Research Article

Simulation-Based Schedule Optimization for Virtual Coupling-Enabled Rail Transit Services with Multiagent Technique

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Virtual coupling (VC) is a train-centric next generation signalling system, which can enable multiple trains to operate in a formation just like one train or decouple separately on-the-run or at station flexibly or as planned. With the aim of optimizing the interdeparture train headway time, providing the variable capacity for diverse passenger demand, maximizing the passenger riding comfort degree, and minimizing passenger travel cost and train operation cost, the dynamic schedule for VC-enabled rail transit services is investigated with the multiagent simulation technique on NetLogo platform. Our contribution is mainly fourfold. First, VC-enabled rail transit entity for simulation is represented with the multiagent technique, including representation of train unit, train convoy, passenger attributes and behavior, and mathematical formula for calculation of the train operation cost and passenger travel cost, as well as passengers riding comfort degree are proposed. Second, the operational principles for flexible and self-organising VC-enabled trains are defined. Third, the VC-enabled train-centric, passenger demand-driven, and agent-based simulation flow and algorithms are developed innovatively, which adopt the ergodic strategy for simulation by traversing each O-D pair demand along each route section over the rail transit network. Finally, we test and discuss the proposed methodology on the designed computational experiment on the NetLogo platform, and the simulation results validated the effectiveness of the proposed methodology. The provided research can effectively support the VC-enabled platoon operation-oriented train service schedule for future study.

1. Introduction

It is recognized that railroads are cost effective, energy efficient, environmentally friendly, and safer. However, under the conventional railway system, dynamic and flexible scheduling is relatively difficult, especially for the large volume of passenger travel demand at peak hours in megacities. It is necessary to make up trains dynamically according to the diverse and uneven operation demand, e.g., increasing capacity supply at peak hours, decreasing capacity at nonpeak hours, matching passenger flow and train traffic more precisely, and implementing energy-efficient train control, by using next generation signalling systems such as virtual coupling (abbreviated as VC). The ever-increasing demand for railway services requires train-centric railway operations shifting from traditional railway signalling infrastructure, i.e., a paradigm towards such a train-to-train communication as the VC technique, and even new methods and advanced models to maintain stable and safe train traffic. The performance and effectiveness of the railway system [1], e.g., infrastructure occupation, feasibility, stability, resilience, robustness, journey time efficiency, and energy efficiency, correlate highly to the quality of the train operation plan and schedule/timetable.

The phenomenon that trains do not follow their initial schedule/timetable takes place frequently due to multiple reasons, which requires a more flexible or dynamic schedules for these train operations, so as to efficiently and proactively manage such dynamics in the complex railway systems [2], to achieve a mobile and intelligent railway transport system, and to bridge between practice and research closer. For sound train operation, e.g., best running time, no conflicts on the lines, free tracks in all the stations,
avoidance of the phenomenon of passengers left behind, the schedule/timetable, or train operation plan is always positioned as the heart of the railway system to control/ optimize the rail operation and to create "high value slots" [3], which is surrounded by several other essential elements, e.g., service goals, network capacity, rolling stock, and infrastructure, in a coordinated and iterative point of view.

Dynamic and automatic timetabling/scheduling is the key part of the intelligent transport organisation, with regard to the determination of the train formation, departure/arrival time, and dwell time dynamically. By using certain commercial or academic railway computer programs/software, e.g., OpenTrack, RailSys, Planning Timetable Generator, DONS, Capacity Management Systems, and OpenTimeTable, it is not difficult to automatically generate and assess timetables rapidly [4]. With regards to the key issues for establishment and success of the railway operation organisation, certain essential elements have to be addressed, e.g., traffic and slots organisation for scheduling, which can be realised by using the slot search engine embedded in RailSys [5].

In general, the main tasks of train scheduling can be categorized as real-time train operation planning, train operation controlling, off-line train timetabling, and train rescheduling [6]. By using the VC-enabled technique, the main motivation of this study is to design the demand-sensitive and flexible train operation plan or schedule to meet passenger demand, enhance passenger riding comfort degree, reduce passenger travel cost (e.g., waiting time and transfer time) and train operation cost, decrease infrastructure occupation (optimize interdeparture time or headway time), and improve capacity utilization, through reconciling flexibility with practical applicability, so as to improve the efficiency and quality of train operation plan and schedule, as well as the self-adaptability of the railway capacity system.

There are two general philosophies of railroad operation: improvised (corresponding to real-time scheduling) and structured (corresponding to master scheduling). The operating philosophy affects the use of simulation in determining the infrastructure that is appropriate for the desired traffic [7]. In normal conditions, scheduling/time-tabling is the procedure of allocating track capacity and time slots for operational train traffic. The improvised operating philosophy is a kind of ad hoc planning (i.e., real-time rescheduling), which includes all changes, e.g., rerouting, retracing, retiming, and reordering, to the timetable that are taken after the disruptions happened in the rail system. In contrast, the structured operating philosophy is a kind of predefined and completed timetabling. In our study, the semistructured train operations' philosophy is adopted, which lies in between the improvised one and the structured one. It is also a part of automation of rail transport to increase the system robustness, demand adaptability [8], service quality, capacity flexibility, and operation reliability, and reduce the gap between daily operational traffic and timetable planning.

In order to improve the flexibility and capacity of European freight railways, Köni and Herbst [9] first proposed the concept of VC train operation. Under the future railway background, Meo et al. [10] proposed the VC technique under ERTMS L3, so as to reduce the train interval and increase capacity by using train-to-train communication. The VC technique is ascribed to the third generation of coupling technology [11], which is based on the ETCS-3 signalling system and an additional layer for V2V communication. VC can enable the train to couple/decouple at station or on-the-run in track section without stopping when necessary, i.e., virtual coupling is a train-centric signalling system, which can enable multiple trains to operate in a formation just like one train or decouple separately on-the-run in the track section (or at station) flexibly (or as planned). For platooning, trains can join in and split from a platoon as planned. The railway traffic planning and management system will be affected by the introduction of VC. The VC technique can realize a very high degree of flexibility and self-organisation, since it allows the train convoys to be coupled and decoupled anywhere and anytime, even on-the-run [12].

Besides the published article by Park et al. [13] provided a behavioral control mechanism, few studies have been taken into account for concrete operating strategies for VC, particularly, towards merge and separation, which is a kind of self-organising behavior of intelligent trains. The VC technique enables a dynamic on-demand use of automatic train units without a fixed schedule or static timetable. It has been recognized that automated technologies, e.g., automated vehicles (AVs), are one of the largest innovations in transportation research. A large proportion of the significant costs in the rail system will be saved due to process automation in the area of planning and operations, which can keep the railways more competitive in the future. The advantage of automation lies in its highly precision and efficiency. With multitrain information synchronization, under the condition of train-to-train communication, VC-enabled trains autonomously recognize each other, i.e., including those ahead of and behind them [14]. Multiple trains are formed to run in formation in the VC scheme. As one of the key railway system components, undoubtedly, the technique of railway traffic planning and management would be affected by the introduction of the VC technique [12]. The dynamics of the VC-enabled schedule mainly reflects on decisions about the coupling/decoupling (i.e., variation of the number of train units in the virtually coupled train set) and interdeparture time/headway time, according to the near real-time passenger demand, which are the key motivations of this study.

