

Basic study on a train control system integrating operational control and safety control

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SUMMARY

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.

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 neither detailed train positions nor speed data are 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:

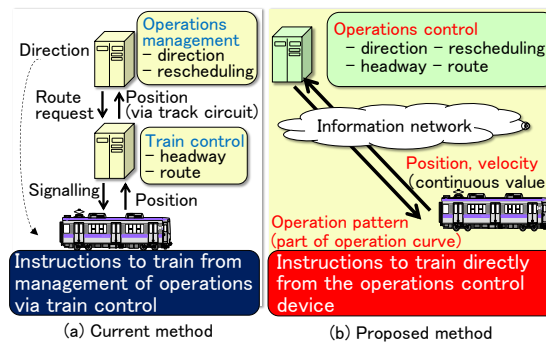


Figure 1: Flow of information for train control

- (1) The central operational control device acquires detailed data from the information network about the train positions and the state of the 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 each equipment. Headways and routes are therefore controlled according to these plans, ensuring safe operation.

In existing wireless train control systems, stopping limit indications 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 control 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 to increase maintenance opportunities (maintenance work can be set even in the daytime) 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 and safe operation schedules rapidly to reflect real-time 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 are planned by using train position data.

The new system, however, consolidates both traffic and safety control using schedules on the basis of train performance curves that include various points such as sections between stations, etc. These curves are created sequentially according to the 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. This is because the safety between trains and the safety of the route are ensured by a control map, which will be described later, instead of the conventional interlocking device.

2.2.1 Control map

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

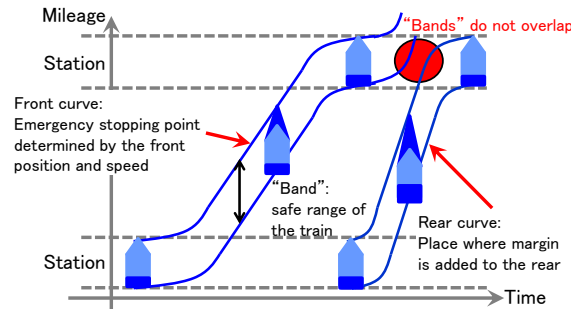


Figure 2: "Band" on the control map

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 Figure 2, a band-like range with two margins is 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 hereinafter referred 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.

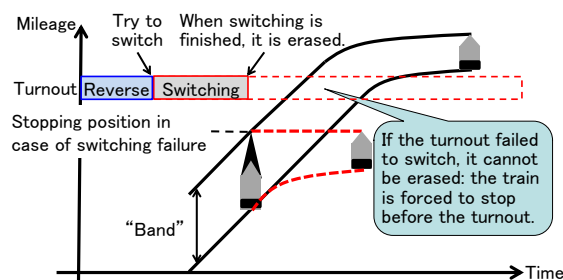


Figure 3: Control of bands and turnout barriers

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 the passage of the train. The barrier will remain on the control map while the turnout is switching and will disappear only when switching is confirmed to have been completed 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

controlled according to the instructions. There may be cases, however, where instructions are not delivered because of disruptions or delays in transmission. The operations control device, therefore, also has a function of collecting data regarding the latest position and speed of each train, and the state of equipment, for sequential scheduling of the control map (Figure 4).

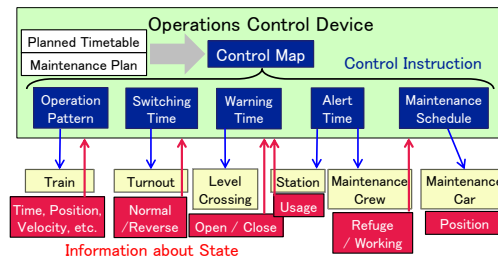


Figure 4: Data flow in operation control

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

2.3 Minimization of headway control around a station

If an accurate timetable and moving blocks are applied and the headway between trains can be shortened by advanced train control, it will be expected to restore the operation quickly and secure transportation capacity in the case of disturbance.

On the premise that the time when the preceding train leaves a station can be forecasted, a method for approaching the following train in such a manner as to make the headway shortest under the fixed block was devised.^[5] In addition, this method is installed in the simulator after making an improvement in that it can be applied sequentially.^[6] On the other hand, we devised a new control method for minimizing the operation interval even under moving blocks.

