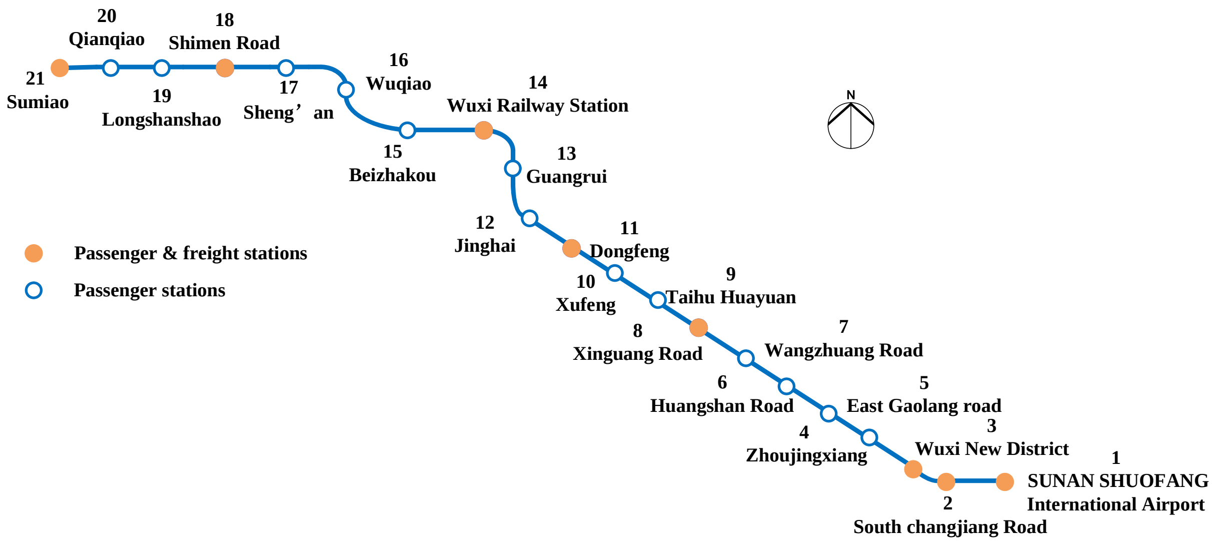

Fig.9. Schematic diagram of Wuxi Metro Line 3

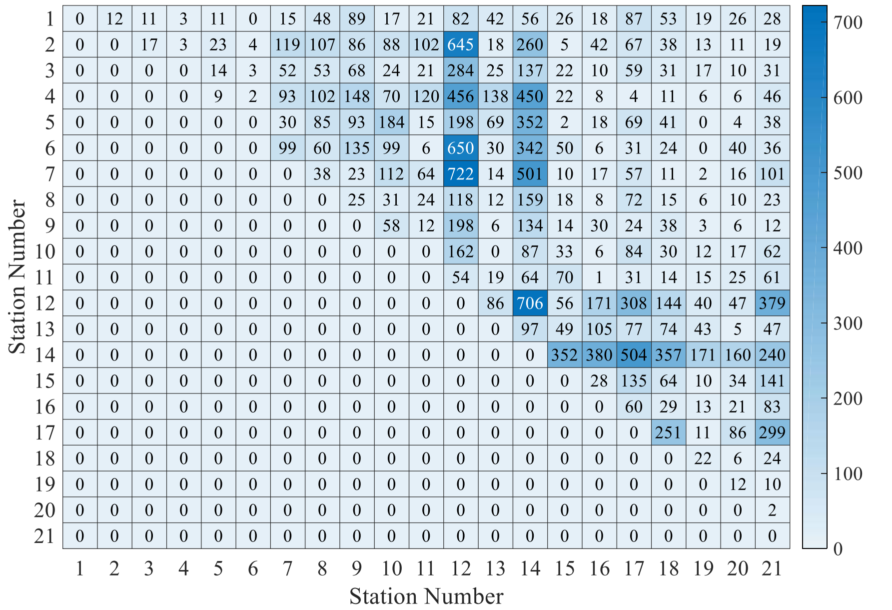

Fig.10. OD of passenger flow

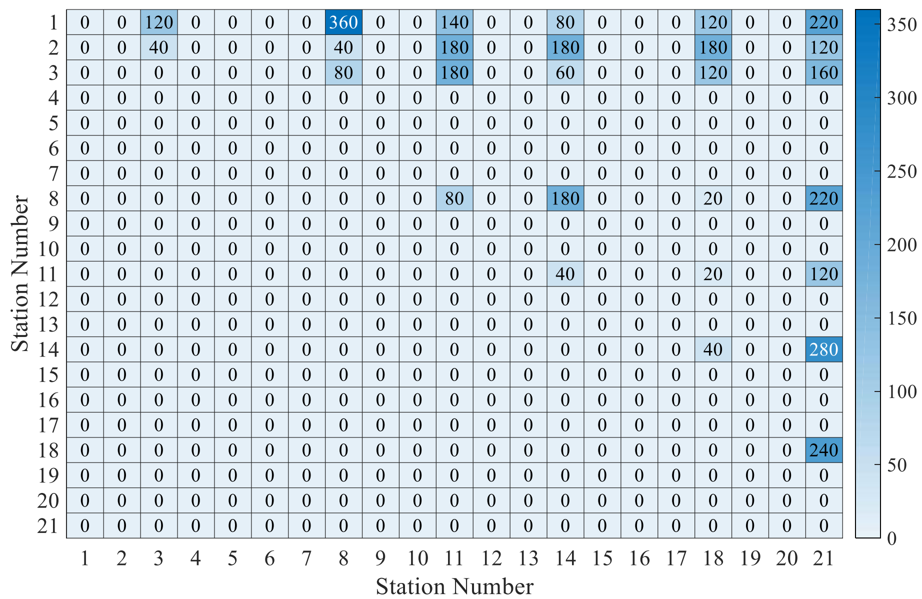

Fig.11. OD of freight flow

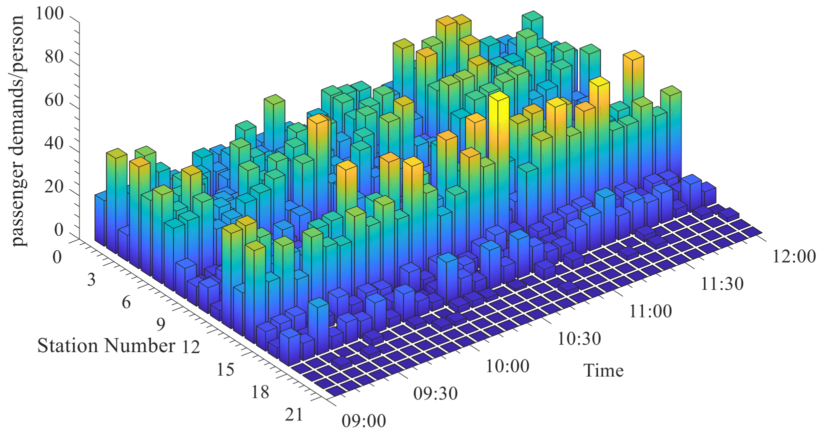

Fig.12. Distribution of passenger flow demand

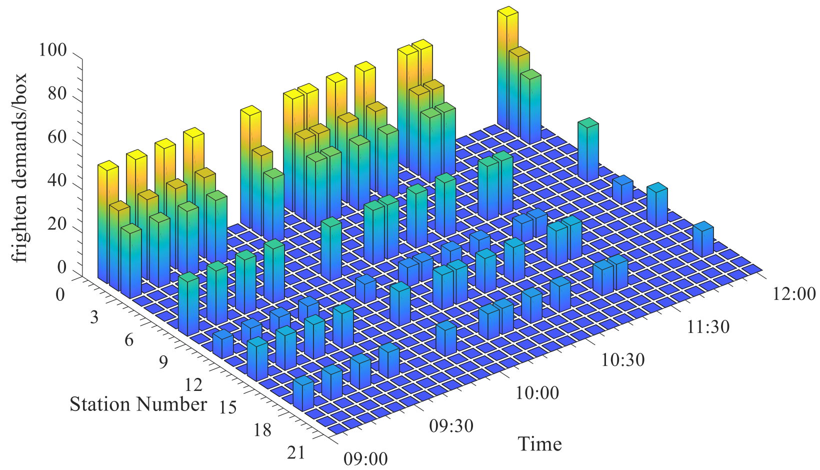

Fig.13. Distribution of freight flow demand

B. Result Analysis

Based on the above data and parameter Settings, based on the above constructed multi-objective programming model, this paper uses the fast, non-dominated sorting genetic algorithm NSGA-Ⅱ to solve the problem on MTLAB 2021 and puts the relevant known parameters and passenger flow and freight flow data under different virtual coupling schemes into the model to solve. Fig.14 is the Pareto front plot after 200 iterations with an initial population of 200. The larger the train's full rate is, the corresponding passenger waiting time decreases, but the more crowded the passenger compartment is, the worse the passenger experience is.

