# A Survey on Control Methods for Virtual Coupling in Railway Operation

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**ABSTRACT** In order to meet the rapid growth of railway transportation demand, the technology that can improve its capacity has been widely concerned. Virtual Coupling (VC) is a new technology to improve capacity by decreasing headways between successive trains. Its basic principle is to control the train formation operation in coordination with the goal of keeping the same speed under the support of data transmission technology such as train-to-train communication. Our paper first reviews the existing theoretical research on train formation operation control, which is divided into four categories: train following, feedback control, optimal control and computational intelligent method. Secondly, by reviewing the related projects in Europe and China, based on the scenario analysis method, five general scenarios and two emergency scenarios in the whole process of VC operation are sorted out. Then, an original, complete list of performance indicators (PIs) is proposed for evaluating the performance of VC in different scenarios. Additionally, the paper gives a brief insight into VC operation by providing an adequate context to understand the proposed PIs.

**INDEX TERMS** Virtual coupling, railway operation, train-following model, feedback control, optimal control, computational intelligent method, performance indicator.

## I. INTRODUCTION

### A. MOTIVATION

RAIL has experienced a sharp increase in demand for passenger and freight transportation, as well as for urban and intercity services, as a mass and environmentally friendly mode of transportation.

For urban rail transit, by the end of 2021, there have been 541 cities in 79 countries and regions (though mainly in Europe and Asia) that have operated urban rail transit lines, with a total mileage of 36000 km and more than 26900 stations, mainly in Europe and Asia. Urban rail transit is the backbone of the transportation system in metropolitan cities such as Beijing, Shanghai and Tokyo, with daily passenger capacity exceeding 10 million people. Under the Communication Based Train Control system (CBTC, currently the advanced train control system), the operation headway in peak hour can be reduced down to 90 seconds [1], thus vastly increasing the transit capacity.

The recent decade has also seen the development of high-speed railway (HSR), most notably the HSR development in China, which has already surpassed 39,000 route-km by the end of 2020 (See Fig. 1) and accounts for two-thirds of all the HSR lines in the world. The rapid expansion of HSR lines in China has led to trunk lines and bottlenecks in the HSR network, such as the bottleneck at the Xuzhou-Bengbu

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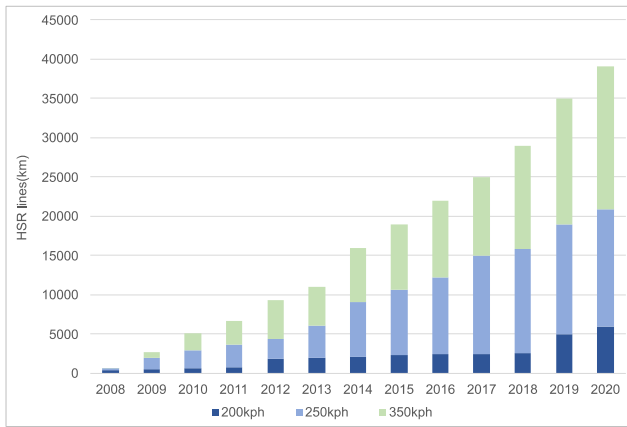
FIGURE 1. Length of China's high-speed rail network*. *Source: based on the Statistical bulletin published by the National Railway Administration of China.
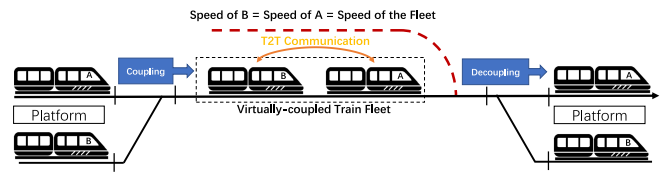


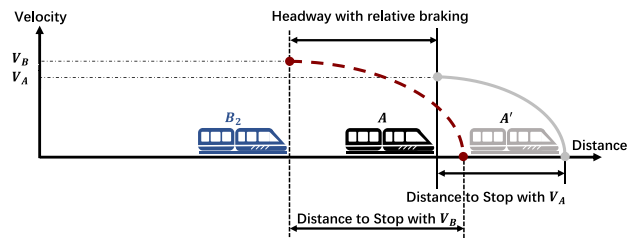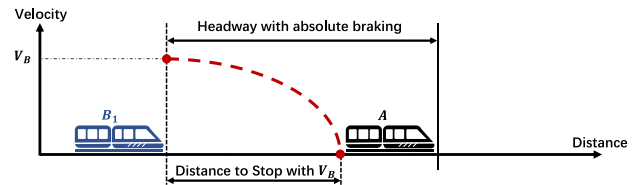FIGURE 2. The illustration of virtual coupling.



FIGURE 3. The comparison of headway with absolute braking and relative braking respectively. Where $v_A$ and $v_B$ are the velocity of Train $A$ and Train $B$, respectively.

segment of the Beijing-Shanghai HSR line. The capacity along this important HSR route is therefore severely limited.

In Europe, there is a sign that rail freight transportation is in decline, and moving towards road transportation instead. This was partly due to the capacity constraint on the railway network, as well as the inflexibility, longer transportation times, and higher prices of the railway system [2], [3].

Facing the urgent needs to reach the system performance limit in the bottleneck section and reduce the cost of flexible freight transportation, people are thinking about how to develop CBTC, China Train Control System (CTCS), European Train Control System (ETCS) and other technologies in the future [4], [5]. The railway should rise to the challenge of using the existing infrastructure to extend the line capacity. So, the technologies for decreasing train headways are meaningful.

## B. CONCEPT OF VIRTUAL COUPLING

With the continuous development of Train-to-Train (T2T) communication, Train-to-Ground (T2G) communication technology, Automatic Train Operation (ATO) and related rail transportation technologies, virtually-coupled train formation or Virtual Coupling (VC) has received considerable attention in recent years. The VC makes the connection between trains no longer an actual physical coupler, but trains maintain short-distance travel together and a consistent velocity by communicating with each other. By means of electronic data transmission, these trains would form a fleet after entering a trunk line. And then, they drive one behind the other with a short headway. The trains leave the formation automatically when they reach a junction or station (See Fig. 2).

The train fleet will keep an absolute-braking distance from the former fleet, as the principle of Moving Block for the traditional safe requirement. For the trains in a fleet, protection from overspeed is a critical problem that needs to be discussed. These trains run with the same velocity, share the same information (temporary speed limits, obstacles), and move forward cooperatively. Theoretically, they could

run at a separation of the relative-braking distance, which could decrease the headway. The comparison of absolute-braking distance (ABD) and relative-braking distance (RBD) is shown in Fig. 3. The Train $A'$ indicated in grey is only the position of Train $A$ where Train $A$ could stop with velocity $V_A$, and is not the real train. Train $B_1$ and Train $B_2$ represent the position where emergency braking is required for Train $B$ under absolute and relative braking distance, respectively. However, the RBD-based method does not consider the different braking performance between two trains. Its practicability has been widely questioned.

It can be seen that normally a large distance must be kept between trains according to the braking curve. The proposed VC can effectively shorten the distance between adjacent trains. Therefore, a large amount of literature focuses on VC control methods, and they usually target different operation scenarios as their research context. The analysis of each scenario of the VC operation process is necessary to achieve better control results. In addition, some indicators have been proposed to evaluate the effectiveness of virtual formation operation, and there is a need to organize these performance indicators in a more focused way.

## C. CONTRIBUTION

VC terminology has been put forward for more than 20 years. It integrates the ideas of cooperative control, T2T communication, relative speed braking distance protection and so on. VC concept involves wireless communication, train control, operation management and other aspects of railway transportation. It could be a disruptive technology

and has become a hot topic in the development trend of train operation. The contribution of this paper is:

(A) Review the research of control methods for VC, and classify these methods into four categories: methods based on the train-following model, feedback control, optimal control and computational intelligent.

(B) Review the projects about VC in Europe and China, respectively. On this basis, describe the operation procedure of VC systematically, and conclude five general scenarios and two emergency scenarios.

(C) Based on literature research, a list of PIs by summarizing the previous studies [6], [7] in VC is proposed for evaluating its performance in different scenarios. Compared with the scattered use of the required indicators in previous studies, the performance indicators are classified and sorted out systematically.

The remainder of the paper is structured as follows. Section II reviews the studies on control methods for VC and related projects. Section III concludes that different scenarios in the whole process of VC operation. An original list of performance indicators is proposed for evaluating the performance of VC in Section IV. Section V concludes the paper.

## II. RESEARCH REVIEWS ON VIRTUAL COUPLING
### A. LITERATURE REVIEW

In recent research, there are several issues under the topic of VC, such as capability analysis, stability, energy saving, speed convergence, speed protection, and performance evaluation [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [42], [43], [44], [45]. First, capability analysis is to calculate and evaluate the capability of a rail line or network through numerical simulations or field trials. And the capability here is evaluated in terms of train separation over the route and time headway at main interlocking areas. The second issue is stability which usually contains local stability and string stability. For local stability, it describes those states of virtually coupled trains that can stay in a certain range around an equilibrium state (e.g., desired spacing and consistent speed) or converge to a given trajectory (e.g., speed profile) under disturbances. String stability is studied to ensure that disturbances of the train states are attenuated upstream of the platoon or string. The third issue, optimization during operation, is to ensure the virtually coupled trains achieve a given objective such as speed convergence, using the energy, etc. The final, fourth issue is about safety, and more specifically train speed and headway protection. The current Automatic Train Protection systems are based on the ABD, so could not meet the headway requirement in VC. New train protection methods and models need to be designed and developed for VC.

For these issues, different methods are studied and applied to solve them. These methods are classified into four categories: 1) Method Based on Train-following Model [8], [9], [10],

[11], [12], [13], [14], [15], [16], [17], 2) Feedback Control [18], [19], [20], [21], [22], [23], [24], [25], 3) Optimal Control [7], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39] and 4) Method Based on Computational Intelligent [42], [43], [44], [45]. Through Table 1, four types of methods map the issues that have already been solved and that are able to be studied.

### 1) METHOD BASED ON TRAIN-FOLLOWING MODEL

Briefly speaking, the car-following(CF) model approach is based on car-following theory and can be used to test control algorithms and design solutions to control problems [4]. Generally speaking, the controller outputs the reference acceleration based on the explicit function of each car-following model, i.e.,

$$u_i = f(x_i) = f(\Delta s_i, \Delta v_i), \tag{1}$$

where $u_i$ is the reference acceleration, $x_i = (\Delta s_i, \Delta v_i)$ is the state for vehicle $i$ denoting the spacing deviation and speed difference with respect to its predecessor, and $f(\cdot)$ represents the function of the car-following model.

