



(11)

**EP 4 682 019 A1**

(12)

**EUROPEAN PATENT APPLICATION**  
published in accordance with Art. 153(4) EPC

(43) Date of publication:  
**21.01.2026 Bulletin 2026/04**

(51) International Patent Classification (IPC):  
**B61L 27/10** <sup>(2022.01)</sup>

(21) Application number: **23952477.0**

(52) Cooperative Patent Classification (CPC):  
**B61L 27/10**

(22) Date of filing: **18.09.2023**

(86) International application number:  
**PCT/CN2023/119488**

(87) International publication number:  
**WO 2025/059811 (27.03.2025 Gazette 2025/13)**

(84) Designated Contracting States:  
**AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC ME MK MT NL NO PL PT RO RS SE SI SK SM TR**  
Designated Extension States:  
**BA**  
Designated Validation States:  
**KH MA MD TN**

- **HUANG, Qiang**  
Zhuzhou, Hunan 412001 (CN)
- **LI, Cheng**  
Zhuzhou, Hunan 412001 (CN)
- **YUAN, Xiwen**  
Zhuzhou, Hunan 412001 (CN)
- **HUANG, Zhikun**  
Zhuzhou, Hunan 412001 (CN)
- **HE, Chuan**  
Zhuzhou, Hunan 412001 (CN)
- **LUO, Jiaxiang**  
Zhuzhou, Hunan 412001 (CN)

(71) Applicant: **CRRC Zhuzhou Electric Locomotive Research Institute Co., Ltd.**  
Zhuzhou, Hunan 412001 (CN)

(74) Representative: **Lorenz Seidler Gossel Part. mbB**  
Widenmayerstr. 23  
80538 München (DE)

(72) Inventors:

- **FENG, Jianghua**  
Zhuzhou, Hunan 412001 (CN)
- **HU, Yunqing**  
Zhuzhou, Hunan 412001 (CN)

(54) **RAIL TRAIN AND OPERATION PLANNING METHOD AND APPARATUS THEREFOR, DEVICE, AND STORAGE MEDIUM**

(57) A rail train and an operation planning method and apparatus therefor, a device, and a storage medium, relating to the technical field of intelligent driving. The method comprises: acquiring planning information of a train formation; acquiring following situation information of a current train in the train formation; and on the basis of the following situation information and the planning information, using a speed planning model to acquire a local operation curve of the current train, wherein the speed planning model comprises a longitudinal dynamics model, a constraint condition, and an objective

function. In the present invention, an operation state of each following train in the train formation can be planned and generated by using the constructed longitudinal dynamics model of the rail train and the collaboratively planned objective function and constraint condition, so that distributed planning and control of the train formation are realized, the calculation load of a single train can be effectively reduced, and the requirements for real-time performance and safety of communication between trains can also be reduced, thereby reducing the cost of the rail train.

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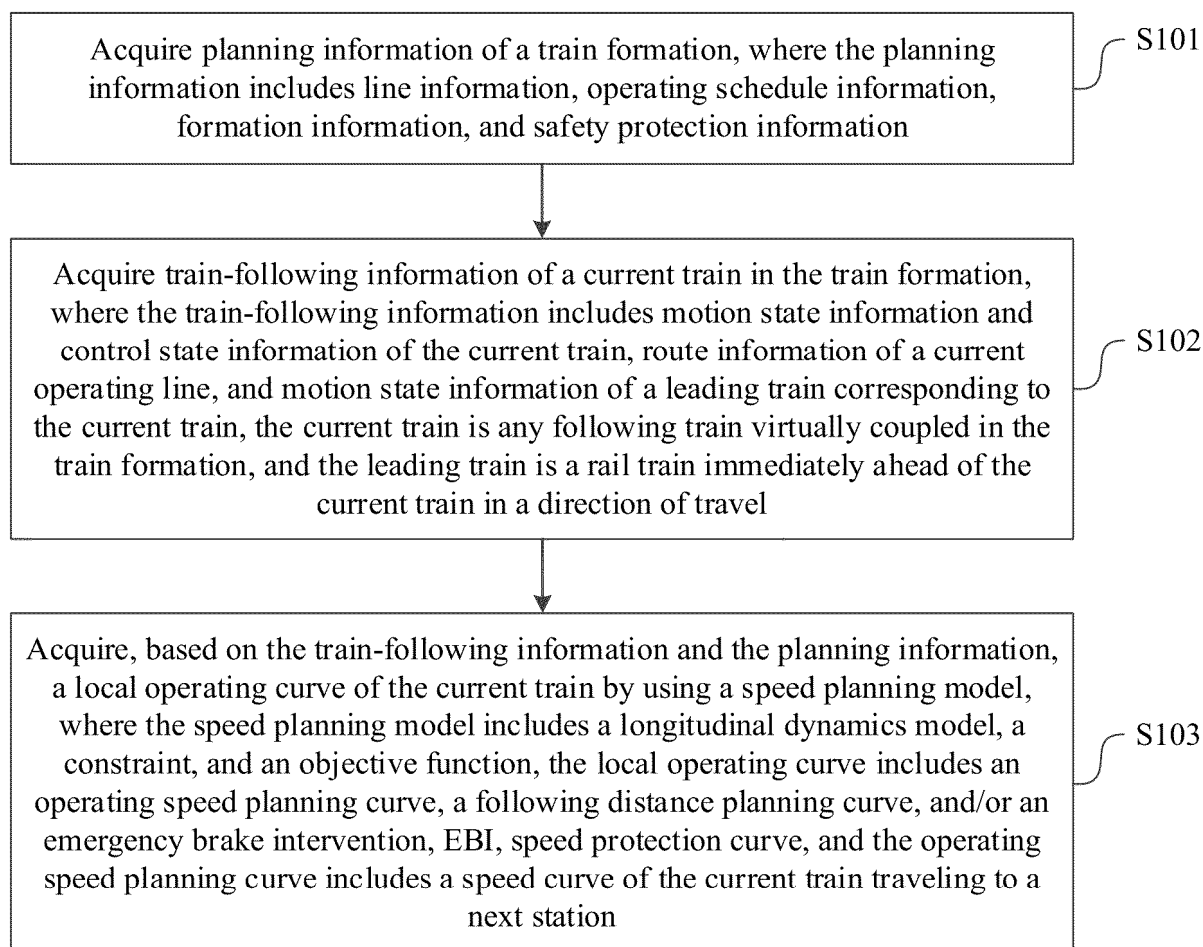


FIG. 1

**Description****FIELD**

- 5 **[0001]** The present disclosure relates to the technical field of intelligent driving, and in particular to a method and an apparatus for planning operation of a rail train, an electronic device, a rail train, and a computer-readable storage medium.

**BACKGROUND**

- 10 **[0002]** To achieve efficient allocation of train transportation capacities, a concept of virtual coupling (VC) emerges. According to this concept, virtual coupling of rail trains (such as autonomous rail rapid transit trains) involves forming a coupled formation with multiple independent rail trains. Within the coupled formation, the rail trains exchange performance and state information of the rail trains via wireless train-to-train communication, enabling close-interval operation similar to operation of mechanically coupled trains by using a collaborative planning and control strategy. After decoupling, each train has its own steering, traction, and braking systems, being capable of operating independently.

- 15 **[0003]** Similar to operation of a single rail train, performance indicators for evaluating operation of a virtually coupled train formation primarily include five items: efficiency, punctuality, stopping accuracy, comfort, and energy efficiency. These five indicators are related each other and constrained each other. To optimize these indicators, within the train formation, planning and control are performed on each independent train based on a single-train constraint and a line constraint, and a leading-train constraint is further taken into consideration for a following train.

- 20 **[0004]** In the related art, collaborative planning and control for the virtually coupled train formation adopt a centralized planning and control solution. However, the centralized planning and control solution requires substantial computational resources and capabilities for each rail train, resulting in a high cost that is in direct proportion to the formation size. Moreover, frequent data exchange between rail trains imposes high requirements on the reliability, real-time performance, and bandwidth of communication. Therefore, at present, there is an urgent need to provide a method for planning operation of the following train in the virtually coupled train formation, enabling distributed planning and control for the train formation, reducing the computational load on each rail train, and reducing requirements on the real-time performance and safety of communication between rail trains.

**SUMMARY**

- 30 **[0005]** The objective of the present disclosure is to provide a method and an apparatus for planning operation of a rail train, an electronic device, a rail train, and a computer-readable storage medium, to plan an operating state of a following train virtually coupled in a train formation, thereby enabling distributed planning and control for the train formation, reducing the computational load on a single train, and reducing requirements on communication between trains.

- 35 **[0006]** To address the above technical issue, a method for planning operation of a rail train is provided according to the present disclosure, and the method includes:

- 40 acquiring planning information of a train formation, where the planning information includes line information, operating schedule information, formation information, and safety protection information;

- acquiring train-following information of a current train in the train formation, where the train-following information includes motion state information and control state information of the current train, route information of a current operating line, and motion state information of a leading train corresponding to the current train, the current train is any following train virtually coupled in the train formation, and the leading train is a rail train immediately ahead of the current train in a direction of travel; and

- 45 acquiring, based on the train-following information and the planning information, a local operating curve of the current train by using a speed planning model, where the speed planning model includes a longitudinal dynamics model, a constraint, and an objective function, the local operating curve includes an operating speed planning curve, a following distance planning curve, and/or an emergency brake intervention, EBI, speed protection curve, and the operating speed planning curve includes a speed curve of the current train traveling to a next station.

- 50 **[0007]** In some embodiments, the acquiring, based on the train-following information and the planning information, a local operating curve of the current train by using a speed planning model includes:

generating, based on the train-following information and the planning information, a current operating speed planning curve and a current following distance planning curve of the current train by using the speed planning model;

generating a current EBI speed protection curve of the current train based on the current following distance planning curve, a safety protection constraint corresponding to the safety protection information, and a target stopping position, where the safety protection constraint includes a safety speed limit constraint and a safety distance constraint;

generating a current minimum safety following distance curve based on the safety protection constraint, the current operating speed planning curve, the current EBI speed protection curve, and a speed planning curve of the leading train;

verifying the current operating speed planning curve and the current following distance planning curve by using the current EBI speed protection curve and the current minimum safety following distance curve, to obtain a current verification result;

in response to the current verification result indicating verification failure, adjusting the safety protection constraint and performing the process of generating, based on the train-following information and the planning information, the current operating speed planning curve and the current following distance planning curve of the current train by using the speed planning model; and

in response to the current verification result indicating verification success, integrating the current operating speed planning curve, the current following distance planning curve, and the current EBI speed protection curve to generate the local operating curve.

**[0008]** In some embodiments, the generating, based on the train-following information and the planning information, a current operating speed planning curve and a current following distance planning curve of the current train by using the speed planning model includes:

solving the speed planning model by using a quadratic programming solver based on current state information of the current train and the planning information, to generate the current operating speed planning curve and the current following distance planning curve of the current train.

