

Article

Receiving Routing Approach for Virtually Coupled Train Sets at a Railway Station

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Abstract: Elaborated in several forms before being formally defined, virtually coupled train sets (VCTS) have become an issue for capacity increase with obvious shorter train intervals. As the station organization strategy is still ambiguous due to the lack of literature, the receiving routing problem for VCTS is studied in particular. First, the existing concept of VCTS is explained, which refers to the virtual connection of trains through safe and reliable communication technology, allowing short-interval collaborative operations without the need for physical equipment. Subsequently, the operating characteristics and receiving requirements are analyzed. With a summary of factors affecting receiving operations, a mathematical model is proposed with the objectives of minimizing operation duration and maximizing effectiveness, which is solved by an improved genetic algorithm (GA) with an elitist and adaptive strategy. Numerical tests are carried out 250 times based on a practical station and EMU parameters. The macro results show the valid pursuit of designed objectives with an average duration of 204.95 s and an efficiency of 91.76%. Microevolution of an optimal scheme indicates that safety requirements are met while the process duration is only 35.83% of the original CTCS-3 mode.

Keywords: virtually coupled train sets (VCTS); multi-objective optimization; improved genetic algorithms (GA); receiving routing problem; train intervals; elitist and adaptive strategy

MSC: 90B06



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1. Introduction

Several methods have been studied in rail traffic for higher capacity and faster organization. The growth in demand for freight and passengers has led to the development of a new generation of signaling and communication solutions for railway transportation. To mitigate the challenge that more productive organization of train operation cannot be implemented under current equipment conditions, the concept of virtually coupled train sets (VCTS) was proposed as “virtually coupled train formations” in 2000 [1,2]. This technology aims to realize the function of a coupler without any physical connection by building trains as automated modules, to improve the flexibility of operation management.

At the end of the 19th century, to distinguish from the absolute distance braking mode in the moving block system, scholars in China proposed the idea of “the Combinatorial Control of the Trains Velocities System” and “relative distance braking mode” [3,4]. However, VTCS has attracted extensive attention and research in recent years. Chief of all, holding to the mission statement to move European railways forward, Shift2Rail proposed and funded research on virtual coupling as part of its innovation program 2 [5], and led its members to deepen this research area in the subsequent years. In practice, CAF with Siemens designed and tested a prototype of VCTS based on the new wireless train backbone, and finally, the trams operated at a fixed distance of 6 m without a physical connection successfully in

2018 [6,7]. This experiment confirmed the potential for the development of VCTS, and subsequent research in this area rapidly expanded.

The introduction, application scenarios, and implementation methods have received significant attention and study. The formal definition and application conditions for VCTS were put forward in 2020 by the Delft University of Technology cooperating with Shift2Rail to conduct the MOVINGRAIL project [8]. The public deliverables with regard to operational scenarios, application roadmap, business risk, and market potential analysis were published subsequently [9–11]. Stickel et al. also interviewed several experts and scholars in the field of VCTS, analyzed the current technical development of the system, and provided a detailed roadmap for VCTS development [12]. Lee and Wu et al. raised skip and stop scheduling, the braking model, and the track resource allocation method first proposed in Korea [13,14]. Chinese enterprises including CRSCD and TCT have analyzed the key technical requirements in application and carried out related theoretical research in the aspects of dynamic train formation and dispatching, station route selection, and the application of security assistance for VCTS, also applying for patents since 2018 [15–17]. Zhang developed a monitoring method using a topological manifold and proved that it is feasible to guarantee the safety of VCTS operation [18]. Lin modeled multiple high-speed trains as a quasi-multi-agent system with the leader–follower model and the experiments obtained the desired tracking and cooperation performance [19]. Against the background of the post-COVID-19 era, VCTS was also considered as a preventive measure by applying it to urban railway transit to reduce the risk of cross-infection [20].

In the case of general acceptance in the railway industry, the capacity and superiority of VCTS have been repeatedly validated and demonstrated. Quaglietta mainly modeled the train following model and conducted a comparative capacity analysis among several signaling systems, finally showing that VCTS can reduce the maximum train interval by 43% compared to ETCS-3 [21,22]. Liu proposed an intelligent dispatching and coordinated control model as an early organization method at a railway station, and the case of Nanjing South Station indicated that the proposed method increased the capacity of the station approaching and departing by 128.36% and 143.44%, respectively [23,24]. Through simulations and calculations of the Japanese Shinkansen high-speed line under VCTS, a promising result was achieved, showing an increase in passenger flow from 15,000 to 23,000 per hour in each direction [25]. VCTS provides ideas for solving some problems in railway transportation, such as minimizing passenger travel time and enterprise operation cost, optimizing the equilibrium of train load rate on short-turn routes, and maximizing energy efficiency [26–28]. The idea of VCTS was also used and analyzed in urban rail traffic and this operational model has the obvious advantage in seating capacity and delay recovery [29,30].

As for solving approach, the repeated application in production scheduling problems has provided a feasible method for solving large-scale optimization problems. Zhou has developed a highly efficient hybrid genetic algorithm that is capable of solving complex timetabling problems and his algorithm has feasibility in solving the combination scheme and train timetable of a heavy-haul railway [31]. Lin built a multiple-train operation model, and the results of an actual data test indicated that the optimization method based on GA is effective [32]. The framework of virtual coupling technology is usually setting up a distributed control center. Liu proposed a distributed model predictive control method (MPC) to maintain a continuous safe distance between trains [33]. Chai et al. proposed a long short-term memory MPC and showed its effectiveness in reducing train speed differences and distances [34]. Jesus defined a robust MPC performing for a metro line and obtained a safer operation of VCTS [35]. In addition, the connection with artificial intelligence is increasingly close [36,37]. Overall, although existing literature has established several models to describe the train set control and operation, only a few studies have focused on the specific operational requirements and processes at the station, which is always the limit section for the railway capacity. A general overview of the basic characteristics and requirements for VCTS operation is in Section 2. Section 3 presents key factors affecting

VCTS operation and the receiving route platform model is mathematically built on this basis. A case study is established to test the proposed method, and the results of both multiple operations and individual schemes are analyzed in Section 4. The final section concludes the given content.

2. Analysis of VCTS Operating Conditions

2.1. Connotation and Advantage of VCTS

The concept of coupling was first used in physics to describe the interaction between circuits. Since then, the concept has been applied in various fields, including the railway industry, to describe the interaction and influence relationships between different components. Recently, VCTS has attracted considerable attention from researchers, and its implementation can be highly feasible due to the advancements in communication and signaling technology. Without actual physical equipment to connect, safe and reliable communication technology can realize the cooperative control of location and speed among trains in a set, to further solve the problem that currently trains with different type specifications cannot be reconnected with a coupler.

Trains can move between an interval less than the absolute braking distance, improving the capacity of the line. At the same time, the coupling and decoupling of trains at crossovers enable greater flexibility in train formation planning.

While most existing research considers several operational states and transitions for VCTS operating in sections, which requires trains to revert to the current communication and signaling mode before entering the station area [21,22], this practice does not fully exploit the advantages of VCTS. Therefore, an improved state adjustment method should be considered.

2.2. Operational Characteristics of VCTS

VCTS forms an invisible connection between adjacent trains through coordinated speed and acceleration control, allowing for train coupling and decoupling. When trains on the same track meet the requirements for speed, follow-up path, performance, etc., the mode of control will switch from moving block to VCTS according to the future operation plan. The coupling process will be relieved under specific circumstances to lengthen train separation to absolute braking distance. The main scenario is that a train set approaches a fork, and the time interval of contiguous trains in different directions should meet the safety requirement for the turnout conversion duration. However, the decoupling process may not always go as planned. The state of coupling will not maintain if the performance difference of the rear vehicle is so large that the train intervals increase inevitably, causing the situation of decoupling.

