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Train Integrity Monitoring System for Freight Trains

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ABSTRACT

Modern railway operating systems require ETCS L3 technology. The core technology of the ETCS L3 system is train integrity monitoring, which continuously provides the current location and states of running trains without full dependency on track-side equipment. ETCS L3-based train integrity monitoring methods for passenger trains based on fixed train formations already exist in present systems. However, freight trains lack a feasible solution because they do not provide electrical power supply to other vehicles except the front-end vehicle and operate under non-fixed train formations. In this paper, we present user requirements, system structure, and system implementation to realize the train integrity monitoring system for freight trains based on ETCS L3. We also propose an algorithm for detecting vehicle separation in freight trains. Additionally, performance analyses were conducted by installing the freight train integrity monitoring system on an actual freight train. As a result of these analyses, we confirmed that the proposed system could be applied as a train integrity monitoring solution for freight trains.

Key Words : ETCS, KTCS, Track Circuit, Moving Authority, Train Integrity Monitoring

Ⅰ. Introduction

European Traffic Control System (ETCS) is classified into three levels: ETCS L1, L2, and L3 according to the transfer procedure of the train control information and the configuring of the trackside devices[1].

In Korea, following the development of KTCS (Korean Train Control System) compatible with ETCS L2, the train control system for KTCS Level 3 high-speed rail that supports automatic train operation is being developed[5,7,11].

The ETCS L1 and L2 use the track circuit installed on the track to detect the train position and determine the movement authority based on a fixed block. ETCS L3 detects the location of the train using the location information transmitted through radio transmission from the train without installing a track circuit and determines the moving authority by applying the moving block concept.

A track circuit was used to detect the presence of a running train on the track. To transmit the detected data, it consisted of an electric circuit to detect the occupancy of a train and a communication module. When a train passes over a track circuit, the electric circuit detects the existence of the train and transmits the position of the train to its onboard equipment.

Movement authority refers to the authority that allows a train to move to a specific location within the constraints of the infrastructure. To control the interval between trains, a fixed blockage was physically applied, and a train entered only when no train occupied the front blockage section. By contrast, moving blockage is a method of controlling train intervals by consecutively changing the blockage sections according to the speed and position of

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Table 1. ETCS Level Characteristics

	Level 1	Level 2	Level 3
train control block	fixed block	fixed block	moving block
information transfer	Line side electronic unit (LEU) transmission	radio transmission	radio transmission
track circuit	O	O	X
railway signal	O	O or X	X

currently running trains. Table 1 lists the main characteristics that distinguish the three ETCS levels.

Figure 1 shows the process of detecting the current location of trains used in ETCS L1, L2, and L3 and creating movement rights.

ETCS L3 reduces the deployment costs by removing the track circuit that provides train location information from the track and minimizes the safe braking distance between trains by applying the movement block concept to movement authority (3) in Figure 1, thereby improving train transportation. To minimize the safe braking distance between trains along with the increase in transport capacity, train integrity monitoring that continuously provides the current location and promptly recognizes dangerous situations, such as separation of running trains, is required.

Generally, passenger trains are in a fixed formation, and power is supplied to each train vehicle. This enables power lines to be connected in loop form between adjacent vehicles, and these power lines are used as train separation signal lines. Therefore, if the intervehicle connector is disconnected owing to an accident during normal train operation, the train separation signal line is also disconnected so that the train separation situation can be detected.

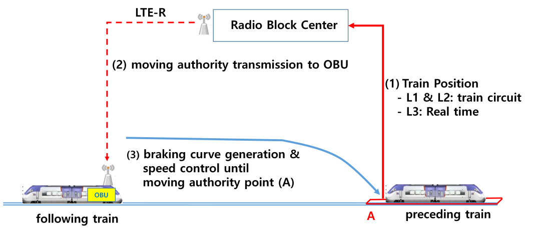

Fig. 1. Train Position Monitoring and Moving Authority Generation Procedure

However, freight electric locomotives or diesel locomotives are operated in a non-fixed formation, and power is supplied only to the front vehicle so that adjacent vehicles are connected by brake pipes that do not require power. When a vehicle is separated from the freight train, the brake tube connected between the vehicles of the train ruptures, the pressure drops rapidly, and the scale of the brake tube indicator drops; thus, the railway engineer can check the separation status of the train.