(1) Premise on approach control

In a simple station as in Figure 5, the speed of following train's speed is limited only by the pattern according to the rear end of the preceding train or the end of the platform track. Switching to acceleration or deceleration shall be performed instantaneously.

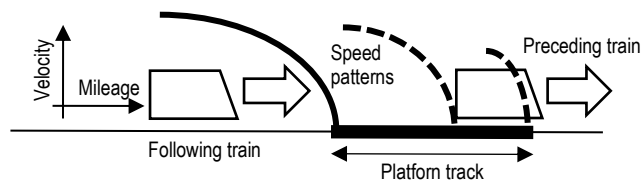


Figure 5: Image of approach under the moving block

Once the position and speed of the preceding train are known, it is possible to properly control the following train. Even if the preceding train suddenly stops, the following train can be safely stopped within the range of the band. Also, even if the preceding train does not depart as planned, control of the following train can be reset by updating the timetable

(2) Ideal approach control

Figure 6 shows an example of ideal control which is also handled that the end of preceding band and the front of following band coincide.

The following train approaching at the maximum deceleration relaxes the deceleration from the time of the departure of the preceding train. The moment the speeds of the preceding train and the following train coincide, the following train turns into acceleration. The following train gradually increases the acceleration so as not to disturb the rear end of the preceding band, and if the acceleration of the front end of the following band and that of the rear end of the preceding band matches, the acceleration becomes constant.

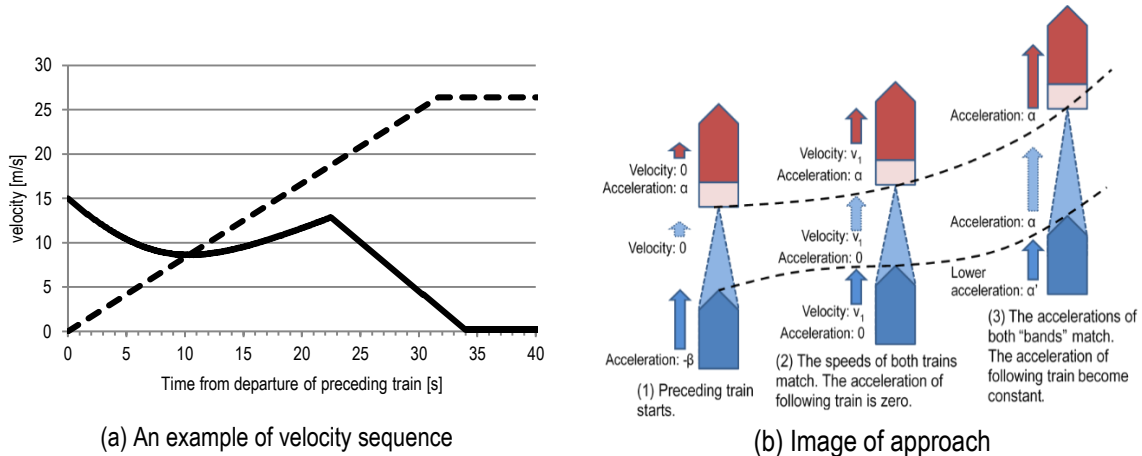


Figure 6: Ideal approach control

(3) Approximate control

Based on the properties in Figure 6, we devised an approximate control with fewer points at which to control the speed of the following train.^[7] Image of the control is shown in Figure 7. Each value is defined by the following formula (1).

$$T_1 = \frac{V_0}{2\alpha + \beta}, T_2 = 2T_1, T_3 = \frac{2(\alpha + \beta)}{\beta(2\alpha + \beta)} V_0, \alpha' = \frac{-\beta + \sqrt{4\alpha\beta + \beta^2}}{2} \dots\dots\dots(1)$$

By changing the acceleration at only two points, it is possible to make the gap between both the bands closer.