**[0009]** In some embodiments, the longitudinal dynamics model includes the following discrete state equations:

$$s_{l(i+1)} = s_{l(i)} + v_{l(i)}\Delta t,$$

$$s_{f(i+1)} = s_{f(i)} + v_{f(i)}\Delta t,$$

$$v_{l(i+1)} = v_{l(i)} + a_{l(i)}\Delta t,$$

$$v_{f(i+1)} = v_{f(i)} + a_{f(i)}\Delta t,$$

$$a_{l(i+1)} = a_{l(i)} + j_{l(i)}\Delta t,$$

$$a_{f(i+1)} = a_{f(i)} + j_{f(i)}\Delta t,$$

$$ma_{l(i)} = F_{tl(i)} + F_{bl(i)} - f_{vl(i)} - f_{gl(i)} - f_{cl(i)},$$

$$ma_{f(i)} = F_{tf(i)} + F_{bf(i)} - f_{vf(i)} - f_{gf(i)} - f_{cf(i)},$$

and

$$d_{f(i)} = s_{l(i)} - s_{f(i)},$$

where

$\Delta t$  represents a discrete time interval,

$s_{l(i)}$ ,  $v_{l(i)}$ ,  $a_{l(i)}$  and  $j_{l(i)}$  represent a position, a speed, an acceleration, and a jerk of the leading train at an  $i$ -th discrete time interval, respectively,

$s_{f(i)}$ ,  $v_{f(i)}$ ,  $a_{f(i)}$  and  $j_{f(i)}$  represent a position, a speed, an acceleration, and a jerk of the current train at the  $i$ -th discrete time interval, respectively,

$d_{f(i)}$  represents a planned following distance of the current train relative to the leading train at the  $i$ -th discrete time interval,

$F_{tl(i)}$ ,  $F_{bl(i)}$ ,  $f_{vl(i)}$ ,  $f_{gl(i)}$  and  $f_{cl(i)}$  represent a traction force, a braking force, a basic resistance, a gradient resistance, and a curve resistance of the leading train at the  $i$ -th discrete time interval, respectively,

$F_{tf(i)}$ ,  $F_{bf(i)}$ ,  $f_{vf(i)}$ ,  $f_{gf(i)}$  and  $f_{cf(i)}$  represent a traction force, a braking force, a basic resistance, a gradient resistance, and a curve resistance of the current train at the  $i$ -th discrete time interval, respectively,

$m$  represents a mass of the rail train,

$i = 0, 1, 2, \dots, n$ , and

$n$  represents the number of discrete time intervals taken by the current train to arrive at the next station.

**[0010]** In some embodiments, the constraint includes an initial state constraint, a stopping state constraint, and an operating state constraint, and the operating state constraint includes at least one of a safety speed limit constraint, a punctuality time constraint, a shared-route-section time constraint, a traffic-light-intersection time constraint, a jerk constraint, and a traction force and braking force constraint.

**[0011]** In some embodiments, the initial state constraint includes  $s_{l(0)} = s_{l0}$ ,  $s_{f(0)} = s_{f0}$ ,  $v_{l(0)} = v_{l0}$ ,  $v_{f(0)} = v_{f0}$ ,  $a_{l(0)} = a_{l0}$ ,  $a_{f(0)} = a_{f0}$ ,  $j_{l(0)} = j_{l0}$ ,  $j_{f(0)} = j_{f0}$ , and  $d_{f(0)} = d_{f0}$ , and the stopping state constraint includes  $s_{l(n)} = s_{ln}$ ,  $s_{f(n)} = s_{fn}$ ,  $v_{l(n)} = 0$ ,  $v_{f(n)} = 0$ ,  $a_{l(n)} = a_{ln}$ ,  $a_{f(n)} = a_{fn}$ ,  $j_{l(n)} = j_{ln}$ ,  $j_{f(n)} = j_{fn}$ , and  $d_{f(n)} = d_{fn}$ , where

$s_{l0}$ ,  $v_{l0}$ ,  $a_{l0}$  and  $j_{l0}$  represent an initial position, an initial speed, an initial acceleration, and an initial jerk of the current train, respectively,

$s_{f0}$ ,  $v_{f0}$ ,  $a_{f0}$  and  $j_{f0}$  represent an initial position, an initial speed, an initial acceleration, and an initial jerk of the leading train, respectively,

$d_{f0}$  represents an initial following distance of the current train relative to the leading train,

$s_{ln}$ ,  $a_{ln}$  and  $j_{ln}$  represent a stopping position, a stopping acceleration, and a stopping jerk of the current train, respectively,

$s_{fn}$ ,  $a_{fn}$  and  $j_{fn}$  represent a stopping position, a stopping acceleration, and a stopping jerk of the leading train, respectively, and

$d_{fn}$  represents a stopping following distance of the current train relative to the leading train.

**[0012]** In some embodiments, in response to the operating state constraint including the safety speed limit constraint, the safety speed limit constraint includes  $0 \leq v_{l(i)} \leq v_{lm(i)}$  and  $0 \leq v_{f(i)} \leq v_{fm(i)}$ , where  $v_{lm(i)}$  and  $v_{fm(i)}$  represent a preset speed limit of the leading train and a preset speed limit of the current train at the  $i$ -th discrete time interval, respectively.

**[0013]** In some embodiments, in response to the operating state constraint including the traffic-light-intersection time constraint, the traffic-light-intersection time constraint includes  $t_{gstart} \leq t_f(s_{in})$  and  $t_{gend} \geq t_f(s_{out})$ , where  $t_f(s_{in})$  represents a time instant at which the leading train is at a starting position  $s_{in}$  of a traffic light intersection,  $t_f(s_{out})$  represents a time instant at which the current train is at an ending position  $s_{out}$  of the traffic light intersection, and  $t_{gstart}$  and  $t_{gend}$  represent a start time instant of a green light phase and an end time instant of the green light phase at the traffic light intersection, respectively.

**[0014]** In some embodiments, in response to the operating state constraint including the punctuality time constraint, the shared-route-section time constraint, the jerk constraint, and the traction force and braking force constraint, the punctuality time constraint includes  $|n * \Delta t - t_f| \leq \Delta t_{fm}$ , the shared-route-section time constraint includes  $t_{dep} - t_{out} \leq \Delta t_{om}$ , the jerk constraint includes  $j_{l(i)} \leq j_{max}$  and  $j_{f(i)} \leq j_{max}$ , and the traction force and braking force constraint includes  $0 \leq F_{tl(i)}$ ,  $F_{tf(i)} \leq F_{tmax}$ ,  $F_{bmin} \leq F_{bl(i)}$ , and  $F_{bf(i)} \leq 0$ , where

$t_f$  represents an arrival time instant at the next station in the operating schedule information,

$\Delta t_{fm}$  represents a preset allowable punctuality error,

$t_{dep}$  represents a time instant at which the train formation to which the current train belongs enters a shared route

section,

$t_{out}$  represents a time instant at which the train formation to which the current train belongs completely leaves the shared route section,

$\Delta t_{om}$  represents a preset maximum departure time period for the train formation,

$j_{max}$  represents a preset upper limit of a jerk of the rail train,

$F_{tf(i)}$  and  $F_{tl(i)}$  represent the traction force of the current train and the traction force of the leading train at the i-th discrete time interval, respectively,

$F_{bf(i)}$  and  $F_{bl(i)}$  represent the braking force of the current train and the braking force of the leading train at the i-th discrete time interval, respectively, and

$F_{tmax}$  and  $F_{bmin}$  represent a preset maximum traction force and a preset maximum braking force, respectively.

**[0015]** In some embodiments, the objective function includes a leading-following train speed difference optimization objective function, a leading-following train following distance optimization objective function, an energy efficiency objective function, and a comfort objective function.

**[0016]** In some embodiments, the objective function is expressed as:

$$\min \sum_{i=0}^n \left[ \omega_v \left( v_{f(i)} - v_{l(i)} \right)^2 + \omega_d \left( d_{f(i)} \right)^2 + \omega_t \left( F_{tl(i)} v_{l(i)} + F_{tf(i)} v_{f(i)} \right) + \omega_j \left( \left( j_{l(i)} \right)^2 + \left( j_{f(i)} \right)^2 \right) \right],$$

where  $\omega_v$ ,  $\omega_d$ ,  $\omega_t$  and  $\omega_j$  represent a preset weight for leading-following train speed difference optimization, a preset weight for leading-following train following distance optimization, a preset weight for energy efficiency, and a preset weight for comfort, respectively.

**[0017]** In some embodiments, before the acquiring, based on the train-following information and the planning information, a local operating curve of the current train by using a speed planning model, the method further includes:

determining whether a current speed and a current following distance of the current train meet a safety protection constraint corresponding to the safety protection information, where the current speed is a speed in the motion state information of the current train, the current following distance is a distance between a position in the motion state information of the leading train and a position in the motion state information of the current train, and the safety protection constraint includes a safety speed limit constraint and a safety distance constraint;

determining, in response to the current speed and the current following distance of the current train meeting the safety protection constraint, whether a virtual coupling entry signal in the control state information is received and whether the current following distance is less than a virtual coupling threshold; and

performing, in response to the virtual coupling entry signal in the control state information being received and the current following distance being less than the virtual coupling threshold, the process of acquiring, based on the train-following information and the planning information, the local operating curve of the current train by using the speed planning model.

**[0018]** An apparatus for planning operation of a rail train is further provided according to an embodiment of the present disclosure. The apparatus includes an information acquisition module, a condition acquisition module, and a collaborative planning module.

**[0019]** The information acquisition module is configured to acquire planning information of a train formation, where the planning information includes line information, operating schedule information, formation information, and safety protection information.

**[0020]** The condition acquisition module is configured to acquire train-following information of a current train in the train formation, where the train-following information includes motion state information and control state information of the current train, route information of a current operating line, and motion state information of a leading train corresponding to the current train, the current train is any following train virtually coupled in the train formation, and the leading train is a rail train immediately ahead of the current train in a direction of travel.

**[0021]** The collaborative planning module is configured to acquire, based on the train-following information and the planning information, a local operating curve of the current train by using a speed planning model, where the speed planning model includes a longitudinal dynamics model, a constraint, and an objective function, the local operating curve includes an operating speed planning curve, a following distance planning curve, and/or an emergency brake intervention, EBI, speed protection curve, and the operating speed planning curve includes a speed curve of the current train traveling to a next station.

**[0022]** An electronic device is further provided according to an embodiment of the present disclosure, and the electronic device includes:

a memory, configured to store a computer program; and

a processor, configured to execute the computer program to perform the method for planning the operation of the rail train described above.

**[0023]** A rail train is further provided according to an embodiment of the present disclosure, including the electronic device described above.

**[0024]** In addition, a computer-readable storage medium is provided according to an embodiment of the present disclosure. The computer-readable storage medium stores a computer program. The computer program is executed by a processor to perform the method for planning the operation of the rail train described above.

**[0025]** A method for planning operation of a rail train is provided according to the present disclosure. The method includes: acquiring planning information of a train formation, where the planning information includes line information, operating schedule information, formation information, and safety protection information; acquiring train-following information of a current train in the train formation, where the train-following information includes motion state information and control state information of the current train, route information of a current operating line, and motion state information of a leading train corresponding to the current train, the current train is any following train virtually coupled in the train formation, and the leading train is a rail train immediately ahead of the current train in a direction of travel; and acquiring, based on the train-following information and the planning information, a local operating curve of the current train by using a speed planning model, where the speed planning model includes a longitudinal dynamics model, a constraint, and an objective function, the local operating curve includes an operating speed planning curve, a following distance planning curve, and/or an emergency brake intervention, EBI, speed protection curve, and the operating speed planning curve includes a speed curve of the current train traveling to a next station.

**[0026]** It can be seen that in the present disclosure, the local operating curve of the current train is acquired by using the speed planning model based on the train-following information and the planning information, and the operating state of the following train in the train formation is planned and generated by using the constructed longitudinal dynamics model of the rail train, as well as the objective function and the constraint for collaborative planning. In this way, distributed planning and control for the train formation can be realized, effectively reducing the computational load on a single train, reducing requirements on the real-time performance and safety of communication between trains, and thereby lowering the cost of the rail train. In addition, an apparatus for planning operation of a rail train, an electronic device, a rail train, and a computer-readable storage medium are further provided according to the present disclosure, all of which likewise have the above beneficial effects.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0027]** Hereinafter drawings to be applied in embodiments of the present disclosure or in the related art are briefly described, in order to illustrate technical solutions according to embodiments of the present disclosure or in the related art more clearly. Apparently, the drawings in the following descriptions are only some embodiments of the present disclosure, and other drawings may be obtained by those skilled in the art based on the provided drawings without any creative effort.

FIG. 1 is a flowchart of a method for planning operation of a rail train according to an embodiment of the present disclosure;

FIG. 2 is a schematic diagram of a system structure of another method for planning operation of a rail train according to an embodiment of the present disclosure;

FIG. 3 is a schematic flowchart of yet another method for planning operation of a rail train according to an embodiment of the present disclosure;

FIG. 4 is a structural block diagram of an apparatus for planning operation of a rail train according to an embodiment of

the present disclosure; and

FIG. 5 is a schematic structural diagram of an electronic device according to an embodiment of the present disclosure.