In recent years, the CF topics have been gaining more importance in control engineering research [10]. CF models have been widely applied in advanced cruising control algorithms as the functional definition. In the following mode of a vehicular platoon, the car-following model regulates the spacing to a desired value and eliminates the speed difference between the following car and its predecessor [11], [12]. For instance, the constant spacing CF model is used as a linear feedback controller, where this model regulates the vehicular platoon to maintain a fixed gap between two successive cars, i.e.,

$$u_i = K_s(s_i - s^*) + K_v \dot{s}_i, \tag{2}$$

where $s^*$ is a fixed and desired distance for vehicles in the platoon, $\dot{s}_i$ is the relative speed $\Delta v$ with respect to the preceding train $i-1$. Nevertheless, it is worth going deep into more advanced control methods, for vehicles with practical dynamics and under complicated scenarios.

The CF models have also been adapted into railway scenarios for train following control. A train-following (TF) model was developed in [8], which ensures that the minimum headway between trains can be maintained.

The difference between CF and TF models is significant. According to [8], TF models should consider the collision-free headway policy due to the specific braking characteristic of trains, e.g., emergency braking curve. Concretely, the following train usually needs to calculate the headway from its predecessor, considering the braking distance of the predecessor under the worst conditions. This concept in TF models is similar to the safety-distance model proposed by [13], but the models themselves are different because of the vehicle dynamics and the road/rail conditions.

The following is a summary of the research in the field of VC of train-following in four issues: capability, safety, stability and optimal.

**TABLE 1.** The similarities and differences of the four approaches classified.

| Method | Capability | Safety | Stability | Optimization |
|---|---|---|---|---|
| A: Train-following Model | Suitable for evaluating the capacity [14], [15], [16] | Suitable for analyzing the dynamics of safety margin/headway [17] | Hardly used for analyzing the stability except for rule-based control strategy | Cannot handle optimization constraints |
| B: Feedback Control | Able to improve the capability [19] | Able to maintain safe operation [20], [21] | Able to guarantee a stable control, often formulated in a linear fashion [22], [23], [24], [25] | Unable to applied to nonlinear optimization control problems because of its linear control model |
| C: Optimal Control | Able to improve the capability [7], [30] | Able to maintain safe operation [31], [32] | Suitable for analyzing the stability [33], [34], [35], [36] | Suitable for modeling nonlinear optimization control problems [37], [38], [39] |
| D: Computational Intelligent Method | Suitable for scenarios where multiple trains converge to form a formation [42] | Has the potential to be used in this area | Able to improve the stability [43], [44] | Suitable for finding the optimal control strategy [45] |

*Capability*: In [14], a VC model and an improved station tracking model were proposed. The proposed models were simulated and verified by numerical calculation and simulation analysis showing that the improved station tracking model has the same capability as the relative moving block, and the VC model has the largest capability. The VC model has the strongest delay recovery ability after the system is subjected to initial delay. A multi-state train-following model was proposed in [15], [16] to simulate VC train operation and evaluate the impact on capacity. The effect of VC on capacity was evaluated using simulations with data from the South West Main Line in the U.K. There were two main differences in train operation conditions in the simulation: whether the trains stop or not and whether the routes are the same. The results show that the VC provides more significant capacity improvements when trains in the formation have different approaches and need to stop: the maximum headways are reduced by 79%, 77% and 43% compared to TPWS, ETCS-2 and ETCS-3, corresponding to maximum spacing reductions of 85%, 64% and 43%, respectively.

*Safety:* Reference [17] analyzed risk factors in realistic operations such as train-train communication delays, extended response times, emergency braking applications and rolling stocks heterogeneity. The concept of dynamic safety margins is adopted to VC, which dynamically changes the train spacing to prevent safety violations in hazardous events such as T2T communication delays. According to the mathematical representation of dynamic safety margins proposed by [16], and combine it with a multi-state VC train-following model, which initially refers to constant safety margins and

is therefore sensitive to real operational risk insensitive. A case study on the U.K. South West Main Line was applied to validate and analyze the proposed model. In the event of a sudden T2T communication channel or ATO failure, VC operation with dynamic safety margins increases the train spacing to a safe distance until normal conditions are restored to ensure safe operation.

*Stability:* The parameters in the train-following model often need to be fine-tuned carefully based on a large number of simulations and field experiments. While these studies usually use a rule-based control strategy derived from TF model, which may fail to control multiple trains to run stably.

*Optimal:* By summarizing the above studies [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], it can be found that the goal of TF model is usually to reduce the gap between the expected speed/distance as in Eq. (2), or to be consistent with the adjacent preceding train. The train-following model cannot handle optimization constraints, such as minimizing energy consumption, while ensuring control effects. Therefore, the TF model is usually not chosen to solve the optimization problem.

### 2) METHOD BASED ON FEEDBACK CONTROL
The feedback control method regulates the spacing deviation from the desired value and eliminates the speed difference between two successive vehicles. Specifically, the feedback controller outputs the reference acceleration based on the errors from the equilibrium state $x^e = (0, 0)$ where no spacing deviation and speed difference, i.e.,

$$u_i = f(x_i) = K_s \Delta s_i + K_v \Delta v_i, \qquad (3)$$

where $x_i = (\Delta s_i, \Delta v_i)$ is the state for vehicle $i$ denoting the spacing deviation and speed difference with respect to its predecessor, $f(\cdot)$ represents the function of the feedback control law, $K_s$ and $K_v$ are the coefficients of the control gain.

Using the control theory, feedback control methods usually can guarantee a stable control where the state of each trains approaches the equilibrium state asymptotically. The feedback control law is often formulated in a linear fashion to simplify the control problem. For example, in [18] a feedback control approach was proposed based on the spacing error and the speed difference between trains in the Virtually Coupled Train Set (VCTS). The stability of the proposed control law is proved mathematically due to its simple linear form.

The following is a summary of the research in the field of VC of feedback control in four issues: capability, safety, stability and optimal.

*Capability:* Based on artificial potential field theory, [19] proposed a leaderless and a leader-following method, and simulated the two approaches, respectively, based on the data of the Beijing subway Batong line. The results show that it can solve not only the problem of excessive passenger density in the direction of large passenger flows but also reduce the capacity waste caused by the uneven distribution of capacity in the direction of small passenger flows. Meanwhile, this method can also reasonably arrange the train density and solve the capacity waste caused by the tidal passenger flow.

*Safety:* Reference [20] proposed a robust gap controller based on the sliding mode control method for the nonlinear train model with uncertainty. Moreover, a method was developed to ensure that coupling and decoupling can be completed before the trains arrive at a specified position while respecting constraints on the jerk and acceleration of the trains. The method's effectiveness is verified by simulating the merge, keep and separation of the scene, and the simulation parameters are taken from Seoul Metro Line 5. In [21], a constraint-force control method based on the Udwadia-Kalaba equation was proposed. Through simulation experiments, it could be found that when the line speed limit was changed, the following trains could still follow the speed of the leading train cooperatively, and the train formation could maintain safe operation.

*Stability:* Dong et al. [22] proposed a cooperative control method for multiple trains based on a moving block system. This method has lower computational cost complexity and is easier to implement. The simulation results show that the speed tracking and acceleration tracking error of trains in the formation converge to 0 quickly, and the control law output from the rear train controller tracks the front train well. Li et al. [23] designed a robust cruise controller based on sampled-data and gave a robust sampled based on the Lyapunov stability theorem in the form of linear matrix inequality sufficient condition for the existence of data cruise control scheduling. This condition ensures that

the high-speed trains can track the desired speed well and that the spacing between adjacent trains is effectively maintained in a stable state. The effectiveness of the proposed control method is verified by two numerical examples, and it is found that when there is a gust of wind disturbance, the influence of the interference gradually decreases as the number of trains $i$ increases. And the controller can control the speed fluctuation of the trains in the formation within a reasonable range, effectively reducing the influence of the gust on the formation operation. References [24], [25] proposed a virtual formation coordinated control method based on a multi-agent system with the objective of safe and stable operation of the train formation. The Simulink module of MATLAB is used to build a simulation test scenario, and the results show that the train formation consisting of 5 trains reaches a stable state at a simulation time of about $700\,seconds$, and the expected distance headway of $181m$ between adjacent unit trains is reached to form a stable state.

*Optimal:* Similar to the TF model, the feedback control [18], [19], [20], [21], [22], [23], [24], [25] takes the deviation from the desired distance and expected speed as the control input to achieve multi-train consistency and cooperative control. Therefore, feedback control is also difficult to be applied to VC optimization control problems.

### 3) METHOD BASED ON OPTIMAL CONTROL

In order to tackle the constraints of a control problem while guaranteeing optimality, optimization-based algorithms are widely studied and applied. Chu [26] first proposed an optimal controller for the vehicular platoon system. This optimization-based method, called linear quadratic regulator (LQR), assumes that the system has linear dynamics and sets the objective function as quadratic

$$J = \int_0^\infty \left( p\Delta s_i^2 + q\Delta v_i^2 + ru_i^2 \right) dt$$
$$\text{s.t.} \quad \dot{x}_i = Ax_i + Bu_i \tag{4}$$

in which $p$, $q$, $r$, $A$ and $B$ are coefficients. By solving this optimization problem, the optimal control $u_i^*$ for vehicle $i$ can be obtained as follows

$$u_i^* = \arg\min_{u_i} J. \tag{5}$$

As an optimization-based control method, model predictive control (MPC) has been extensively studied due to its ability to handle control systems with hard constraints on controls and states [27]. This method is used in the heavy-duty vehicle platoon control problem in [28], the control architecture has two layers. The upper layer is designed for trajectory planning, and the lower layer calculates control variables to track the planned trajectory. The advantage of this kind of control method is that the safety constraints can be handled in the lower MPC layer. In railway scenarios, safe spacing and overspeed protection are often considered in the controller design, formulated as extra constraints to the

optimal control problem because of the advantage of MPC. Xun et al. [29] proposed a self-triggered cooperative control for headway regulation of trains and tested the algorithm during cruising operation with constant objective speed.

The following continues the review of the application of MPC methods in VC for the railway from four issues.

*Capability:* Felez et al. [7] used a distributed model predictive control (MPC) architecture to design and adopt optimal control formulations for the leading train and following train controllers, respectively, which rely on the numerical solution of the finite-horizon optimal control problem. The results show that the MPC-based short prediction horizon strategy can reduce the distance between trains compared to moving block, which leads to a significant increase in line capacity. Reference [30] proposed a VCTS cruise control method based on model predictive control. It enables the trains in the formation to keep a small interval distance while ensuring safety. Simulation tests are set up with three scenarios: normal operation, presence of disturbance and emergency braking. The simulation results show that the controller can make VCTS converge to a stable state and can better handle the disturbance caused by other trains' state changes. Even in emergency situations, the train queue can be secured in time. In VC mode, the inter-train distance is 20% smaller than that in relative moving block system(MBS) mode and about three times smaller than that in absolute MBS mode, indicating that the controller proposed in this paper can further improve the efficiency of train operation.