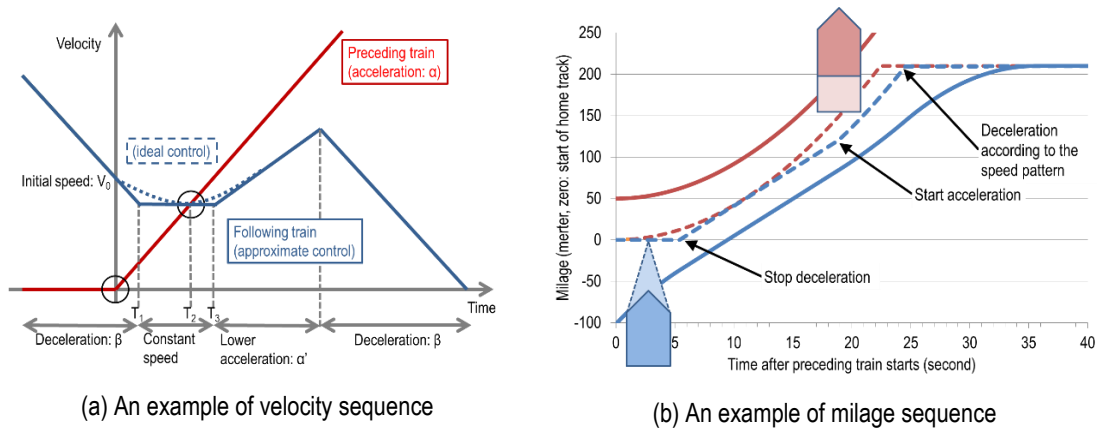


Figure 7: Image of approximate control

3 STUDY OF SYSTEM ARCHITECTURE

3.1 Network Load

Given that the operation of an entire line in the new system depends solely on the operations control device, there is concern about a risk of bottlenecks forming due to the concentration of information (i.e. control instructions and status information) channelled into 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 the 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 the conventional system as a reference, an example of a centralized network was set up (Figure 8).

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 are sent to the equipment.

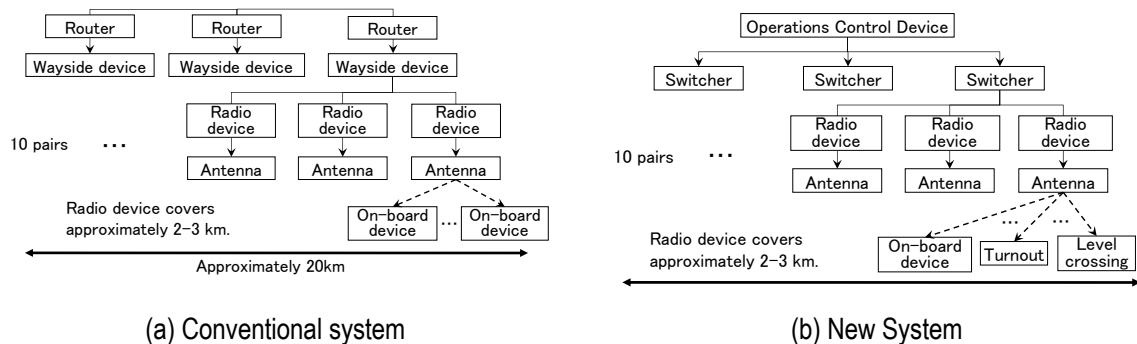


Figure 8: An example of network architecture

(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.

Table 1: An example of the format of control data

Content	Type	Volume	Remarks
Time stamp	Integer	2byte	
Serial number	Integer	2byte	Number of control map
Sender ID	Integer	2byte	Identifying line
Destination ID	Integer	2byte	Identifying device type
Position	Integer	2byte	Position of destination device
Instruction core		14byte by 10	10 time points (5sec / 0.5 sec)
On-board ID	integer	2byte	
Time point	float	4byte	
Position	float	4byte	Operations control device manages stopping limit point.
Velocity	float	4byte	
Redundant code		30byte	
Sum of volume		180byte	

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 times interruptions are repeated consecutively 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" from the operations control device was assumed to be the same volume as is contained in the five-second "band", i.e., a band for five seconds from the current time on the schedule.