The aim of this study is to derive optimal dynamic schedule for VC-enabled rail transit services using the multiagent simulation technique on the NetLogo platform, i.e., to optimize interdeparture time or headway time, to improve the onboard passengers' riding comfort, and to minimize the passenger travel cost and the train operation cost. Therefore, the study gives the following contributions to the literature:
(1) Representation of VC-enabled rail transit entity for agent-based simulation, including representation of VC-enabled train unit, representation of VC-enabled train convoy, representation of passenger attributes and behavior in VC-enabled environment, and development of the mathematical formula for calculation of the train operation cost and passenger travel cost, as well as passengers riding comfort degree

(2) Defining operational principles for flexible and self-organising VC-enabled trains

(3) For the first time, the VC-enabled train centric, passenger demand-driven, and agent-based simulation flow and algorithms are developed

(4) The proposed representation method, operational principles, simulation flow, and algorithms are applied on the computational experiments for optimal schedule simulation with NetLogo

The article outline is as follows. In Section 2, a literature review on VC-enabled train services is provided. Section 3 describes the problem of schedule optimization for VC-enabled rail transit services considered in this study in detail. The representation of VC-enabled rail transit entity for agent-based simulation is demonstrated in Section 4. Section 5 defines operational principles for flexible and self-organising VC-enabled trains. VC-enabled train-centric, passenger demand-driven, and agent-based simulation flow and algorithms are developed in Section 6. Section 7 demonstrates the application of the proposed representation method, operational principles, and simulation flow and algorithms on the computational experiments for optimal schedule simulation with NetLogo. Finally, the conclusions are provided in Section 8.

2. Literature Review

Integrated automatic and dynamic timetabling models can provide fast solutions which allow analyses of multiple operational scenarios. Cacchiani and Toth [15] reported an extensive review of timetabling models. Bešinović et al. [16] introduced deterministic microscopic models for computing accurate track blocking times that can support macroscopic models to build acceptable, feasible, and stable timetables. For completely automated generation of timetable, the microscopic models have been incorporated in a multilevel timetabling framework, i.e., efficient automatic conversion between microscopic and macroscopic networks.

For VC in railway operations, the constant distance gap policy is not applicable [12] due to the relative distance depending on speed, although for a given (cruising) speed, a constant time gap policy can provide a constant distance. Under VC, due to incorporation of relative braking distances between trains and therefore reduction of path conflicts, certain changes have taken place when planning the railway traffic, comparing with the conventional railway traffic planning and management, especially for platoon’s planning. So, there exists a necessary and practical requirement to develop dynamic schedule for virtual coupling.

Most of the existing literature about VC and automation focused on the optimal design of the train control system from the perspective of safety constraints for local and string stability [17] in infinite time or neglecting the temporal dimension, e.g., adaptive cruise control (ACC), cooperative adaptive cruise control (CACC) [18–20], leading-follower trains’ gap control based on sliding mode control with a nonlinear and uncertain train model [13], model predictive control approach [21], Lagrangian control of traffic flow [22], the intra-platoon car-following gaps of VC-enabled trains and the inter-platoon car-following gaps of coupling trains, trajectory planning, and dynamic train following behavior and mechanism [23], under the connected and automated environment, considering the possibility of chain collisions or collision avoidance. Even most of their topics are control oriented rather than traffic flow theory or operation planning. And most of the VC cases description referred to only one leading train and one following train, despite the relative concepts and principles can be extendible to multiple trains. Few existing literature have been found about VC-enabled train operation planning or scheduling, e.g., the number of train units in one virtually coupled train formation [24, 25] (in operational practice, the allowable maximum length of train is limited by the factors such as the signalling system, the length of platform, and the length of siding line), when to recouple or decouple the dynamic train headway. It is necessary to introduce or study the train operation plan, the scheduling and rescheduling mechanism for the VC-enabled multitrain communication-based control systems, order optimization of heterogeneous train units in the train convoy [26], possible VC of passenger trains with heterogeneous speed, and VC of mixed passenger and freight trains.

Under VC, the virtually coupled train set (VCTS) or train convoy based on vehicle-to-vehicle communication is viewed as one train by the interlocking systems [12]; trains are required to complete the coupling/decoupling process and reach a new state, e.g., coupled state, within a specified distance or time [27], which implies that the entire coupling/decoupling procedure for every train must be concerned particularly by the operational strategies, and the conventional static preprogrammed strategies or timetables may fail to meet these variant operating conditions.

Platoon is one of the cooperative VC modes and different from the train convoy or VCTS. To certain extent, VCTS has a similar platoon concept to the connected autonomous vehicle platoon, in that the desired distance between the trains in the platoon, e.g., maintaining the safe spacing and consistent running speed, is explored to ensure the stability and efficiency of the train platoon [28]. Compared with the fixed train formation, VCTS can meet the operational demands of a tidal passenger flow much better, under the limited track and train resource conditions, because the number of train units in one VCTS can be adjusted flexibly to match the variable-capacity supply with the passenger demand. For train traffic conflicts of mainline railways forecasting and control in real time, Munirandi [26] proposed a novel blockchain-enabled VC of automatic train operation, e.g., architecture of the autonomous conflict control system centering on blockchain infrastructure database and
blockchain train database, and also described seven variants of VC strategies.

Besides the reduced service headway, VC railway signalling technology could potentially enable a service more in line with the passenger demand pattern, especially for the reason that trains move in a much more predictable environment than cars. Van Aken et al. [25] discussed how to determine the best number of trains to group together in case of temporarily unavailable tracks. VC-enabled train services [29], i.e., virtually coupled train sets/formations or train convoys, are with variable train length of several multiple units (MUs); particularly, they are worth applying to address massive demand in dense areas and making the railway market more attractive with provision of on-demand train services. The number of vehicles of each MU can be fixed or variable. Aoun et al. [29] analysed three maneuvers for investigating the benefits of VC over conventional railway signalling systems according to nonstopping cases and stopping cases and considered 80 operational scenarios in total. Cao et al. [30] explained and simulated the operation mode of VCTS. In this study, we also use the multiagent simulation technique on the NetLogo platform. For more details about the multiagent technique, one can refer to the literature review section in [31].

3. Problem Statement

It is believed that when the cooperative movement of trains are optimized, the gap between these trains in different directions can be shortened to the minimum, along with the simultaneous increment of train traffic density and flow rate [32]. The problem of schedule optimization for VC-enabled rail transit services considered in this study is as follows:

(1) By considering the dynamic passenger demand and operation procedure of virtually coupled-enabled trains, taking flexible variable-capacity operation (provision) into account, the main objective of this study is to decrease infrastructure occupation (i.e., optimize interdeparture time or headway time) and enhance capacity utilization and target to maintain the train always running in the optimal state, improve the on-board passengers’ riding comfort, and minimize the passenger travel cost and the train operation cost, so as to provide on-demand and flexible variable-capacity rail transit service by adopting near batch-matching policy.