The prominent role of the leading train in dynamic tracking during coupling in a section is a key focus of VCTS, and it serves as the basis for the literature review. The coupling status between trains is a critical aspect of railway operations, and the leading train plays a significant role in ensuring the safe and efficient passage of the train group through the section. However, current research in the field of station operations is limited, and the majority of existing studies propose that train sets undergo dynamic decoupling when approaching a station, prioritizing the independence of individual trains for safe entry into their respective tracks due to concerns over the potential for collisions or other safety risks.

Only the case in which the trains are completely coupled and running steadily is described in detail here. Under this situation, trains move at the same speed and acceleration as the preceding vehicle, which is acceptable to all trains depending on various factors, such as traction characteristics, movement resistance, and braking capabilities. A schematic diagram is also given to calculate train intervals under this stable condition (see Figure 1).

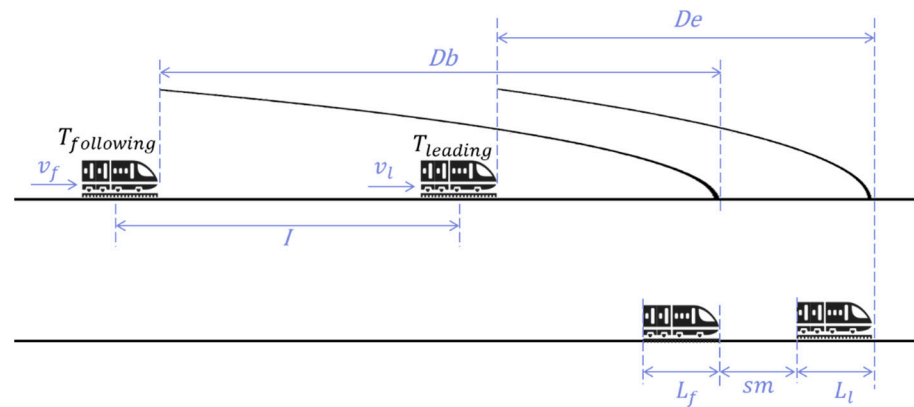


Figure 1. A schematic example of interval calculation is proposed based on two adjacent trains running under VCTS.

Here, the train interval (I) is calculated as the distance between the midpoints of the leading train (TR_l) and the following one (TR_f). This approach considers the braking distance (Db), including a safety margin (sm) to further ensure safety and reduce the rate of train collisions. In the case of accidents or emergencies, the leading train (TR_l) will apply emergency braking at its current speed v_l , denoted as De . The equation derived from Figure 1 can be expressed as follows:

$$De(v_l) + I - \frac{1}{2}L_f + \frac{1}{2}L_l - Db(v_f) = sm + L_l, \quad (1)$$

where L_l and L_f are the lengths of trains TR_l and TR_f , respectively, and their velocities v_l and v_f are considered as the main factors in calculating their respective braking distances. The formula for I can be rearranged as:

$$I = Db(v_f) - De(v_l) + sm + \frac{1}{2}(L_l + L_f), \quad (2)$$

where the analysis and modeling of train intervals in the following sections are simplified, and the method proposed by Zhu [38] is adopted to calculate Db . To meet the demanding response and control delay requirements of the VCTS system, an automated train control system (ATO) is employed. In the ATO system, driver reaction time is assumed to be negligible, and the braking curve without response time is as shown in Figure 2.

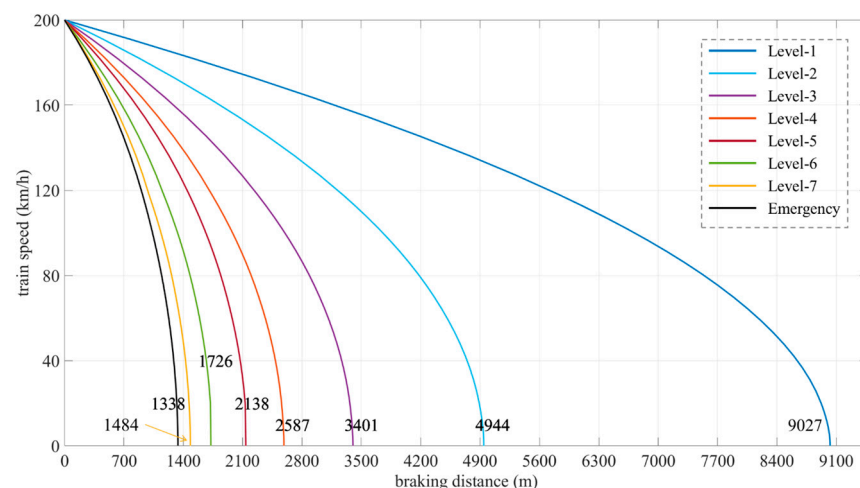


Figure 2. The distance–speed curves of different levels for trains braking from 200 km/h reflect multiple characteristics of their process.

2.3. Train receiving Requirements for VCTS at Station

The carrying capacity of the entire railway system is always limited by stations in accordance with the existing procedures for receiving trains. This method is even less suitable for VTCS and requires adjustment. Due to the limitations of practical conditions, application requirements, current facilities, and equipment, a station cannot receive more than one train at a time. The decoupling process of a train set entering a station should instead be realized by the position relationship among platforms, turnouts, and other equipment. At present, an interlocking system with a microcomputer as the core is mainly used in rail stations, enabling logical inspection and subsequent control of interlocking equipment in the stations, and connecting with the block-signaling system. This architecture is the technical prerequisite for a railway station to receive VCTS. At the same time, regarding the smaller interval which is the most obvious feature of this technology, the constraints become stricter than before, and station operation regulations will need adjustment.

The time interval between two trains at a station shows the minimum interval required to handle the procedure of receiving or departure. The current standard is insufficient to meet the intensive receiving requirements. The constraint acting on a train will change its function object to the whole train set instead of the individual train. The safety requirements of node equipment such as switches are used to constrain the train set for VCTS.

Unlike releasing the route and switches after the rail of the train crosses the route completely, the concept of receiving route is no longer applicable for VCTS, and the process is executed by taking the turnout as the main reference. Combining the characteristics of an automatic hump, the switch automatic centralized control system will store a hunting plan for the break-up of trains ahead of time. Based on this idea, the switches on planned routes can be manipulated automatically. The switches will stay in the same direction while considering the consecutive assignment of a train in a set. Similarly, the direction and transfer time of turnouts should be arranged in advance according to the subsequent operation of the train sets, as well as the direction, if trains pass continuously.

In addition to meeting the required safety conditions, the overall service quality should be fully considered. To accommodate VCTS, the facilities, operation mode, and organization process at a station will undergo disruptive changes with the above-mentioned contents.

3. Mathematics Model and Formulation

3.1. Factors Affecting the Operation of VCTS

In actual operation, a station receiving trains via VCTS must ensure that various parameters between the rail station and trains are matched and confirmed, such as the station's topological network, allowable through speed, and conversion duration of switches of different types, as well as the performance of the trains. By comprehensively considering constraint conditions, the model can generate a corresponding receiving plan, and then determine the entering section and moment of each train in the set. To illustrate the influenced factors and operation constraints of trains in the same direction, the example of TR_l and TR_f is still used here.

