Basic Study on a Train Control System Integrating Operational and Safety Control

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We propose a train operation control system for drawing up operation curves composed of pairs of precise train position and precise operation time, and controlling trains and ground facilities according to the plan. This system realizes more flexible control than that of the conventional system by controlling the on-board device and the ground device according to the train performance curve from the central device, where the management of operations function and the safety control function are integrated. In this report, we describe the control method based on “band” with a margin for safety added to the operation curve, and the requirements for securing safety. In addition, we have confirmed by the simulator that there is no bottleneck in the transmission path, even though the information concentrates on the central device.

Keywords: operational control, safety control, radio communication train control, train performance curve, availability

1. Introduction

By recalculating arrival and departure times, and train performance curves in real time for groups of trains in the light of actual traffic conditions based on data acquisition from the network, it is possible to create a system which offers more flexible and safer train operation. In order to build such a system, it is necessary to coordinate and organize various factors, including specific control methods but also safety, availability, and real time functions, etc.

As a first step towards building a train operation system that could apply train performance curves re-calculated in real time, existing train control and wayside equipment control systems were examined in order to draft a set of basic specifications. Based on these basic specifications, the load on the network for a system architecture that concentrated the system logic in a centralized operations control device, was verified using a simulator. The next step was to fix the necessary requirements for guaranteeing safety, and evaluate system availability. This paper first presents an outline of the designed system, and requirements for guaranteeing safety, and then describes the results of the availability evaluation.

2. Functional integration of safety control and operations management

2.1 Outline

Recent years have seen the introduction of wireless transmission train control systems [1] in which wayside devices acquire detailed train position and speed data via radio transmission from the train. In addition, detailed control instructions can be sent to individual trains from the ground control unit when they have been identified.

Figure 1 (a) shows however that in existing train operation systems, management of operations and safety control (train control) are clearly separated. Operations are managed on the basis of train presence on individual track circuits, which means that detailed train position or speed data is not utilized.

Figure 1 (b) shows the new train operation system proposed in this paper, which consolidates management of operations and train control [2, 3]. The new method makes it possible to exploit more accurate information acquired through the wireless train control system.

The new operation method can be described as follows:

(1) The central operational control device acquires detailed data from the information network about train position and the state of equipment.
(2) This detailed data is input to the operations control device to generate safe train operation and wayside equipment control plans.
(3) The operations control device then transmits these plans to the relevant train and piece of equipment.

Headways and routes are therefore controlled according to these plans, ensuring safe operation.

Fig. 1 Flow of information for train control
In existing wireless train control systems, stopping limit indicators are transmitted to the train, and a suitable braking pattern is generated to protect the train. By contrast, the new system, generates a precise train performance curve through the operations management device. Safety is secured by controlling the train and the wayside facility (turnout, level crossing, etc.) according to this plan. It is expected that this system will not only improve services for passengers but also increase maintenance efficiency and save energy.

The operations control device is capable of generating precise driving instructions instantly; however, there may be situations where trains are unable to follow the plan because of delays due to prolonged boarding, equipment failure, etc. and therefore, the system has to be able to generate fresh, safe operation schedules rapidly to reflect real traffic conditions.

### 2.2 Control method

Conventionally, trains are operated on the basis of a simple timetable showing arrival and departure times at stations, which is planned through an operations management system. Headways and routes are controlled through the signal system. Collisions are avoided and routes planned by using train position data.

The new system however consolidates both traffic and safety control using schedules with train performance curves that include various points such as sections between stations, etc. These curves are created sequentially according to train position and equipment status.

Thus, for example, even if the departure of a preceding train is delayed, the impact of this can be mitigated by controlling the speed of the following train and shortening the headway. It is therefore possible to produce safe running patterns and simplify interlocking logic.

#### 2.2.1 Control map

In the new system, the operations control device has a function to create a “control map” (Fig. 2), instead of a timetable, to guarantee the safety of train operations under its direct control. Unlike conventional timetables, a control map defines the correspondence between the position (vertical axis) and the time (horizontal axis) over a whole section. At stations with multiple branch lines, the control map is represented in a multilayered manner.

#### 2.2.2 Headway control

Two successive trains can be safely operated by satisfying the following two requirements:

1. **Track occupancy of any section by the preceding train must never overlap with that of the following train.**
2. **Safe headway must be kept.**

Therefore, as shown in Fig. 2, a band-like range with two margins are set around the train position on the control map. For the front, the brake distance is set, and for the rear, the maximum distance that the train runs during the transmission delay is set. This range is referred to hereinafter as “band”. Any malfunction will release the emergency brake, ensuring that the train never deviates from its “band.”

The above requirement (1) is achieved by not allowing “bands” to overlap, while (2) is ensured by the margins set before and after the “band.”

The operations control device therefore exclusively manages the bands to avoid any overlap.

#### 2.2.3 Route control

Setting a safe route is critical for operational safety. The control map not only shows barriers, representing turnouts and level crossings, but also barriers corresponding to maintenance crews and locations where equipment has failed. Figure 3 illustrates the case of turnout control.