*Safety:* Xun et al. [31], and Chen et al. [32] designed a coordinated collision mitigation approach for virtually coupled trains by using MPC, with the optimization goal of minimizing the hazard of train collision within the platoon. It is compared with adaptive cruise control and maximum braking control through numerical simulation. The effectiveness of the control algorithm proposed in this paper is verified, and a safe collision avoidance control method is provided for the emergency braking and parking scene of formation trains.

*Stability:* Liu et al. [33] proposed an analytical optimal control method for virtually coupled train formation stability. The proposed control method is an analytic optimal linear feedback control law that enables all trains in the formation to maintain stable spacing and consistent speed operation while ensuring local stability and string stability. To verify the proposed control law, numerical simulation experiments are conducted. The results show that the controller parameters selected in the stable region can ensure the stability of the trains in virtual formation even under the influence of initial disturbances. A nonlinear model predictive control system was designed in [34]. The nonlinear distance control objective function and the continuous variable speed limit in the inter-station are considered in the constraints. Simulation experiments were conducted based on actual data from a subway system, and the results showed that the trains temporarily deviated from the desired state under the speed limit. However, all trains will eventually adjust to the desired state automatically, proving this method's

effectiveness. Liu et al. [35] also considered the constraints caused by the change of speed limit and traction and braking performance, proposed a distributed model predictive control (DMPC) method to ensure the stability of virtual formation, and modeled the constrained optimal control problem in the DMPC framework. Numerical simulation results show that the proposed control algorithm can maintain local stability and string stability under different initial disturbances and speed limits. At the same time, the average computing time of the distributed controller is $0.21s$, which is more efficient and closer to the control cycle of 200ms compared to the centralized algorithm. In addition, the effects of uncertain interference and communication delays on stability are discussed in [36], while an integrated algorithm is proposed to improve further MPC's computational efficiency, which satisfies the computational time within 200ms in a certain prediction time.

*Optimal:* Yan et al. [37] developed a distributed cooperative method for multiple trains using MPC and ant colony optimization to optimize energy consumption. In [38], a cooperative model predictive control (CMPC) strategy with a multi-objective rolling optimization scheme was proposed. This method uses the optimization objective of the total line capacity, energy consumption and rides comfort of train formation. Compared with the traditional manual control strategy, this method improves the line capacity and energy consumption of the entire railroad section by 59.9% and 5.3%, respectively. Wu et al. [39] proposed a virtually coupled train formation (VCTF) control method based on the MPC framework. The optimization objectives are to train spacing error, speed error and passenger comfort, and the constraints such as line speed, train formation collision avoidance, traction/braking performance and VCTF stability are considered. The VC operation control problem is transformed into a constrained quadratic programming problem. A coasting control strategy is also proposed in this paper to improve the output of the MPC controller. Simulation results show that the control method can reduce both tracking error and output acceleration and reduce operating energy consumption compared with a proportional differential controller. The operational performance of VCTF is analyzed by studying a subway line. And the simulation results show that compared with the train operation mode based on communication, the VCTF operation mode can improve the peak capacity and quality during service in normal hours.

### 4) METHOD BASED ON COMPUTATIONAL INTELLIGENT

Since the problem of the operation and control of virtually coupled trains is a relatively new and promising field, more research is underway and there is an urgent need to study advanced intelligent methods.

The existing research using computational intelligence methods is reviewed below.

*Capability:* Reference [42] focuses on the scene where trains on different tracks form a virtual coupled train set at the designated position and enter the same platform for

stopping. The virtual formation is modeled based on the cooperative game model, and the particle swarm optimization algorithm is used to solve the problem. A simulation scenario is designed for validation and the results show that the cooperative game model is more flexible in adapting to the changing environment. By using the cooperative game-based optimization method, the running time is reduced.

*Safety:* No literature on this field has been found yet, but it has the potential to be used in this area. Artificial intelligence methods such as deep (reinforcement) learning currently have limited application in VC. Part of the reason is the difficulty of securing the algorithms, which hinders their practical application in controllers. Such intelligent algorithms are not negligible means of implementation in the face of autonomous learning decisions for future controllers. Safe reinforcement learning algorithms can be considered to learn the optimal controller by modifying the optimal criterion or changing the exploration process [40], ensuring that the system operates in a safe region while achieving a minimal impact on the controller behavior [41].

*Stability:* References [43], [44] combined deep learning with a MPC method considering the effect of communication delay of unit trains in the platoon. The Long Short-Term Memory (LSTM) neural network is used to predict the platoon's operating state of the preceding unit train. And the predicted state information is provided to the rear train model prediction controller to improve the tracking control accuracy of the rear train. The simulation results show that this method has a better control effect compared with the traditional MPC method and can improve the stability of the train fleet.

*Optimal:* Reference [45] built the architecture of virtually coupled trains as industrial Internet of Things. They developed a cooperative control algorithm based on reinforcement learning (RL) to achieve global optimization. The method uses the artificial potential field (APF) function as a reward function in the reinforcement learning process to reduce the computational complexity of RL in finding the optimal control strategy. The simulation results show that the proposed RL-based cooperative control method can make the IoT-based VCTS perform well.

## B. PROJECTS REVIEW

The rail industry is facing Perception, Communication, Control, and Safety issues for implementing VC in practice.

(A) *Perception:* In VC mode, more information (such as the distance between trains, and the velocity difference between successive trains) needs to be collected, proceeded and perceived in time. And more precise is also needed. That is the basis of VC.

(B) *Communication:* VC brings the demand for high real-time communication with the ability of flexible networking between trains.

(C) *Control:* The dynamics of train and point are complex. The cooperation of trains and points requires reliable and accurate control. The control performance is a critical issue for operating VC.

(D) *Safety:* The traditional braking model and protection principle are not applicable for the safe operation of trains in a platoon. A new mechanism for automatic train protection is needed.

### 1) PROJECTS IN EUROPE

Shift2Rail is the first European rail initiative to seek focused research and innovation (R&I) and market-driven solutions by accelerating the integration of new and advanced technologies into innovative rail product solutions [46]. There have been three Shift2Rail projects that specifically address the concept of VC. These are MOVINGRAIL, CONNECTA2, and X2RAIL-3. In MOVINGRAIL, the impacts of VC on different segments of the railway market, as well as the communication technology for VC, were investigated and assessed [47]. The CONNECTA2 project aims to contribute to the Shift2Rail's next generation of TCMS architectures and components, including the key technologies supporting the development of the "virtual coupling" concept [48]. X2RAIL-3 is a project under the Innovation Program 2 of Shift2Rail. It is part of a long-term strategy towards a flexible, real-time, intelligent train control management and decision support system. Different from MOVINGRAIL, X2Rail-3 will focus on the overall functional requirements and safety analysis of the solution, and the technological solution and the associated business case respectively [49], [50].

"Closer Running" is the title of an RSSB research project in the United Kingdom (U.K.) [51]. The current U.K. railway infrastructure is unable to support the increased usage. It is considered that autonomous train (AT) operation will offer significant benefits to the U.K. railway network, e.g., increasing the railway network capacity. The significant benefits stem from ATs being able to use moving block signaling, thus potentially meaning ATs can operate much closer together. The technologies have been investigated for coupling and uncoupling of trains on the move, also called Seamless Interchangeability (SI) operation [52].

The next generation train (NGT) project, funded by the German Aerospace Center (DLR), focused on providing a rail service with shorter travel times and reductions in specific energy consumption, noise emissions, and wear while increasing passenger safety and comfort and reducing life cycle costs [53]. One of its important contributions is the research on T2T communication since 2007. Traditionally, the train reports its location to the ground and receives commands from the control center. However, direct T2T communication is not applied widely in current train control system solutions. The development of specifications for T2T communication will provide great support for the VC operation [54].

### 2) PROJECTS IN CHINA

At the same time, several projects on VC were also launched in China. In 2018, the NSFC (National Natural Science Foundation of China) launched the project on "The Basic

**TABLE 2.** Project review.

| Organization/ Institution | Projects | Objectives | Methodology | Contributions | Current state |
|---|---|---|---|---|---|
| Shift2Rail | MOVINGRAIL | This project aims at identifying operational procedures for Moving Block signalling, as well as assessing communication technologies and impacts of VC. | By identifying operational procedures for Moving Block and VC signalling, the market potentials, potential business risks and possible migration issues for VC are determined. | First, the impacts of different railway market segments on costs, performance and operator needs are evaluated. Second, it provides a roadmap for the introduction of VC. | Finish |
| Shift2Rail | CONNECTA-2 | The project aims at developing the ability to implement SIL4 functions in the Train Control Monitoring System (TCMS) and supporting the development of the VC. | Reduced operational ineffectiveness of TCMS with VC implementation and tests. | TCMS has the capability of SIL4 functionality to support VC operations. | Finish |
| Shift2Rail | X2RAIL-3 | The aim of this project is to explore the innovative concept of VC to bring trains closer to each other for flexible, real-time, intelligent traffic control management and decision support systems. | This activity reduces LCC and enhances system reliability by analysing new signalling concepts (VC) in order to go beyond the limitation of the current signalling approach for trains and units separation. | This project defines the overall functional, performance and safety requirement of the VCTS, identifying the possible technological architecture of the solution as well as characterizing the functionality and its business case. | Finish |
| RSSB | Closer Running | The purpose of this research has been to help provide a definition for "closer running" to take forward the idea of reducing the headway of individual trains to increase capacity. | It has identified the improvements needed to support the closer running concept – moving block European Rail Traffic Management System Level 3, CBTC, high-integrity switch technology and significant improvements to traffic control. | This research has been to develop a structured implementation road map that can help the railway industry to reduce the separation between consecutive trains safely. Some initial ideas contributing to support the closer running concept are summarised. | Finish |
| German Aerospace Center (DLR) | Next Generation Train | The DLR's transport research is dedicated to solving problems in "Next Generation Train", which includes how to make rail transport safer, more efficient, more environmentally friendly and how trains should be best configured in the future. | The distance between the virtually coupled trains is controlled through reliable ranging sensors and wireless T2T communications that allow exchange of the relative location of each train. It focuses on reliable T2T communications and on-board multi-sensor train localization. | This research pioneered the investigation and use of magnetic signatures for train localization. This solution with magnetic signatures enables GPS-free localization. Furthermore, the expected effects on a railway system operated with VC and slip coaching are clarified. | Finish |
| National Natural Science Foundation of China | The Basic Theory and Key Technology of The Integration of Train Operation Control and Dynamic Dispatching for High-speed Railway | One of objectives of this project is to study how to ensure that formation trains can quickly return and maintain stable formation operation under the influence of disturbance conditions, to improve the utilization of line resources and train resources. | A safety-limited speed difference calculation method based on a relative coordinate system is proposed, and MPC-based control algorithms are proposed for deceleration and emergency braking scenarios, respectively. | The proposed control algorithm can effectively reduce the collision risk of formation trains in complex scenarios and provide a safe collision avoidance control idea for the cooperative operation of formation trains. | Ongoing |
| CRRC | | The goal is to explore virtual coupling/ decoupling technology for train groups. | Improve transportation efficiency and shorten departure intervals. | Construction of virtually coupled train control mode using multi-intelligent system cooperative control technology. | Ongoing |
| The Outlines of Smart Urban Rail Development | Beijing Subway Line 11 West Section | To develop flexible train composition and cooperative formation technology to enhance the intelligence level of urban rail train operation system. | Developed the Autonomous Virtual Coupled Operating System (AVCOS) is undergoing technology validation and advancement. | Autonomous VC can reduce operational energy consumption by 29%, average passenger waiting time by 40%, and total costs by more than 25%. | Ongoing |

Theory and Key Technology of The Integration of Train Operation Control and Dynamic Dispatching for High-speed Railway" [55]. It includes the basic principle, framework, and methods of coordinated operation control for the high-speed train. In 2020, being with CRC (China Railway Company), NSFC launched another project on the operation

control theory and method of autonomous coordinated train for high-speed railways. It focuses on the safety of multi-train coordinated operation, especially on the protection mechanism and optimized control technology in a platoon. Its features include the operation of multiple trains with consistent speed and interval, and the same concept as VC.