The shorter interval requirement of VCTS emphasizes the need for increased attention to safety conditions at turnouts. In addition to ensuring the required safety interval, it is important to allow adequate interval time to ensure safe and efficient train operations. This includes consideration of the conversion duration of switches when selecting paths for contiguous trains that may be traveling in different directions. This demand can be required at switch s , so that

$$t_{f,s} - t_{l,s} \geq \theta_l^s \cdot \theta_f^s \cdot \mu_{l,f}^s \cdot T_{c,s} + \frac{l}{v_{f,s}}, \quad (3)$$

where $t_{f,s}$ is the moment that TR_f passes through switch s since the head of the train set enters the throat of a station. θ_l^s is a Boolean variable that expresses whether switch s is on the planned route of TR_l or not, while $\mu_{l,f}^s$ is a Boolean variable that identifies whether

switch s needs to change its direction if TR_l and TR_f pass continuously through it, denoted by 1 for yes and 0 for no. $T_{c,s}$ represents the conversion duration for switch s , and $v_{f,s}$ represents the velocity of TR_f at switch s . Except for conflicts in the same direction, the potential collision risk between trains at common nodes on routes in opposite directions should be avoided. The safety condition for turnouts at a cross node is shown as:

$$\theta_l^s \cdot \theta_{Ol}^s \cdot |t_{l,s} - t_{Ol,s}| - T_{c,s} \geq \frac{I + 0.5 \times (L_l + L_{Ol})}{v_{f,s}}, \quad (4)$$

where Ol represents train T_{Ol} running in the opposite direction to T_l . To ensure the proper functioning of station equipment and the comfort of passengers during braking, speed restrictions must be set at the station. This can be achieved by establishing a time interval between switches, such as switch s and switch r , that are passed in a succession by the same train, as follows:

$$t_{i,r} - t_{i,s} > T_{s-r}, \quad (5)$$

where T_{s-r} represents the minimum time separation limitation to travel through switch s and switch r . In addition to the interval and speed requirements for safety and efficiency, it is crucial to select appropriate receiving routes and ensure that trains operate as planned. According to the rules and regulations of railway passenger traffic organization, a platform can only accommodate one train or a coupled EMU group. Therefore, the corresponding arrival and departure line must be available before the receiving application starts, and this can be constrained as follows:

$$\sum_{q=1}^p \sum_{l=1}^n x_{l,q} \varphi_q = 0, \quad (6)$$

where $x_{l,q}$ and φ_q are both Boolean variables indicating whether the train l stops at or passes through the station track q , and whether the arrival–departure track q is occupied or not, respectively, with 1 denoting yes and 0 denoting no. The variables p and n represent the total number of arrival–departure tracks at a station and the number of approaching trains, respectively. Here, l also presents the progression order of trains in a batch. Additionally, due to the limited capacity of the station platform and the requirement for the uniqueness of arrival and departure lines, which can be expressed as follows:

$$\sum_{l=1}^n x_{l,q} = 1, \quad (7)$$

to prohibit the repeated selection of the same track in the same batch. Moreover, in complex stations, there may be multiple receiving routes leading to a single station line, and trains are only allowed to travel on one selected receiving route or through route, which is expressed as follows:

$$\sum_{u=1}^{v_q} y_q^u = 1, \quad (8)$$

where v_q represents the number of feasible receiving routes for arrival and departure lines q , and y_q^u is a Boolean variable that identifies whether receiving route u is selected, where 1 denotes yes and 0 denotes no.

In an extreme organization environment, station scheduling may allow a receiving train to stop at the mainline under special circumstances, after which procedure this main line can no longer be used and all the trains passing through in the same direction must go ahead of the arrived and stopped trains. The constraints that apply order to the main line can be expressed as follows:

$$\sum_{l=1}^n x_{l,q} \cdot l > \sum_{l=1}^n \lambda_l \cdot l, \quad (9)$$

where λ_l is a Boolean variable used to determine whether train numbered l is passing through or not, where 1 denoted yes and 0 denoted no.

3.2. Establishment of Receiving Routing Model

A comprehensive theory of receiving schedules for VCTS is still lacking, and the approach posed requires mainly basic and essential elements. In the consideration of the comprehensive factors above in terms of security, the efficiency analysis and pursuit are further considered. The total duration of the receiving process is the most important type of efficiency evaluation, after which the benefits of an organization schedule are preferred. The first optimization objective is set as minimizing the total operation time of the train set, which is shown as follows:

$$\min Z_1 = t_{l,c} + \lambda_l \cdot \frac{L_l}{v_{l,c}}, \quad (10)$$

where node c represents the judge points of train operation. Taking the moment that the first train head in a set enters the throat of a station as the timing point, the total duration Z_1 is the moment that the head of train l stops at the designated track destination for the arrived train. As for passing trains, timing stops when the trail moves out of the station throat area total according to the operational plan. The process of the total length of the passing train driving through the exit of the throat area is regarded as uniform linear motion.

As each track at the station serves different functions and is used differently, the level of convenience and safety provided by each arrival and departure line varies, particularly when matched with trains that have specific operational tasks. In consequence, the other objective is to maximize the effectiveness of the selected route application scheme. This maximum objective measures the overall value of the scheme for the whole train set, which is expressed as follows:

$$\max Z_2 = \sum_{q=1}^p \sum_{l=1}^n x_{l,q} \cdot \omega_{l,q}, \quad (11)$$

where $\omega_{i,q}$ represents efficiency values when train i utilizes track q , whose value ranges from 0 to 1 according to the station organization and train sets operation plan.

The opposite types and dimensions of the above optimization objectives need to be unified as the subsequent process of adjustment to a common optimization direction of minimization, nondimensionalization, and normalization, and finally weights allocation. Processing the maximization goal can be expressed as:

$$\min Z'_2 = - \sum_{q=1}^p \sum_{l=1}^n x_{l,q} \cdot \omega_{l,q}, \quad (12)$$

after which the next handler is to make both objective values under the standard, as follows:

$$f(Z_1) = \frac{Z_1 - Z_1^{\min}}{Z_1^{\max} - Z_1^{\min} + \sigma}, \quad (13)$$

$$f(Z'_2) = \frac{Z'_2 - Z_2'^{\min}}{Z_2'^{\max} - Z_2'^{\min} + \sigma}, \quad (14)$$

where $\min$ and $\max$ slant above the letters that represent the value of their primaries are the maximum and minimum respectively. Meanwhile, the setting of σ , a minimally positive number in the denominator, is to avoid calculating mistakes. The weights assignment for objectives is determined by the operating requirements and benefit expectation subjectively, and the final target expression can be shown as:

$$\min Z = \lambda_1 f(Z_1) + \lambda_2 f(Z'_2), \quad (15)$$

$$\lambda_1 + \lambda_2 = 1, \quad (16)$$

where $\lambda_1 > \lambda_2$ is considered to prioritize organizational safety.

4. Solution Approach Based on a Genetic Algorithm

Genetic algorithms are a heuristic technology widely used with high robustness, scalability, and implicit parallelism. The standard GA iterates through a population, using

selection, crossover, and mutation steps to produce results. To solve the receiving route allocation problem, a common research area in engineering management, an improved GA with an elitist and adaptive strategy is used.

4.1. Rules of Chromosome Encoding and Decoding

The chromosome to describe the route selected by trains is encoded by a real-coded rule (see Figure 3). Each gene in the chromosome corresponds to a train, with a character representing the chosen route. In this way, the length of the chromosome is equal to the number of trains in the receiving process. The decoding process can be obtained quickly, and the generated scheme can be analyzed easily.

Chromosome	$\sum q \cdot x_{1,q}$	$\sum q \cdot x_{2,q}$	...	$\sum q \cdot x_{l,q}$	...	$\sum q \cdot x_{n,q}$
Implication	Route selected for train numbered 1	Route selected for train numbered 2	...	Route selected for train numbered l	...	Route selected for train numbered n

Figure 3. The form of the real-coded chromosome is an intuitive reflection of its practical meaning.

4.2. Generation of an Initial Population

The chromosome encoding process considers both biodiversity and population superiority. Formulas (7) and (8) ensure the required route uniqueness as well as arrival and departure lines uniqueness analyzed in the second section. Multiple judgment and comparison processes will be performed (see Figure 4).