(2) The key variables considered in this study include headway time and flexible variable-capacity of trains (i.e., variation of the number of train units in a virtually coupled train formation)

(3) How the railway’s capacity is used depends on the infrastructure layout and on the frequency and distribution of traffic. Given the dynamic short-term passenger demand, construct a feasible online or near real-time train scheduling with the guaranteed quality of service from both passenger and operation perspective, i.e., determine the frequency and distribution of train traffic under VC and the best number of trains to group together (adjust dynamically the number of train units in the virtually coupled train formation to match the passenger travel demand more accurately and flexibly) by connecting the timetables and operational traffic into one loop, by performing the near real-time traffic management of VC-enabled train-centric railway operations, by merging timetable planning (dynamic preprogrammed train operation strategies), dispatching, and train operation [11], according to the new current trend [2].

(4) The core problem is to determine dynamically the number of train units in a train convoy and the optimal train headway time, by considering the temporal-spatial correlation and cooperation between dynamic passenger travel demand and variable rail capacity supply. This is also a kind of near real-time dynamic scheduling, i.e., focus on short-term and ad hoc passenger demand, combining train operation planning with scheduling/timetabling, merge timetable planning and traffic operating. Service changes typically occur in stations. Take the passengers adapted travel behavior into account when scheduling/timetabling. And this consideration often results in a dynamically changed scheduling/timetabling, so as to meet the time-dependent passenger demand better.

(5) The simulation flow and algorithm adopt the ergodic strategy by traversing each O-D pair demand along each route on the rail transit network [33] with the multiagent technique on the NetLogo platform.

To develop the simulation flow and algorithms for schedule optimization for VC-enabled rail transit services with the multiagent technique, the following assumptions are made throughout this study.

Assumption 1. The passengers are frequent users. The time slice-based transit demand OD matrix is generated in the many-origin-to-many-destination capacitated rail transit networks. Passengers are assumed to arrive at stations randomly according to a Poisson distribution. The passenger OD demand matrix is assumed symmetric, and only the unidirectional track line (e.g., upstream or downstream) is considered in the network. Passengers can board and alight the trains at any junction or station.

Assumption 2. The train can overtake any other trains at any station node and the vice versa. Any stations or junctions can be designated as skip-stop points. Junctions/stations have sufficient capacities to accommodate the inbound/outbound trains. Trains can couple/decouple at any station or on-the-run.

Assumption 3. VC-enabled train units are homogeneous rather than with largely varying braking and acceleration capabilities. And each of them has the same volume of carrying capacity and number of seats. Trains can be located real-time and accurately on the network.
Assumption 4. The available fleet size is sufficient. The routes and frequencies of the train lines are predetermined and adjusted accordingly and iteratively. The train running time on the rail track is deterministic. The operation patterns of the trains adopt the same headway time in the same network [31], i.e., the headway times among all the trains within a certain study period in the same rail transit network keep invariant.

The problem has some similarities with variable train formation of the operation planning problem [34, 35], which, however, has two remarkable differences with regard to our problem. First, unnecessarily originating from a depot, the follower trains can couple/combine with or split from its leader at any station, even on-the-run at track section, i.e., train compositions can be modified anywhere if necessary, rather than only at certain stations. Second, it is rather than a pure train-unit assignment problem with a given train trip, and instead, it leads to a combination of train traffic organisation and timetabling. Compared with a given train trip, and instead, it leads to a combination of train traffic organisation and timetabling. Compared with a given train trip, and instead, it leads to a combination of train traffic organisation and timetabling.

4. Representation of VC-Enabled Rail Transit Entity for Agent-Based Simulation

For the train traffic and passenger flow, different from those under conventional rail operation environment [36], i.e., the feature of them lies in between the weak-controllable-autonomous traffic and strong-controllable-organised traffic, under the VC environment, both the automation and controllability of them have been improved greatly, and its self-organising feature is much stronger.

Besides the railway physical network (which is composed of links and nodes), the simulation entities of rail transit also include VC-enabled train unit, VC-enabled train convoy, and passengers. From the perspective of train operation and organisation, combined with GIS, GPS, and telecommunication technique, the operation process of the VC-enabled train convoy can be modularized and schematized.

In VCTS, the train units can recouple/decouple during operation according to transportation demands and plans [37]; thus, dynamic operation planning is necessary for train units coupling/decoupling under the VC system, and the number of train units in one virtually coupled train formation is variable. The optimal number of train units in one virtually coupled train formation depends on the flexible match between the rail transit capacity and the passenger travel demand as accurate as possible.

According to Wu et al. and Li et al. [24, 28], the desired distance \(d_{\text{desire}}\) between the trains in the platoon, i.e., the idea intradistance gap between trains, can be calculated as

\[d_{\text{desire}} = k_{tc} \cdot v_t + d_0,\]

where \(k_{tc}\) denotes the tracking time coefficient, \(v_t\) denotes the following train speed in the platoon, and \(d_0\) denotes the safe distance margin.

4.1. Representation of VC-Enabled Train Unit. Under the condition of train-to-train communication, trains autonomously recognize each other, i.e., including those ahead of and behind them [14]. Each autonomous train unit can be taken as an agent. By using the technique of the modern cyber network, automatic control, big data, train-train communication, artificial intelligence, and sensor, the functions of the train unit agent include self-perception, self-recognition, self-adaptation, self-learning, self-decision, and actively matching the passenger demand. The VC-enabled train unit agents have the options to move, couple, decouple, setback, split, platoon, combine, service, or wait, and each train unit agent acts individually. Cooperation mechanisms among agents should observe the operation rules of VC-enabled train units as well as the passenger travel demand pattern. According to the formal VC concept, the cross communication of intracoupled train units has to be negotiated locally, while the global behavior of the inter-coupled train formations has to follow the instruction authorized by the advanced automatic control system, e.g., ETCS. In this way, under the next generation signalling systems, i.e., VC, the intelligent train agents could negotiate and exchange individual scheduling decisions about position, velocity, accelerating, and braking to optimize global service levels and demand satisfaction and could impact the self-organising services on various performance indicators, e.g., flexibility, capacity, and resilience.

Like in the conventional signalling system, the driving process of VC-enabled train unit still observe the principle of Davis equation. Not very likely in the conventional railway system, the train type in a station node can be classified as originating, arriving, departing, passing by, destination, coupling, decoupling, and platooning. While, a train’ routes can be characterized by the interdeparture time (headway time), arrival time, and by pass-through time at station nodes. A VC-enabled train unit on the railway transit route is represented by a 7-tuple topological component, namely, VC-enabled train unit = (time, position, train travel direction, activity, maximal carrying capacity, number of seats, and number of onboard passengers), where the item time includes two elements, i.e., time (arr/dep), where arr means the arrival time and dep means the departure time. The item position includes two elements, i.e., position \((h^t, h^s)\), where \(h^t\) means the time gap with its preceding train and \(h^s\) means the time gap with its successive train. The item activity includes six elements, i.e., depart, arrive, couple, decouple, dwell at station, and run in track section.