CRRC (China Railway Signal & Communication Corporation) is also carrying out research on VC. It is mainly for the demand of flexible coupling in China's trunk railway and intercity railway. The capacity under different coupling modes is analyzed [24], [25], [56].

In March 2020, China Urban Rail Transit Association issued "The Outlines of Smart Urban Rail Development" [57], which includes the technology on coordinated train formation operation and virtual formation. Under the guidance of this program, rail transit manufacturers are carrying out technical research and develope relevant products in response to the demand for urban rail transit to improve the traffic capacity [58].

In general, some critical indicators are proposed through these projects.

(A) The positioning accuracy of the train should be better than $1m$, and the perceived continuity shall not be less than 99%. The prediction accuracy of vehicle traction, braking force and braking distance is more than 99%, with the allowable error being $\pm1\%$.

(B) The wireless communication bandwidth between nodes in a tunnel should not be less than $50Mbps$, the delay shall be less than $10ms$, and the communication distance should not be less than $500m$ in NLOS (Non line of sight) communication.

(C) The tracking distance of metro train formation (three or more trains) at the speed of $200km/h$ is $80m$, and the difference of arrival time of all trains in the formation is less than $3s$.

(D) The automatic train protection function meets the requirements of SIL-4, and the minimum dynamic tracking interval should be reduced to $80meters$ when trains run at $80km/h$.

## III. SCENARIO-BASED ANALYSIS OF VC OPERATION

By reviewing these projects and related research, we can see that, under VC mode train will go through three stages: coupling, running with VC operation and decoupling from the VCTS. Combined with the current high-speed train operation progress, the VC mode refers to a progress that the train departs from the station and arrives at the destination, the whole progress should include five general scenarios: train departure, train coupling, run in VC, train decoupling and stop at station and two emergency scenarios: emergency brake when the first train receive emergency braking signal, emergency brake when a train receives emergency braking signal except for the first train. In order to further study the formation operation process, the scenario-based analysis method is used to analyze the VC operation process.

When running in VC mode, the train formation has the characteristics of T2T communication, and with the same speed for trains and the same interval between trains. So, we select the status of train communication (whether interrupted or not), train speed (speed difference) and position (space/interval difference) as system state parameters. We use these state parameters as the conditions for making a transition from one scenario to another. In the following, we introduce the general scenarios for normal operation and for emergency operation, respectively.

### A. GENERAL SCENARIOS (GS)
#### 1) GS-1 TRAIN DEPARTURE

After departing from the platform, a train could share its speed, location, destination, train diagram and other information with the trains running immediately in front on the same section and the trains that will follow it into the same section through T2T communication. Based on this information, it can be judged whether it has the conditions of VC operation. When the conditions are met, each train will start to make a formation. The conditions include:

(A) Check the timetable if the train is planned to operate in VC mode.

(B) Check if the distance between the front and rear trains is enough or not for VC operation. Trains should be coupled within the set space range (such as relative distance is less than the specified value). The space range should consider the relative position of trains, the ability and the efficiency of VC operation. For urban rail transit, it could be set as $100m$ and for high-speed railway could be set as $5km$.

#### 2) GS-2 TRAIN COUPLING

After the formation conditions are confirmed, the formation process begins. In the process of making a formation, each train is coordinated and controlled to avoid collision. The conditions for completing the process of making a formation are:

(A) T2T communication remains active.

(B) The speed of each train tends to be consistent with the expected speed of formation, and slight deviation is allowed. The deviation value should be less than one specified value, which needs further study.

(C) The distance headway intervals between adjacent trains tend to be consistent with the expected distance headway interval, and slight deviation is allowed. The deviation value should be less than a specified value. The range of specified values remains to be further studied.

It is worth noting that we did not consider a special case of joining the formation: when the train departs, there is already a train formation running. In this scenario, according to the location of the train joining the formation, there are many strategies for a train to join the formation. It can be used as the head train to join the formation, or in the middle or
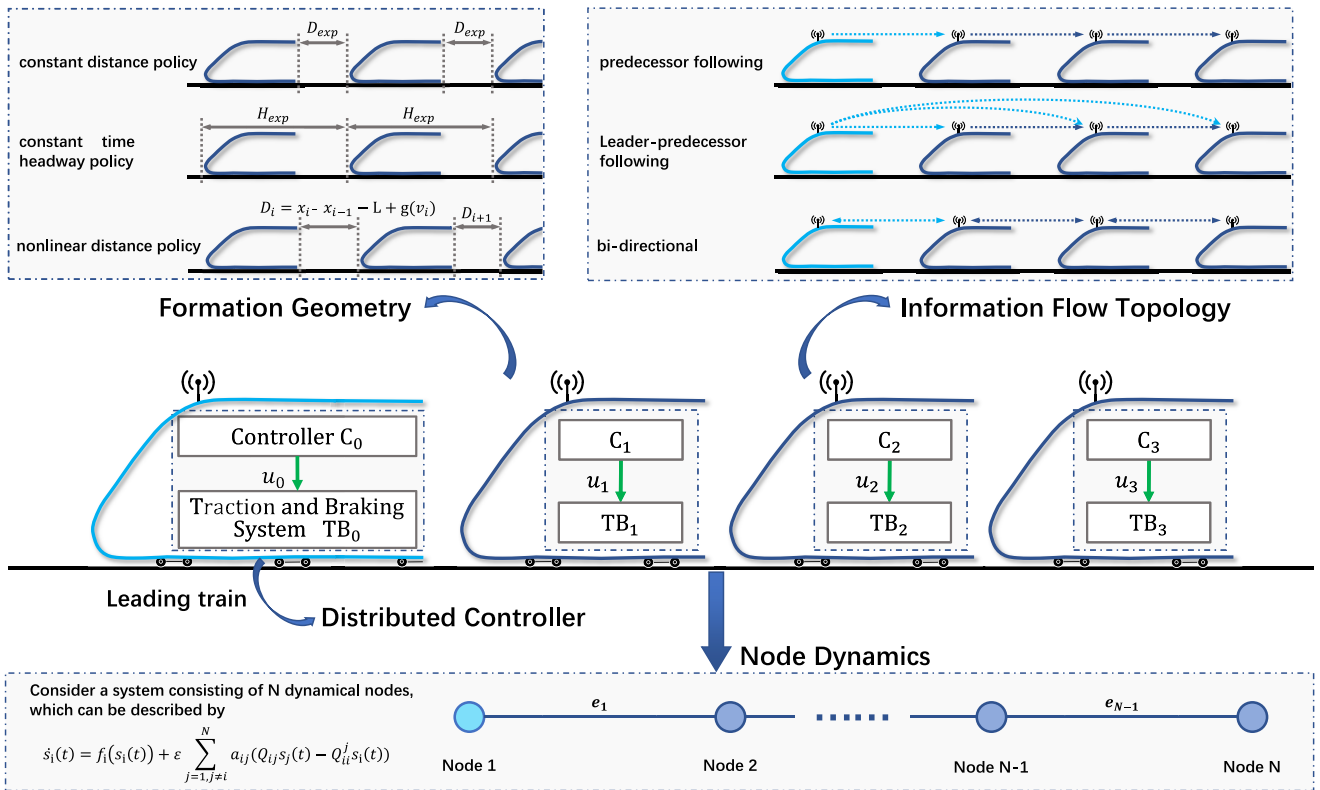
**FIGURE 4.** Four major components of a platoon. (1) node dynamics, where $s_i$ is the state variable of node $i$, $f_i$ donates the local dynamics of node $i$, $\varepsilon > 0$ is coupling strength, $a_{ij}$ is the outer coupling matrix, $Q$ is inner matrix. (2) information flow topology. (3) distributed controller, where $u_i$ is the control signal for $i - th$ train, $C_i$ denotes the controller, and $TB_i$ denotes the traction and braking system. (4) formation geometry, where $D_{exp}$ is the expected distance, $H_{exp}$ is the expected time headway, $x_i$ and $v_i$ are the position and velocity of train $i$, $g(v_i)$ is a nonlinear function of train speed.

at the end of the formation. The corresponding operation control methods need to be studied but are not included in this paper. The merge mode defined in [20] is a basic case of train coupling.

### 3) GS-3 RUN IN VC

During the normal operation in VC mode, the special control methods should be designed for some special scenes, such as temporary speed limit, poor T2T communication and steep track. The objective of these control methods is to avoid unintentional decoupling and ensure smooth operation.

The conditions of entering the speed limit section are as follows: the speed limit drops/rises within a certain distance ahead. Due to the influence of the speed limit, it will cause the fluctuation of formation speed. Whether the amplitude of this fluctuation decreases or increases in the process of transmitting backward along the queue, resulting in the decoupling of VCTS needs to be studied.

The conditions of entering the poor communication section are: the T2T communication delay is greater than a certain value/or the packet loss rate is greater than a certain value, which needs to be studied.

When the formation trains approach the junction of the station ahead, they enter the stage of decoupling. The distance from the junction shall be related to the operation

speed of the formation trains, etc., and the specific value remains to be studied.

Other scenarios exist that could cause unintentional decoupling. For example, during a temporary speed limit, a feedback control mechanism should be designed to avoid unintentional decoupling [59].

Once the formation is made, trains run in VC mode. Referring to the related literature of vehicle formation [60], [61], in theory, the formation can be divided according to the characteristics of node dynamics, information flow topology, distributed controller and formation geometry. Fig. 4 shows the framework of a platoon of four trains. The following characteristics can depict a formation effectively:

(A) Node Dynamics (ND): The ND component denotes the train longitudinal dynamics. The train dynamics can be classified into linear and nonlinear models. The nonlinear dynamic model is closer to reality and more commonly used.

(B) Information Flow Topology (IFT): The IFT component describes how trains exchange information with others. The commonly used topologies include predecessor following (PF), leader-predecessor following (LPF), and bi-directional (BD). Fig. 4 shows these three methods, with different colors representing the information transmission of different trains,

where bright blue indicates the leading train and dark blue indicates the following trains. The arrow indicates the direction of information transmission. Among them, the LPF and BD are more suitable for the railway.