However, in some freight trains, the air filling in the brake pipe is quickly completed when the pressure in the brake pipe is lowered due to vehicle separation; thus, a change in the scale of the brake pipe indicator is not recognized.

ETCS L3 targets a train operating speed of up to 350 km/h without a track circuit; therefore, if it is not detected quickly when a train is separated, it will cause operational problems, such as collision with a subsequent train. Therefore, a new train-separation detection method is required for freight trains is required [2,9].

In this study, we present the system requirements and structure for the implementation of a KTCS L3-based freight train integrity monitoring system and an algorithm for train separation detection in freight trains. Additionally, performance analyses were performed by installing a train integrity monitoring system on an actual freight train, and the applicability of the proposed train integrity monitoring system was verified as a method for detecting train separation in a freight train.

Ⅱ. Implementation of the Train Integrity Monitoring System

In this section, the main requirements that the system should have when applying the KTCS L3-based train integrity monitoring system to freight trains are analyzed, and the system architecture, train integrity monitoring algorithm, and hardware specifications for implementing these requirements are presented.

2.1 System Requirements

The following requirements are considered for the implementation of the KTCS L3 train integrity monitoring system for freight trains operated in harsh environments, where power is supplied only to the engine room of the train [3-6,10].

- A train integrity monitoring system must be able to determine the conductor (overall length) of the train.
- A train integrity monitoring system must determine the current location and speed of a train.
- A train-integrity monitoring system must be able to detect changes in the conductor length of a train in real time.
- The training integrity monitoring systems must support a battery life that can last for at least 24 h.
- The total weight of the train integrity monitoring system must be within 5 kg.
- Train integrity monitoring system must be able to minimize train engineer's intervention.

2.2 System Architecture

The proposed train integrity monitoring system consists of two devices (a train integrity front-end device (TIFD), train integrity rear-end device (TIRD)) and a server (train integrity manager (TIM)), as shown in figure 2. The TIFD and TIRD were installed on the front and rear vehicles of the same train. The TIM server was installed at a train control center. The TIFD consists of two communication interfaces (LTE-R and LoRa), GPS, brake tube process monitoring (BTPM), and a microcontrol unit (MCU) that controls and manages all of these modules. In contrast to TIFD, TIRD adds battery life management (BLM) to its own power supply and excludes BTPM. The TIM server consists of an LTE-R communication interface, graphic user interface (GUI), pairing management (PM), train separation monitoring and decision (TSMD), and TIM parameter configuration (TIMPC).

In the two communication interfaces installed on each device, LoRa was connected through direct communication between the TIFD and TIRD, and LTE-R was connected through indirect communication between the TIFD and TIRD through a base station. The TIRD simultaneously transmits a message containing the transmission time and current location information at 1-second intervals to the TIFD through both the LoRa and LTE-R interfaces.

The GPS installed on each device was used to estimate the current location and speed of the train. In the TIFD, the BTPM automatically detects the change in air pressure in the brake pipe connected throughout the vehicle in the form of contact information (on, off) and is mounted on the main board in the form of a clay board.