## DETAILED DESCRIPTION

**[0028]** In order to make the objective, the technical solutions and advantages of the embodiments of the present disclosure more clear, the technical solutions in the embodiments of the present disclosure are described below clearly and completely in conjunction with the drawings in the embodiments of the present disclosure. Apparently, the embodiments described are only some embodiments of the present disclosure, rather than all the embodiments. All other embodiments obtained by those skilled in the art based on the embodiments in the present disclosure without any creative work fall within the protection scope of the present disclosure.

**[0029]** Reference is made to FIG. 1, which is a flowchart of a method for planning operation of a rail train according to an embodiment of the present disclosure. The method includes the following steps 101 to 103.

**[0030]** In step 101, planning information of a train formation is acquired, where the planning information includes line information, operating schedule information, formation information, and safety protection information.

**[0031]** It should be understood that the train formation in this embodiment is a coupled formation consisting of two or more rail trains (such as autonomous rail rapid transit trains). For example, the coupled formation is formed with multiple independent autonomous rail rapid transit trains through virtual coupling.

**[0032]** In an embodiment, the planning information of the train formation is information that is preset for planning the operation of the train formation. The specific content of the planning information in this embodiment is determined by designers according to practical scenarios and user requirements. For example, the planning information of the train formation includes line information, operating schedule information, formation information, and safety protection information. The line information includes information about an operating line of the train formation, such as positions of stations on the operating line and positions of traffic light intersections on the operating line. The operating schedule information includes time information of the train formation arriving at and leaving the stations on the operating line (for example, the timetable shown in FIG. 2). The formation information includes information related to the train formation, such as a total length of the train formation, and formation sequences and lengths of all rail trains in the train formation. The safety protection information includes information for ensuring safe operation of the rail train, such as a train speed limit, a speed limit for a special section (such as a departure section, an arrival section, and an intersection), a curve speed limit, and a gradient speed limit. As shown in FIG. 2, a current train acquires the line information, the operating schedule information (the timetable), the formation information, and the safety protection information included in the planning information through a scheduling and decision module.

**[0033]** It should be noted that the specific manner by which a processor acquires the planning information of the train formation in this step may be determined by designers according to practical scenarios and user requirements. For example, the processor directly reads the planning information stored in advance, or receives all or part of the planning information via a network. The manner by which the processor acquires the planning information is not limited in this embodiment.

**[0034]** In step 102, train-following information of the current train in the train formation is acquired, where the train-following information includes motion state information and control state information of the current train, route information of a current operating line, and motion state information of a leading train corresponding to the current train, the current train is any following train virtually coupled in the train formation, and the leading train is a rail train immediately ahead of the current train in a direction of travel.

**[0035]** It should be understood that the current train in an embodiment is any following train in the train formation, that is, the train formation includes a rail train ahead of the current train in the direction of travel. For example, a rail train in the train formation, except for the first rail train in the direction of travel, employs the method provided in this embodiment to plan and generate a local operating curve. Alternatively, a server in a wireless communication connection with all rail trains in the train formation employs the method provided in this embodiment to plan and generate an operating speed planning curve of the following train in the train formation. The manner is not limited in this embodiment.

**[0036]** In an embodiment, the train-following information of the current train includes information regarding a following condition of the current train relative to the leading train. Within the train formation, the leading train is the rail train immediately ahead of the current train in the direction of travel of the current train, that is, the nearest rail train ahead of the current train, such as a preceding rail train that is virtually coupled with the current train.

**[0037]** In an embodiment, the specific content of the train-following information of the current train is determined by designers according to practical scenarios and user requirements. For example, the train-following information includes the motion state information and the control state information of the current train. The motion state information indicates a current motion state of the current train, and includes a current position (i.e., position information), a current speed (i.e., speed information), a current acceleration (i.e., acceleration information), and a current jerk (i.e., jerk information) of the

current train. The motion state information is used to calculate a distance between the current train and the leading train, determine overspeed for safety protection, and determine a constraint for a starting point of speed planning. As shown in FIG. 2, the current train acquires the position information (an x-coordinate and a y-coordinate), the speed information, the acceleration information, and the jerk information of a host train (the current train) through a host-train positioning module.

The control state information indicates a current control state of the current train, and includes a current actual operating mode and a virtual coupling entry signal of the current train. The control state information is used to determine a next control mode based on the operating state of the current train and enable safe coupling of the virtual coupling. As shown in FIG. 2, the current train acquires the current actual operating mode and the virtual coupling entry signal of the host train through a host-train state module.

**[0038]** In an embodiment, the train-following information further includes the route information of the current operating line. The route information of the current operating line refers to global route information of the current operating line for the current train. For example, the route information of the current operating line includes positions, curvatures, and gradients of all route points along the current operating line, which are used for calculating gradient resistances and curve resistances encountered by the current train during operation. As shown in FIG. 2, the current train acquires the positions (x-coordinates and y-coordinates), the curvatures, and the gradients of all route points along the current operating line through a line map module. The train-following information further includes the motion state information of the leading train corresponding to the current train. The motion state information of the leading train refers to current motion state information of the leading train, and includes a current position, a current speed, a current acceleration, and a current jerk of the leading train. When the leading train operates in an autonomous driving mode, the motion state information of the leading train further includes a speed planning curve of the leading train, so as to facilitate subsequent calculations. As shown in FIG. 2, the current train acquires the current position (an x-coordinate and a y-coordinate), the current speed, the current acceleration, and the current jerk of a preceding train (that is, the leading train), as well as a leading-train planning route (for example, the speed planning curve of the leading train) when the preceding train operates in the autonomous driving mode, through a train-to-train communication module.

**[0039]** In step 103, a local operating curve of the current train is acquired by using a speed planning model based on the train-following information and the planning information, where the speed planning model includes a longitudinal dynamics model, a constraint, and an objective function, the local operating curve includes an operating speed planning curve, a following distance planning curve, and/or an emergency brake intervention, EBI, speed protection curve, and the operating speed planning curve includes a speed curve of the current train traveling to a next station.

**[0040]** It should be understood that the local operating curve in an embodiment is an operating curve of the current train traveling to the next station. The local operating curve includes at least one of the operating speed planning curve, the following distance planning curve, and the EBI speed protection curve (that is, a speed curve corresponding to an EBI curve). As shown in FIG. 2, the current train acquires the local operating curve including the operating speed planning curve (a reference speed curve), the following distance planning curve (a target following distance curve), and the EBI speed protection curve (an EBI speed curve) through a collaborative planning module. Thus, the current train is controlled through a collaborative control module based on the local operating curve, thereby ensuring safe operation of the current train in a virtual coupling state.

**[0041]** The speed planning model in this embodiment is a model for planning and generating an operating speed curve (that is, the operating speed planning curve) of a virtually coupled following train (that is, the current train). The speed planning model includes the longitudinal dynamics model of the virtually coupled rail train, as well as the objective function and the constraint for collaborative planning, such that the processor is able to generate the operating speed planning curve of the current train in the train formation by using the speed planning model based on the acquired current state information of the current train and the planning information, thereby planning operating speeds of the rail trains in the train formation. In an embodiment, the speed planning model further plans and generates a distance curve (that is, the following distance planning curve) of the current train relative to the leading train, while planning and generating the operating speed planning curve of the current train.

**[0042]** In this embodiment, by performing longitudinal dynamics modeling on the virtually coupled rail train, the longitudinal dynamics model is acquired. The specific content of the longitudinal dynamics model in the speed planning model according to the embodiment is determined by designers according to practical scenarios and user requirements. For example, in a case of planning and generating the operating speed planning curve and the following distance planning curve of the current train by using the speed planning model, the longitudinal dynamics model adopts a single-mass model to characterize the motion and force conditions of the leading train and the current train, which are virtually coupled. The longitudinal dynamics model includes the following discrete state space equations:

$$s_{l(i+1)} = s_{l(i)} + v_{l(i)} \Delta t ,$$

$$s_{f(i+1)} = s_{f(i)} + v_{f(i)} \Delta t,$$

$$v_{l(i+1)} = v_{l(i)} + a_{l(i)} \Delta t,$$

$$v_{f(i+1)} = v_{f(i)} + a_{f(i)} \Delta t,$$

$$a_{l(i+1)} = a_{l(i)} + j_{l(i)} \Delta t,$$

$$a_{f(i+1)} = a_{f(i)} + j_{f(i)} \Delta t,$$

$$ma_{l(i)} = F_{tl(i)} + F_{bl(i)} - f_{vl(i)} - f_{gl(i)} - f_{cl(i)},$$

$$ma_{f(i)} = F_{tf(i)} + F_{bf(i)} - f_{vf(i)} - f_{gf(i)} - f_{cf(i)},$$

and

$$d_{f(i)} = s_{l(i)} - s_{f(i)},$$

where  $\Delta t$  represents a discrete time interval,  $s_{l(i)}$ ,  $v_{l(i)}$ ,  $a_{l(i)}$  and  $j_{l(i)}$  represent a position, a speed, an acceleration, and a jerk of the leading train at an  $i$ -th discrete time interval, respectively,  $s_{f(i)}$ ,  $v_{f(i)}$ ,  $a_{f(i)}$  and  $j_{f(i)}$  represent a position, a speed, an acceleration, and a jerk of the current train at the  $i$ -th discrete time interval, respectively,  $d_{f(i)}$  represents a planned following distance of the current train relative to the leading train at the  $i$ -th discrete time interval,  $F_{tl(i)}$ ,  $F_{bl(i)}$ ,  $f_{vl(i)}$ ,  $f_{gl(i)}$  and  $f_{cl(i)}$  represent a traction force, a braking force, a basic resistance, a gradient resistance, and a curve resistance of the leading train at the  $i$ -th discrete time interval, respectively,  $F_{tf(i)}$ ,  $F_{bf(i)}$ ,  $f_{vf(i)}$ ,  $f_{gf(i)}$  and  $f_{cf(i)}$  represent a traction force, a braking force, a basic resistance, a gradient resistance, and a curve resistance of the current train at the  $i$ -th discrete time interval, respectively,  $i = 0, 1, 2, \dots, n$ ,  $n$  represents the number of discrete time intervals taken by the current train to arrive at the next station, and  $m$  represents a mass of the rail train. That is, a mass of the leading train and a mass of the current train are identical in this embodiment. In other embodiments, the longitudinal dynamics model is adjusted to adopt different masses for the leading train and the current train. Alternatively, the longitudinal dynamics model may employ other methods to characterize the motion and force conditions of virtually coupled rail trains, which is not limited in this embodiment.

**[0043]** In this embodiment, the specific content of the constraint in the speed planning model is determined by designers according to practical scenarios and user requirements. For example, the constraint includes an initial state constraint, a stopping state constraint, and an operating state constraint. The operating state constraint includes at least one of a safety speed limit constraint, a punctuality time constraint, a shared-route-section time constraint, a traffic-light-intersection time constraint, a jerk constraint, and a traction force and braking force constraint. For example, the operating state constraint includes the safety speed limit constraint, the punctuality time constraint, the shared-route-section time constraint, the traffic-light-intersection time constraint, the jerk constraint, and the traction force and braking force constraint.

**[0044]** In an embodiment, the initial state constraint is a constraint on an initial state of the speed planning of the current train at a current moment. For example, the initial state constraint includes  $s_{l(0)} = s_{l0}$ ,  $s_{f(0)} = s_{f0}$ ,  $v_{l(0)} = 0$ ,  $v_{f(0)} = 0$ ,  $a_{l(0)} = a_{l0}$ ,  $a_{f(0)} = a_{f0}$ ,  $j_{l(0)} = j_{l0}$ ,  $j_{f(0)} = j_{f0}$  and  $d_{f(0)} = d_{f0}$ . Here,  $s_{l0}$ ,  $v_{l0}$ ,  $a_{l0}$  and  $j_{l0}$  represent an initial position, an initial speed, an initial acceleration, and an initial jerk of the current train, respectively, that is, the position information, the speed information, the acceleration information, and the jerk information in the motion state information of the current train, respectively.  $s_{f0}$ ,  $v_{f0}$ ,  $a_{f0}$  and  $j_{f0}$  represent an initial position, an initial speed, an initial acceleration, and an initial jerk of the leading train, respectively, that is, the position, the speed, the acceleration, and the jerk in the motion state information of the leading train, respectively.  $d_{f0}$  represents an initial following distance of the current train relative to the leading train, that is, a distance between the position in the motion state information of the leading train and the position in the motion state information of the current train.