Fig.14 shows the operation diagram of a group of optimization results of virtual coupling trains, and Table V shows the distribution of rolling stocks and carriages. The average full load rate of trains on the whole line during the study period was 84.2%. Compared with the current operation scheme, the waiting time of passengers increases by about 11197min; that is, the average waiting time of passengers increases by about 0.65min. The average load rate of the whole line increased by about 16.5% during the study period. As seen from Fig.13, in this set of optimization results, the operation scheme of each car in the virtual coupling train is different, and the crossover operation will be carried out at different stations. At the same time, this scheme can meet the travel demand of all passengers and goods in the whole line.

The train operation diagram is shown in Fig.15. Before train 13, the inter-station operation is obvious, the total number of stops is small, and the virtual reconnection trains are fewer and concentrated in several large passenger sections for virtual reconnection, which is due to the non-peak passenger flow during this period, the number of passengers arriving during the discrete-time is small and concentrated in several large passenger stations, such as Shuofang Airport, Xufeng, Jinghai, Wuxi Railway Station, Shengan, Shimen Road and other stations.

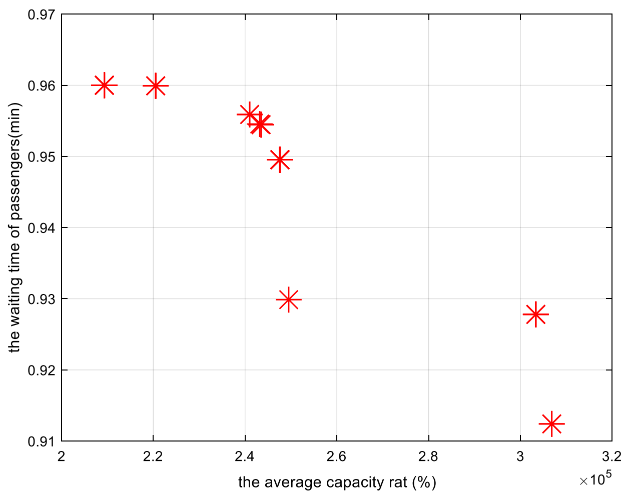

Fig.14. The Pareto front

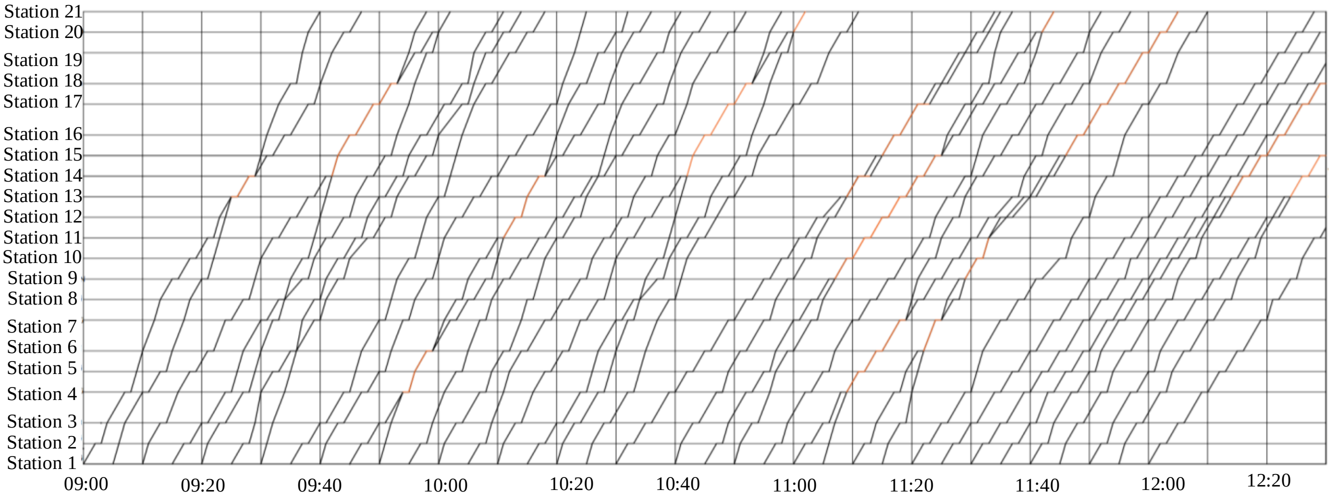

Fig.15. Optimal train operating diagram

In order to reduce passenger waiting time, it is necessary to match relatively high capacity in some sections while organizing inter-station stops and virtual reconnection of trains with stations in other sections with relatively low passenger demand to start passenger and cargo transportation better. After the 14th train, the total number of train stops gradually increases, and the number of virtual reconnection trains gradually increases. The operation intervals are relatively scattered, caused by the beginning of passenger flow to the peak. such as Beizhakou-Sumiao.