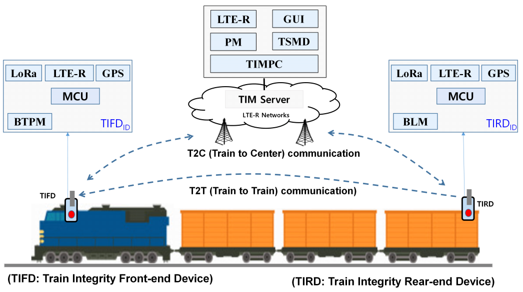

Fig. 2. Train Integrity Monitoring System

2.3 Train Integrity Monitoring Algorithm

The train integrity monitoring algorithm consists of two steps. One is the pairing process and the other is the train separation detection process. The pairing process determines a pair of TIFD and TIRD installed on the same train. The train-separation detection process detects the separation of running trains. As shown in figure 3, the pairing process starts when a train engineer keys a train number after the TIFD power is turned on. The TIFD sends a registration

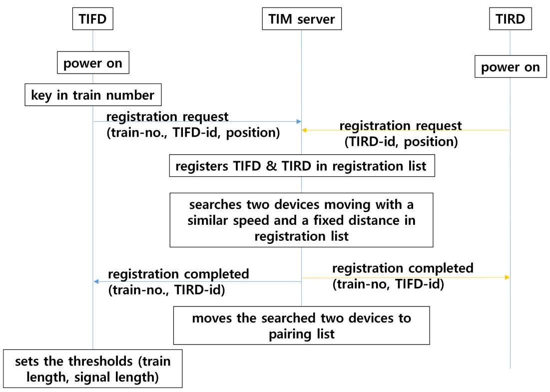

Fig. 3. Pairing Process

request message that contains information such as the train number, device ID, and current position. The TIRD also sent a registration message containing its device ID and current position, excluding the train number. After receiving a registration request message, the TIM server registers the device in its registration list and searches for two devices moving at a similar speed and fixed distance in its registration list. If the TIM server finds a pair that satisfies these conditions, it knows that the two devices are installed on the same train, and these devices are moved into its pairing list. The TIM server then sent a complete registration message to the two devices. The registered message contains the device ID of the other pairing that communicates with each other. Finally, TIFD sets the real train length (RTL) and threshold of the received signal strength indicator (TRSSI) to determine the train separation. The RTL is set as the distance between the paired TIFD and TIRD of the train. The TRSSI is set as a sufficient RSSI value to determine train separation in GPS-shaded areas such as tunnels.

The proposed pairing process identifies a pairing device installed on the same train only when the train is moved. It is possible to automatically set up a pair of devices without phone calls among the train engineers. The engineer's interventions are simply to attach/detach a TIRD device from the rear vehicle of a train and input the train number to the TIFD installed in the operator's room.

Figure 4 shows the train separation detection process. The TIRD receives GPS data periodically during train operation and extracts the position and reception time from it. The TIFD transmits a TIRD status message containing these data to both the TIM server and TIFD through the LTE-R and LoRa interfaces.

Upon receiving a TIRD status message, the TIFD sends a TIFD status message to the TIM server. In addition to the TIRD position and reception time of the received TIRD status message, The TIFD status message contained the GPS position and reception time. The TIFD then monitors whether train separation has occurred or not. To determine train separation, TIFD calculates the current train length

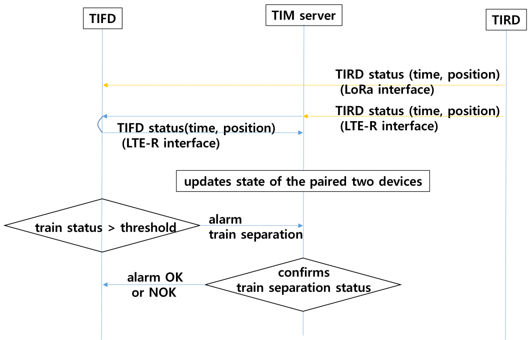

Fig. 4. Train Separation Detection Process

(CTL) using (1) and compares it with (2).

$$CTL = TIFD.position - TIRD.position \quad (1)$$

$$\text{If } (CTL \geq (RTL + \tau)) \text{ trains the separation,} \quad (2)$$
$$\text{otherwise, Normal state.}$$

where τ is the maximum distance tolerance error. The τ may be estimated through measurement during train operation or may be estimated using the maximum position tolerance value of GPS. By (2), if CTL is equal to or greater than (RTL + τ), the TIFD sends an alarm message to the TIM server to finalize the train separation. If the TIFD receives an OK alarm message from the TIM server, it rings the alarm bell of the TIFD.