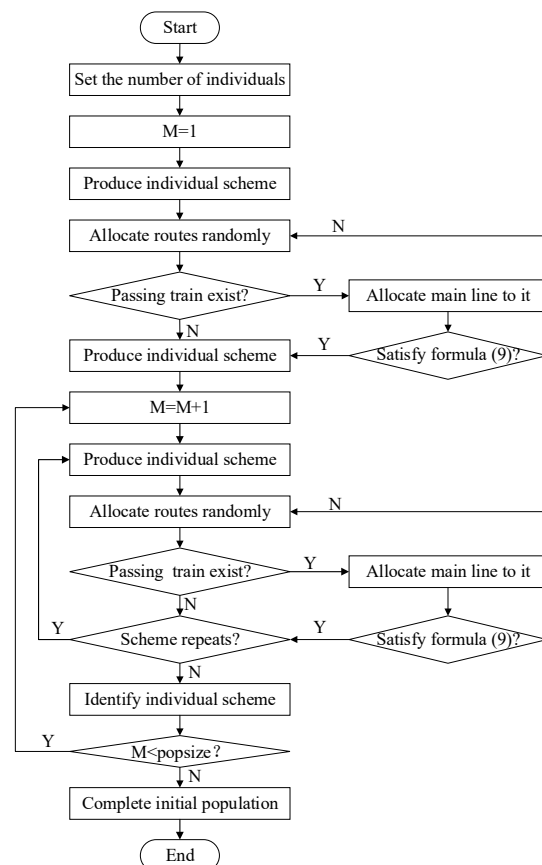


Figure 4. The individual genotype is valued by train tasks to ensure its superiority and diversity in the process of population initialization.

First, it needs to judge whether there are passing-through trains in the approaching VCTS. If there are, priority is given to the allocation of the main line for them, and then assigning routes to the others. After valuing a newly generated individual, it will be compared with the existing individuals. If there are duplicates, the subsequent one will be regenerated until it becomes unique in the population. The cycle ends with enough individuals for the initial population.

4.3. Fitness Function Setting

For the designed fitness with consideration of operational safety and efficiency, the corresponding distinction between compulsory and optional constraints is put forward. The efficiency-oriented soft constraints mainly point to the optimization objective of the model for the higher benefit, establishing indexes *fitn1* and *fitn2*. The hard constraints to ensure safety include the factors analyzed as Formulas (3), (6) and (9) for the establishment of *fitn3* to *fitn7*. The method of relative calculation is adopted in the comprehensive evaluation of the above indications, which can be described as follows:

$$fitn = \lambda_1 \frac{fitn1 + fitn2}{2} + \lambda_2 \frac{fitn3 + fitn4 + fitn5 + fitn6 + fitn7}{5}, \quad (17)$$

$$\lambda_1 + \lambda_2 = 1, \quad (18)$$

$$\lambda_1 < \lambda_2, \quad (19)$$

where λ_1 and λ_2 indicate the weight allocations of efficiency and safety, where security requirements take precedence. The sub-fitness for every individual can be explained in the corresponding evaluation items:

fitn1: the total operation time of the train set

$$fitn1 = 1 - \frac{Z_1 - Z_1^{min}}{Z_1^{max} - Z_1^{min} + 0.001}, \quad (20)$$

fitn2: the effectiveness of the selected route application scheme

$$fitn2 = \frac{Z_2 - Z_2^{min}}{Z_2^{max} - Z_2^{min} + 0.001}, \quad (21)$$

fitn3: the constraints of switch transition time for trains in the same direction

$$fitn3 = \begin{cases} 1, & \text{The individual satisfies the Formula(3)} \\ 0, & \text{otherwise} \end{cases} \quad (22)$$

fitn4: the constraints of occupation conflict for trains in different directions

$$fitn4 = \begin{cases} 1, & \text{The individual satisfies the Formula(4)} \\ 0, & \text{otherwise} \end{cases} \quad (23)$$

fitn5: the constraints of train operating speed

$$fitn5 = \begin{cases} 1, & \text{The individual satisfies the Formula(5)} \\ 0, & \text{otherwise} \end{cases} \quad (24)$$

fitn6: the constraints of unoccupied corresponding arrival and departure lines

$$fitn6 = \begin{cases} 1, & \text{The individual satisfies the Formula(6)} \\ 0, & \text{otherwise} \end{cases} \quad (25)$$

fitn7: the constraints of applying the order of the main line

$$fitn7 = \begin{cases} 1, & \text{The individual satisfies the Formula(9)} \\ 0, & \text{otherwise} \end{cases} \quad (26)$$

4.4. Algorithm Termination Condition

The standard GA process will record the number of population evolution when it reaches the preset value of iterations, and then termination will come into play. Reasonable iterations set in advance are beneficial to obtain optimal results in a short time. Due to the limited number of station lines as well as route allocation options, the early termination condition is also designed here to avoid the unnecessary iterative process resulting in the disappearance of the optimal solution. It will work when the same fittest phenotype is obtained during continuous population evolution, whose time is also set before the algorithm runs.

4.5. Genetic Operators with Elitist and Adaptive Strategies

GA produces a new population iteration following the steps of selection, crossover, and mutation. These strategies can increase the speed of finding the optimal solution from a limited number of options.

The first step is roulette wheel selection, assigning a probability to each individual based on their fitness:

$$\phi(i) = \frac{fitn(i)}{\sum fitn(i)}, \quad (27)$$

where $\phi(i)$ indicates the probability of individual i being the chosen one. The higher the fitness, the greater the chance of being passed on to the next generation. The elitist selection method replaces the last offspring individual with the parent individual which currently has the highest fitness.

Crossover and mutation are crucial in the convergence and computational quality of the algorithm. An adaptive strategy adjusts the probability of individuals. Individuals with higher fitness than average have a lower probability of crossover and mutation. The variables marked as $P_c(i)$ and $P_m(i)$ are calculated as follows:

$$P_c(i) = \begin{cases} \frac{k_1(fitn_{max}-fitn(i))}{fitn_{max}-fitn_{avg}}, & fitn(i) \geq fitn_{avg} \\ k_2, & fitn(i) < fitn_{avg} \end{cases}, \quad (28)$$

$$P_m(i) = \begin{cases} \frac{k_3(fitn_{max}-fitn(i))}{fitn_{max}-fitn_{avg}}, & fitn(i) \geq fitn_{avg} \\ k_4, & fitn(i) < fitn_{avg} \end{cases}, \quad (29)$$

where $fitn_{max}$, $fitn_{avg}$ represent the maximum and average fitness value of the population respectively, and k_1 , k_2 , k_3 , and k_4 are constants used to implement the adaptive strategy satisfying that $k_1 < k_2$ and $k_3 < k_4$. It follows that $P_c(i)$ and $P_m(i)$ can eliminate or improve the undesirable individual.

Specific operation methods of one-point crossover and simple mutation are designed. The judge condition is that there is no same scheme in offspring as the one after crossover or mutation. Taking the crossover process as an example, the detailed steps are as follows:

1. Calculate the number of chromosomes for crossover as $M \cdot P_c$ (M is the total number of individuals in a generation).
2. Compare a randomly generated number between 0 and 1 with P_c . If $P_c(i)$ is greater and the genotypes of adjacent chromosomes are different, perform crossover.
3. Generate a random number u ($u \leq n$).
4. Exchange all genes after gene point u to obtain two new progenies from two adjacent chromosomes.

5. Check if the constraints on the individuals after crossover are met. If yes, the crossover operation is completed. Otherwise, repeat the second step.

For simple mutation, a gene of a child is randomly changed, and the basic steps and verifications are similar to the crossover approach.

The improved GA proposed utilizes elitism to preserve the best solution found so far, preventing loss or premature elimination and avoiding local optima. The adaptive strategy dynamically adjusts the crossover and mutation rate based on the fitness of the current population, enabling effective exploration or exploitation of the search space. These strategies enhance the algorithm's efficiency and effectiveness in searching for the optimal solution while avoiding premature convergence to local optima.