**[0045]** In an embodiment, the stopping state constraint is a state constraint when the rail train arrives at the next station. To ensure that the rail train stops completely and stably at the next station, the stopping state constraint includes  $s_{l(n)} = S_{ln}$ ,  $s_{f(n)} = s_{fn}$ ,  $v_{l(n)} = v_{ln}$ ,  $v_{f(n)} = v_{fn}$ ,  $a_{l(n)} = a_{ln}$ ,  $a_{f(n)} = a_{fn}$ ,  $j_{l(n)} = j_{ln}$ ,  $j_{f(n)} = j_{fn}$  and  $d_{f(n)} = d_{fn}$ . Here,  $s_{ln}$ ,  $v_{ln}$ ,  $a_{ln}$  and  $j_{ln}$  represent a stopping position, a stopping speed, a stopping acceleration, and a stopping jerk of the current train, respectively, such as a preset position, a preset speed, a preset acceleration, and a preset jerk of the current train at the next station as required.

operationally according to line information or route information.  $s_{fn}$ ,  $v_{fn}$ ,  $a_{fn}$  and  $j_{fn}$  represent a stopping position, a stopping speed, a stopping acceleration, and a stopping jerk of the leading train, respectively, such as a preset position, a preset speed, a preset acceleration, and a preset jerk of the leading train at the next station as required operationally according to line information or route information.  $d_{fn}$  represents a stopping following distance of the current train relative to the leading train. Here, both  $v_{fn}$  and  $v_{fn}$  may be set to 0, that is,  $v_{fn} = 0$  and  $v_{fn} = 0$ . In other words, both the stopping speed of the current train and the stopping speed of the leading train may be 0. For example, the stopping speed of the current train and the stopping speed of the leading train at their respective preset positions (that is, stopping positions) at the next station may be 0.

**[0046]** In an embodiment, the operating state constraint is a constraint imposed on the rail train during travelling between stations, including the safety speed limit constraint, the punctuality time constraint, the shared-route-section time constraint, the traffic-light-intersection time constraint, the jerk constraint, and the traction force and braking force constraint. For example, from a safety perspective, the speed of the current train during operation should not exceed a safety speed limit value. That is, the safety speed limit constraint in the operating state constraint includes  $0 \leq v_{li} \leq v_{lm(i)}$  and  $0 \leq v_{ci} \leq v_{cm(i)}$ , where  $v_{lm(i)}$  and  $v_{cm(i)}$  represent a preset speed limit of the leading train and a preset speed limit of the current train at the  $i$ -th discrete time interval, respectively, such as preset speed limits at corresponding positions of the current operating line in the safety protection information.

**[0047]** In an embodiment, the preset speed limits  $v_{lm(i)}$  and  $v_{cm(i)}$  are acquired. The specific manner for acquiring the preset speed limits  $v_{lm(i)}$  and  $v_{cm(i)}$  is determined by designers. For example, the processor of the current train calculates, based on the safety protection information and the formation information, the preset speed limits of both the current train and the leading train at their respective corresponding positions of the current operating line through a safety protection model. For example, based on train speed limits, speed limits for a special section (such as a departure section, an arrival section, and an intersection), curve speed limits, and gradient speed limits of both the current train and the leading train in the safety protection information, as well as a length of the current train and/or a dynamic length (where a minimum safety following distance varies with a formation speed) of the train formation in the formation information, the preset speed limits (such as speed limit curves) of both the current train and the leading train in the train formation at their respective corresponding positions of the current operating line are calculated through the safety protection model.

**[0048]** In an embodiment, the operating schedule information (such as the timetable shown in FIG. 2) specifies a time instant at which the train formation arrives at the next station. To ensure punctual operation of the rail trains in the train formation, the punctuality time constraint in the operating state constraint includes  $|n \cdot \Delta t - t_f| \leq \Delta t_{fm}$ , where  $t_f$  represents an arrival time instant at the next station in the operating schedule information, and  $\Delta t_{fm}$  represents a preset allowable punctuality error. That is, in the present embodiment, the punctuality time constraint is configured to achieve the objective of arriving at the station on time.

**[0049]** In an embodiment, a departure time period determines a duration for which the train formation passes through a shared route section. To ensure that the train formation passes through the shared route section rapidly and avoid obstructing operation of subsequent rail trains outside the train formation, the shared-route-section time constraint in the operating state constraint includes  $t_{dep} - t_{out} \leq \Delta t_{om}$ , where  $t_{dep}$  represents a time instant at which the train formation to which the current train belongs enters the shared route section,  $t_{out}$  represents a time instant at which the train formation to which the current train belongs completely leaves the shared route section, and  $\Delta t_{om}$  represents a preset maximum departure time period for the train formation. That is, in the present embodiment, the operating state constraint is configured to achieve the time objective of passing through the shared route section rapidly, avoiding obstructing operation of the subsequent rail trains outside the train formation.

**[0050]** In an embodiment, in a case that the line information includes position information (such as a starting position and an ending position) of a traffic light intersection during operation of the rail train (such as an autonomous rail rapid transit train), the traffic-light-intersection time constraint in the operating state constraint includes  $t_{gstart} \leq t(s_{in})$  and  $t_{gend} \geq t(s_{out})$ , to ensure the train formation to safely pass through the traffic light intersection. Here,  $t(s_{in})$  represents a time instant at which the leading train is at the starting position  $s_{in}$  of the traffic light intersection,  $t(s_{out})$  represents a time instant at which the current train is at the ending position  $s_{out}$  of the traffic light intersection, and  $t_{gstart}$  and  $t_{gend}$  represent a start time instant of a green light phase and an end time instant of the green light phase at the traffic light intersection, respectively. For example, a traffic light at the traffic light intersection determines a duration for which the train formation passes through the intersection, and thus the processor obtains a phase of the traffic light (for example, the green light phase) at the traffic light intersection. Based on the green light phase and the length of the train formation, the time instant (such as  $t(s_{in})$ ) at which the train formation to which the current train belongs enters the traffic light intersection and the time instant (such as  $t(s_{out})$ ) at which the train formation leaves the traffic light intersection are determined. For instance, a dynamic programming method is employed to determine whether to decelerate and wait for a next green light phase, thereby determining the time instant at which the train formation enters the traffic light intersection and the time instant at which the train formation leaves the traffic light intersection.

**[0051]** In an embodiment, the comfort of riding the rail train is evaluated by using a jerk of the rail train. To ensure the comfort of riding the train formation, the jerk constraint in the operating state constraint includes  $j_{li} \leq j_{max}$  and  $j_{ci} \leq j_{max}$ ,

where  $j_{max}$  represents a preset upper limit of the jerk of the rail train. That is, in the present embodiment, the jerk constraint is configured to achieve the objective of smooth and comfortable operation of the train.

**[0052]** In an embodiment, traction and braking capabilities of the rail train determine a maximum traction force and a maximum braking force for the rail train. The traction force and braking force constraint in the operating state constraint includes  $0 \leq F_{tl(i)}, F_{tf(i)} \leq F_{tmax}, F_{bmin} \leq F_{bl(i)}$  and  $F_{bf(i)} \leq 0$ , where  $j_{max}$  represents the preset upper limit of the jerk of the rail train,  $F_{tl(i)}$  and  $F_{tf(i)}$  represent the traction force of the current train and the traction force of the leading train at the  $i$ -th discrete time interval, respectively,  $F_{bl(i)}$  and  $F_{bf(i)}$  represent the braking force of the current train and the braking force of the leading train at the  $i$ -th discrete time interval, respectively, and  $F_{tmax}$  and  $F_{bmin}$  represent a preset maximum traction force and a preset maximum braking force, respectively,  $F_{bmin}$  being a negative value.

**[0053]** It should be noted that the specific content of the objective function in the speed planning model according to the embodiments is determined by designers according to practical scenarios and user requirements. For example, the objective function includes a leading-following train speed difference optimization objective function, a leading-following train following distance optimization objective function, an energy efficiency objective function, and a comfort objective function, so as to comprehensively take energy efficiency of the rail train and the comfort of riding the rail train into consideration. For example, the objective function is expressed as:

$$\min \sum_{i=0}^n \left[ \omega_v \left( v_{f(i)} - v_{l(i)} \right)^2 + \omega_d \left( d_{f(i)} \right)^2 + \omega_t \left( F_{tl(i)} v_{l(i)} + F_{tf(i)} v_{f(i)} \right) + \omega_j \left( \left( j_{l(i)} \right)^2 + \left( j_{f(i)} \right)^2 \right) \right],$$

where  $\omega_v$ ,  $\omega_d$ ,  $\omega_t$ , and  $\omega_j$  represent a preset weight for leading-following train speed difference optimization, a preset weight for leading-following train following distance optimization, a preset weight for energy efficiency, and a preset weight for comfort, respectively. The specific values of  $\omega_v$ ,  $\omega_d$ ,  $\omega_t$  and  $\omega_j$  are not limited in the present embodiment, and such values may be set or adjusted by designers or users according to actual requirements to obtain reference speed curves reflecting different objective preferences.

**[0054]** It can be understood that the specific manner by which the processor obtains the local operating curve of the current train by using the speed planning model based on the train-following information and the planning information may be determined by the designers. For example, the processor is configured to: generate, based on the train-following information and the planning information, a current operating speed planning curve of the current train and a current following distance planning curve of the current train by using the speed planning model; generate a current EBI speed protection curve of the current train based on the current following distance planning curve, the safety protection constraint corresponding to the safety protection information, and a target stopping position (for example, the stopping position of the current train at the next station); and integrate the current operating speed planning curve, the current following distance planning curve, and the current EBI speed protection curve to generate the local operating curve.

**[0055]** In an embodiment, to ensure the accuracy of the obtained local operating curve, the processor in the present embodiment is further configured to perform verification on the local operating curve, so as to obtain a safe local operating curve. As shown in FIG. 3, in this process, the processor is configured to: generate the current operating speed planning curve and the current following distance planning curve of the current train by using the speed planning model based on the train-following information and the planning information; generate the current EBI speed protection curve (such as a host-train EBI speed curve in FIG. 3) of the current train based on the current following distance planning curve, the safety protection constraint corresponding to the safety protection information, and the target stopping position, where the safety protection constraint includes a safety speed limit constraint and a safety distance constraint; generate a current minimum safety following distance curve (such as a host-train minimum safety following distance curve in FIG. 3) based on the safety protection constraint, the current operating speed planning curve, the current EBI speed protection curve, and the speed planning curve of the leading train; verify the current operating speed planning curve and the current following distance planning curve by using the current EBI speed protection curve and the current minimum safety following distance curve, to obtain a current verification result; in response to the current verification result indicating verification failure, adjust the safety protection constraint and perform the process of generating, based on the train-following information and the planning information, the current operating speed planning curve and the current following distance planning curve of the current train by using the speed planning model; and in response to the current verification result indicating verification success, integrate the current operating speed planning curve, the current following distance planning curve, and the current EBI speed protection curve to generate the local operating curve. That is, when the current verification result indicates verification failure, the processor may adjust the safety protection constraint corresponding to the safety protection information in the planning information, such as  $v_{lm(i)}$  and  $v_{fm(i)}$  in the aforementioned safety speed limit constraint and/or the safety distance constraint, so as to generate a current operating speed planning curve and a current following distance planning curve for a next iteration by using the adjusted safety protection constraint, thereby proceeding with the iteration.