The TIM server relays a message to the TIFD whenever it receives a TIRD-status message. After receiving the TIFD status message, the TIM server updates the states of the paired TIFD and TIRD. Upon receiving an alarm message from the TIFD, the TIM server checks for the presence of another TIRD attached to the train attached the TIFD. If there is another TIRD, the TIM server sends "no alarm" message to the TIFD. This occurs when the number of train vehicles at the start station is reduced at the intermediate station. That is, it occurs when a train engineer attaches another TIRD to the newly formed rear-end vehicle of the train without detaching the existing TIRD. If there are no other TIRD, the TIM server sends an "alarm message" to the TIFD.

In contrast, the RSSI threshold is used to determine whether trains are separated in GPS-shaded areas such as tunnels. If a train is running in a tunnel section, the TIFD compares the TRSSI with the received current RSSI (CRSSI) from the TIRD, using (3).

$$\text{If (CRSSI} \geq \text{TRSSI) Train separation} \quad \text{Otherwise, Normal state} \tag{3}$$

As a result of the comparison of Equation (3), if the CRSSI value is greater than or equal to the TRSSI value, it is determined as train separation; if not, it is determined as a normal state. Train separation is a serious event, and it is difficult to judge train separation from a single comparison result. Therefore, the final judgment of train separation was made after receiving more than a few messages. Additionally, the engineer decides to separate the train by synthesizing various events that can determine the separation of the train, such as the status of the contact interface of the brake pipe and side lamp.

2.4 Hardware Specifications

Figure 5 shows the hardware structure of the training-integrity monitoring system.

Table 2 lists the specifications of the main items used in the hardware prototype.

Table 2. Hardware Specification

Item	Specification
GPS	· Satellite: GPS, GLONASS, BeiDou, Galileo
LoRa	· 900MHz (ISM Band)
LTE-R	· 700 MHz LTE, FDD (B28)
MCU	· ARM 3358 CPU
Interface	· Ethernet: 100Base-T · Serial: RS232/RS422/RS485 · 3.3V TTL · SIM: Micro SIM · Micro USB
Power	· AC/DC Adaptor (5V DC, 3A) · Li Polymer Battery (3.7 DC, 20,000mAh)
S/W	· OS Linux Debian 9.x · C++ language

Ⅲ. Performance Analysis and Results

A performance test of the train integrity monitoring system was conducted on freight trains operating at

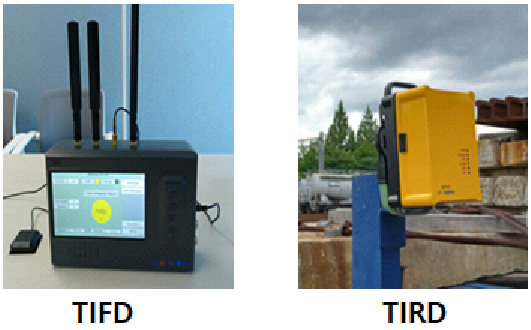

Fig. 5. Hardware Structure for Train Integrity Monitoring

Dongbaek Mountain Station and Dogye Station in Gangwon-do. A Solan Tunnel is present in this section. It is approximately 16.2 km length and is the longest tunnel in our country. The test conditions were as follows.