(C) Distributed Controller (DC): The DC component describes the controller of the platoon system for achieving control objectives, such as linear controller, feedback controller, and optimal controller.

(D) Formation Geometry (FG): The FG component denotes the desired inter-vehicle distance of the platoon system. The desired distance is allowed to change within a certain range. So, it is called range policy in many studies. The common policies include constant distance policy, constant time headway policy, and nonlinear distance policy.

### 4) GS-4 TRAIN DECOUPLING

The main task of train decoupling is to adjust the tracking interval between trains, which should be larger than the time for operating the switch in junction area and satisfy the arrival time specified in the timetable. The decoupling shall be started before entering the junction area. The formation is disbanded when all trains obtain movement authority meeting the safety protection conditions. Here, we can obtain the following conditions for judging if the decoupling is completed:

(A) Each train has its movement authority.

(B) This movement authority meets the safety protection conditions.

Here, we do not discuss the special case where the train leaves the formation while the other trains keep the formation running. This case is similar to the special case of joining the formation, which is complex and will not be discussed here. The separation mode defined in [20] is a basic case of Train Decoupling.

### 5) GS-5 STOP AT STATION

After the train is decoupled from the formation, it will enter the corresponding track and stop steadily according to the stop information specified in the timetable. So far, the train has finished its service under VC mode operation.

### B. EMERGENCY SCENARIOS (ES)

During regular operation in the above general scenarios, if a train exceeds the speed limit in a formation, the service braking should be applied to that train first and coordinated control with service braking for other trains in this. The emergency scenarios are activated if the train still exceeds the emergency braking speed limit. These include "Emergency brake when the first train receives emergency braking signal" and "Emergency brake when a train receives emergency braking signal except for the first train."

### 1) ES-1 EMERGENCY BRAKE WHEN THE FIRST TRAIN RECEIVES EMERGENCY BRAKING SIGNAL

Firstly, trains are coupling, running in VC mode, or decoupling. Once the first train receives the emergency braking command, all trains in the formation will start emergency braking immediately to ensure safety. Then, different braking strategies are implemented according to where the train is in the formation.

The train emergency braking effect is not only related to its own braking performance, track conditions such as slippery, weather such as windy, will also affect the braking effect, so it is necessary to assess and reduce the risk of collision.

If the train is the first train, the following strategy will be implemented:

(A) The train will judge whether it can stop in front of the dangerous point. If yes, continuously apply the maximum brake until it stops. If not, go to step (B).

(B) Once the train judge it cannot stop in front of the dangerous point, it informs other trains in the formation and continuously applies the maximum brake until it stops.

(C) Judge whether the leader train continues to operate, and if it continues to operate, return to step (A).

Or, if the train is not the first train, a different strategy will be implemented as follows:

(A) The train assesses the risk of collision, according to the braking performance information in real time. Since the formation may be a heterogeneous queue, the braking distance of each train is different. To reduce the risk of collision, the best strategy is to minimize the speed difference between the adjacent trains at the time of the collision.

(B) The train adjusts its braking force according to the above strategy until it stops.

(C) If the train is still running, return to step (A).

Emergency braking is not expected to be used frequently. This is because that, as the distance between trains in the formation is shortened, the use of emergency braking may result in a distance between adjacent trains less than the safety distance or even a collision and train derailment. Therefore, emergency braking should be used with caution, and existing academic studies and projects of VC on this aspect are relatively few. Research in this area should be strengthened.

In an emergency situation, all trains in the fleet start braking with their maximum braking force. If the braking performance of the following train is weaker than the leading train, in order to avoid collisions between trains in the fleet, we discuss them in 3 cases:

(A) When forming a VCTS, be sure to confirm that the maximum braking force of the following train is not less than the leading train.

(B) In VC operation, if a train is found to lose part of its braking performance, immediately issue a warning and organize decoupling.

(C) If the loss of braking performance of a train is only discovered during emergency braking, the collision risk is immediately assessed, and generate a cooperative control method with the object of minimizing the collision risk to minimize the probability of collision of trains in the formation.

### 2) ES-2 EMERGENCY BRAKE WHEN A TRAIN RECEIVES EMERGENCY BRAKING SIGNAL EXCEPT FOR THE FIRST TRAIN

Once a train except for the first train receives an emergency braking command during it is coupling, running in VC mode, or decoupling, different braking strategies are implemented according to where the train is at in the formation.

If the train is at the tail of the formation, it brakes following the rules for emergency braking This is similar to the rules specified in the signaling system/train control system. The other trains will continue to run as a formation. A special case is where there is only one train after the tail train brakes. This train will run as a single train.

If the train is in the middle of the formation, the trains at its front take this condition as the tail train brakes, and operate as specified in the scenario when the tail train receives an emergency braking command. For the trains at their back, they will stop as specified in scenario ES-1.

### C. THE WHOLE PROCESS OF OPERATION WITHIN VC MODE

Through the above scenario-based analysis, we designed five general scenarios: train departure, train coupling, run in VC, train decoupling and stop at station, and two emergency scenarios, including "Emergency brake when the first train receives emergency braking signal" and "Emergency brake when a train receives emergency braking signal except for the first train." These five scenarios together cover the whole process of operation in VC mode. Following the state flow diagram of [16] developed for CTCS (Chinese Train Control System) in China, we present a state flow diagram for VC operation in Fig. 5.

### D. THE ARCHITECTURE OF VC OPERATION CONTROLLER

The architecture of VC operation controller has two general types (see in Fig. 6). One is a centralized controller and the other is distributed controller.

The centralized train control architecture is more complex. The controller needs to control all trains in the VCTS simultaneously and superimposed on the signaling system. In practice, the centralized control mode needs high costs. It is necessary not only to equip necessary on-board equipment, including speed sensors and radar, but also to establish communication links between each train in the VCTS and the Centralized Traffic Control (CTC), and CTC is needed to implement the control law. Completing the optimization problem of multiple trains in the whole system, it will bring a great computational burden.

The distributed train control architectures are relatively simple to implement. The preceding train follows the signaling system implemented in the line (e.g., CBTC), while the following train only makes decisions based on the information transmitted from the preceding train [7]. Each train needs only on-board sensors to sense its position relative to the preceding train and to receive data such as distance and speed information and braking demand data transmitted from the preceding train. That is, each train has its own on-board controller and needs only T2T communication and data from other on-board sensors. Through the distributed controller architecture, the amount of calculation can be dispersed on each device to save computing time, while the centralized control calculation consumes a longer time.

## IV. PERFORMANCE INDICATORS FOR VC OPERATION

There have been several methods proposed in the existing research on the performance of VC. These studies can be classified in terms of different academic point of view they address: capability analysis, string stability, and speed convergence. Here, the representative and feasible ones from these indicators are selected and sorted out systematically to analyze the effectiveness of the operation in VC. We divide the selected indicators into four Performance Indicator (PI) categories. They are general index, index for train coupling, index for running in VC and index for train decoupling.

### A. GENERAL INDICATORS

In the whole process of operation in VC mode, no matter what stage the train formation is currently in, some indices need to be calculated and analyzed, and they are classified as general indicators.

• The Expected Time Headway

It refers to the expected time headway between trains in the virtually coupled train formation. It can be used to calculate the number of trains to pass through per unit time.

$$PI_{01} \quad H_{\exp} = H^{1,2} = \cdots = H^{n-1,n}, \tag{6}$$

where $n$ stands for the number of trains in the VCTS.

• The Expected Distance Headway

It refers to the expected distance interval between trains in the virtually coupled train formation. It is used to calculate the number of trains that could run in a given section. These 2 indicators can evaluate the efficiency of VC operation in time and space dimension respectively.

$$PI_{02} \quad D_{\exp} = D^{1,2} = \cdots = D^{n-1,n}, \tag{7}$$

where $n$ stands for the number of trains in the VCTS.

• Difference from Safety Protection Speed

It refers to the difference between the current train speed ($V^i$) and the ATP safety protection speed ($V_{safe}$). It is useful to observe how far is the train speed from a dangerous state.

$$PI_{03} \quad \Delta V_{\text{safe}}^i = V^i - V_{\text{safe}}, \tag{8}$$
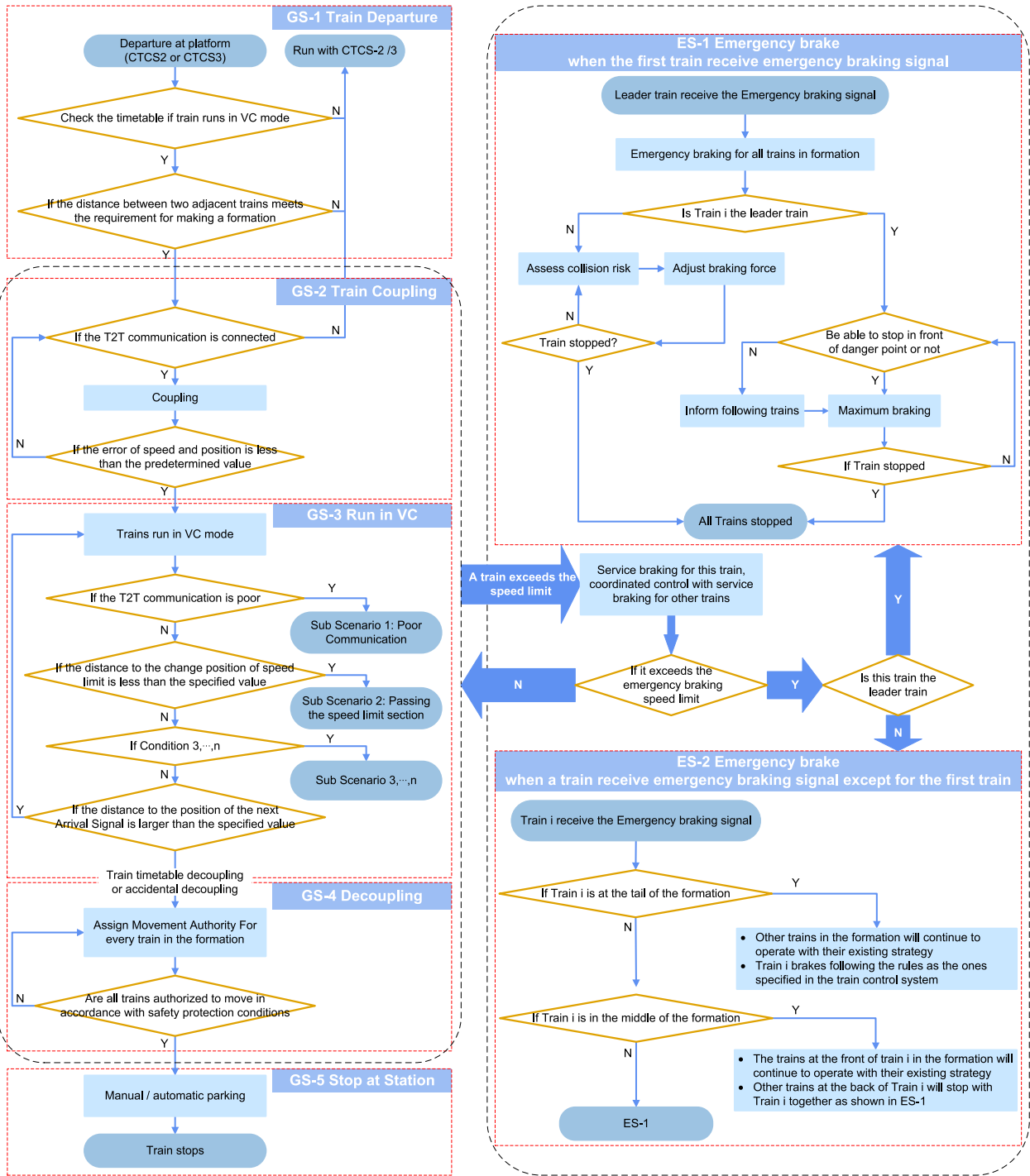
where $i = 1, 2, \ldots, n$.