**[0056]** In an embodiment, the specific manner of generating, based on the train-following information and the planning

information, the current operating speed planning curve and the current following distance planning curve of the current train by using the speed planning model described above, that is, the specific solving method of the speed planning model, is determined by designers according to practical scenarios and user requirements. For example, since solving the planning problem requires a multi-step manner, a dynamic programming method is first used to decide, based on the phase of the traffic light, how the rail train behaves at the traffic light intersection, that is, whether the rail train decelerates and waits for the next green light phase, or passes through the traffic light intersection during the current green light phase, aiming to prevent the rail train from stopping at the traffic light intersection. The time instants (such as the aforementioned  $t_i$  ( $s_{in}$ ) and  $t_i$  ( $s_{out}$ )) at which the rail train passes through the traffic light intersection are then calculated based on the decision result. In this embodiment, the optimal control problem of the speed planning model is transformed into a quadratic programming (QP) problem to generate the speed planning curve. That is, in this embodiment, the processor solves the speed planning model by using a quadratic programming solver based on the current state information of the current train and the planning information, to generate the speed planning curve of the current train.

**[0057]** For example, taking CVXOPT (a convex optimization package based on the Python programming language) in Python (a computer programming language) as an example, the processor in this embodiment imports a solver (matrix) from the CVXOPT library by using the following code.

```
from cvxopt import solvers, matrix;
```

**[0058]** In an embodiment, the processor mathematically transforms the constraint and the objective function in the speed planning model into a standard form of the quadratic programming problem, thereby obtaining the corresponding components in the standard form, such as a Hessian matrix P and a gradient matrix q corresponding to the objective function, as well as a coefficient matrix G and an upper bound h for an inequality constraint and a coefficient matrix A and a matrix b for an equality constraint, corresponding to the constraint. These matrices are represented programmatically using the matrix() function, as illustrated in the following code snippet.

```
P = matrix(P);
```

```
q = matrix(q);
```

```
G = matrix(G);
```

```
h = matrix(h);
```

```
A = matrix(A);
```

```
b = matrix(b);
```

**[0059]** In an embodiment, the processor solves the QP problem using the solvers.qp() function (an optimization function) to obtain the speed planning curve. The specific code may be implemented as: Sol = solvers.qp(P, q, G, h, A, b).

**[0060]** The specific type of the quadratic programming solver employed by the processor in this embodiment is not limited. For example, the quadratic programming solver may be a quadratic programming solver provided by the CVXOPT library as described above, or may be any other quadratic programming solver such as operator splitting quadratic program (OSQP, an open-source quadratic programming solver) or QPOASES (an active-set solver that can be developed structurally), which is not limited in this embodiment.

**[0061]** It should be noted that, as shown in FIG. 3, before step 103, the processor is configured to: determine whether a current speed (a host-train current speed) and a current following distance (a host-train current following distance) of the current train meet the safety protection constraint corresponding to the safety protection information; determine, in response to the current speed and the current following distance of the current train meeting the safety protection constraint, whether a virtual coupling entry signal in the control state information is received and whether the current following distance is less than a virtual coupling threshold; and perform the step 103 in response to the virtual coupling entry signal in the control state information being received and the current following distance being less than the virtual coupling threshold. Here, the current speed is a speed in the motion state information of the current train, the current following distance is a distance between a position in the motion state information of the leading train and a position in the motion state information of the current train, and the safety protection constraint includes the safety speed limit constraint and the safety distance constraint.

**[0062]** In an embodiment, in response to the current speed or the current following distance of the current train not meeting the safety protection constraint, as shown in FIG. 3, an emergency brake command is triggered to promptly brake the current train, thereby ensuring the operating safety of the rail train. For example, the triggered emergency brake command is sent to the collaborative control module shown in FIG. 2, to control the braking of the current train through the

collaborative control module. In response to the virtual coupling entry signal not being received or the current following distance not being less than the virtual coupling threshold, the process is directly terminated as shown in FIG. 3. Alternatively, when the current following distance is not less than the virtual coupling threshold, the speed of the current train is increased to reduce the distance between the current train and the leading train. This embodiment does not impose any limitations in this regard.

**[0063]** According to the embodiments of the present disclosure, the local operating curve of the current train is acquired by using the speed planning model based on the train-following information and the planning information, and the operating state of the following train in the train formation is planned and generated by using the constructed longitudinal dynamics model of the rail train, as well as the objective function and the constraint for collaborative planning. In this way, distributed planning and control for the train formation can be realized, effectively reducing the computational load on a single train, reducing requirements on the real-time performance and safety of communication between trains, and thereby lowering the cost of the rail train.

**[0064]** Corresponding to the above-described method embodiments, an apparatus for planning operation of a rail train is further provided according to an embodiment of the present disclosure. The apparatus for planning the operation of the rail train described below and the method for planning the operation of the rail train described above may be correspondingly referred to each other.

**[0065]** Reference is made to FIG. 4, which is a structural block diagram of an apparatus for planning operation of a rail train according to an embodiment of the present disclosure. The apparatus includes an information acquisition module 10, a condition acquisition module 20, and a collaborative planning module 30.

**[0066]** The information acquisition module 10 is configured to acquire planning information of a train formation, where the planning information includes line information, operating schedule information, formation information, and safety protection information.

**[0067]** The condition acquisition module 20 is configured to acquire train-following information of a current train in the train formation, where the train-following information includes motion state information and control state information of the current train, route information of a current operating line, and motion state information of a leading train corresponding to the current train, the current train is any following train virtually coupled in the train formation, and the leading train is a rail train immediately ahead of the current train in a direction of travel.

**[0068]** The collaborative planning module 30 is configured to acquire, based on the train-following information and the planning information, a local operating curve of the current train by using a speed planning model, where the speed planning model includes a longitudinal dynamics model, a constraint, and an objective function, the local operating curve includes an operating speed planning curve, a following distance planning curve, and/or an emergency brake intervention, EBI, speed protection curve, and the operating speed planning curve includes a speed curve of the current train traveling to a next station.

**[0069]** In some embodiments, the collaborative planning module 30 includes a planning generation sub-module, a first curve generation sub-module, a second curve generation sub-module, a verification sub-module, an adjustment sub-module, and an integration sub-module.

**[0070]** The planning generation sub-module is configured to generate, based on the train-following information and the planning information, a current operating speed planning curve and a current following distance planning curve of the current train by using the speed planning model.

**[0071]** The first curve generation sub-module is configured to generate a current EBI speed protection curve of the current train based on the current following distance planning curve, a safety protection constraint corresponding to the safety protection information, and a target stopping position, where the safety protection constraint includes a safety speed limit constraint and a safety distance constraint.

**[0072]** The second curve generation sub-module is configured to generate a current minimum safety following distance curve based on the safety protection constraint, the current operating speed planning curve, the current EBI speed protection curve, and a speed planning curve of the leading train.

**[0073]** The verification sub-module is configured to verify the current operating speed planning curve and the current following distance planning curve by using the current EBI speed protection curve and the current minimum safety following distance curve, to obtain a current verification result.

**[0074]** The adjustment sub-module is configured to, in response to the current verification result indicating verification failure, adjust the safety protection constraint and send a start signal to the planning generation sub-module.

**[0075]** The integration sub-module is configured to, in response to the current verification result indicating verification success, integrate the current operating speed planning curve, the current following distance planning curve, and the current EBI speed protection curve to generate the local operating curve.

**[0076]** In some embodiments, the planning generation sub-module is further configured to solve the speed planning model by using a quadratic programming solver based on current state information of the current train and the planning information, to generate the current operating speed planning curve and the current following distance planning curve of the current train.

[0077] In some embodiments, the longitudinal dynamics model includes the following discrete state equations:

$$s_{l(i+1)} = s_{l(i)} + v_{l(i)}\Delta t,$$

$$s_{f(i+1)} = s_{f(i)} + v_{f(i)}\Delta t,$$

$$v_{l(i+1)} = v_{l(i)} + a_{l(i)}\Delta t,$$

$$v_{f(i+1)} = v_{f(i)} + a_{f(i)}\Delta t,$$

$$a_{l(i+1)} = a_{l(i)} + j_{l(i)}\Delta t,$$

$$a_{f(i+1)} = a_{f(i)} + j_{f(i)}\Delta t,$$

$$ma_{l(i)} = F_{tl(i)} + F_{bl(i)} - f_{vl(i)} - f_{gl(i)} - f_{cl(i)},$$

$$ma_{f(i)} = F_{tf(i)} + F_{bf(i)} - f_{vf(i)} - f_{gf(i)} - f_{cf(i)},$$

and

$$d_{f(i)} = s_{l(i)} - s_{f(i)},$$

where

$\Delta t$  represents a discrete time interval,

$s_{l(i)}$ ,  $v_{l(i)}$ ,  $a_{l(i)}$  and  $j_{l(i)}$  represent a position, a speed, an acceleration, and a jerk of the leading train at an  $i$ -th discrete time interval, respectively,

$s_{f(i)}$ ,  $v_{f(i)}$ ,  $a_{f(i)}$  and  $j_{f(i)}$  represent a position, a speed, an acceleration, and a jerk of the current train at the  $i$ -th discrete time interval, respectively,

$d_{f(i)}$  represents a planned following distance of the current train relative to the leading train at the  $i$ -th discrete time interval,

$F_{tl(i)}$ ,  $F_{bl(i)}$ ,  $f_{vl(i)}$ ,  $f_{gl(i)}$  and  $f_{cl(i)}$  represent a traction force, a braking force, a basic resistance, a gradient resistance, and a curve resistance of the leading train at the  $i$ -th discrete time interval, respectively,

$F_{tf(i)}$ ,  $F_{bf(i)}$ ,  $f_{vf(i)}$ ,  $f_{gf(i)}$  and  $f_{cf(i)}$  represent a traction force, a braking force, a basic resistance, a gradient resistance, and a curve resistance of the current train at the  $i$ -th discrete time interval, respectively,

$m$  represents a mass of the rail train,

$i = 0, 1, 2, \dots, n$ , and

$n$  represents the number of discrete time intervals taken by the current train to arrive at the next station.

[0078] In some embodiments, the constraint includes an initial state constraint, a stopping state constraint, and an operating state constraint, and the operating state constraint includes at least one of a safety speed limit constraint, a punctuality time constraint, a shared-route-section time constraint, a traffic-light-intersection time constraint, a jerk constraint, and a traction force and braking force constraint.

**[0079]** In some embodiments, the initial state constraint includes  $s_{l(0)} = s_{l0}$ ,  $s_{f(0)} = s_{f0}$ ,  $v_{l(0)} = v_{l0}$ ,  $v_{f(0)} = v_{f0}$ ,  $a_{l(0)} = a_{l0}$ ,  $a_{f(0)} = a_{f0}$ ,  $j_{l(0)} = j_{l0}$ ,  $j_{f(0)} = j_{f0}$ , and  $d_{f(0)} = d_{f0}$ , and the stopping state constraint includes  $s_{l(n)} = s_{ln}$ ,  $s_{f(n)} = s_{fn}$ ,  $v_{l(n)} = 0$ ,  $v_{f(n)} = 0$ ,  $a_{l(n)} = a_{ln}$ ,  $a_{f(n)} = a_{fn}$ ,  $j_{l(n)} = j_{ln}$ ,  $j_{f(n)} = j_{fn}$ , and  $d_{f(n)} = d_{fn}$ , where

$s_{l0}$ ,  $v_{l0}$ ,  $a_{l0}$  and  $j_{l0}$  represent an initial position, an initial speed, an initial acceleration, and an initial jerk of the current train, respectively,  
 $s_{f0}$ ,  $v_{f0}$ ,  $a_{f0}$  and  $j_{f0}$  represent an initial position, an initial speed, an initial acceleration, and an initial jerk of the leading train, respectively,  
 $d_{f0}$  represents an initial following distance of the current train relative to the leading train,  
 $s_{ln}$ ,  $v_{ln}$ ,  $a_{ln}$  and  $j_{ln}$  represent a stopping position, a stopping acceleration, and a stopping jerk of the current train, respectively,  
 $s_{fn}$ ,  $v_{fn}$ ,  $a_{fn}$  and  $j_{fn}$  represent a stopping position, a stopping acceleration, and a stopping jerk of the leading train, respectively, and  
 $d_{fn}$  represents a stopping following distance of the current train relative to the leading train.