According to [31], the operation cost of each train agent \(i\) on route \(r\) can be calculated as follows:
where $N$ is the number of stations in the railway network, $t_{i,i+1}^{lr}$ means running time of train $l$ on route $r$ between station $i$ and station $i+1$, $c^+$ means the unserved passenger shortage cost per time unit, $m_r$ means the number of train unit in a virtually coupled train formation, decision variables, $C_{\text{max}}$ means the maximal carrying capacity of the train unit, and $d_{i,i+1}^{lr}$ means the passenger demand volume for train $l$ on route $r$ between station $i$ and station $i+1$. It can be obtained based on the passenger arrival rate of station $i$ and the passenger assignment rate to other stations on the same route when simulation.

So, the total operation cost of train formation on route $r$ can be calculated as follows:

$$c_{\text{ts}, \text{total}} = \sum_{r=1}^{N} c_{\text{ts}},$$  

where $c_{\text{ts}}$ is the operation cost of each train $l$ on route $r$ and $c_{\text{ts}} = c_{\text{rs}}$, $l_r$ is the number of train formation running on route $r$, and $l_r = T/h_r$, where $T$ is the study period and $h_r$ is the interdeparture or headway time of trains on route $r$ (decision variable).

### 4.2. Representation of VC-Enabled Train Convoy

From the perspective of terminology, with regards to VCTS and train convoys, coupling and decoupling are used. For platooning, joining and splitting are used instead, i.e., platoon joining and splitting occur within a train convoy when applied to virtually coupled trains. VCTS is a kind of a connected and automated vehicle convoy, and the existing ATO (automatic train operation) algorithm based on single train behavior should be extended, so as to adapt to nature of the virtually coupled train convoy, i.e., the multitrain coordinated control with slim headway time. And it is a kind of self-organising rail traffic for evolution of decentralized mobility, and the VC-enabled train unit in the convoy can share position, velocity, and destination, with the convergence of speed and headway time. From the perspective of networked control, the train convoy can be described from following perspectives [38, 39]:

(i) Node dynamics (including tractive effort, braking force, and running resistance)

(ii) Train convoy headway time for formation geometry (fixed headway time or nonlinear headway time relating to speed)

(iii) Information flow topology of the train convoy (integration of information flow topology and distributed controller, describing the sender/receiver object of current train information)

For communication topology of the train convoy, there are two typical solutions [12]: one is that the leading train is taken as the master and all other trains in the convoy communicate bidirectionally both with the master and their immediate predecessor. The other one is that an intermediate train is taken as the role of the master, then the leading train has to provide ATP (automatic train protection) commands to the master for movement authorities with respect to train traffic outside the convoy. We prefer the former in this study. The main function of the master train is to dictate the reference speed profile of the entire VCTS, e.g., determination of its own optimal train trajectory (relative dynamic distance, velocity, and acceleration), and then, the other trains in the convoy just follow their predecessor, leading to train-following behavior. In case of train platoons, possible topologies include fully connected mode and chain-like mode [40]. Liu et al. [17] proposed the position, velocity, and operation status-space equation for the leading train and the following train under the virtually coupled condition. The status of the VC-enabled train convoy can be described as follows:

(i) Unstable state, which can be described with the mKdV equation

(ii) Metastable state, which can be described with the Korteweg-de Vries (KdV) equation

(iii) Stable state, which can be described with the Burgers’ equation

Whether the leading train coupled with the following trains depends on the following conditions:

(i) There is larger volume of passengers waiting at the front station in the running direction of the leading train, and the passenger demand is greater than the available carrying capacity of the incoming leading train.

(ii) The running direction of the following train is similar to the leading train

(iii) The following train has enough available carrying capacity

(iv) Coupling strategy of the VC-enabled train convoy [26]: dynamic priority and passenger driven

(v) The passingthrough capacity of the front station/junction in the running direction of the incoming leading train is less than the sum of the following trains that need to pass by this bottleneck

### 4.3. Representation of Passenger Attributes and Behavior in VC-Enabled Environment

In the rail transit physical network, the passenger flow type and its corresponding action sequence can be classified as follows:

(i) Departing passenger (action sequence: source, origin, ride, and destination)
(ii) Passing through passenger (action sequence: ride, arrival, dwell, and departure)

(iii) Arriving passenger (action sequence: ride and sink)

The travel cost of each passenger agent on route \( r \) can be calculated as follows:

\[
ptc = \sum_{i=1}^{N-1} t_{i,i+1}^l \ast (1 - cdlri) + \text{waiting time} + \text{dwell time},
\]

\[ \text{if } 0 < D_{i,i+1} \leq \sum_{l, i} m_i^l \ast Z \ast l_{ri} \]

\[ \text{if } \sum_{l, i} m_i^l \ast Z \ast l_{ri} < D_{i,i+1} \leq \sum_{l, i} m_i^l \ast C_{\max} \ast l_{ri} \]

\[ \text{if } D_{i,i+1} > \sum_{l, i} m_i^l \ast C_{\max} \ast l_{ri} \]

where \( cdlri \) means the onboard passenger riding comfort degree in track section \( i \) of route \( r \) on train \( l \), \( t_{i,i+1}^l \) means the running time of train \( l \) on route \( r \) between station \( i \) and station \( i+1 \), and \( N \) means the number of stations in the railway network.

And in urban public transit, based on Assumption 4 (the operation patterns of the trains adopt the same headway time in the same network), similar to the majority of the previous studies, we approximate the mean waiting time of passengers at stops as half of the headway between the arrival of two successive trains on the same path [41, 42]. And the dwell time is designed as the headway time in the VC-enabled self-organising railway system; thus, the travel cost of each passenger can be estimated as follows:

\[
ptc = \sum_{i=1}^{N-1} t_{i,i+1}^l \ast (1 - cdlri) + 1.5 \ast \text{headway time},
\]

\[ \text{if } 0 < D_{i,i+1} \leq \sum_{l, i} m_i^l \ast Z \ast l_{ri} \]

\[ \text{if } \sum_{l, i} m_i^l \ast Z \ast l_{ri} < D_{i,i+1} \leq \sum_{l, i} m_i^l \ast C_{\max} \ast l_{ri} \]

\[ \text{if } D_{i,i+1} > \sum_{l, i} m_i^l \ast C_{\max} \ast l_{ri} \]

where \( cdlravg \) means the average comfort degree of train \( l \) on route \( r \) and \( n \) means the number of track sections on route \( r \).