Therefore, it is necessary to match the corresponding capacity to complete passenger transportation in a timely and priority manner. After the 27th train, station stop trains started to appear, and the number of train stops increased significantly. The number of virtual reconnection trains decreased and concentrated in the large passenger flow section.

This is because the passenger flow mini-peak has arrived, and the passenger flow demand is still growing until the passenger flow peak arrives. The passenger flow base in this period was large and scattered in each station; organizing frequent inter-station stops could no longer meet the passenger flow waiting demand in each station, so organizing trains to stop evenly in each station and organizing virtual reconnection of small group trains into large group trains in some passenger flow sections in need, which can better reduce passenger waiting time and improve transportation efficiency.

The carriages allocation is shown in Table IV. Train 3 is a specific freight train, and the number of freight carriages is significantly larger before train 13; this is because, in the early part of the study period, the number of passengers is low, and only the corresponding capacity needs to be matched, with a surplus capacity to meet the demand for larger freight flows in that period. After the 13th train, the number of freight cars is significantly reduced, and more frequent pure passenger trains are operated, such as train 18, train 22, and train 26. This is because this is when Wuxi Metro Line 3 transitions from off-peak to peak passenger traffic, and the passenger demand gradually increases. Hence, it must match the corresponding capacity to start passenger traffic transportation. After the 26th train and until the end of the study period, 11 trains were attacked, 7 of which were purely passenger trains, because during this period, the peak passenger flow gradually arrived and the passenger demand surged, so it was necessary to match the corresponding capacity to start passenger transport.

As the passenger flow considered in this paper is relatively large, most train cars are passenger trains, and only a small portion is used for cargo transportation. As can be seen from Table IV, in the case of denser passenger demand, freight cars are allocated as little as possible, and mixed passenger and freight trains are operated when the passenger demand is small or a small number of freight trains can be operated according to the situation to provide services for cargo transportation.

TABLE IV Allocation of train carriages

NO.	Passenger/Freight carriages allocation (rolling stocks)	Passenger/Freight capacity (persons/containers)	NO.	Passenger/Freight carriages allocation (rolling stocks)	Passenger/Freight capacity (persons/containers)
1	2/1	659/214	19	2/1	687/469
2	1/2	564/537	20	2/1	1435/178
3	3/0	1454/0	21	1/2	754/826
4	0/3	0/826	22	3/0	1264/0
5	2/1	626/178	23	2/1	815/469
6	3/0	1435/0	24	1/2	426/736
7	1/2	494/826	25	2/1	834/78
8	1/2	671/469	26	3/0	1094/0
9	2/1	952/148	27	1/2	671/537
10	1/2	834/736	28	3/0	1652/0
11	2/1	885/314	29	3/0	1885/0
12	1/2	942/896	30	2/1	942/177
13	2/1	955/314	31	3/0	1355/0
14	2/1	731/177	32	3/0	1431/0
15	2/1	489/51	33	2/1	689/148
16	2/1	672/78	34	3/0	1272/0
17	2/1	824/314	35	3/0	1524/0
18	3/0	1529/0	36	2/1	429/226

TABLE V Comparison of experimental results

NO.	Program	Passenger waiting time/min	Average full load rate/%
1	Small coupling trains for passenger transport	144488	0.5675
2	Small coupling trains for passenger and freight transport	144488	0.7059
3	Passenger transport under virtual coupling conditions (minimum transport unit is a small coupling of trains)	164488	0.6898
4	Passenger and freight transport in virtual coupling conditions (minimum transport unit is a small coupling train)	199296	0.8716
5	Large coupling trains for passenger transport	188099	0.4866
6	Large coupling trains for passenger and freight transport	188099	0.7662
7	Passenger transport under virtual coupling conditions (minimum transport unit is a large couple of trains)	205318	0.5886
8	Passenger and freight transport in virtual coupling conditions (minimum transport unit is a large couple of trains)	249035	0.8881

The above results further illustrate that the virtual coupling-based passenger and freight cooperative transportation proposed in this paper can better use rail transportation resources and bring certain economic benefits. It should be noted that the passenger waiting time is affected by the change in the number of stops, but the excessive number of stops will lead to the loss of some cargo flow and reduce the average full load rate of the whole line.