**[0080]** In some embodiments, in response to the operating state constraint including the safety speed limit constraint, the safety speed limit constraint includes  $0 \leq v_{l(i)} \leq v_{lm(i)}$  and  $0 \leq v_{f(i)} \leq v_{fm(i)}$ , where  $v_{lm(i)}$  and  $v_{fm(i)}$  represent a preset speed limit of the leading train and a preset speed limit of the current train at the  $i$ -th discrete time interval, respectively.

**[0081]** In some embodiments, in response to the operating state constraint including the traffic-light-intersection time constraint, the traffic-light-intersection time constraint includes  $t_{gstart} \leq t_f(s_{in})$  and  $t_{gend} \geq t_f(s_{out})$ , where  $t_f(s_{in})$  represents a time instant at which the leading train is at a starting position  $s_{in}$  of a traffic light intersection,  $t_f(s_{out})$  represents a time instant at which the current train is at an ending position  $s_{out}$  of the traffic light intersection, and  $t_{gstart}$  and  $t_{gend}$  represent a start time instant of a green light phase and an end time instant of the green light phase at the traffic light intersection, respectively.

**[0082]** In some embodiments, in response to the operating state constraint including the punctuality time constraint, the shared-route-section time constraint, the jerk constraint, and the traction force and braking force constraint, the punctuality time constraint includes  $|n \cdot \Delta t - t_f| \leq \Delta t_{fm}$ , the shared-route-section time constraint includes  $t_{dep} - t_{out} \leq \Delta t_{om}$ , the jerk constraint includes  $j_{l(i)} \leq j_{max}$  and  $j_{f(i)} \leq j_{max}$ , and the traction force and braking force constraint includes  $0 \leq F_{tl(i)}$ ,  $F_{tf(i)} \leq F_{tmax}$ ,  $F_{bmin} \leq F_{bl(i)}$ , and  $F_{bf(i)} \leq 0$ , where

$t_f$  represents an arrival time instant at the next station in the operating schedule information,  
 $\Delta t_{fm}$  represents a preset allowable punctuality error,  
 $t_{dep}$  represents a time instant at which the train formation to which the current train belongs enters a shared route section,  
 $t_{out}$  represents a time instant at which the train formation to which the current train belongs completely leaves the shared route section,  
 $\Delta t_{om}$  represents a preset maximum departure time period for the train formation,  
 $j_{max}$  represents a preset upper limit of a jerk of the rail train,  
 $F_{tl(i)}$  and  $F_{tf(i)}$  represent the traction force of the current train and the traction force of the leading train at the  $i$ -th discrete time interval, respectively,  
 $F_{bf(i)}$  and  $F_{bl(i)}$  represent the braking force of the current train and the braking force of the leading train at the  $i$ -th discrete time interval, respectively, and  
 $F_{tmax}$  and  $F_{bmin}$  represent a preset maximum traction force and a preset maximum braking force, respectively.

**[0083]** In some embodiments, the objective function includes a leading-following train speed difference optimization objective function, a leading-following train following distance optimization objective function, an energy efficiency objective function, and a comfort objective function.

**[0084]** In some embodiments, the objective function is expressed as:

$$\min \sum_{i=0}^n \left[ \omega_v \left( v_{f(i)} - v_{l(i)} \right)^2 + \omega_d \left( d_{f(i)} \right)^2 + \omega_t \left( F_{tl(i)} v_{l(i)} + F_{tf(i)} v_{f(i)} \right) + \omega_j \left( \left( j_{l(i)} \right)^2 + \left( j_{f(i)} \right)^2 \right) \right],$$

where  $\omega_v$ ,  $\omega_d$ ,  $\omega_t$  and  $\omega_j$  represent a preset weight for leading-following train speed difference optimization, a preset weight for leading-following train following distance optimization, a preset weight for energy efficiency, and a preset weight for comfort, respectively.

**[0085]** In some embodiments, the apparatus further includes a constraint determination module and a virtual coupling determination module.

**[0086]** The constraint determination module is configured to determine whether a current speed and a current following

distance of the current train meet a safety protection constraint corresponding to the safety protection information, where the current speed is a speed in the motion state information of the current train, the current following distance is a distance between a position in the motion state information of the leading train and a position in the motion state information of the current train, and the safety protection constraint includes a safety speed limit constraint and a safety distance constraint.

**[0087]** The virtual coupling determination module is configured to:

determine, in response to the current speed and the current following distance of the current train meeting the safety protection constraint, whether a virtual coupling entry signal in the control state information is received and whether the current following distance is less than a virtual coupling threshold; and

send, in response to the virtual coupling entry signal in the control state information being received and the current following distance being less than the virtual coupling threshold, a start signal to the collaborative planning module.

**[0088]** According to the embodiments of the present disclosure, the collaborative planning module 30 acquires the local operating curve of the current train by using the speed planning model based on the train-following information and the planning information, and plans and generates the operating state of the following train in the train formation by using the constructed longitudinal dynamics model of the rail train, as well as the objective function and the constraint for collaborative planning. In this way, distributed planning and control for the train formation can be realized, effectively reducing the computational load on a single train, reducing requirements on the real-time performance and safety of communication between trains, and thereby lowering the cost of the rail train.

**[0089]** Corresponding to the above-described method embodiments, an electronic device is further provided according to the embodiment of the present disclosure. The electronic device described below and the method for planning the operation of the rail train described above may be correspondingly referred to each other.

**[0090]** Reference is made to FIG. 5, which is a schematic structural diagram of an electronic device according to an embodiment of the present disclosure. The electronic device includes:

a memory D1, configured to store a computer program; and

a processor D2, configured to execute the computer program to perform the method for planning the operation of the rail train provided in the above method embodiments.

**[0091]** In some embodiments, the electronic device may be an electronic device arranged on a rail train (such as an autonomous rail rapid transit train), or may be a server wirelessly connected to the rail train.

**[0092]** Corresponding to the above embodiment of the electronic device, a rail train is further provided according to the present disclosure. The rail train described below may be correspondingly referenced with the electronic device described above.

**[0093]** The rail train includes the electronic device as provided in the above embodiment.

**[0094]** The rail train provided in the present embodiment may be an autonomous rail rapid transit train.

**[0095]** Corresponding to the above method embodiments, a computer-readable storage medium is further provided according to the embodiment of the present disclosure. The computer-readable storage medium described below may be correspondingly referenced with the method for planning the operation of the rail train described above.

**[0096]** A computer-readable storage medium is provided according to the embodiment of the present disclosure. The computer-readable storage medium stores a computer program. The computer program is executed by a processor to perform the method for planning the operation of the rail train provided in the above method embodiments.

**[0097]** The computer-readable storage medium may be a readable storage media storing program codes, such as a U disk, a mobile hard disk, a read-only memory (ROM), a random access memory (RAM), a magnetic disc or an optical disc.

**[0098]** The embodiments in the specification are described in a progressive manner. Each of the embodiments mainly focuses on differences from other embodiments, and references can be made to each other for the same or similar parts among the embodiments. Regarding the apparatus, the electronic device, the rail train and the computer-readable storage medium disclosed in the embodiments, they correspond to the method disclosed in the embodiments and thus the descriptions are relatively brief, and related parts may be seen from the description of the method.

**[0099]** The above provides detailed descriptions of the method and the apparatus for planning the operation of the rail train, the electronic device, the rail train, and the computer-readable storage medium provided according to the present disclosure. The principle and implementation of the present disclosure are illustrated by using specific embodiments herein. The descriptions of the above embodiments are only used to facilitate understanding of the method and the core idea of the present disclosure. It should be noted that, several improvements and modifications may be made by those skilled in the art to the present disclosure without departing from the principle of the present disclosure, and these improvements and modifications also fall within the protection scope of the claims of the present disclosure.

## Claims

## 1. A method for planning operation of a rail train, comprising:

acquiring planning information of a train formation, wherein the planning information comprises line information, operating schedule information, formation information, and safety protection information;  
 acquiring train-following information of a current train in the train formation, wherein the train-following information comprises motion state information and control state information of the current train, route information of a current operating line, and motion state information of a leading train corresponding to the current train, the current train is any following train virtually coupled in the train formation, and the leading train is a rail train immediately ahead of the current train in a direction of travel; and  
 acquiring, based on the train-following information and the planning information, a local operating curve of the current train by using a speed planning model, wherein the speed planning model comprises a longitudinal dynamics model, a constraint, and an objective function, the local operating curve comprises an operating speed planning curve, a following distance planning curve, and/or an emergency brake intervention, EBI, speed protection curve, and the operating speed planning curve comprises a speed curve of the current train traveling to a next station.

## 2. The method for planning the operation of the rail train according to claim 1, wherein the acquiring, based on the train-following information and the planning information, a local operating curve of the current train by using a speed planning model comprises:

generating, based on the train-following information and the planning information, a current operating speed planning curve and a current following distance planning curve of the current train by using the speed planning model;  
 generating a current EBI speed protection curve of the current train based on the current following distance planning curve, a safety protection constraint corresponding to the safety protection information, and a target stopping position, wherein the safety protection constraint comprises a safety speed limit constraint and a safety distance constraint;  
 generating a current minimum safety following distance curve based on the safety protection constraint, the current operating speed planning curve, the current EBI speed protection curve, and a speed planning curve of the leading train;  
 verifying the current operating speed planning curve and the current following distance planning curve by using the current EBI speed protection curve and the current minimum safety following distance curve, to obtain a current verification result;  
 in response to the current verification result indicating verification failure, adjusting the safety protection constraint and performing the process of generating, based on the train-following information and the planning information, the current operating speed planning curve and the current following distance planning curve of the current train by using the speed planning model; and  
 in response to the current verification result indicating verification success, integrating the current operating speed planning curve, the current following distance planning curve, and the current EBI speed protection curve to generate the local operating curve.

3. The method for planning the operation of the rail train according to claim 2, wherein the generating, based on the train-following information and the planning information, a current operating speed planning curve and a current following distance planning curve of the current train by using the speed planning model comprises:  
 solving the speed planning model by using a quadratic programming solver based on current state information of the current train and the planning information, to generate the current operating speed planning curve and the current following distance planning curve of the current train.

## 4. The method for planning the operation of the rail train according to claim 1, wherein the longitudinal dynamics model comprises the following discrete state equations:

$$s_{l(i+1)} = s_{l(i)} + v_{l(i)} \Delta t,$$

$$s_{f(i+1)} = s_{f(i)} + v_{f(i)} \Delta t,$$

$$v_{l(i+1)} = v_{l(i)} + a_{l(i)} \Delta t,$$

$$v_{f(i+1)} = v_{f(i)} + a_{f(i)} \Delta t,$$

$$a_{l(i+1)} = a_{l(i)} + j_{l(i)} \Delta t,$$

$$a_{f(i+1)} = a_{f(i)} + j_{f(i)} \Delta t,$$

$$ma_{l(i)} = F_{tl(i)} + F_{bl(i)} - f_{vl(i)} - f_{gl(i)} - f_{cl(i)},$$

$$ma_{f(i)} = F_{tf(i)} + F_{bf(i)} - f_{vf(i)} - f_{gf(i)} - f_{cf(i)},$$

and

$$d_{f(i)} = s_{l(i)} - s_{f(i)},$$

wherein

$\Delta t$  represents a discrete time interval,

$s_{l(i)}$ ,  $v_{l(i)}$ ,  $a_{l(i)}$  and  $j_{l(i)}$  represent a position, a speed, an acceleration, and a jerk of the leading train at an i-th discrete time interval, respectively,

$s_{f(i)}$ ,  $v_{f(i)}$ ,  $a_{f(i)}$  and  $j_{f(i)}$  represent a position, a speed, an acceleration, and a jerk of the current train at the i-th discrete time interval, respectively,

$d_{f(i)}$  represents a planned following distance of the current train relative to the leading train at the i-th discrete time interval,

$F_{tl(i)}$ ,  $F_{bl(i)}$ ,  $f_{vl(i)}$ ,  $f_{gl(i)}$  and  $f_{cl(i)}$  represent a traction force, a braking force, a basic resistance, a gradient resistance, and a curve resistance of the leading train at the i-th discrete time interval, respectively,

$F_{tf(i)}$ ,  $F_{bf(i)}$ ,  $f_{vf(i)}$ ,  $f_{gf(i)}$  and  $f_{cf(i)}$  represent a traction force, a braking force, a basic resistance, a gradient resistance, and a curve resistance of the current train at the i-th discrete time interval, respectively,

$m$  represents a mass of the rail train,

$i = 0, 1, 2, \dots, n$ , and

$n$  represents the number of discrete time intervals taken by the current train to arrive at the next station.