The total passenger travel time in track section \( i \) of route \( r \) on train \( l \) can be computed as follows:

\[
ptc_{irl} = ptc \ast pirl,
\]

i.e.,

\[
ptc_{irl} = ptc \ast pirl = \left( \sum_{i=1}^{N-1} t_{i,i+1}^l \ast (1 - cdlri) + 1.5 \ast \text{headway time} \right) \ast pirl,
\]

where \( pirl \) is the number of passengers in track section \( i \) of route \( r \) on onboard train \( l \).
5. Defining Operational Principles for Flexible and Self-Organising Virtually Coupled Enabled Trains

Regarding the operational procedures, e.g., convoying on the run, platooning, cooperative merging, and cooperative departing, VC-enabled trains can provide flexible and self-organising intelligent railway operations. Quaglietta et al. [43] described the multistate flowchart of the train-following process in the rail track sections. According to the multistate train-following behavior, the complete process chain for VC-enabled train flow operation plan from coupling to decoupling can be summarized as follows:

Merging into a convoy $\rightarrow$ coupling $\rightarrow$ maintaining the convoy $\rightarrow$ joining in a platoon $\rightarrow$ platooning $\rightarrow$ splitting from the platoon $\rightarrow$ maintaining the convoy $\rightarrow$ diverging from the convoy $\rightarrow$ decoupling.

According to the structure of the traffic flow under VC [12], in the VC environment (Figure 1) in junction areas for closer merging, assume train A (from direction 2) as the leading one and train B (from direction 1) as the following one in the later train convoys; the procedure for coupling train convoys on the run when passing through a junction (point area) can be summarized as follows:

(i) Train A decelerates to point speed
(ii) Switch the train unit to be coupled, i.e., train A and train B, from moving block to VC, after train A passing through the point
(iii) Train B approaches train A, before train B passing through the junction. At this moment, the distance gap between train A and train B is greater than the safety distance.
(iv) Train A accelerates while the distance gap between train A and train B is greater than safety distance
(v) Train A and train B form a VC-enabled train convoy while their distance gap reaches the safety distance, and their velocities are equal when a platoon is formed. Platoon is one of the cooperative VC modes and different from the train convoy or VCTS. Also, a platoon is a set of trains that move cooperatively as close as possible to maximize track capacity by using cooperative adaptive control.

According to the structure of the traffic flow under VC [12], in the VC environment (Figure 2) in junction areas, the procedure for decoupling or diverging train convoys on the run when passing through a junction can be summarized as follows:

(i) Train A (the leader, via direction 2 later) and train B (the follower, via direction 3 later) run in a VC-enabled convoy from direction 1, while their distance gap equals the safety distance
(ii) Train B slows down, and the distance gap between train A and train B become larger than safety distance
(iii) Switch the train unit to be decoupled, i.e., train A and train B, from VC to moving block, after train A passing the point and running in direction 2
(iv) Train B approaches the point
(v) Train B accelerates and passes through the point running in direction 3

These procedures can be extended in stations or hub areas, where the individual trains of a train convoy have to be decoupled/distributed to several station tracks and rejoined/recoupled to a train convoy when leaving the station as necessary. For the first time in the literature, Quaglietta [44] developed the operational principles and capacity occupation models under VC, which lay the foundation for planning techniques, e.g., timetable design, for train operations under VC, though they have not considered the passenger demand simultaneously. And they are defined in detail several cases of operational principles according to the velocity difference between the leader ($V_A$) and the follower ($V_B$), e.g., $V_B > V_A$, $V_B < V_A$ cruising mode, $V_B < V_A$ following mode, $V_B = V_A$ coupled running, $V_B = V_A$ coupled running/decoupling at points, diverging routes, and converging routes. In our study, we adopt these operational principles.
Besides the layout of the track and/or junctions, the interactions among the trains running on the same track could determine the type of movement that the train will perform [29]. Considering the train movement over an interlocking area or a track, the operational scenarios for VC-enabled train services include the trains running on a plain line (stopping cases or nonstopping cases), merging or diverging at a junction (stopping cases or nonstopping cases), which relate to trains following mutually in the same direction. For trains running under VC, Quaglietta [45] illustrated the state flow diagram of the VC-enabled train-following model, which identified five different operational states and corresponding transitions; moreover, they proposed a multistate train-following model for VC, aiming at the simulation of VC-enabled operations and assessment of capacity impacts.

![Simulation flowchart for VC-enabled flexible train operation scheduling.](image)
Similar to the conventional signalling environment, when scheduling, the potential conflicts that need to be identified include conflicts at track sections or routes, conflicts at stops, connection/coupling conflicts, and deadlock conflicts. It is recommended to integrate time-related dispatching (e.g., set recovery times to ensure the punctuality of trains) and location-related dispatching (e.g., designated reference points) methods together, i.e., temporal-spatial cooperation technique. In the physical rail transit network, the reference point can be a station route, a track or line section, and other infrastructure elements (e.g., point, track, and junction). Anyway, Robustness in Critical Points (RCP) should be put as the first priority, so as to ensure the robustness of the whole VC-enabled rail traffic network.

6. VC-Enabled Train-Centric, Passenger Demand-Driven, and Agent-Based Simulation Flow and Algorithms

In order to develop simulation models to analyse dynamics and interactions of self-organising railway traffic under VC-enabled systems, we connect the self-organising decision-making and passenger assignment methods together for VC-enabled intelligent rail traffic simulation. The matching strategies for passengers-vehicles can be divided as instant matching and batch matching; for the VC-enabled train service in this study, we adopt the near instant matching strategy, i.e., the additional and unnecessary waiting time can be neglected. The simulation objective is to pursue the optimal variation of the car unit number in train formation on route and headway time, to maximize passenger-riding comfort degree on route, and to minimize train operation cost as well as passenger travel cost. As mentioned before, the simulation flow adopts the ergodic strategy by traversing each O-D pair demand along each route section over the rail transit network. The simulation flowchart for VC-enabled flexible train operation scheduling is illustrated as Figure 3. And the corresponding algorithms are shown as Algorithms 1 and 2.

7. Computational Experiments for Optimal Schedule Simulation with NetLogo

7.1. Experimental Design. Simulation of train operations under next generation signalling systems, such as virtual coupling, is pioneering in the public transport system it envisaged, and algorithms specification required making a series of assumptions about plausible characteristics of future VC-enabled rail transit systems as mentioned before. NetLogo [49] can provide a programmable modelling environment and adapt to simulate the complex system that evolves with time, by which the modeler can instruct thousands of independent agents to run, so as to explore the diverse behaviors and interactions among the agents. The
internal mechanism and principle of NetLogo are agent techniques, so NetLogo has the advantages in simulating multiagent systems. As this study is relatively pioneering in the public transport system it envisaged, our proposed ideas are tested on a mesoscopic hypothetical rail transit network built on the NetLogo platform (i.e., Y-type network of rail transit), which can lay the foundation for the applicability and generalizability of the study. The transit network is assumed to be given as an 8-node rail network with 2-track lines, i.e., the trunk line (with the red color) and the branch line (with the blue color), as illustrated in Figure 4. The link length of the network configuration is shown in Table 1. In the hypothetical Y-type network of rail transit, node 4 (with green color) is a pivotal station for two lines. And the capacity of each node is shown in Table 2. The alighting proportion of each station node is set as a random number between 0 and 1.