As the model constructed in this paper is a mathematical optimization model with generality, the model can be extended by giving specific values of some decision variables to meet the special needs in practice. To further illustrate the effectiveness of the cooperative optimization method based on virtual coupling, the mathematical models constructed in this paper are solved for virtual coupling, passenger and freight transportation in fixed coupling, and passenger transportation only in fixed coupling mode, respectively. The results obtained in different cases are shown in Table IV.

The full load rate is one indicator that reflects the quality of the train operation plan. As seen from Table V, since secondary waiting for passengers is not allowed in this paper, passenger-freight collaborative transportation under fixed coupling mode cannot match the time-varying demand of passenger flow. Freight flow well, and many large coupling passenger trains are needed to meet the requirements of passenger transportation service. As a result, the average load rate of the scheme obtained by carrying out passenger and cargo co-transportation under the traditional fixed small coupling mode is inferior to that under the traditional fixed large coupling mode. It further illustrates the importance of combining virtual coupling operation organization mode to carry out passenger and cargo collaborative transportation.

In addition, this paper compares and analyzes the passenger flow demand and load factor under the traditional fixed coupling transportation scheme and the transportation scheme obtained in this paper, as shown in Fig.16.

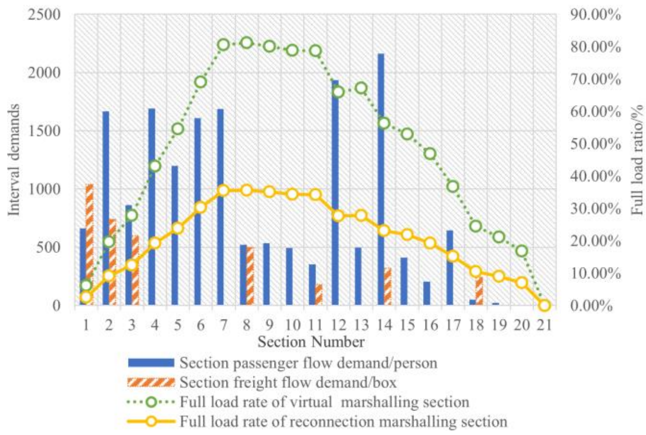

Fig.16. Comparison of full load rate between fixed and virtual coupling

The results show that the load ratio of the virtual coupling train operation scheme is 5% to 50% higher than that of the fixed coupling train operation scheme in different sections. Compared with the fixed large coupling passenger train, the virtual coupling train operation scheme carries out passenger transportation. Although the virtual coupling mode will increase the waiting time of passengers to a certain extent (only increase the average waiting time of passengers by about 0.65 minutes, and there is no secondary waiting situation for all passengers), it can increase the average load rate of about 38.5%, and greatly improve the transportation efficiency and operation revenue. Especially in the case of the same traffic volume, the revenue advantage brought by carrying out cargo transportation will be more obvious when transporting high-value goods. However, it is worth noting that the transportation of high-value goods has higher requirements for service quality and higher requirements for the stability of goods sources. Therefore, from the perspective of economics, considering the transportation of goods with different values and the stability of goods sources and other factors, as well as more refined operating cost analysis, it will be further research direction to study the integrated optimization of passenger and freight collaborative transportation based on virtual coupling.

V. CONCLUSION

Based on the virtual coupling organization mode, this paper studies the optimization of urban rail transit's passenger and freight collaborative transportation scheme. It establishes a mathematical optimization model to minimize the passenger waiting time and maximize the average full load rate to make cooperative optimization decisions on the train coupling scheme, train operation diagram, and passenger and freight transportation scheme. The case studies show that:

(1) Compared with the fixed single coupling operation mode, the virtual coupling operation mode can better respond to the changes in passenger demand and improve the average full load rate of trains. Compared with the current large coupling operation mode, the virtual group operation mode can increase the average train loading rate by about 10.2% while only increasing the average waiting time of passengers by about 1 minute.

(2) Compared with the single-passenger transportation mode, the virtual coupling mode can increase the average load rate by about 38.5% when the average waiting time of passengers is only increased by about 0.65 min, and no passenger has to wait twice.

(3) Although the virtual coupling mode is difficult to operate and solve the model, the virtual coupling mode can be combined with the advantages of passenger and freight collaborative transportation to achieve a better match between train capacity and demand. It is worth noting that the model constructed in this paper is a more general mathematical optimization model, and the model can be degraded to a traditional single coupling transportation optimization model when there is no cargo flow input for a given set of stopping schemes.

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