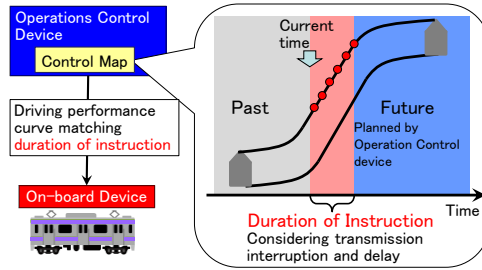


Figure 9: Control instructions

Figure 9 illustrates control data being sent to an on-board device. In the case where the control data band is shorter than 5 seconds, the on-board device will not have sufficient control data even if the number of times of data transmission interruptions is not more than 3, i.e., the maximum allowable number, which triggers the application of the emergency brake. Conversely, if the control data exceeds 5 seconds, this indicates the transmission of redundant information and an increase in the burden on the transmission path.

(4) Results of the simulation

In order to verify the load on the network in 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 devices about 2.3 times as many as the ones in the actual system, 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 10 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.

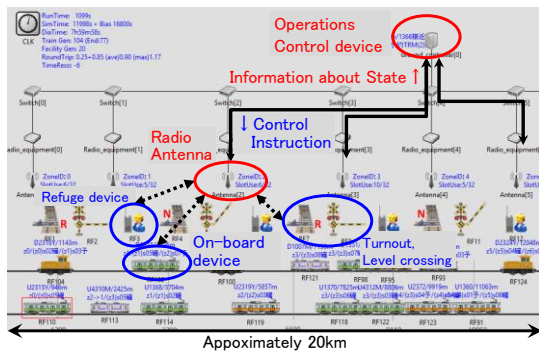


Figure 10: Image of simulation by "TCNET"

Table 2: Configuration and result of the simulation

		8 trains	30 trains	
Configuration	Number of antenna	10		
	Communicable device	36 per antenna		
	Transmission cycle (second)	1 sec		
	Transmission speed (bps)	wired:10M,wireless:64k		
	Length of packet (byte)	wired:7740,wireless:180		
Result	Line utilization (wired)	Operation control => switcher	12.9%	12.9%
		Switcher => operation control	13.3%	12.7%
		Switcher => radio device	1.3%	1.3%
	(wireless)	Radio device => switcher	1.3%	1.2%
		Antenna => on-board	21.6%	32.9%
		On-board => antenna	11.3%	23.0%
Round-trip time (second)		Ave.: 0.90, Max.:1.17		

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 taking 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 either 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 so as 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 applied and an alert is sent to the operations control device.

3.2.2 Safety analysis

A safety analysis was made with respect to 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 analysed by FMEA (Failure Mode and Effect Analysis) and FTA (Fault Tree Analysis).

(1) FMEA

Table 3 shows the FMEA on the control map.

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
Operations control device	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
	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		

A recognition error in a device leads to 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 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 being forced to stop by means of setting the allowable number of times of transmission disruption and the maximum delay.

(2) FTA

Events that could lead to an accident were clarified using FTA; collision and derailment were set as top events (Figure 11).

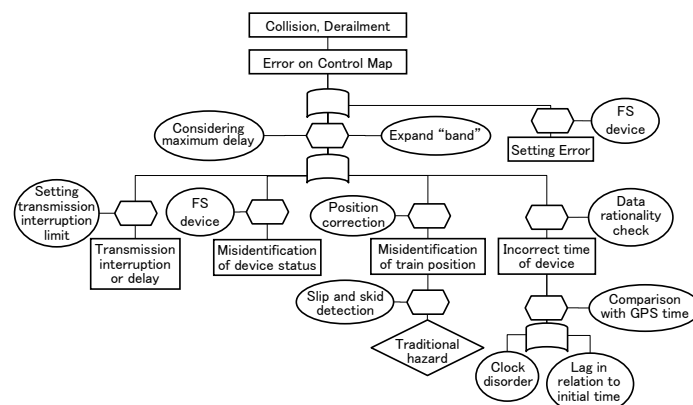


Figure 11: FTA for establishing a control map

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 that for stopping a train 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

The availability of this system is reduced at times due to safety control and device malfunction. In this report, we focus on the latter case, then compared the conventional and the new system (Figure 12).