**FIGURE 5.** The typical flow chart of the whole VC operation.

- Speed Deviation of Trains

It refers to the difference between the current train speed ($V^i$) and the expected speed ($V_{exp}$) of the train formation. It is useful to observe the fluctuation of how far is the train speed from the expected state for VC operation.

$$PI_{04} \quad \Delta V^i = V^i - V_{exp}, \tag{9}$$

where $i = 1, 2, \ldots, n$.

In principle, the relationship between the difference from safety protection speed and the speed deviation of trains shall be $\Delta V^i < \Delta V^i_{safe}$, otherwise protective measures will be triggered during the operation of VCTS.

- Maximum Speed Deviation

It refers to the maximum difference between the current speed ($V^i$) of the train and the expected speed ($V_{exp}$) of the train formation. This indicator is intended to reflect the
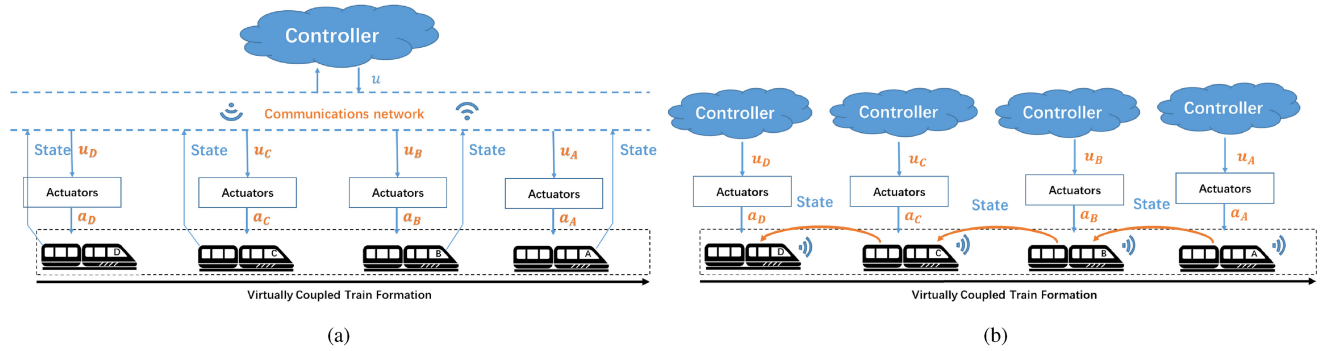
**FIGURE 6.** The general architecture of VC operation controller. (a)Centralized controller. (b)Distributed controller, where $u_i$ is the control commands, and the $a_i$ is the control law.

limit case of difference between current speed of the train and the expected speed for VC operation. The lower the maximum speed deviation, the better performance for the train fleet controller.

$$PI_{05} \quad \Delta V_{\max}^i = \max\left\{\Delta V^i\right\} = \max\left\{V^i - V_{\exp}\right\}, \quad (10)$$

where $i = 1, 2, \ldots, n$.

### B. INDICATORS FOR TRAIN COUPLING
When entering the coupling mode, the rapidity and control effect of the process has become the focus of attention. The dispatcher is responsible for scheduling the coupling sections and the controller designer shall focus on this category of indicators.

- Time for Train Coupling

It refers to the time from trains receiving the command of "Coupling Start" ($T_{CS}$) to the moment of "Coupling Complete" ($T_{CC}$). The moment of "Coupling Complete" is the time when the deviation of speed and position is less than the predetermined value. We expect the time for train coupling is as short as possible. Obviously, it is related to the initial state and objective state, such as the initial speed and position of trains. The comparison could be made if any cases have the same initial state and objective state by using this indicator.

$$PI_{06} \quad T_{\text{coupling}} = T_{CC} - T_{CS} \quad (11)$$

- Distance for Train Coupling

It refers to the distance ($S_{TC}^i$) traveled for each train in the virtually-coupled train formation from receiving the command of "Coupling Start" ($S_{CS}^i$) to the position of "Coupling Complete" ($S_{CC}^i$). During the coupling process, the travel distance of each train may be different. Due to the uncertainty of the position of the following train, the operation distance of the last train is selected. We expect that the distance for train coupling is as short as possible because the track limits resources in the railway. If fewer tracks are occupied for train coupling, other trains could use more tracks.

$$PI_{07} \quad S_{\text{coupling}} = S_{TC}^N = S_{CC}^N - S_{CS}^N, \quad (12)$$

where $N$ stands for the last train in the VCTS.

- Deviation of Distance Headway

It refers to the difference between the current train time headway ($H_{\text{coupling}}^{i,i+1}$) and the expected time headway ($H_{\exp\_coupling}$) during the coupling process. It is useful to observe the fluctuation of how far the time headway from the expected state during the formation process.

$$PI_{08} \quad \Delta H_{\text{coupling}}^{i,i+1} = H_{\text{coupling}}^{i,i+1} - H_{\exp\_coupling}, \quad (13)$$

where $i = 1, 2, \ldots, n - 1$.

- Deviation of Distance Headway

It refers to the difference between the current train distance ($D_{\text{coupling}}^{i,i+1}$) and the expected distance headway ($D_{\exp\_coupling}$) during the formation process. It is helpful to observe the fluctuation of the difference between the distance of adjacent trains from the expected distance headway during the formation process.

$$PI_{09} \quad \Delta D_{\text{coupling}}^{i,i+1} = D_{\text{coupling}}^{i,i+1} - D_{\exp\_coupling}, \quad (14)$$

where $i = 1, 2, \ldots, n - 1$.

### C. INDICATORS FOR RUNNING IN VC
After the train formation, except for the general indicators, it should also focus on the control effect. Firstly, the deviation and overshoot between each train and the expected speed and distance in the formation are evaluated from absolute error and relative error. Secondly, unexpected deconstruction may be caused by external interference, so it is necessary to evaluate the stability of the formation. This category of indicators needs more attention from controller designers.

- Maximum speed overshoot percentage

It refers to the maximum percentage of speed deviation ($\Delta V_{VC}^i$) to the expected speed ($V_{exp\_VC}$). For example, we will think it's worse when $\Delta V_{VC}^i = 1m/s$ for train fleet runs at $10m/s$ than it runs at $100m/s$. This is an important indicator to evaluate the control performance.

$$PI_{10} \quad \sigma V_{\max\_VC}^i = \max\left\{\frac{\Delta V_{VC}^i}{V_{\exp\_VC}} \times 100\%\right\}, \quad (15)$$

where $i = 1, 2, \ldots, n$.

- Maximum Distance Headway Deviation

This indicator can be divided into two aspects respectively. One is for the absolute deviation. It refers to the maximum difference between the current distance headway ($D_{VC}^{i,i+1}$) of trains and the expected distance headway ($D_{exp\_VC}$) of the train formation during the operation in the VC process. This indicator is intended to reflect a limit of train distance headway fluctuation during the VC process.

$$PI_{11} \quad \Delta D_{\max\_VC}^i = \max\left\{ D_{VC}^{i,i+1} - D_{exp\_VC} \right\}, \quad (16)$$

where $i = 1, 2, \ldots, n - 1$.

The other is for the relative deviation. It refers to the maximum percentage of distance deviation ($\Delta D_{VC}^{i,i+1}$) to the expected distance headway ($D_{exp\_VC}$). When a fleet accelerates or decelerates from speed A to speed B, the distance headway interval between successive trains increases or decreases. The maximum distance headway overshoot percentage should be as low as possible.

$$PI_{11} \quad \sigma D_{\max\_VC}^i = \max\left\{ \frac{\Delta D_{VC}^{i,i+1}}{D_{exp\_VC}} \times 100\% \right\}, \quad (17)$$

where $i = 1, 2, \ldots, n - 1$.

- Stability of Train Formation

It refers to designated signals such as speed deviation and interval deviation that will not continue to expand backward along with the train formation. This indicator is intended to reflect whether the train formation is stable. And it is an important indicator to evaluate the effect of the control algorithm.

$PI_{12}$ For a system of a VCTS platoon with length N, $l_\infty$ string stable if and only if

$$\|\Delta x_{i+1}\|_{l_\infty} \le \|\Delta x_i\|_{l_\infty} \text{ for } \forall i \in \{1, 2, \ldots, N-1\}, (18)$$

where $x_i$ donates the signal of interest, e.g., disturbance in velocity or gap, $\|\Delta S_i\|$ denotes the $l_\infty$ norm of $\Delta x_i(t)$, given as $\|\Delta x_i\|_{l_\infty} = \sup(\Delta x_i(t))$ for $t \in (0, \infty)$.

### D. INDICATORS FOR TRAIN DECOUPLING

When entering the decoupling model, the rapidity and control effect of the process has become the focus of attention. The dispatcher who is responsible for the scheduling of the decoupling sections and the controller designer shall focus on this category of indicators.