If the turnout fails to switch to the correct route corresponding to the train schedule, a rectangular “barrier” appears at the turnout position. I.e., the switch command is set according to the time of passage of the train. The barrier will remain on the control map while the turnout is switching and will only disappear once completed switching has been confirmed by the operations control device. If switching failed, the barrier will not disappear and the train stops before the turnout.

This control method can also be used to guarantee safety around level crossings and to protect track-working crews.

#### 2.2.4 Transmission of instructions and information

Control data for each train and each piece of equipment is acquired according to the control map scheduled by the operations control device, and transmitted to each relevant train and piece of equipment which are then con-
controlled according to the instructions. There may be cases however where instructions are not delivered because of a disruption to or delays in transmission. The operations control device therefore also has a function which collects data on the latest position and speed of each train, and state of equipment, for sequential scheduling of the control map (Fig. 4).

The control map in the new system consolidates operational and safety control shortening the time required to control equipment. Since the plan can be rescheduled very rapidly in response to real traffic conditions or problems, it should help improve robustness of the system against disruption due to changes in train operation. Furthermore, it makes it possible to reduce ground facilities.

3. Study of system architecture

3.1 Network load

Given that operation of an entire line in the new system depends solely on the operations control device, there is concern of a risk of bottlenecks forming due to concentration of information (i.e. control instructions and status information) channeled in and out of the operations control device. The “TCNET” [4] (network simulator for wireless train control system developed by RTRI), was therefore used to calculate the load on the network, taking into account the performance of the wireless communication system.

(1) Number of devices in the system

Assuming an existing general wireless train control system [1] (hereinafter referred to as “conventional system”), the maximum number of trains allowed within the area covered by the radio devices was set to 16. In contrast to this, in this system, 20 devices (turnouts, level crossings, refuge devices) can be added to the 16 on-board devices per area.

(2) Network architecture

Using a conventional system as a reference, a centralized example of a network was set up (Fig. 5).

In conventional systems, wayside devices in each area communicate with on-board devices to receive the location of trains which is transmitted to central traffic control. For trains located near area boundaries, wayside devices transmit information between them. In the new system, the operations control device communicates with each terminal device via radio bases so that data about the status of each device can be acquired and control instructions sent to the system.

(3) Format of control data

An example of the format given to control data for transmission between the operations control device and on-board equipment is shown in Table 1.

The volume of data required for one train was calculated on the assumption that the transmission cycle is 1 second, and that the update cycle of the control map is 0.5 seconds. The admissible number of consecutive interruptions was set at 3 for transmissions between the operations control device and on-board equipment, while the maximum transmission delay was set at 2 seconds. The volume of data per “control data transmission” from the operations control device was set to be the volume of data included per five-second “band,” counted as five seconds from the current time on the schedule.

Figure 6 illustrates control data being sent to an on-board device. If the control data band is shorter than 5 seconds, and the number of data transmission interruptions has exceeded the maximum of 3 seconds, the on-board device will not have sufficient control data, which may trigger release of the emergency brake. Conversely, if the control data exceeds 5 seconds, this indicates transmission of redundant information increasing the burden on the transmission path.

![Fig. 5 An example of the network architecture](image)

Table 1 An example of the format of control data

| Content          | Type | Volume | Remarks                        |
|------------------|------|--------|--------------------------------|
| Time stamp       | int  | 2byte  |                                |
| Serial number    | int  | 2byte  | Number of control map          |
| Sender ID        | int  | 2byte  | Identifying line               |
| Destination ID   | int  | 2byte  | Identifying device type        |
| Position         | int  | 2byte  | Position of destination device |
| Instruction core | 14byte by 10 | 10 time points (5sec / 0.5 sec) |
| On-board ID      | int  | 2byte  |                                |
| Time point       | float| 4byte  |                                |
| Position         | float| 4byte  | Operations control device      |
| Velocity         | float| 4byte  | manages stopping limit point.  |
| Redundant code   | float| 3byte  |                                |
| Sum of volume    |      | 180byte|                                |
(4) Results of simulation

In order to verify the load on the network using the new system, a transmission under the conditions mentioned in (1) to (3) was simulated using an imaginary timetable. Compared to the actual system, the volume of data being transmitted is about 2.5 times more, for about 2.3 times as many devices, and the radio transmission performance is assumed to be 64 kbps as opposed to the 9.6 kbps of the conventional system. In order to simplify the experiment, the volume of data transmitted to any device was kept at 180 bytes, and it was assumed that there were no transmission errors in the network.

Figure 7 illustrates the network, while Table 2 gives the results. The line use rate around the operations control device remained within 15%, and no bottlenecks were seen.

3.2 Requirement of safety

3.2.1 Fundamental safety requirements

In the new system, control instructions are transmitted to all devices from the operations control device, and each train or piece of equipment is controlled according to the information.

In the control map, bands and barriers do not overlap because of the exclusive logic. An additional safety margin is also added around each band or barrier to take into account delays in receiving data.

Train position and equipment status data is collected by the operations control device, and then the control map is rescheduled. Each piece of equipment has its own control data based on the same control map. When an abnormality is detected, or train position or equipment status cannot be determined, the bands and barriers on the control map are expanded to secure the safety of the train.