Consider one direction that trains run in the unidirectional double track rail line, i.e., from upstream to downstream. For the train operation mode, trains can fully straight run through trunk-branch lines (Figure 5). In this mode, both the trunk route and the branch route originate from station node 1. On the trunk route, the train can run from station nodes 1 to 6 back and forth. While on the

```
Input: time horizon T, mesoscopic network of rail transit, dwell time, OD demand matrix, alighting proportion of stations, seat and maximal carrying capacity of train unit, empty seat average cost per time unit, unserved passenger shortage cost per time unit, in vehicle travel time on track section, route r, and route set R
Output: variation of the car unit number in train formation on route, headway time, passenger-riding comfort degree on route, train operation cost, and passenger travel cost
While terminate criteria are not reached do
   Randomly generate headway time of train formations
   Compute the number of trains running in the network
   Compute the OD demand matrix
   Randomly allocate the trains to each route r
   Foreach: r ∈ R
      Compute the carrying capacity on route r
      Label the trains running on route r
      Foreach OD pair (i, j)
         If passenger demand of OD pair (i, j) can be satisfied
            Compute passenger-riding comfort degree on pair (i, j)
            Compute passenger travel cost on pair (i, j)
            Compute train operation cost on pair (i, j)
         else
            Compute the number of train unit (ncar) needed to be virtually coupled
            Randomly choose the number of ncar train formation
         End If
      End Foreach
      Foreach train formation with original label
         Compute the seat number and carrying capacity
      End Foreach
      Foreach train formation with lately updated label
         Compute the seat number and carrying capacity
      End Foreach
      Compute passenger-riding comfort degree on OD pair (i, j)
      Compute passenger travel cost on OD pair (i, j)
      Compute train operation cost on OD pair (i, j)
   End Foreach
End While
Compute variation of car unit numbers in train formation on each route
Compute passenger riding comfort degree on each route, respectively
Compute average passenger-riding comfort degree on all routes
Compute passenger travel cost on each route, respectively
Compute total passenger travel cost on all routes
Compute train operation cost on each route, respectively
Compute total train operation cost on all routes
Determine the desired headway time of train formations
```

**Algorithm 2:** Simulation flow for virtually coupled train formation in the rail network.
branch route, the train can also travel to and fro between station nodes 1 and 8, and in each single direction journey of the round-trip trajectory, it has to go through the intermediate pivotal station node 4. This kind of operation mode can reduce the transfer cost for passengers boarding and alighting trains on different lines. It is assumed that the trains can be overtaken and stop-skip for virtually coupling/decoupling in all intermediate stations. The alternative paths are given as follows: the trunk route is designated as route $R_1$, i.e., route $R_1$: 1-2-3-4-5-6; and the branch route is designated as route $R_2$, i.e., route $R_2$: 1-2-3-4-7-8. The average train speed is set as 14.6 m/s. The maximal carrying capacity of each train unit is set as 600 persons, and the number of its seat is set as 350. From the society-economy perspective, the empty seat average cost per time unit is estimated as 10 RMB, and the unserved passenger shortage cost per time unit 8 RMB.

7.2. Simulation Results. By using the simulation platform NetLogo, the rail transit network (Figure 4) is setup as the simulation environment, and then, the passenger OD demand matrix is generated following the random Poisson arrival rates and demand distribution proportion.

According to simulation flowchart (Figure 3) and simulation flow Algorithms 1 and 2, after 500 ticks of simulation run within 15 min, the variation of VC-enabled car unit numbers in train formation on route $R_1$ and $R_2$ can be achieved, respectively (Figures 6 and 7), also the headway time for train formations operation in the Y-type rail transit network (Figure 8), the passenger riding comfort degree on routes $R_1$ and $R_2$, as well as the average comfort degree on both routes (Figure 9), the train operation cost (Figure 10), the passenger travel cost (Figure 11), and the passenger flow distribution profile on both routes (Figures 12 and 13). Correspondingly, in Figures 6 and 7, the meaning of the line legends in the figure is explained in Tables 3 and 4. And in Figures 12 and 13, the meaning of the line legends in the figure is explained in Tables 5 and 6.

Among these series of simulation results, the desirable average passenger-riding comfort degree on both routes of the Y-type rail transit network is achieved as 0.623627 (on route $R_1$ 0.57552 and on route $R_2$ 0.671733, respectively), at the total cost of 2968.695 hours for passengers’ travel on both routes.
Figure 6: Variation of car unit numbers in VC-enabled train formation on route $R_1$.

Figure 7: Variation of car unit numbers in VC-enabled train formation on route $R_2$.

Figure 8: Headway time profile of VC-enabled train traffic in the Y-type rail transit network.
routes (on route $R_1$ 1726.826 hours and on route $R_2$ 1241.869 hours, respectively), and 3070.717 RMB for trains operation on both routes (on route $R_1$ 1680.649 RMB and on route $R_2$ 1390.068 RMB, respectively) individually. Particularly, at this desirable average passenger-riding comfort degree point, the desired headway time for train traffic in the network is 300 seconds. The details of the desired key simulation results are shown in Table 7.

7.3. Discussion. Usually, it is publicly recognized that the customers’ preference should be the right paradigm in the market-oriented environment. From this point of view, given the stochastic passenger demand, the best number of train units can be obtained to group together and form train convoys flexibly on time by using the VC technique over 500 ticks of simulation runs (as illustrated in Figures 6 and 7), when the desired passenger-riding comfort degree is
achieved. Meanwhile, the headway time for train operation on the Y-type rail transit network is most adaptable, i.e., 300 seconds. On the other hand, when the minimum total passenger travel cost (2308.859 hours) is taken into account, the corresponding desired headway time for the train formation is 194 seconds, and the average passenger-riding comfort degree is 0.36532.

As far as the passenger travel time is concerned, due to the near instant matching strategy, passengers needless to transfer, so it can save the unnecessary transfer time. Also, it can ensure as less as possible the number of passengers left behind due to the variable-capacity supply. Meanwhile, in the VC-enabled service mode, train formations can be grouped together without stopping and run as a platoon or one train past/through certain bottleneck in the physical rail transit network, so as to reduce the number of train path. And furthermore, it can save the unnecessary additional waiting time or scheduling/rescheduling time before the bottleneck.

Third, when the minimum total train operation cost (2926.208 RMB) is concerned, the corresponding desired headway time for the train formation is 185 seconds, and the average passenger-riding comfort degree is 0.367213. What need to be stressed is that the train operation cost consists of two parts, i.e., the empty seat cost due to insufficient passenger demand and the unserved passenger shortage cost due to insufficient capacity supply. Moreover, the desirable average passenger-riding comfort degree is not very high enough (only 0.623627 in most desirable scenarios). By combining these phenomena with the minimum total train operation cost (2926.208 RMB) and its corresponding headway time (185 seconds), we can conclude that the total passenger demand is relatively large.