5. Case Study

5.1. Station Background Setting

A specific type of Chinese high-speed railway is selected as an example to demonstrate the concurrent receiving route allocation problem in a station in Henan province under VCTS. It is assumed that train technology, station facilities, and equipment are suitable for the operation of VCTS. The adjusted rule ensures that the time interval between EMUs in opposite directions to occupy the same switch is greater than 60 s. However, the realization of a brand-new receiving method without a complete process of route locking and releasing requires an innovative approach to judging the position of EMUs and their safety relation. The station diagram with newly added position judgment nodes is shown (see Figure 5).

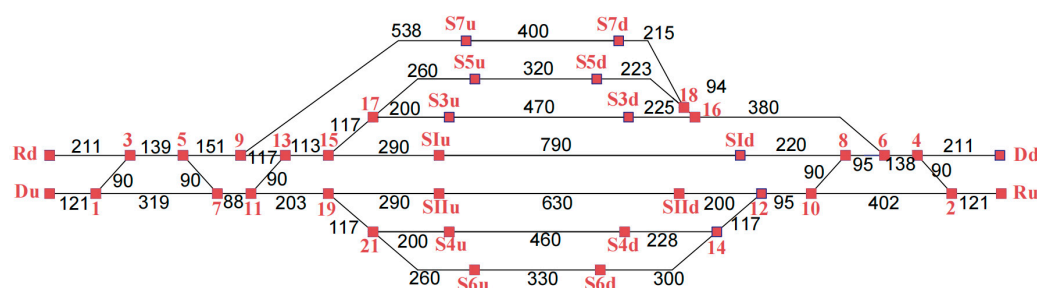


Figure 5. Nodes are reset to suit the applications for VCTS and their distances are given as black numbers.

The nodes whose set expression is $\{R_d, D_d, R_u, D_u\} \cup \{S_{Id}, S_{Iu}, S_{IIId}, S_{IIu} \dots S_{7d}, S_{7u}\} \cup \{1, 3, 5 \dots 21\} \cup \{2, 4, 6 \dots 18\}$ are represented as squares, where $\{R_d, D_d, R_u, D_u\}$ represents the entrance or exit points of the station throat area reflecting the organization of receiving and despatching in different directions, and $\{S_{Id}, S_{Iu}, S_{IIId}, S_{IIu} \dots S_{7d}, S_{7u}\}$ indicates the nodes for train stopping on respective main lines or station tracks. The final $\{1, 3, 5 \dots 21\} \cup \{2, 4, 6 \dots 18\}$ indicates the number of switches, whose minimum number is 42. Its specific parameters restrict the EMU operation in the station, especially in the terms of train speeds and intervals (see Table 1).

Table 1. Required technical parameters and operating conditions of turnout [39].

Index	Performance
Allowable lateral through speed (km/h)	80
Allowable straight through speed (km/h)	350
Total length of turnout (mm)	6900
Distance between tracks (mm)	4600
Conversion duration (s)	13

Various performances of station lines and their corresponding platforms should be quantified comprehensively. The operating capacity in the station is specified as well as working habits (see Table 2).

Table 2. The operating capacity or working habits of the arrival and departure lines and their corresponding platforms are set according to their application and function.

Operating Capacity or Working Habit	Number of Station Line						
	I	II	3	4	5	6	7
Train passing through	1	1	0.05	0.05	0.05	0.05	0.05
Train reception on up direction	0.1	0.5	0.7	1	0.7	1	0.6
Train reception on down direction	0.5	0.1	1	0.7	1	0.7	1
Train departure on up direction	0.1	0.5	0.7	1	0.7	1	0.6
Train departure on down direction	0.5	0.1	1	0.7	1	0.7	1
Shutting in and out of the depot	0.8	0.8	1	0.6	1	0.6	0.9
Serving and technical inspection	0.5	0.5	0.8	0.8	0.9	0.9	1
Passenger alighting and boarding	0.2	0.2	1	1	1	1	1
Passengers' walking distance	0.1	0.1	0.9	0.8	1	0.7	1

5.2. Scenario Setting and Operation Process

Two train sets pull into the station at distinct speeds from opposite directions, respectively. The international standard numbered ISO 2631-5:2018, where the assessment of the relationship between acceleration and health effects states that passengers will be in good comfort with a braking acceleration lower than 0.63 m/s^2 , is used here to compare the adaptability of braking modes and confirm train interval [40]. Level-2 braking mode is selected to accommodate multiple factors of organization performance, passenger comfort, and operational safety. The acceleration a_2 with a_e for emergency braking is given below [38] (see Table 3).

Table 3. Acceleration (m/s^2) under various ranges of speed is calculated based on a known formula for the basic resistance of a train ($\omega_0 = 0.5 + 0.001v + 0.00013v^2$).

Degree	Range of Speed ($\frac{\text{km}}{\text{h}}$)				
	0–5	5–20	20–70	70–118	118–200
Level-2	0.2470	$0.2180 + 0.0057956v$	0.3339	$0.3694 - 0.0005066v$	$0.3847 - 0.000637v$
Emergency	0.9990	$0.8820 + 0.0234000v$	1.3500	$1.3879 - 0.0005418v$	$1.8752 - 0.004672v$

The scenario is assumed that 40 s after the head of VCTS from the down direction passes node R_d , the other arrives at point R_u . Taking the VCTS from the down direction as an example, EMUs whose lengths are all 211 m approach station at the same speed of 80 km/h. s According to Formula (2), I_u can be calculated with a safety margin valuing half of the EMU total length as follows:

$$I_u = Db\left(80 \frac{\text{km}}{\text{h}}\right) - De\left(80 \frac{\text{km}}{\text{h}}\right) + \frac{211m}{2} + \frac{1}{2}(211m + 211m) \quad (30)$$

Taking an approximation of the result, the final interval value is 900 m. The same process is applied for the up direction (see Table 4).

Table 4. Specific paraments are set for both VCTS in the case study.

Index	VCTS from Down Direction	VCTS from Up Direction
Number of EMUs	D_1, D_2, D_3	U_1, U_2
Full length (m)	211	211
Approach speed (km/h)	80	75
Train interval (m)	900	850
Braking model	Level-2	Level-2

Respective properties and operational requirements are given to further evaluate whether the proposed method can effectively match the tracks with various EMUs. EMU D_2 will pass through from down to up direction with no stop, while the others require stopping operation. Transit trains numbered as D_1 , D_2 , and U_2 own different priority degrees in the aspects of serving content, technical inspection, and passenger service quality according to their own technical characteristics and transportation tasks. The received train U_1 takes this station as the terminus, and after stopping and serving passengers it will be controlled into the depot (see Table 5).

Table 5. Specific operational requirements with varying importance for VCTS.

Operating Requirement	Number of Trains				
	D_1	D_2	D_3	U_1	U_2
Train passing through	0	1	0	0	0
Train reception on up direction	0	0	0	1	1
Train reception on down direction	1	0	1	0	0
Train departure on up direction	0	0	0	0	0
Train departure on down direction	0	0	0	0	0
Shutting in and out of the depot	0	0	0	1	0
Serving and technical inspection	0.9	0	0.8	0	0.6
Passengers' alighting and boarding	0.9	0	0	1	0.9
Passengers' walking distance	0.8	0	0	0.9	0.3

Algorithm parameters are assigned before calculation according to their corresponding requirements. The values are given as $\lambda_1 = 0.6$ and $\lambda_2 = 0.4$ for the higher requirements for safety, while $k_1 = 0.4$, $k_2 = 0.6$, $k_3 = 0.001$, and $k_4 = 0.005$ for better evolutionary effects. The initial population is 300, and the maximum number of iterations is 100. At the same time, the early termination will take when the same optimal individual is obtained for 10 continuous generations of evolution. MATLAB software was used for programming.