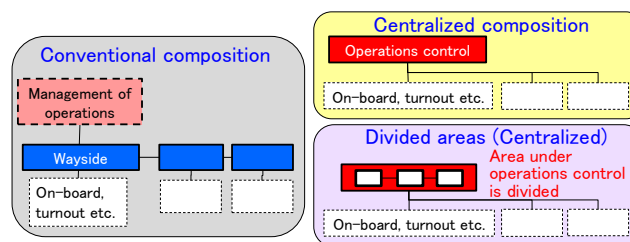


Figure 12: Configurations of the devices

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 in which the internal area is divided.

Table 4 shows a model line with 3 wayside devices

Table 4: Devices in the system

Device	Conventional	Centralized	Divided areas
Operations control	1	1	3
Network	1	1	1
Wayside	3		
Turnout control	6	6	6
On-board	3	3	3
Refuge	3	3	3
Total	17	14	16

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 devices (on-board devices, turnouts, 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 the system availability calculated on the above assumption are shown in Table 5 and Figure 13.

	Conventional	Centralized	Divided areas
Failure frequency (per year)	1.49	1.23	1.40
Total downtime (hour)	1.58	1.40	1.28
Mean time to repair (hour)	1.06	1.14	0.92
System availability (%)	99.982	99.984	99.985

Table 5: System availability in each configuration

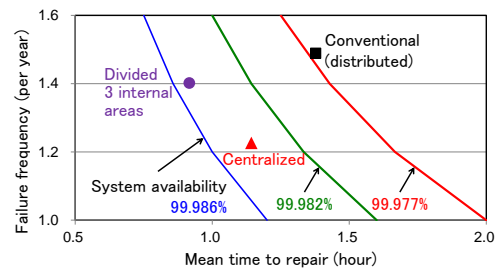


Figure 13: System availability in each configuration

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 VERIFICATION OF CONTROL

As for the function of ensuring safety, we demonstrated with the simulator that the train can be stopped in cases where something wrong occurs. We also demonstrated that approach control can be performed to shorten the headway between the preceding train departing from a station and the following train approaching the station in order to confirm the function of improving performance.

4.1 Optimal approach control

The nearly optimal approach control at the station described in Section 2.3 was demonstrated with the above-mentioned simulator "TCNET". Assuming that the departure time of the preceding train is known, at the moment the preceding train departs, the following train starts speed control to shorten the headway regardless of the scheduled control. The screen of the simulation is shown in Figure 14, and the changes in the speed and position of the following train are shown in Figure 15.

As shown in Figure 15, it can be seen that the headway until the following train arrives at the station is shortened.

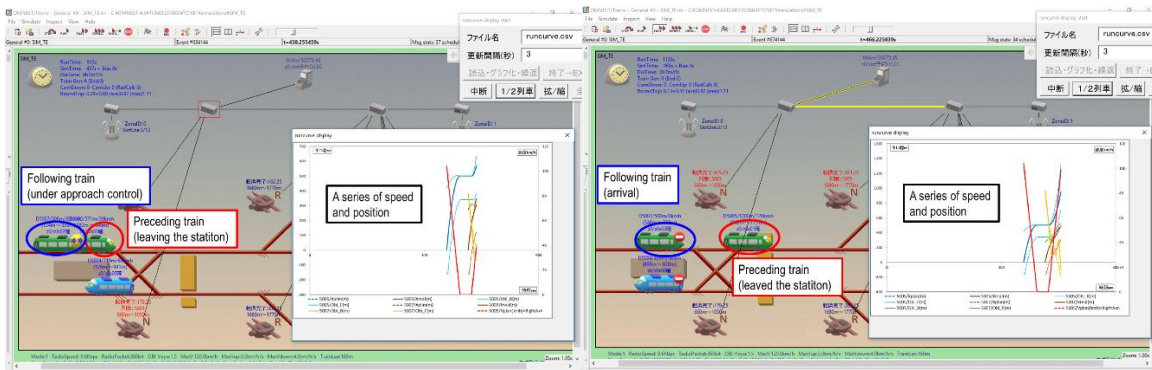


Figure 14: Demonstration of approach control (left: under control, right: stopped)