According to train-following behavior, there are two kinds of gaps of VC-enabled trains, i.e., the intra-platoon car-following gaps and the inter-platoon car-following gaps. In this study, we prefer the latter. In the current realization method for VC in this study, besides the actual passenger demand, the number of train units that can be virtually coupled depends on the initial number of trains operating on the route, which can be explained in an example as given Pseudocode 1. Due to the possibility of passengers left behind, this shortcoming in Algorithm 2

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**Figure 12:** Passenger flow distribution profile on track section of route $R_1$.

**Figure 13:** Passenger flow distribution profile on track section of route $R_2$. 

---

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design is also a reason that decrease the passenger-riding comfort degree in general, which needs to be improved in the future study.

7.4. Platoon Operation Oriented Future Study. The leading or master train in the VC-enabled train convoy determines the reference speed profile or optimal train trajectory based on the timetable, guidelines, expertise, and ATO algorithms. Generation of train trajectory and tracking of multiple virtually connected trains in a convoy is a nontrivial issue [50]. A platoon is a set of trains that move cooperatively as close as possible using cooperative adaptive control to maximize track capacity, which means that trains run synchronously with respect to operation control, and the platoon decision may affect the timetable and rolling stock allocation [12]. Similarly, joining or splitting a platoon can occur at stations or on-the-run.

Table 3: Explanation of line legends in Figure 6.

<table>
<thead>
<tr>
<th>Line legends</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>car126</td>
<td>Initial variation of car unit numbers in train formation in the track section between station node 1 and station node 2 on route R1 over 500 ticks of simulation runs. Due to the possibility that the passenger demand maybe greater than the initial carrying capacity supply, by considering the virtually coupled situations, the partially updated variation of car unit numbers in train formation in the track section between station node 1 and station node 2 on route R1 over 500 ticks of simulation runs.</td>
</tr>
<tr>
<td>car1261</td>
<td>Initial variation of car unit numbers in train formation in the track section between station node 2 and station node 3 on route R1 over 500 ticks of simulation runs. Due to the possibility that the passenger demand maybe greater than the initial carrying capacity supply, by considering the virtually coupled situations, the partially updated variation of car unit numbers in train formation in the track section between station node 2 and station node 3 on route R1 over 500 ticks of simulation runs.</td>
</tr>
<tr>
<td>car12623</td>
<td>Initial variation of car unit numbers in train formation in the track section between station node 3 and station node 4 on route R1 over 500 ticks of simulation runs. Due to the possibility that the passenger demand maybe greater than the initial carrying capacity supply, by considering the virtually coupled situations, the partially updated variation of car unit numbers in train formation in the track section between station node 3 and station node 4 on route R1 over 500 ticks of simulation runs.</td>
</tr>
<tr>
<td>car126231</td>
<td>Initial variation of car unit numbers in train formation in the track section between station node 3 and station node 4 on route R1 over 500 ticks of simulation runs. Due to the possibility that the passenger demand maybe greater than the initial carrying capacity supply, by considering the virtually coupled situations, the partially updated variation of car unit numbers in train formation in the track section between station node 3 and station node 4 on route R1 over 500 ticks of simulation runs.</td>
</tr>
<tr>
<td>car12634</td>
<td>Initial variation of car unit numbers in train formation in the track section between station node 4 and station node 5 on route R1 over 500 ticks of simulation runs. Due to the possibility that the passenger demand maybe greater than the initial carrying capacity supply, by considering the virtually coupled situations, the partially updated variation of car unit numbers in train formation in the track section between station node 4 and station node 5 on route R1 over 500 ticks of simulation runs.</td>
</tr>
<tr>
<td>car12645</td>
<td>Initial variation of car unit numbers in train formation in the track section between station node 5 and station node 6 on route R1 over 500 ticks of simulation runs. Due to the possibility that the passenger demand maybe greater than the initial carrying capacity supply, by considering the virtually coupled situations, the partially updated variation of car unit numbers in train formation in the track section between station node 5 and station node 6 on route R1 over 500 ticks of simulation runs.</td>
</tr>
<tr>
<td>car126451</td>
<td>Initial variation of car unit numbers in train formation in the track section between station node 5 and station node 6 on route R1 over 500 ticks of simulation runs. Due to the possibility that the passenger demand maybe greater than the initial carrying capacity supply, by considering the virtually coupled situations, the partially updated variation of car unit numbers in train formation in the track section between station node 5 and station node 6 on route R1 over 500 ticks of simulation runs.</td>
</tr>
</tbody>
</table>

Platooning or platoon is recognized as a kind of ideal status, which all of the train operations should be oriented as possible as they can. In general, the normal relation between railway traffic control and train operation can be simplified as shown in Figure 14 [51]. In the future study, we could induce the optimal dynamic train operation plan by inversing this relation, i.e., starting from the known optimal railway traffic control status and taking platoon status as the reference scheme to seek the optimal timetable/schedule and train operation plan inversely (e.g., to determine the speed, time, and location where the virtual coupling/decoupling takes place) and shift from off-line planning to real-time traffic management solutions, which is shown in Figure 15. This is a kind of VC-enabled platoon-oriented train operation scheduling scheme. Meanwhile, it is necessary to set train operating rules for constraint generation, set the basic schedule structure (arrival time, departure time, through time, connection relationship, coupling, and decoupling),
Table 4: Explanation of line legends in Figure 7.

<table>
<thead>
<tr>
<th>Line legends</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>car128</td>
<td>Initial variation of car unit numbers in train formation in the track section between station node 1 and station node 2 on route $R_2$ over 500 ticks of simulation runs. Due to the possibility that the passenger demand maybe greater than the initial carrying capacity supply, by considering the virtually coupled situations, the partially updated variation of car unit numbers in train formation in the track section between station node 1 and station node 2 on route $R_2$ over 500 ticks of simulation runs.</td>
</tr>
<tr>
<td>car1281</td>
<td>Initial variation of car unit numbers in train formation in the track section between station node 2 and station node 3 on route $R_2$ over 500 ticks of simulation runs. Due to the possibility that the passenger demand maybe greater than the initial carrying capacity supply, by considering the virtually coupled situations, the partially updated variation of car unit numbers in train formation in the track section between station node 2 and station node 3 on route $R_2$ over 500 ticks of simulation runs.</td>
</tr>
<tr>
<td>car12823</td>
<td>Initial variation of car unit numbers in train formation in the track section between station node 3 and station node 4 on route $R_2$ over 500 ticks of simulation runs. Due to the possibility that the passenger demand maybe greater than the initial carrying capacity supply, by considering the virtually coupled situations, the partially updated variation of car unit numbers in train formation in the track section between station node 3 and station node 4 on route $R_2$ over 500 ticks of simulation runs.</td>
</tr>
<tr>
<td>car12834</td>
<td>Initial variation of car unit numbers in train formation in the track section between station node 4 and station node 5 on route $R_2$ over 500 ticks of simulation runs. Due to the possibility that the passenger demand maybe greater than the initial carrying capacity supply, by considering the virtually coupled situations, the partially updated variation of car unit numbers in train formation in the track section between station node 4 and station node 5 on route $R_2$ over 500 ticks of simulation runs.</td>
</tr>
<tr>
<td>car12847</td>
<td>Initial variation of car unit numbers in train formation in the track section between station node 5 and station node 6 on route $R_2$ over 500 ticks of simulation runs. Due to the possibility that the passenger demand maybe greater than the initial carrying capacity supply, by considering the virtually coupled situations, the partially updated variation of car unit numbers in train formation in the track section between station node 5 and station node 6 on route $R_2$ over 500 ticks of simulation runs.</td>
</tr>
<tr>
<td>car12878</td>
<td>Initial variation of car unit numbers in train formation in the track section between station node 7 and station node 8 on route $R_2$ over 500 ticks of simulation runs. Due to the possibility that the passenger demand maybe greater than the initial carrying capacity supply, by considering the virtually coupled situations, the partially updated variation of car unit numbers in train formation in the track section between station node 7 and station node 8 on route $R_2$ over 500 ticks of simulation runs.</td>
</tr>
</tbody>
</table>

Table 5: Explanation of line legends in Figure 12.