- Time for Train Decoupling

It refers to the time ($T_{DS}$) from trains receiving the command of "Decoupling Start" to the moment ($T_{DC}$) of "Decoupling Complete." The moment of "Decoupling Complete" is each train has its movement authority and this movement authority meets the safety protection conditions. The role of this indicator is the same as PI_06 for coupling.

$$PI_{13} \quad T_{decoupling} = T_{DC} - T_{DS} \quad (19)$$

- Distance for Train Decoupling

It refers to the distance ($S_{DS}$) traveled for each train receiving the command of "Decoupling Start" to the position ($S_{DC}$) of "Decoupling Complete." The role of this indicator is the same as PI_07 for coupling, and it is useful to evaluate the efficiency of the train decoupling process.

$$PI_{14} \quad S_{decoupling} = S_{DC} - S_{DS} \quad (20)$$

- Deviation of Train Time Headway

It refers to the difference between the current train time headway ($H_{decoupling}^{i,i+1}$) and the expected time headway ($H_{exp\_decoupling}$) during the decoupling process. The role of this indicator is the same as PI_08 for coupling.

$$PI_{15} \quad \Delta H_{decoupling}^{i,i+1} = H_{decoupling}^{i,i+1} - H_{exp\_decoupling} \quad (21)$$

- Deviation of Distance Headway

It refers to the difference between the current train distance ($D_{decoupling}^{i,i+1}$) and the expected distance headway ($I_{exp\_decoupling}$) during the decoupling process. The role of this indicator is the same as PI_09 for coupling and could also observe the control algorithm's effect with PI_16.

$$PI_{16} \quad \Delta D_{decoupling}^{i,i+1} = D_{decoupling}^{i,i+1} - D_{exp\_decoupling}, \quad (22)$$

To summarize, the structure of the proposed set of PIs is given in Fig. 7. It consists of a list of seventeen PIs which cover the whole operation process in VC and its single stage. It should be noted that Fig. 7 groups the indicators by colors because these indicators are used for evaluating efficiency, safety and control performance, respectively.

## V. CONCLUSION

In the paper, we present a comprehensive review of VC, a new technology that is designed to improve transportation capacity by compressing train tracking time headway in railway. In the automatic block section, the minimum headway time between two rear trains running in the same direction, it is the largest among the train tracking headway time, the train departure tracking headway time, the train arrival tracking headway time and the train passing tracking headway time. Firstly, this paper reviews the existing theoretical research on train formation operation control, which is divided into four categories: train following, feedback control, optimal control and computational intelligent method. Secondly, by reviewing the related projects in Europe and China, based on the scenario analysis method, five basic scenarios and two emergency scenarios in the whole process of VC operation are sorted out. Then, we propose an original, complete list of PIs by summarizing the previous study in VC. It consists of a hierarchical list of 16 indicators divided into two levels: 5 general performance indicators to evaluate the performance of the whole operation process in VC. And 11 other performance indicators to evaluate the performance of every single stage of VC operation, including train coupling, running in VC and train decoupling. Additionally, the
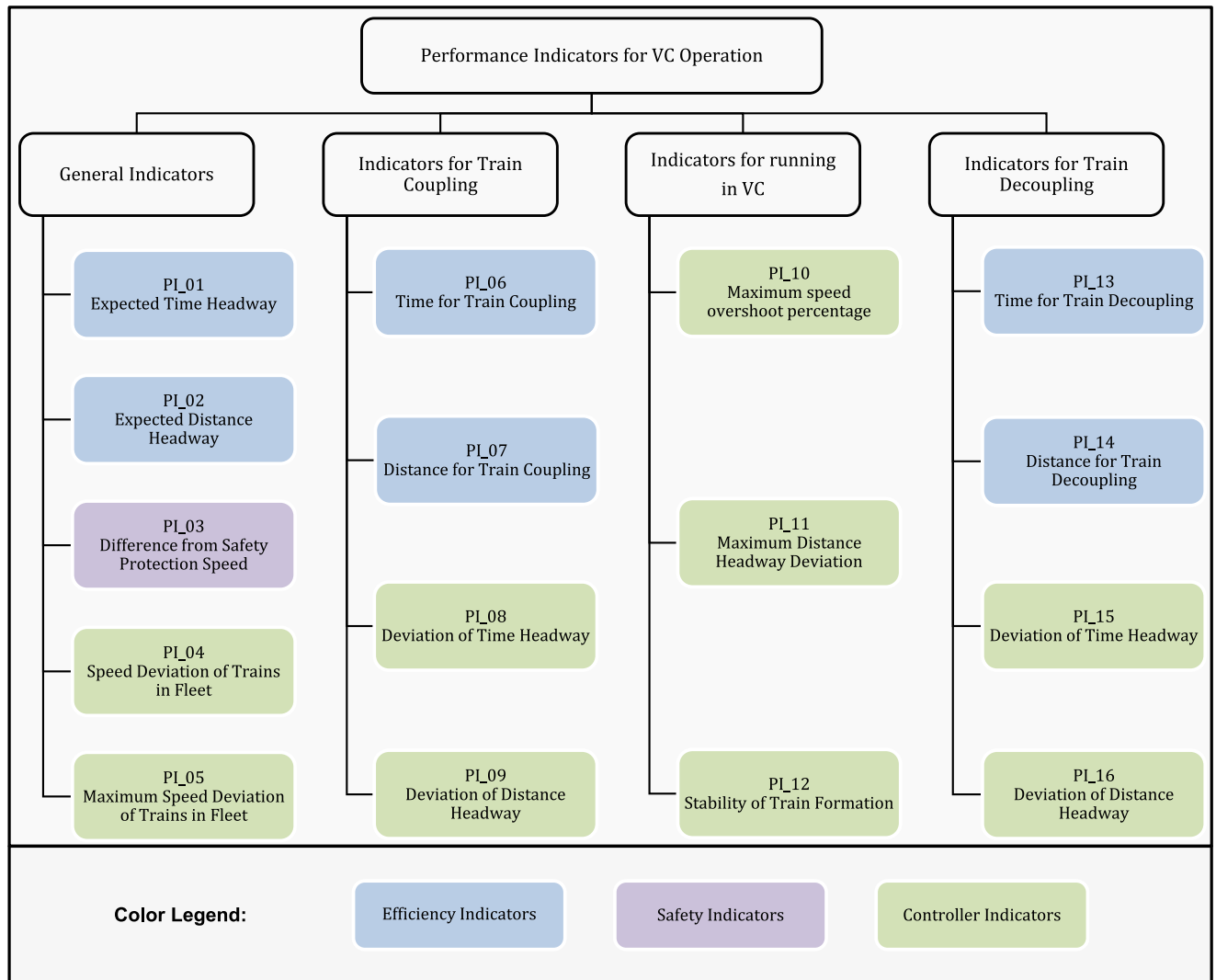
**FIGURE 7.** Structure of the proposed set of PIs.

paper gives a brief insight into VC operation by providing an adequate context to understand the proposed PIs.

For future work, current research on VC train operation mainly focuses on the operation of trains in sections, and few studies involve complex operation scenarios such as trains of different tracks coupling into the same track for virtually coupled operation, or decoupling through the junction. In such complex scenarios, the coupling and decoupling control of VCTS can be combined with the optimal management of train operation scheduling to achieve efficient virtually coupled train operation control and scheduling. Secondly, T2T communication is an important technology for VC, the parameters considered in the current research are relatively simple. As an important technology of VC, T2T communication should be fully combined with an automatic operation system to analyze the control requirements under different communication conditions in actual operation. In the future, we can compare the existing communication system with the communication conditions needed for train formation operation, and optimize the train control method for virtual

formation operation on this basis [53], [62]. Moreover, in an emergency braking situation, the trains in the formation start braking with maximum braking force. If the following train has weaker braking performance than the preceding train, how to avoid collision of trains in the formation is a question worth thinking about. We have briefly described some of our current ideas in Section III-B, and the issue should be studied in more detail in the future.

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## REFERENCES

[1] B. Han, W. Dai, and H. Zhang, "Statistics and analysis of urban rail transit operation in the world," *Urban Rapid Rail Transit*, vol. 32, no. 1, pp. 9–14, 2019.

[2] U. Bock and G. Bikker, "Design and development of a future freight train concept–'Virtually coupled train formations'" *IFAC Proc. Vol.*, vol. 33, no. 9, pp. 395–400, Jun. 2000.

[3] A. D. de Rivera, C. T. Dick, and M. M. Parkes, "Balancing the service benefits and mainline delay disbenefits of operating shorter freight trains," *Transp. Res. Rec.*, vol. 2675, no. 10, pp. 303–316, May 2021.

[4] C. Williams, "The next ETCS level?" in *Proc. IEEE Int. Conf. Intell. Rail Transp. (ICIRT)*, Birmingham, U.K., Aug. 2016, pp. 75–79.

[5] J. Lin, J. Dang, and Y. Min, "NGCTCS: Next-generation chinese train control system," *J. Eng. Sci. Technol. Rev.*, vol. 9, pp. 122–130, Nov. 2016.

[6] T. Song, T. Tang, J. Xun, H. Wang, and S. Gao, "Train headway adjustment using potential function based on multi-agent formation control," in *Proc. Int. Conf. Intell. Rail Transp. (ICIRT)*, 2018, pp. 1–5.

[7] J. Felez, Y. Kim, and F. Borrelli, "A model predictive control approach for virtual coupling in railways," *IEEE Trans. Intell. Transp. Syst.*, vol. 20, no. 7, pp. 2728–2739, Jul. 2019.

[8] B. Ning, "Absolute braking and relative distance braking—Train operation control modes in moving block systems," in *Proc. WIT Trans. Built Environ.*, vol. 37, Aug. 1998, pp. 991–1000.

[9] R. Liu, "Simulation model of speed control for the moving-block systems under ERTMS level 3," in *Proc. IEEE Int. Conf. Intell. Rail Transp. (ICIRT)*, Birmingham, U.K., 2016, pp. 322–327.

[10] M. Brackstone and M. McDonald, "Car-following: A historical review," *Transp. Res. F, Traffic Psychol. Behav.*, vol. 2, no. 4, pp. 181–196, 1999.

[11] M. Wang, W. Daamen, S. P. Hoogendoorn, and B. van Arem, "Rolling horizon control framework for driver assistance systems. Part I: Mathematical formulation and non-cooperative systems," *Transp. Res. C, Emerg. Technol*, vol. 40, pp. 271–289, Mar. 2014.

[12] M. Wang, W. Daamen, S. P. Hoogendoorn, and B. van Arem, "Rolling horizon control framework for driver assistance systems. Part II: Cooperative sensing and cooperative control," *Transp. Res. C, Emerg. Technol.*, vol. 40, pp. 290–311, Mar. 2014.

[13] P. G. Gipps, "A behavioural car-following model for computer simulation," *Transp. Res. B, Methodol.*, vol. 15, no. 2, pp. 105–111, Apr. 1981.

[14] J. Xun, M. Chen, B. Ning, T. Tang, and H. Dong, "Train tracking performance measurement under virtual coupling in subway," *J. Beijing Jiaotong Univ.*, vol. 43, no. 1, pp. 96–103, Feb. 2019.

[15] E. Quaglietta and R. M. P. Goverde, "Exploring virtual coupling: Operational principles and analysis," in *Proc. 10th ASPECT Conf. Inst. Railway Signalling Eng.*, 2019, pp. 1–13.

[16] E. Quaglietta, M. Wang, and R. M. P. Goverde, "A multi-state train-following model for the analysis of virtual coupling railway operations," *J. Rail Transp. Plan. Manag.*, vol. 15, Sep. 2020, Art. no. 100195.

[17] E. Quaglietta, P. Spartalis, M. Wang, R. M. P. Goverde, and P. V. Koningsbruggen, "Modelling and analysis of virtual coupling with dynamic safety margin considering risk factors in railway operations," *J. Rail Transport Plan. Manag.*, vol. 22, Jun. 2022, Art. no. 100313.