5. The method for planning the operation of the rail train according to claim 4, wherein the constraint comprises an initial state constraint, a stopping state constraint, and an operating state constraint, and the operating state constraint comprises at least one of a safety speed limit constraint, a punctuality time constraint, a shared-route-section time constraint, a traffic-light-intersection time constraint, a jerk constraint, and a traction force and braking force constraint.

6. The method for planning the operation of the rail train according to claim 5, wherein the initial state constraint comprises  $s_{l(0)} = s_{l0}$ ,  $s_{f(0)} = s_{f0}$ ,  $v_{l(0)} = v_{l0}$ ,  $v_{f(0)} = v_{f0}$ ,  $a_{l(0)} = a_{l0}$ ,  $a_{f(0)} = a_{f0}$ ,  $j_{l(0)} = j_{l0}$ ,  $j_{f(0)} = j_{f0}$ , and  $d_{f(0)} = d_{f0}$ , and

the stopping state constraint comprises  $s_{l(n)} = s_{ln}$ ,  $s_{f(n)} = s_{fn}$ ,  $v_{l(n)} = 0$ ,  $v_{f(n)} = 0$ ,  $a_{l(n)} = a_{ln}$ ,  $a_{f(n)} = a_{fn}$ ,  $j_{l(n)} = j_{ln}$ ,  $j_{f(n)} = j_{fn}$ , and  $d_{f(n)} = d_{fn}$ , wherein

$s_{l0}$ ,  $v_{l0}$ ,  $a_{l0}$  and  $j_{l0}$  represent an initial position, an initial speed, an initial acceleration, and an initial jerk of the current train, respectively,

$s_{f0}$ ,  $v_{f0}$ ,  $a_{f0}$  and  $j_{f0}$  represent an initial position, an initial speed, an initial acceleration, and an initial jerk of the leading train, respectively,

$d_{f0}$  represents an initial following distance of the current train relative to the leading train,

$s_{ln}$ ,  $a_{ln}$  and  $j_{ln}$  represent a stopping position, a stopping acceleration, and a stopping jerk of the current train, respectively,

$s_{fn}$ ,  $a_{fn}$  and  $j_{fn}$  represent a stopping position, a stopping acceleration, and a stopping jerk of the leading train,

respectively, and

$d_{fm}$  represents a stopping following distance of the current train relative to the leading train.

7. The method for planning the operation of the rail train according to claim 5, wherein, in response to the operating state constraint comprising the safety speed limit constraint, the safety speed limit constraint comprises  $0 \leq v_{l(i)} \leq v_{im(i)}$  and  $0 \leq v_{f(i)} \leq v_{fm(i)}$ , wherein  $v_{lm(i)}$  and  $v_{fm(i)}$  represent a preset speed limit of the leading train and a preset speed limit of the current train at the i-th discrete time interval, respectively.

8. The method for planning the operation of the rail train according to claim 5, wherein, in response to the operating state constraint comprising the traffic-light-intersection time constraint, the traffic-light-intersection time constraint comprises  $t_{gstart} \leq t(s_{in})$  and  $t_{gend} \geq t(s_{out})$ , wherein  $t(s_{in})$  represents a time instant at which the leading train is at a starting position  $s_{in}$  of a traffic light intersection,  $t(s_{out})$  represents a time instant at which the current train is at an ending position  $s_{out}$  of the traffic light intersection, and  $t_{gstart}$  and  $t_{gend}$  represent a start time instant of a green light phase and an end time instant of the green light phase at the traffic light intersection, respectively.

9. The method for planning the operation of the rail train according to claim 5, wherein, in response to the operating state constraint comprising the punctuality time constraint, the shared-route-section time constraint, the jerk constraint, and the traction force and braking force constraint, the punctuality time constraint comprises  $|n * \Delta t - t_f| \leq \Delta t_{fm}$ , the shared-route-section time constraint comprises  $t_{dep} - t_{out} \leq \Delta t_{om}$ , the jerk constraint comprises  $j_{l(i)} \leq j_{max}$  and  $j_{f(i)} \leq j_{max}$ , and the traction force and braking force constraint comprises  $0 \leq F_{tl(i)}, F_{tf(i)} \leq F_{tmax}, F_{bmin} \leq F_{bl(i)},$  and  $F_{bf(i)} \leq 0$ , wherein

$t_f$  represents an arrival time instant at the next station in the operating schedule information,

$\Delta t_{fm}$  represents a preset allowable punctuality error,

$t_{dep}$  represents a time instant at which the train formation to which the current train belongs enters a shared route section,

$t_{out}$  represents a time instant at which the train formation to which the current train belongs completely leaves the shared route section,

$\Delta t_{om}$  represents a preset maximum departure time period for the train formation,

$j_{max}$  represents a preset upper limit of a jerk of the rail train,

$F_{tl(i)}$  and  $F_{tf(i)}$  represent the traction force of the current train and the traction force of the leading train at the i-th discrete time interval, respectively,

$F_{bl(i)}$  and  $F_{bf(i)}$  represent the braking force of the current train and the braking force of the leading train at the i-th discrete time interval, respectively, and

$F_{tmax}$  and  $F_{bmin}$  represent a preset maximum traction force and a preset maximum braking force, respectively.

10. The method for planning the operation of the rail train according to claim 4, wherein the objective function comprises a leading-following train speed difference optimization objective function, a leading-following train following distance optimization objective function, an energy efficiency objective function, and a comfort objective function.

11. The method for planning the operation of the rail train according to claim 10, wherein the objective function is expressed as:

$$\min \sum_{i=0}^n \left[ \omega_v \left( v_{f(i)} - v_{l(i)} \right)^2 + \omega_d \left( d_{f(i)} \right)^2 + \omega_t \left( F_{tl(i)} v_{l(i)} + F_{tf(i)} v_{f(i)} \right) + \omega_j \left( \left( j_{l(i)} \right)^2 + \left( j_{f(i)} \right)^2 \right) \right],$$

wherein  $\omega_v$ ,  $\omega_d$ ,  $\omega_t$  and  $\omega_j$  represent a preset weight for leading-following train speed difference optimization, a preset weight for leading-following train following distance optimization, a preset weight for energy efficiency, and a preset weight for comfort, respectively.

12. The method for planning the operation of the rail train according to any one of claims 1 to 11, wherein before the acquiring, based on the train-following information and the planning information, a local operating curve of the current train by using a speed planning model, the method further comprises:

determining whether a current speed and a current following distance of the current train meet a safety protection constraint corresponding to the safety protection information, wherein the current speed is a speed in the motion state information of the current train, the current following distance is a distance between a position in the motion state information of the leading train and a position in the motion state information of the current train, and the

safety protection constraint comprises a safety speed limit constraint and a safety distance constraint; determining, in response to the current speed and the current following distance of the current train meeting the safety protection constraint, whether a virtual coupling entry signal in the control state information is received and whether the current following distance is less than a virtual coupling threshold; and  
 5 performing, in response to the virtual coupling entry signal in the control state information being received and the current following distance being less than the virtual coupling threshold, the process of acquiring, based on the train-following information and the planning information, the local operating curve of the current train by using the speed planning model.

10 **13.** An apparatus for planning operation of a rail train, comprising:

an information acquisition module, configured to acquire planning information of a train formation, wherein the planning information comprises line information, operating schedule information, formation information, and safety protection information;

15 a condition acquisition module, configured to acquire train-following information of a current train in the train formation, wherein the train-following information comprises motion state information and control state information of the current train, route information of a current operating line, and motion state information of a leading train corresponding to the current train, the current train is any following train virtually coupled in the train formation, and the leading train is a rail train immediately ahead of the current train in a direction of travel; and

20 a collaborative planning module, configured to acquire, based on the train-following information and the planning information, a local operating curve of the current train by using a speed planning model, wherein the speed planning model comprises a longitudinal dynamics model, a constraint, and an objective function, the local operating curve comprises an operating speed planning curve, a following distance planning curve, and/or an emergency brake intervention, EBI, speed protection curve, and the operating speed planning curve comprises a  
 25 speed curve of the current train traveling to a next station.

**14.** An electronic device, comprising:

a memory, configured to store a computer program; and

30 a processor, configured to execute the computer program to perform the method for planning the operation of the rail train according to any one of claims 1 to 12.

**15.** A rail train, comprising the electronic device according to claim 14.

35 **16.** A computer-readable storage medium, storing a computer program, wherein the computer program is executed by a processor to perform the method for planning the operation of the rail train according to any one of claims 1 to 12.