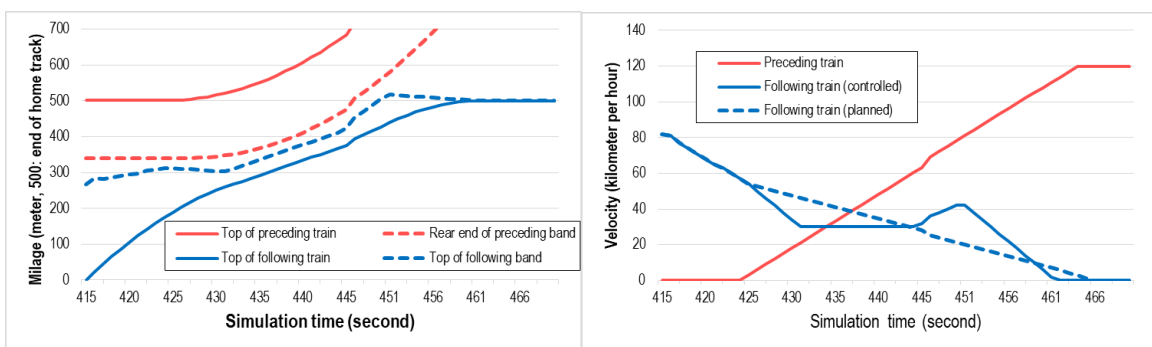


Figure 15: Result of approach control (left: mileage, right: velocity)

4.2 Safe control

We have also demonstrated using "TCNET" that the train can be safely stopped even if a transmission error occurs between the central operations control device and each train. The screen of the simulation is shown in Figure 16.

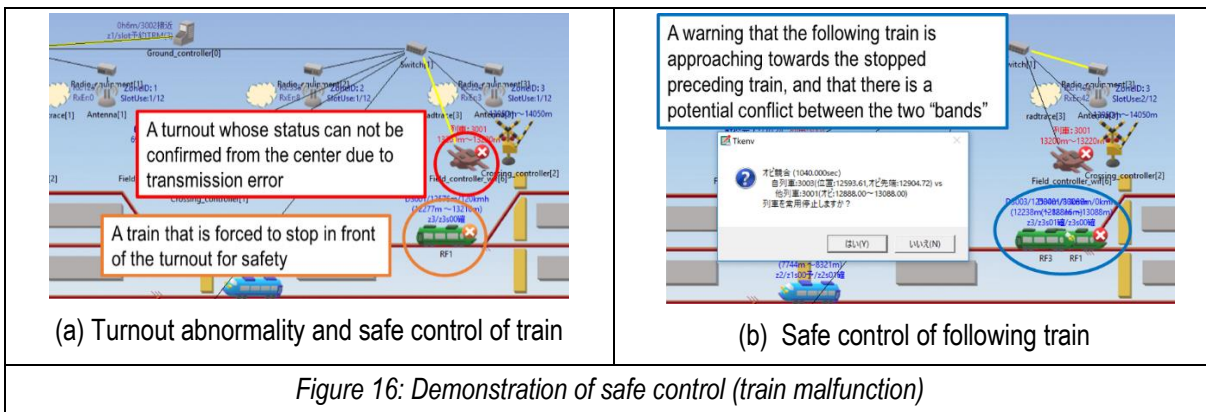


Figure 16: Demonstration of safe control (train malfunction)

The train can be stopped even if the operations control device can not recognize the train position due to three consecutive transmission errors. Similarly, the following train can be safely stopped even if the preceding train suddenly stops.

We demonstrated that even if a transmission error occurs between the turnout and the operations control device, the approaching train can be safely stopped before the turnout.

The train can be safely stopped within the "band" even if transmission errors occur in the turnout and the direction of the route cannot be confirmed. The same safety control can be performed even if the turnout cannot be switched.

5 CONCLUSION

We designed a highly flexible train operation system in which data are acquired with due consideration for train operating conditions and device status from an information network being used to transmit operation plans. The paper also summarizes the system's requirements for safety, availability and data transmission therein.

In order to design a system for operating trains according to planned train performance curves, the control method of trains, turnouts, etc. were investigated, and then we 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, and 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 better availability as conventional systems.

Furthermore, we implemented the basic safety control and train approach control in a simulator, and demonstrated that the function can be realized in an environment including the entire network.

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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