5.3. Performance Analysis of Multiple Operations

The designed algorithm steps were repeated 250 times to obtain macroscopic results. The iterations were carried out an average of 26.23 times to obtain the result of an optimal individual in each process. As a result, 58 schedules were obtained for the receiving route allocation question above, of which the occurrence of a single scheme is from 1 to 14. The massive outcome reflects the satisfaction of overall efficiency and process duration.

The frequency of efficiency values is shown, also representing the final scheme to which they belong (see Figure 6). Scatter points make triangles in the efficiency–frequency diagram with an average of 0.9176, which shows the basic trend that the better efficiency was gained, the more often the scheme appears. This pattern can also be seen in the efficiency–frequency histogram (see Figure 7). The right deviation feature with a rapid cumulative percentage curve gives a consequence of preference and pursuit of high efficiency. The general operation time is 50% lower than the current CTCS-3 model. Because different optimization results can improve performance to different degrees, an individual analysis selected for specific analysis will be proposed in the next section.

For a particular EMU, the duration for its stopping or passing process on each track at station is determined by the value under the specified approaching speed and braking mode. Since the number of tracks is fixed, five operation completion times will eventually appear according to the station lines chosen by D_3 to stop with different distribution probabilities (see Figure 8). The durations shorter than or equal to 205.40 s with not much difference in values take up 74.8% of the results as a whole, while the average duration of 250 repetitions is 204.95 s. Although the last one duration is much longer than other schemes, its efficiency for D_3 is as high as 0.9111, which is still a valid result of the objective function (see Table 6).

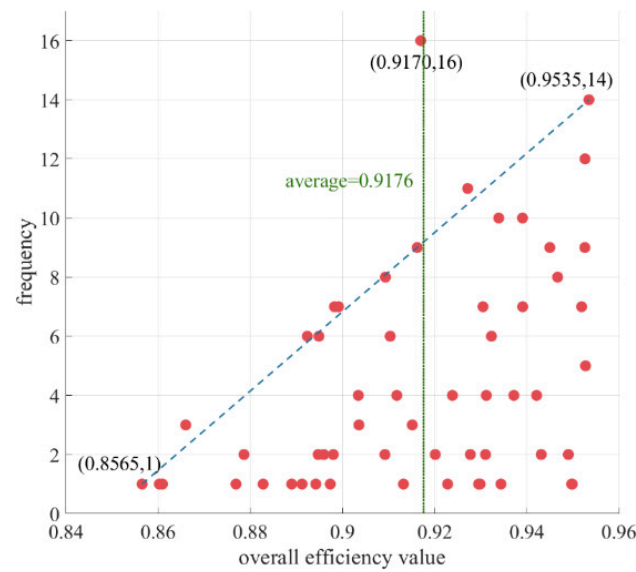


Figure 6. More profitable schemes were repeated more often, while the others have less frequent occurrences.

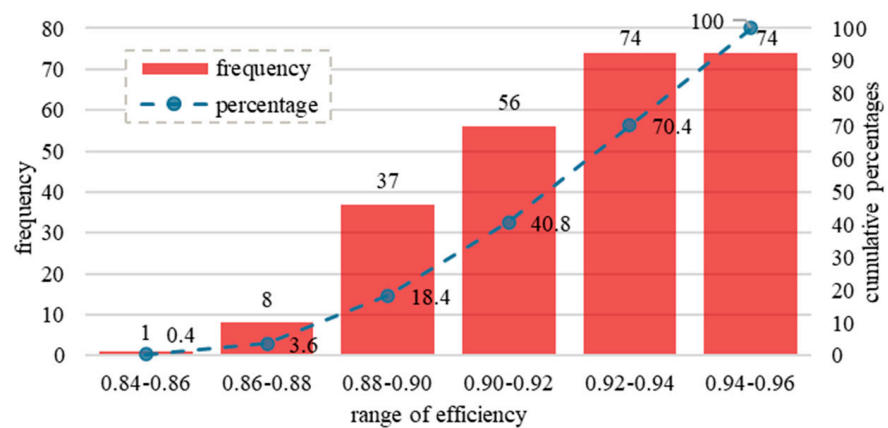


Figure 7. The histogram and summation curve report the situation of right inclination.

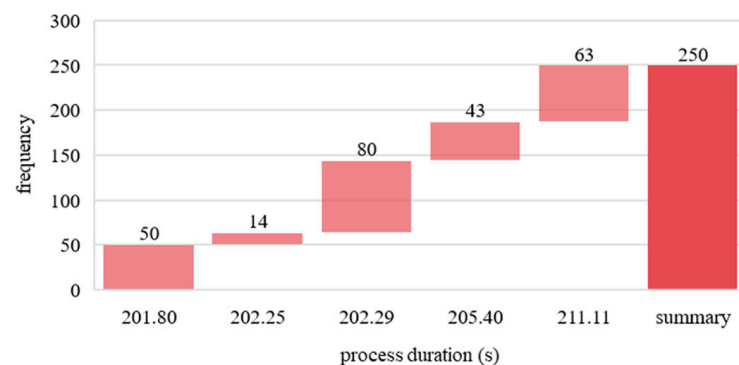
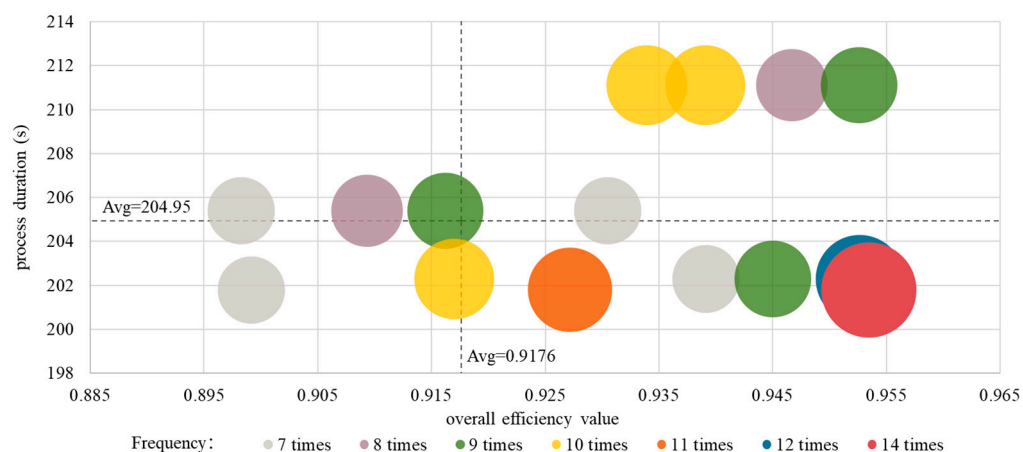


Figure 8. The selection results mainly focus on the first four durations with short operation time, as the last one is well out of the former range.

Table 6. Cooperative optimization is closely linked to the relationship between duration and efficiency.

Index	Value				
Process duration (s)	201.80	202.25	202.29	205.40	211.11
Track selected by D_3	5	6	7	4	3
Efficiency for D_3	0.9556	0.7889	1	0.7444	0.9111
Frequency	50	14	80	43	63
Cumulative percent (%)	20.0	5.6	32.0	17.2	25.2

To analyze the performance of the calculated results, 16 representative schemes obtained 7 times or more are selected, totaling 145, with a success rate of 58%. A bubble chart (see Figure 9) is used to visualize the results and the dotted lines represent the average values of process duration and efficiency, dividing the chart into four regions. The upper-left area represents schemes that take longer time and have poor benefits, which most of the selected schemes do not belong to. On the contrary, the bottom-right area contains the better part of the optimized results, indicating that the obtained schedules are effective under the safety requirements of the scenario. Notably, the allocation scheme with the highest efficiency and shortest duration is fortunately obtained most times, and further micro-analyses of this scheme will be conducted in the next subsection.