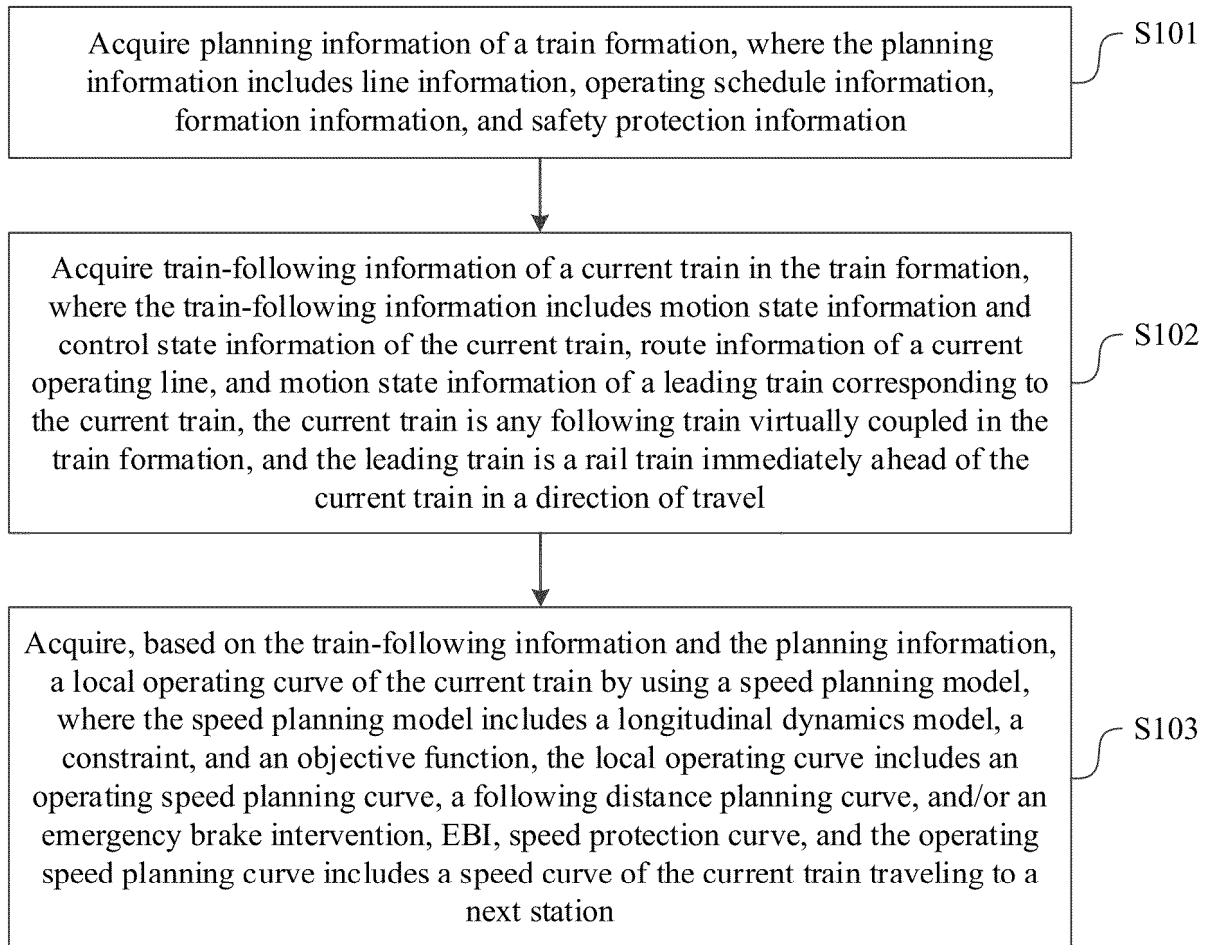


FIG. 1

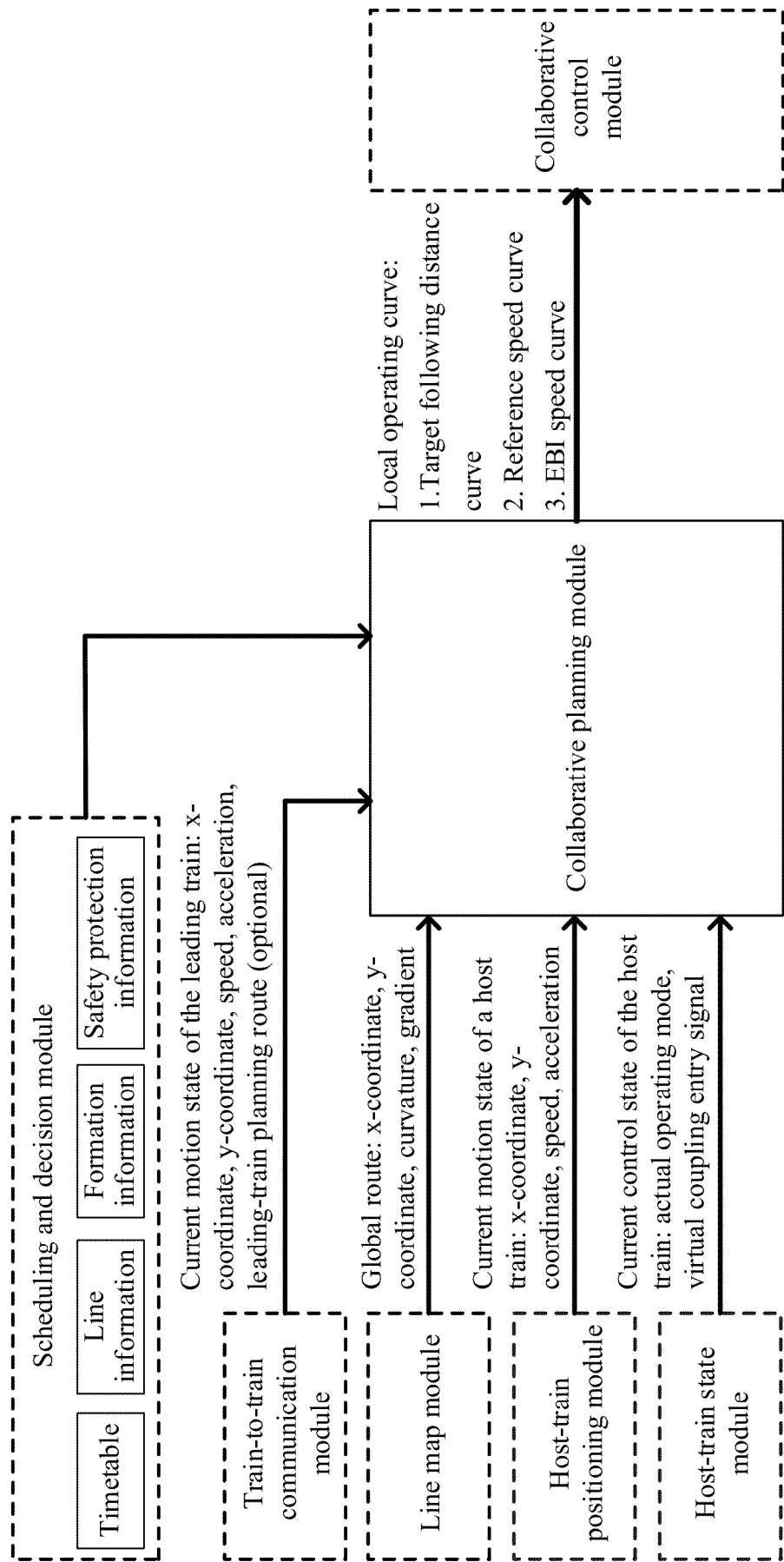


FIG. 2

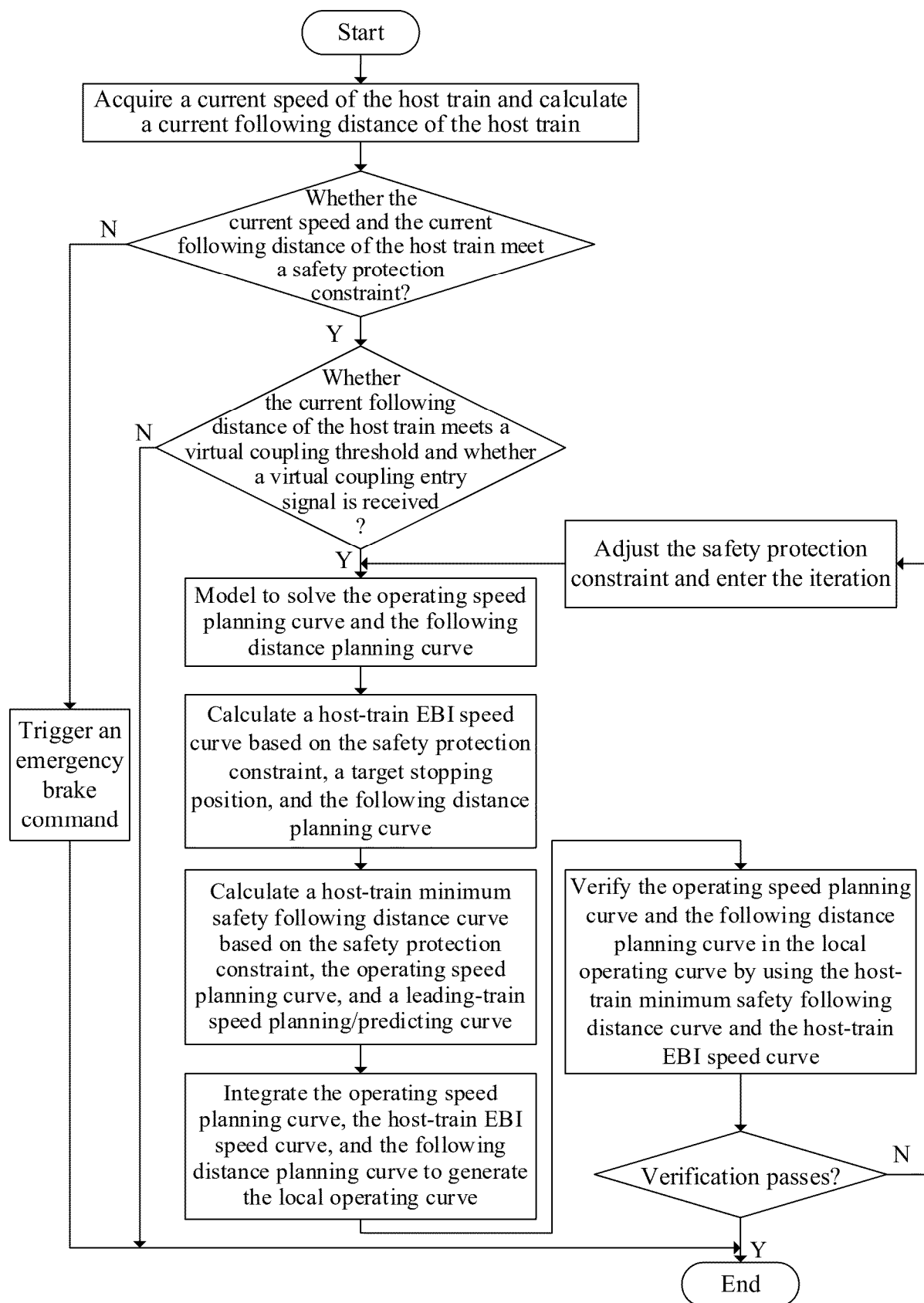


FIG. 3

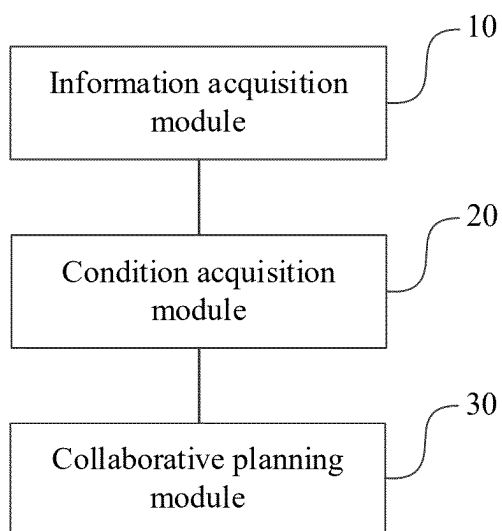


**FIG. 4**

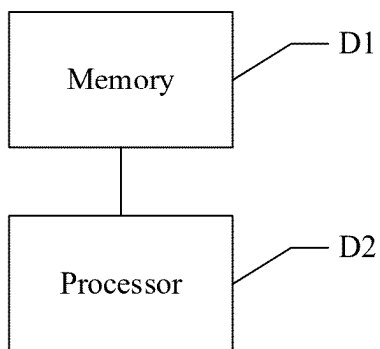


**FIG. 5**

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/CN2023/119488

## A. CLASSIFICATION OF SUBJECT MATTER

B61L 27/10(2022.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC: B61L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

CNABS: CNTXT; CNKI; VEN; USTXT; WOTXT; GBTXT; JPTXT; EPTXT; Web of Science: 中车株洲, 冯江华, 胡云卿, 黄强, 李程, 编组, 编队, 连挂, 协同, 列车, 机车, 电车, 领头车, 领导车, 领航车, 跟随车, 速度, 间距, 间隔, 约束条件, 目标函数, 校验, 验证, marshaling, coupl+, train, tram, leading, following, speed, velocity, distance, verif+

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages                                                  | Relevant to claim No. |
|-----------|-------------------------------------------------------------------------------------------------------------------------------------|-----------------------|
| X         | CN 116080725 A (BEIJING JIAOTONG UNIVERSITY et al.) 09 May 2023 (2023-05-09) description, paragraphs [0110]-[0211], and figures 1-6 | 1, 4-10, 12-16        |
| X         | CN 116090336 A (BEIJING JIAOTONG UNIVERSITY et al.) 09 May 2023 (2023-05-09) description, paragraphs [0117]-[0237], and figures 1-7 | 1, 4-10, 12-16        |
| X         | CN 116620359 A (BEIJING JIAOTONG UNIVERSITY) 22 August 2023 (2023-08-22) description, paragraphs [0063]-[0145], and figures 1-8     | 1, 4-10, 12-16        |
| A         | CN 113415317 A (CHONGQING JIAOTONG UNIVERSITY) 21 September 2021 (2021-09-21) entire document                                       | 1-16                  |
| A         | WO 2023043684 A1 (UNIVERSITY OF WASHINGTON et al.) 23 March 2023 (2023-03-23) entire document                                       | 1-16                  |

☐ Further documents are listed in the continuation of Box C.☒ See patent family annex.

|                                                                                                                                                                         |                                                                                                                                                                                                                                                  |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| * Special categories of cited documents:                                                                                                                                | "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention                                              |
| "A" document defining the general state of the art which is not considered to be of particular relevance                                                                | "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone                                                                     |
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Date of the actual completion of the international search

08 October 2023

Date of mailing of the international search report

04 November 2023

Name and mailing address of the ISA/CN

China National Intellectual Property Administration (ISA/  
CN)  
China No. 6, Xitucheng Road, Jimenqiao, Haidian District,  
Beijing 100088

Authorized officer

Telephone No.

## INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

**PCT/CN2023/119488**

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