[18] C. Di Meo, M. Di Vaio, F. Flammini, R. Nardone, S. Santini, and V. Vittorini, "ERTMS/ETCS virtual coupling: Proof of concept and numerical analysis," *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 6, pp. 2545–2556, Jun. 2020.

[19] Q. Zhao and H. Wang, "A multi-train cooperative control method of urban railway transportation based on artificial potential field," in *Proc. Chin. Autom. Congr. (CAC)*, 2019, pp. 1350–1355.

[20] J. Park, B.-H. Lee, and Y. Eun, "Virtual coupling of railway vehicles: Gap reference for merge and separation, robust control, and position measurement," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 2, pp. 1085–1096, Feb. 2022.

[21] B. Wang, D. Yang, X. Zhang, and X. Jia, "Constraint-force driven control design for rail vehicle virtual coupling," *J. Vib. Control*, vol. 28, nos. 5–6, pp. 551–563, 2022.

[22] H. Dong, S. Gao, and B. Ning, "Cooperative control synthesis and stability analysis of multiple trains under moving signaling systems," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 10, pp. 2730–2738, Oct. 2016.

[23] S. Li, L. Yang, K. Li, and Z. Gao, "Robust sampled-data cruise control scheduling of high speed train," *Transp. Res. C, Emerg. Technol.*, vol. 46, pp. 274–283, Sep. 2014.

[24] L. Liu, P. Wang, W. Wei, Q. Li, and B. Zhang, "Intelligent dispatching and coordinated control method at railway stations for virtually coupled train sets," in *Proc. IEEE Intell. Transp. Syst. Conf. (ITSC)*, Auckland, New Zealand, Oct. 2019, pp. 607–612.

[25] L. Liu, P. Wang, B. Zhang, and W. Wei, "Coordinated control method of virtually coupled train formation based on multi agent system," in *Proc. Int. Conf. Smart Veh. Technol. Transp. Commun. Appl.*, Oct. 2018, pp. 225–233.

[26] K.-C. Chu, "Decentralized control of high-speed vehicular strings," *Transp. Sci.*, vol. 8, no. 4, pp. 361–384, 1974.

[27] D. Q. Mayne, J. B. Rawlings, C. V. Rao, and P. O. M. Scokaert, "Constrained model predictive control: Stability and optimality," *Automatica*, vol. 36, no. 6, pp. 789–814, 2000.

[28] V. Turri, B. Besselink, and K. H. Johansson, "Cooperative look-ahead control for fuel-efficient and safe heavy-duty vehicle platooning," *IEEE Trans. Control Syst. Technol.*, vol. 25, no. 1, pp. 12–28, Jan. 2017.

[29] J. Xun, J. Yin, R. Liu, F. Liu, Y. Zhou, and T. Tang, "Cooperative control of high-speed trains for headway regulation: A self-triggered model predictive control based approach," *Transp. Res. C, Emerg. Technol.*, vol. 102, pp. 106–120, May 2019.

[30] J. She, K. Li, L. Yuan, Y. Zhou, and S. Su, "Cruising control approach for virtually coupled train set based on model predictive control," in *Proc. IEEE 23rd Int. Conf. Intell. Transp. Syst. (ITSC)*, 2020, pp. 1–6.

[31] J. Xun, M. Chen, Y. Liu, and F. Liu, "An overspeed protection mechanism for virtual coupling in railway," *IEEE Access*, vol. 8, pp. 187400–187410, 2020.

[32] M. Chen, J. Xun, and Y. Liu, "A coordinated collision mitigation approach for virtual coupling trains by using model predictive control," in *Proc. IEEE 23rd Int. Conf. Intell. Transp. Syst. (ITSC)*, Rhodes, Greece, 2020, pp. 1–6.

[33] Y. Liu, Y. Zhou, S. Su, J. Xun, and T. Tang, "An analytical optimal control approach for virtually coupled high-speed trains with local and string stability," *Transp. Res. C, Emerg. Technol.*, vol. 125, Apr. 2021, Art. no. 102886.

[34] X. Luo, H. Liu, L. Zhang, and J. Xun, "A model predictive control based inter-station driving strategy for virtual coupling trains in railway system," in *Proc. IEEE Int. Intell. Transp. Syst. Conf. (ITSC)*, 2021, pp. 3927–3932.

[35] Y. Liu, R. Liu, C. Wei, J. Xun, and T. Tang, "Distributed model predictive control strategy for constrained high-speed virtually coupled train set," *IEEE Trans. Veh. Technol.*, vol. 71, no. 1, pp. 171–183, Jan. 2022.

[36] Y. Liu, Y. Zhou, S. Su, J. Xun, and T. Tang, "Control strategy for stable formation of high-speed virtually coupled trains with disturbances and delays," *Comput.-Aided Civil Infrastruct. Eng.*, to be published.

[37] X. Yan, B.-G. Cai, B. Ning, and W. ShangGuan, "Moving horizon optimization of dynamic trajectory planning for high-speed train operation," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 5, pp. 1258–1270, May 2016.

[38] H. Liu, L. Yang, and H. Yang, "Cooperative optimal control of the following operation of high-speed trains," *IEEE Trans. Intell. Transp. Syst.*, vol. 23, no. 10, pp. 17744–17755, Oct. 2022.

[39] Z. Wu, C. Gao, and T. Tang, "A virtually coupled metro train platoon control approach based on model predictive control," *IEEE Access*, vol. 9, pp. 56354–56363, 2021.

[40] G. Javier and F. Fernando, "A comprehensive survey on safe reinforcement learning," *J. Mach. Learn. Res.*, vol. 16, pp. 1437–1480, Aug. 2015.

[41] Z. Marvi and B. Kiumarsi, "Safe reinforcement learning: A control barrier function optimization approach," *Int. J. Robust Nonlinear Control*, vol. 31, pp. 1923–1940, Apr. 2021.

[42] Q. Wang, M. Chai, H. Wang, L. Chen, and J. Lv, "Train operation strategy optimization of virtual coupling: A cooperative game based approach," in *Proc. IEEE Int. Intell. Transp. Syst. Conf. (ITSC)*, 2021, pp. 3933–3938.

[43] H. Su, M. Chai, L. Chen, and J. Lv, "Deep learning-based model predictive control for virtual coupling railways operation," in *Proc. IEEE Int. Intell. Transp. Syst. Conf. (ITSC)*, 2021, pp. 3490–3495.

[44] M. Chai, H. Su, and H. Liu, "Long short-term memory-based model predictive control for virtual coupling in railways," *Wireless Commun. Mobile Comput.*, vol. 2022, Jan. 2022, Art. no. 1859709.

[45] H. Wang et al., "A reinforcement learning empowered cooperative control approach for IIoT-based virtually coupled train sets," *IEEE Trans. Ind. Informat.*, vol. 17, no. 7, pp. 4935–4945, Jul. 2021.

[46] "The rail joint undertaking." Shift2Rail. 2019. [Online]. Available: http://www.shift2rail.org

[47] E. Quaglietta. "Market potential and operational scenarios for virtual coupling." MOVINGRAIL. Jul. 2019. [Online]. Available: https://movingrail.eu/images/Deliverables/D41-MOVINGRAIL_Market-Potential-and-Operational-Scenarios-for-VC-20200707.pdf

[48] J. Goikoetxea, I. Lopez, P. A. Perez, I. Celaya, and O. Sanchez, "Virtual coupling of trains: First implementation and tests," in *Proc. 12th World Congr. Railway Res. (WCRR)*, Tokyo, Japan, 2019.

[49] "IP2 (advanced traffic management and control systems) technical demonstrators." Shift2Rail. 2016. [Online]. Available: https://projects.shift2rail.org/s2r_ip_TD_r.aspx?ip=2&td=aa1f0995-1402-4e7b-a905-49fba1bc6f71

[50] M. Schenker, R. Parise, and J. Goikoetxea, "Concept and performance analysis of virtual coupling for railway vehicles," in *Proc. 3rd SmartRaCon Sci. Seminar*, vol. 38, 2021, pp. 81–91.

[51] I. Mitchell. "Closer running: Is it feasible?" RailUK. May 2016. [Online]. Available: https://www.railuk.com/rail-news/closer-running-is-it feasible

[52] J. E. Pickering, J. Davies, and K. J. Burnham, "Development of model prototype to investigate closer running autonomous train operation: Seamless interchangeability," in *Proc. 23rd Int. Conf. System Theory Control Comput. (ICSTCC)*, 2019, pp. 572–579.

[53] T. Siefkes. "NGT HST ultra-high-speed train set." DLR TRANSPORT. 2020. [Online]. Available: https://verkehrsforschung.dlr.de/en/projects/ngt-hst

[54] H. Song, W. Wu, H. Dong, and E. Schnieder, "Propagation and safety analysis of the train-to-train communication system," *IET Microw. Antennas Propag.*, vol. 13, pp. 2324–2329, Oct. 2019.

[55] P. Gao. "The kick-off meeting for the basic theory and key technology of the integration of high-speed railway operation control and dynamic dispatching was successfully held." Beijing Jiaotong University News. Jan. 2018. [Online]. Available: http://news.bjtu.edu.cn/info/1044/27533.html

[56] Y. Wang, L. Liu, J. Liu, and J. Shi, "Carrying capacity calculation method of regional rail transit line based on flexible train formation," in *Proc. IEEE 23rd Int. Conf. Intell. Transp. Syst. (ITSC)*, Rhodes, Greece, 2020, pp. 1–6.

[57] *The Outlines of Smart Urban Rail Development*, China Assoc. Metros, Beijing, China, 2020.

[58] Q. Zhou, C. Zhang, F. Bao, L. Zhang, and X. Xiao, "The safety braking protection model of virtually coupled train platoon in subway," in *Proc. 10th Inst. Electr. Electron. Eng. Int. Conf. Cyber Technol. Autom. Control Intell. Syst. (CYBER)*, 2020, pp. 401–406.

[59] T. Song, *Research on the Cooperative Operation Control of Formation Trains Passing Through the Speed Limit Sections*, Beijing Jiaotong Univ., Beijing, China, 2020.

[60] S. Feng, Y. Zhang, S. E. Li, Z. Cao, H. X. Liu, and L. Li, "String stability for vehicular platoon control: Definitions and analysis methods," *Annu. Rev. Control*, vol. 47, pp. 81–97, Jan. 2019.

[61] S. E. Li, Y. Zheng, K. Li, and J. Wang, "An overview of vehicular platoon control under the four-component framework," in *Proc. IEEE Intell. Veh. Symp. (IV)*, 2015, pp. 286–291, doi: 10.1109/IVS.2015.7225700.

[62] H. Q. Le, A. Lehner, and S. Sand, "Performance analysis of ITS-G5 for dynamic train coupling application," in *Communication Technologies for Vehicles*. Cham, Switzerland: Springer Int., 2015, pp. 129–140.

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