**Figure 9.** Scheme concentration occurs in the bottom-right area, which means the approaches here are operating fast and efficiently.

5.4. Results Analysis for Obtaining an Individual Scenario

The process selected here for specific analysis, whose early termination condition was triggered and breaks up the calculation at 19 iterations of evolution, iterated quickly to get results. Although the maximum fitness is relatively stable, the average fitness variation in the evolutionary process showed that the overall performance of the population is improving generation after generation (see Figure 10). The relative evaluation method used to calculate the fitness value and the maximum in every generation is calculated based on the overall fitness, so it is normal for it to decrease to a small extent. It can be stated that the constraints play a role in promoting the outcome quality in several forms.

The optimal route allocation scheme was obtained as [7, 1, 5, 4, 6], which achieves an effective overall organization of train sets of 92.55% within a total operation time of 201.80 s (see Table 7). The conditions such as route uniqueness and arrival and departure lines uniqueness that are met can be determined directly.

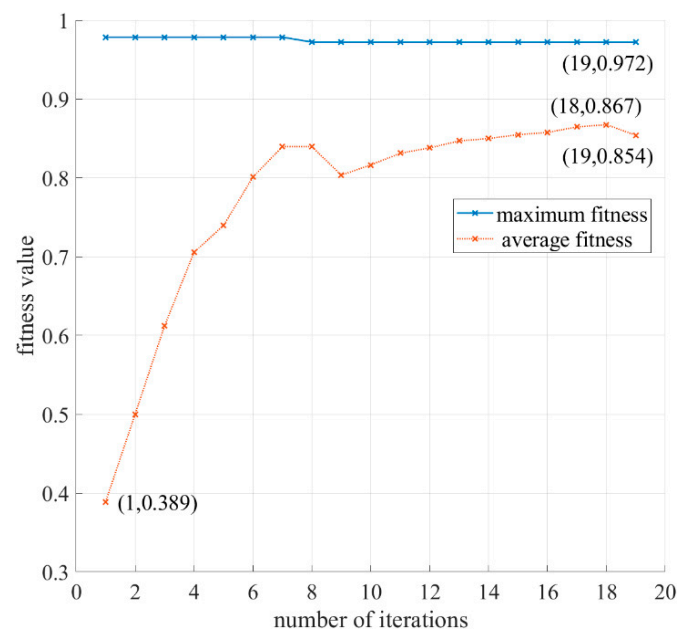


Figure 10. Changing curve of fitness reflects the optimistic effect of the optimization model to a certain extent.

Table 7. The overall performance of the final operation scheme is promising.

EMUs	Selected Track	Operation Duration (s)	Timing Range (s)	Effectiveness (%)
D_1	7	102.21	0–102.21	100.00
D_2	1	123.80	50.04–173.84	100.00
D_3	5	101.72	100.08–201.80	95.56
U_1	4	104.17	40.00–144.17	85.13
U_2	6	101.39	90.98–192.36	94.64
Overall		533.29	201.80	92.55

The further safety performance analysis focuses on the used node, judging whether the time interval and speed meet the requirements or not by the detailed operation procedure (see Tables 8 and 9).

Table 8. Node occupation time for VCTS is identified by starting time (ST, s) and finish time (FT, s), while IS (km/h) is shown here to determine whether the speed meets the requirements (from the down direction).

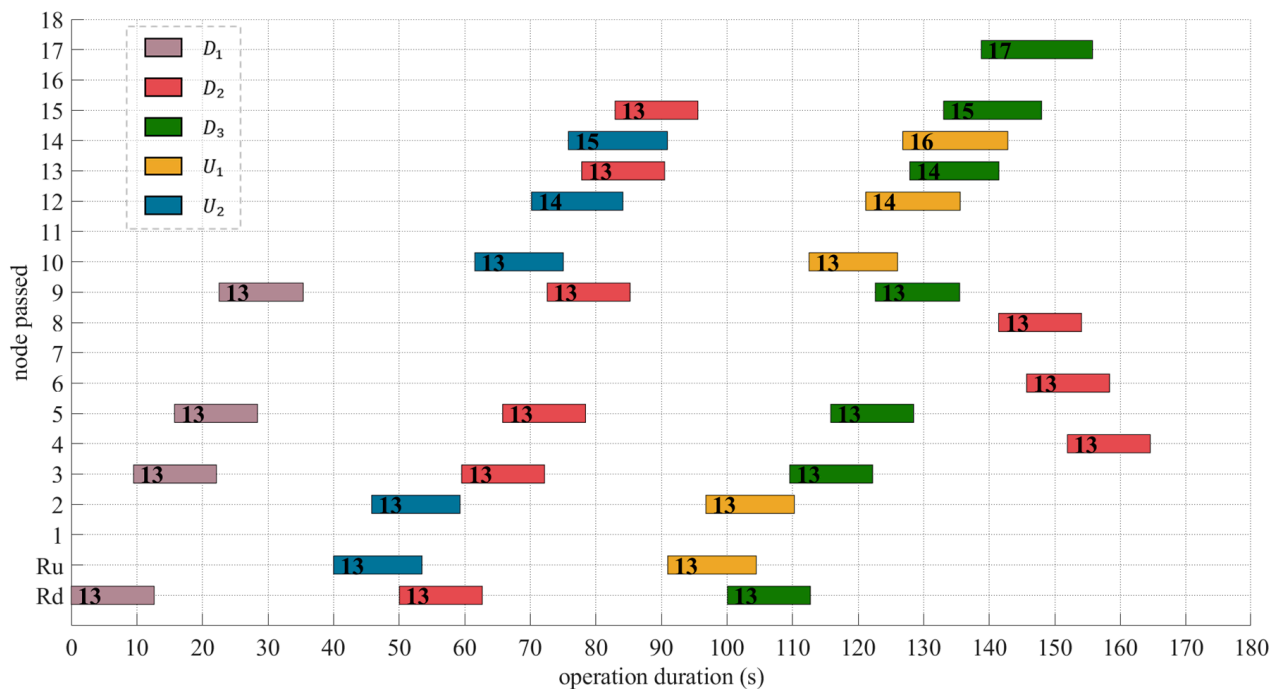
EMUs	Index	Nodes											D_d
		R_d	1	3	5	7	9	11	13	15	17	Stop	
D_1	ST	0.00	—	9.50	15.75	—	22.55	—	—	—	—	102.21	—
	FT	12.65	—	22.14	28.40	—	35.37	—	—	—	—	—	—
	IS	80.00	—	80.00	80.00	—	80.00	—	—	—	—	0.00	—
D_2	ST	50.04	—	59.54	65.79	—	72.59	—	77.85	82.94	—	131.54	161.19
	FT	62.69	—	72.18	78.44	—	85.23	—	90.50	95.58	—	144.18	173.84
	IS	80.00	—	80.00	80.00	—	80.00	—	80.00	80.00	—	80.00	80.00
D_3	ST	100.08	—	109.58	115.83	—	122.63	—	127.89	133.04	138.79	201.80	—
	FT	112.73	—	122.22	128.48	—	135.49	—	141.49	147.98	155.76	—	—
	IS	80.00	—	80.00	80.00	—	80.00	—	80.00	76.43	69.63	0.00	—

Table 9. Node occupation situation for VCTS from the up direction.