Train length : 20 cars × 15 m (1 car length) × 300 m
- Packet size: 30 bytes
- Train speed: 0 to 80 km

Under these test conditions, the change in train length owing to the movement of trains in the remaining sections, except for the tunnels, is shown in Figure 6. The maximum and minimum and average lengths of the train were 346 m, 257 m, and 291 m, respectively, and the standard deviation was 8.28 m. From this result, if the maximum distance estimation error value τ is set to 50 m or more, train separation can be determined as train separation if the CTL value is 350 m (RTL (300 m) + τ (50 m)) or more. Under the same test conditions, the packet transmission performance test results showed a success rate of 100% in LTE-R and 57% in LoRa when 8082 packets

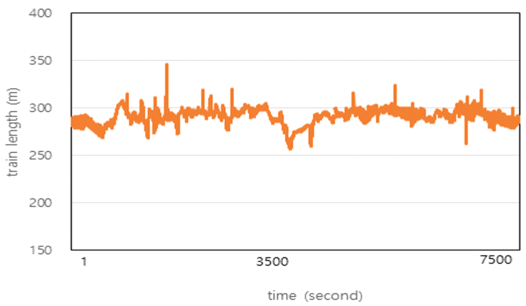

Fig. 6. Train length variation according to train movement

were transmitted simultaneously through the LTE-R and LoRa interfaces.

Figure 7 shows the test configuration for measuring the LoRa RSSI value in the Solan tunnel section in Gangwon-do Province. A TIRD was installed within the Solan Tunnel, and a TIFD was installed on the front vehicle of a train running in an open section. The TIM server manually sets up the fairings of the two devices before testing. The TIRD in the tunnel transmitted an RSSI value every second.

Figure 8 shows the RSSI values measured at the TIFD installed in front of the train. The RSSI value of the TIFD was set to zero before the train began. The received RSSI value of the TIFD increases as the train approaches the TIRD point installed within the tunnel, and slowly decreases after the train passes the TIRD point. These results in Figure 8 show that, if the received RSSI in the tunnel section falls by under -110 dB, it can be used as a threshold for warning that the train is separated.

Although the RSSI value of the LoRa signal is used for distance monitoring only in tunnel environments, interference and security issues remain to be solved. The inference of the LoRa from the adjacent channel can be reduced by controlling the radio channel power or the spreading factor. The algorithm and key-distribution scheme for security and authentication were studied and recommended by the LoRa Alliance[8]. Additionally, the security implementation of the train integrity system was performed.

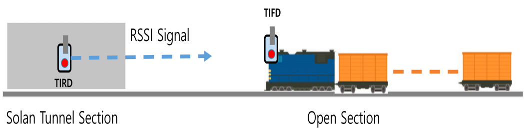

Fig. 7. Test configuration to measure LoRA RSSI values measured by TIFD module in the tunnel

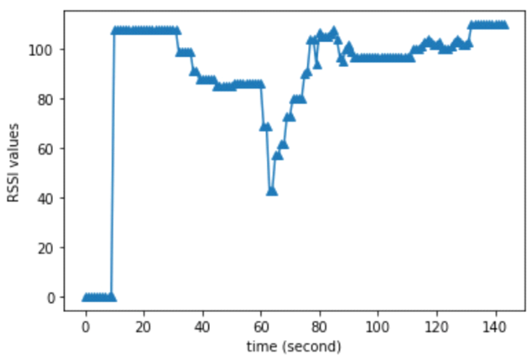

Fig. 8. LoRa RSSI values received by TIFD according to distance between TIFD and TIRD in the tunnel

Ⅳ. Conclusions

In this study, as the railway operating system is transformed into ETCS L3, we investigate the train integrity monitoring function for freight trains currently in operation and present a new train integrity monitoring function to address the constraints.

Additionally, the system requirements and structure for the implementation of an ETCS L3-based freight train integrity monitoring system were presented to realize the integrity monitoring function over ETCS L3-based freight trains, and an algorithm for detecting the unexpected separation of freight trains was proposed. To analyze the performance, the proposed freight integrity monitoring system was mounted on actual freight trains. The results confirmed that the proposed system can be applied as a training-integrity monitoring system for freight trains.

Further studies are aimed at analyzing the performance of the proposed system and estimating the exact threshold by conducting extensive tests over a long period in environments with various train lengths and tunnels.

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