Each train is controlled to be within the band defined on the control map. Should there be a risk of a train escaping the boundaries of this band, the emergency brake is released and an alert is sent to the operations control device.

3.2.2 Safety analysis

A safety analysis was made of the control method in the new system. Unlike conventional systems, control data is based on a control map transmitted to each piece of equipment or device by the operations control device. The impact of an error in the control map, which is the basis of the control data, was analyzed by FMEA (Failure Mode and Effect Analysis) and FTA (Fault Tree Analysis).

(1) FMEA

Table 3 shows the FMEA on the control map.

A recognition error in a device leads an error on the control map, but the knock-on effect of this is prevented by sliding or skidding detection, correct position checking, and the device’s FS (fail safe) functions. Safety is also secured by maximizing the band length and default setting of barriers. This could raise concerns about increased train delays, so measures need to be taken to shorten transmission delays.

Table 3  FMEA concerning the control map

| Device          | Failure mode               | Effect                  | Detection                      | Safe control      |
|-----------------|----------------------------|-------------------------|--------------------------------|-------------------|
| On-board, turnout, level crossing, etc. | Incorrect position       | Error of control map    | Detect slip and skid, checking corrected position | Expand band       |
|                 | Incorrect device status    |                         | Use fail safe device           | Set barrier       |
|                 | Clock malfunction          | Old control map         | Rationality check of time stamp | Expand band       |
|                 | No information             | Cannot set new band     | Set transmission interruption limit, maximum delay | Set barrier       |
|                 | Error on control map       | Collision, derailment   | Use fail safe device           | No output         |
| Operations control device | Clock malfunction         | Difference of entire system time | Compare with GPS time, rationality check of time stamp | Emergent brake, output alert |
|                 | No information             | Device shutdown         | Set transmission interruption limit, maximum delay |                   |
intervals, etc.

Errors in the control map in the operations control device are detected by the FS device. Timing problems (clock malfunction), are corrected by the time given on the GPS and time stamp cross-checking.

If a device fails to transmit control data, because of a malfunction in transmission for example, the train will be kept safe by stopping it, by setting allowable transmission disruption times and maximum delay.

(2) FTA

Events that could lead to an accident were clarified using FTA; collision and derailment were set as top events (Fig. 8).

The analysis identified the causes of errors in the control map leading to the top event and confirmed that countermeasures prevent the top event.

3.2.3 Control system requirements

(1) Time synchronization

In order to prevent lags in timing between devices, clocks are synchronized periodically to keep them within the admissible tolerance. If the tolerance is exceeded a process similar to train stopping is triggered.

(2) Protocol for control information transmission

The following two conditions were established for the operations control device, in order to guarantee the safe operation of all other devices. First, in order to understand resulting control instructions from the device, control data must be transmitted at a certain time (longer at least than the allowable transmission interruption) before the start of control. Second, in order for the control information of all the devices to correspond with each other, the control map is to be updated after receiving the confirmation of the receipt of information from all the devices. Accordingly, the maximum transmission time is the update interval.

3.3 System availability requirements

3.3.1 Comparison with conventional systems

Lower availability is at times due to safety control and device malfunction. This report focused on the latter case, then compared the conventional and the new system (Fig. 9).

The new system has a centralized architecture, in contrast to the distributed type. Therefore, wayside equipment is not necessary and the frequency of equipment failures can be reduced. Furthermore, to reduce the influence of failure of the operations control device, a design was proposed which divides the internal area.

Table 4 shows a model line with 3 wayside devices.

3.3.2 Calculation of system availability

In calculating the availability, we set these assumptions.

(1) Failure frequency of each device is $10^{-5}$ per hour.
(2) Time to repair the device is 2 hours for the operations control device, wayside device, network, and 1 hour for the other device (on-board device, turnout, etc.).
(3) Parameters for the area affected by the failure are set. The whole area corresponds to a maximum value of 1.

The results of system availability calculated on the above assumption are shown in Table 5 and Fig. 10.

![Fig. 8 FTA for establishing a control map](image)

![Fig. 9 Configurations of the devices](image)

![Fig. 10 System availability in each configuration](image)
Since wayside devices are unnecessary in a centralized system, availability improves in any configuration compared with the conventional model. Of the three, the design with 3 internal areas proved to give the best system availability.

4. Conclusion

A highly flexible train operation system was designed which acquires data from an information network which is used to transmit operation plans that take into account train operating conditions and device status. The paper also summarizes the system’s requirements for safety, availability and data transmission therein.

In order to design a system which operates trains according to planned train performance curves, the control method of trains, turnouts, etc., and then created the basic specifications. Based on these specifications, we examined the requirements for securing train safety and evaluated the system availability.

The following findings were made: first, all devices must be controlled with the same schedule, therefore the control map must be updated in no less time than the maximum transmission delay. Second, even if the control logic is centralized, there is no risk of bottlenecks forming on the transmission path. Finally, it is possible to build a system that has just as good availability as conventional systems.

The new system is expected to reduce the number of facilities and allow more flexible operation to meet passenger needs. Future work will aim to formulate a train control logic and build a traffic control system adaptable to disruptions.

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