EMUs	Index	Nodes									
		R_u	2	4	6	8	10	12	14	Stop	D_u
U_1	ST	40.00	45.81	—	—	—	61.55	70.19	75.81	144.17	—
	FT	53.49	59.30	—	—	—	75.04	84.13	90.91	—	—
	IS	75.00	75.00	—	—	—	75.00	75.00	75.00	—	—
D_2	ST	—	—	151.92	145.71	141.44	—	—	—	—	—
	FT	—	—	164.57	158.36	154.08	—	—	—	—	—
	IS	—	—	80.00	80.00	80.00	—	—	—	—	—
U_2	ST	90.98	96.78	—	—	—	112.53	121.17	126.82	192.36	—
	FT	104.46	110.27	—	—	—	126.03	135.58	142.84	—	—
	IS	75.00	75.00	—	—	—	75.00	75.00	72.64	—	—

Here, timing from the situation that D_1 arrived at node R_d , the specific operation process is recorded. The moment that the head of an EMU reaches the nodes is taken as the starting time of this node marked as ST, while its tail completely moves out of the node is the moment to record the finish time marked as FT. The initial speed (IS) for each EMU is also recorded at the moment of its corresponding ST at a specific node.

The occupied time window is given for more intuitive determination (see Figure 11). The operating intervals of turnout in the same VCTS are all greater than 30 s, satisfying the requirements of a 15 s switch conversion time and the time interval between two trains at the station. It is worth mentioning that under the habit and performance of the organization, this scheme avoids the crossing between EMUs from opposite directions, by which the safety of station operation is greatly improved. Due to the constraints of approaching speed, trains operate under speeds below the allowable lateral through speed and straight through speed at turnouts, meeting the safety requirements of turnout usage and train connection and intersection.

**Figure 11.** The connection usage of each node can be used to calculate the spacing relation for trains and determine whether the use of the turnout conforms to the set security requirements under VCTS.

The superiority of VCTS can also be reflected by comparing it with the existing operating mode. In the CTCS-3 environment, it is ideally set that after the completion of the previous train operation task, the duration from releasing the existing route to building a new one for meeting the next train lasts for 30 s.

The total receiving process duration under the same scheme is 563.29 s and its connection usage of nodes is much lower in density (see Figure 12). The operation under VCTS is only 35.83% of the original CTCS-3 mode, proving that VCTS is a promising direction for further improvement of carrying capacity balanced with safety and comfort.

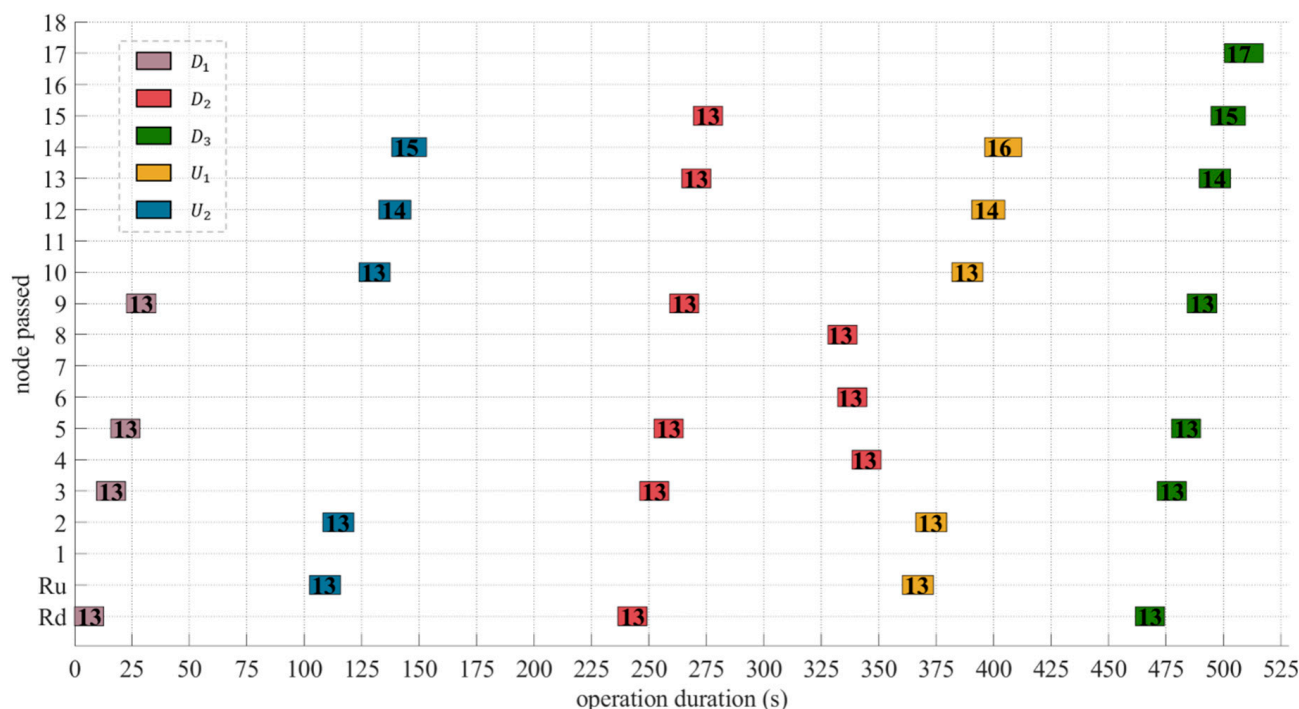


Figure 12. The connection usage of nodes under the operation environment of CTCS-3 is much sparser than VCTS.

In conclusion, the results from the example demonstrate that the optimized scheme satisfies the constraints of applying order, route uniqueness, and arrival and departure line uniqueness of the main line, ensuring safe train operations. The safety of the node usage is ensured through several steps. The arrival and departure times of trains at station nodes are recorded, as well as their speed and occupied time window. Then, it is checked that the time interval and passing speed of the node usage meet the requirements. By comparing the operating modes of VCTS and CTCS-3, VCTS has promising potential in balancing carrying capacity, operational safety, and passenger comfort.

6. Discussion, Conclusions, and Future Research

Recently, VCTS research has been gaining more attention, although relevant literature on station organization under VCTS is still lacking. Most of the existing research focuses on simulation experiments, which verify the safety and superiority of VCTS. In addition, VCTS has improved the accuracy and delay requirements for obtaining train position, speed, and status. However, the existing studies treat stations as nodes or sections without fully considering the safety constraint strategies specific to stations, treating high-speed trains as a single particle, which has certain limitations, and relatively little attention has been paid to the train dynamics model. The difficulty in developing a new interlocking solution suitable for VCTS contributes to the railway capacity bottleneck caused by station organization limitations. This highlights the need for a new station operation mechanism, which has yet to be extensively researched. This paper introduces the concept of VCTS, explores

its operation characteristics and receiving requirements, and proposes an improved GA-based receiving routing model. We adjust the safety constraints by referring to the current interlocking relationship, with a focus on improving adaptation to VCTS. In this study, passenger comfort is considered to select the braking level. The train operation process is accurately described based on traction and braking calculations, and the duration of station nodes occupied by trains with a given length can be obtained. To verify the effectiveness of the designed method and the performance of VCTS, a numerical test is conducted on a specific case. The proposed approach demonstrates the ability to identify high-quality solutions that meet requirements, as evidenced by multiple successful operations, with a balance between objectives. In the single analysis of an optimal solution, it is shown that the receiving route allocation scheme can satisfy the safety requirements of practical operation, costing only 35.83% of the time under the existing CTCS-3 mode. The findings highlight the significance of the VCTS mode in future technological innovation and revolution.

While the proposed method has demonstrated reasonable performance, it is important to acknowledge that there are limitations. The operating conditions, parameters, and line conditions used in the study are idealistic and simplified, and may not fully reflect the complexities of actual scenarios. To overcome these limitations, it is recommended that the whole scene of sections and stations be considered as an operational environment. At the same time, it is important to explore the potential use of VCTS in organizing railway freight, despite the challenges that may arise from diverse safety constraints and varying train conditions. This would involve a more in-depth analysis of the complex cooperation required among trains in tasks such as receiving, dispatching, passing through, and even shunting organization. By taking these factors into account, researchers can gain a more comprehensive understanding of the challenges and limitations that may arise when implementing the proposed method in practice, and work to develop solutions.

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