<table>
<thead>
<tr>
<th>Line legends</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>nump12-1</td>
<td>The volume of passenger demand between station O-D pair (1, 2) on route $R_1$</td>
</tr>
<tr>
<td>nump23-1</td>
<td>The volume of passenger demand between station O-D pair (2, 3) on route $R_1$</td>
</tr>
<tr>
<td>nump34-1</td>
<td>The volume of passenger demand between station O-D pair (3, 4) on route $R_1$</td>
</tr>
<tr>
<td>nump45-1</td>
<td>The volume of passenger demand between station O-D pair (4, 5) on route $R_1$</td>
</tr>
<tr>
<td>nump56</td>
<td>The volume of passenger demand between station O-D pair (5, 6) on route $R_1$</td>
</tr>
</tbody>
</table>

Table 6: Explanation of line legends in Figure 13.

<table>
<thead>
<tr>
<th>Line legends</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>nump12-2</td>
<td>The volume of passenger demand between station O-D pair (1, 2) on route $R_2$</td>
</tr>
<tr>
<td>nump23-2</td>
<td>The volume of passenger demand between station O-D pair (2, 3) on route $R_2$</td>
</tr>
<tr>
<td>nump34-2</td>
<td>The volume of passenger demand between station O-D pair (3, 4) on route $R_2$</td>
</tr>
<tr>
<td>nump47-2</td>
<td>The volume of passenger demand between station O-D pair (4, 7) on route $R_2$</td>
</tr>
<tr>
<td>Nump78</td>
<td>The volume of passenger demand between station O-D pair (7, 8) on route $R_2$</td>
</tr>
</tbody>
</table>
Table 7: The details of the desired key simulation results.

<table>
<thead>
<tr>
<th>Route</th>
<th>Passenger-riding comfort degree</th>
<th>Passenger travel cost (hour)</th>
<th>Train operation cost (RMB)</th>
<th>Desired headway time (second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Route R1</td>
<td>0.57552</td>
<td>1726.826</td>
<td>1680.649</td>
<td></td>
</tr>
<tr>
<td>Route R2</td>
<td>0.671733</td>
<td>1241.869</td>
<td>1390.068</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>—</td>
<td>2968.695</td>
<td>3070.717</td>
<td>300</td>
</tr>
<tr>
<td>Average</td>
<td>0.623627</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Initially set the number of trains (car_ini) operating on the route.
If initial carrying capacity (capa) < current passenger demand (nump):
Compute the number of passengers left behind (numpleft): numpleft = capa − nump
Compute the number of trains (ncar) needed to be virtually coupled:
ncar = numpleft/capa
if ncar < car_ini
   randomly choose the number of ncar train units to be virtually coupled
else
   There would be still some passengers left behind
Endif
Endif

**Pseudocode 1:** Pseudocode for explanation of the possibility of passengers left behind.

Figure 14: Conventional integrated relation between railway traffic control and train operations.

Figure 15: VC-enabled platoon-oriented train operation scheduling scheme [52].
and fine-tune the related parameters for these rules when operating.

8. Conclusions

This study investigated the simulation-based schedule optimization for VC-enabled rail transit services with the multiagent technique, by connecting the timetables and operational traffic into one loop, in line with the newly current trend. To a certain extent, such an equation can be held as timetabling + train operation planning = real-time dynamic scheduling. We use an agent to represent the VC-enabled rail transit entity, i.e., VC-enabled train unit, VC-enabled train convoy, and passengers. We defined operational principles for flexible and self-organising VC-enabled trains. More importantly, we developed the VC-enabled train-centric, passenger demand-driven, and agent-based simulation flow and algorithms and then adopted the ergodic strategy for simulation by traversing each O-D pair demand along each route section over the rail transit network. We designed the computational experiment to test the proposed methodology on the NetLogo platform, and the simulation results series validated the effectiveness of the proposed methodology.

Given the dynamic short-term passenger demand, using the proposed methodology, we can construct a feasible online or near real-time VC-enabled train scheduling with the guaranteed quality of service from both passenger and operation perspective, i.e., optimize the interdeparture headway time, maximize the passenger-riding comfort degree, and minimize the passenger travel cost and train operation cost. On the other hand, the VC-enabled train services can provide variable capacity so as to meet the diverse passenger demand more accurately. For the attractiveness of rail transport, the train scheduling or operation plan represents the key elements. Through shorter headway times and variable-capacity provision via the VC technique, railway infrastructure utilization and service level can be increased significantly. Passenger-riding comfort on board the vehicles is a constraint; it has to be guaranteed that none of the trains is ever overcrowded in the ideal status. Simulation results show that the desired headway time of the train traffic in the designed network can be achieved at 300 seconds, at the desirable average passenger-riding comfort degree point 0.623627, at the total cost of 2968.695 hours passenger travel time, and 3070.717 RMB for trains’ operation costs.

Besides capacity, operational costs, running time, and waiting time, some additional objects could also be considered when deciding which trains should form VC-enabled platoons [12], e.g., punctuality and energy efficiency. More complete and enriched multiple-objective optimization for VC-enabled train services would be one of the themes for further study. The simulation study lays the foundation for the further study incorporating the available real-time data into the simulation model in the future research, which just needs to replace the data in the experimental design sector with the data of the real case.

In terms of the estimated times for implementation of VC, according to scenario-based roadmaps for each market segment [12], e.g., high speed, mainline, regional, urban, and freight, both optimistic and pessimistic scenario supporting the urban market would be the first one to fulfill the target of deploying VC, before the years 2035 (optimistic scenario) and 2045 (pessimistic scenario), respectively. For highly frequent train services or platoons, e.g., metro trains, the VC-enabled technique could be better off by using the dynamic operation strategy. Future research will focus on platoon operation oriented VC-enabled train service schedule as discussed in Section 7.4, so as to build a more robust and flexible schedule, with increased capacity, improved safety, better customer service, and more in line with the self-organising feature of the VC-enabled technique.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The author declares that there are no conflicts of interest.

References


