DEVELOPMENT OF A NEW LEVEL CROSSING CONTROL SYSTEM UTILIZING COMMERCIAL MOBILE NETWORK AND GNSS

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ABSTRACT

East Japan Railway Company is working to streamline its facilities as the number of workers decreases due to the declining birth-rate and aging population in Japan. The analysis of life cycle costs related to signalling equipment shows that the majority of the costs are for level crossing safety equipment. A new developing level crossing control system depending upon mobile networks and GNSS, will streamline the equipment and improve level crossing safety and reliability by reducing the train detecting sensors, which are usually equipped with track circuits, level crossing emergency signals, which inform danger at level crossings to the driver, and the dedicated cables. There are many issues to be addressed in order to use mobile networks and GNSS before applying to the train control system, and it is necessary to establish methods to ensure safety and required level of availability. In our previous paper, we conducted an FMEA/FTA analysis to identify hazardous events for this system. This paper proposes an advanced method for level crossing control including train speed control and suggests the ways to ensure the safety and reliability of the system according to the previous hazardous analysis. As the running test result of the prototype devices on the Hachiko Line, the probability of mobile network disconnection between the control server and the on-board device was 9.9×10^{-7}/h. Localization error rate using GNSS was calculated as 0.18% to the actual distance. The running test result showed that safety and reliability of the system meet the level required for revenue service. We are targeting to start using this system on the Hachiko Line in 2025 as first revenue service.

Keywords: level crossing, mobile network, GNSS.

1 INTRODUCTION

The electric department of East Japan Railway Company is working to streamline its facilities as the number of workers decreases due to the declining birth-rate and aging population. The Signalling Division in the electric department maintains a variety of equipment, including signal, interlocking system, track circuit, point machine and level crossing equipment. According to the survey, level crossing equipment at local branches cost 34% of the total maintenance costs of all signal facilities, and the number of fault responses to level crossings accounts for 75% of the total number of fault responses. On the other hand, level crossing equipment is required to have the same level of safety in rural areas as in the Tokyo metropolitan area, and investments are continuously being made to improve safety. We have been working since 2018 on a new system development project to streamline level crossing equipment while increasing safety, especially on rural routes that are difficult to maintain [1]. The new system will reduce field equipment and improve safety by utilizing the general-purpose technologies of mobile networks and GNSS for level crossing control. There are many challenges to utilizing general-purpose mobile network and GNSS for railway safety equipment, and it is necessary to establish a methodology to ensure safety and achieve a certain level of availability. In this paper, we propose a new level crossing control method that utilizes general-purpose technology and a concept for ensuring safety. A prototype of the system was developed, and its safety and reliability was verified through running tests on actual trains.

WIT Transactions on The Built Environment, Vol 213, © 2022 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/CR220151

2 OVERVIEW OF SYSTEM

2.1 Legacy level crossing control system

Fig. 1 shows the configuration of our legacy level crossing control system. In the legacy system, a sensor installed on the side of the railway tracks detects trains approaching or passing through the level crossing and controls the level crossing warning. When an emergency button is pressed due to an obstruction on the level crossing road or an obstruction is detected by the obstacle detector, the system notifies the driver of the abnormality by flickering emergency signal installed far away from the level crossing so that the driver makes arrangement to stop the train to avoid a collision. Each device transmits information via cables, and since sensors and emergency signals are installed far from the level crossing, the length of the cables is enormous. These many devices installed on the side of the railway tracks and the cables that connect them have inflated the cost of maintenance.

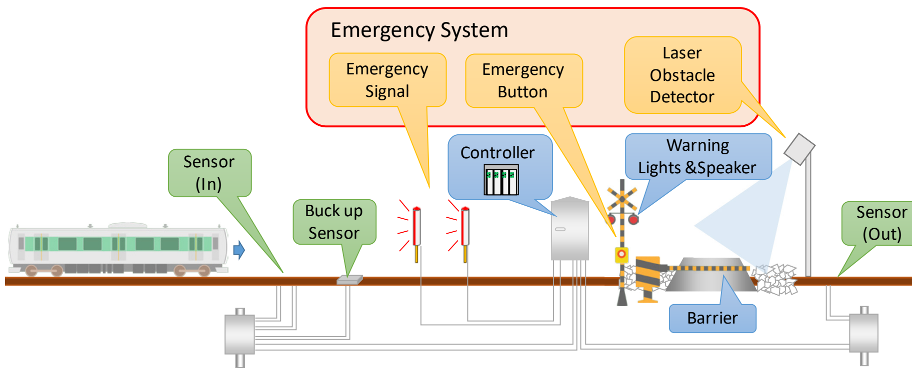

Figure 1: Configuration of legacy level crossing control and emergency system.

2.2 New level crossing control system

In the new system, the concept is to utilize general-purpose technology to reduce field equipment and cables, which are factors that increase maintenance costs in conventional systems. A configuration of the new system is shown in Fig. 2. In the new system, the control server controls level crossings and emergency signal by exchanging information with on-board device, level crossing device, and interface device with interlocking device via mobile networks. The on-board device uses the train position calculated from GNSS speed information to control level crossings and emergency signal.

The features of the new system are listed below.

1. Streamlining of facilities

- Reduction of sensors
  The on-board device to localize the train position utilizing GNSS reduces the number of sensors which have been used to localize the train position until now.
- Reduction of emergency signal
  The system in which the driver is notified of a level crossing obstacle by the blinking emergency signal installed at the site as well as the sound of an alarm in the cab reduces the number of emergency signal.

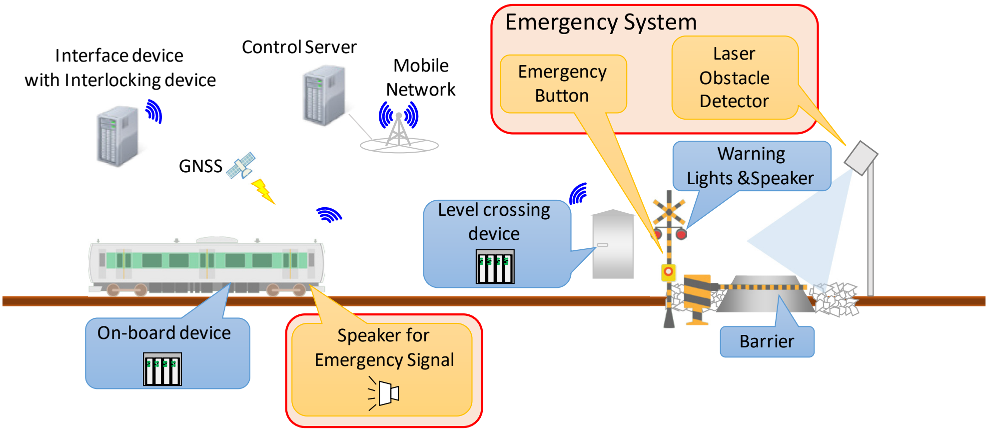

Figure 2: Configuration of new level crossing control and emergency system.

- Reduction of cables
  One server for each control is installed in a train line, and information is transmitted to and from each system (on-board device, level crossing device, and interface device with interlocking device) using mobile networks, thereby reducing the amount of control cables.

2. Improvement of safety

- Train control linked to level crossing status
  By monitoring the level crossing status by a control server and transmitting the status to the train, train control can be performed in accordance with the level crossing status.
  Example 1: Braking a train by identifying a no-barrier condition at a level crossing.
  Example 2: Output a speed profile to stop before a level crossing when an emergency signal is activated.
- Improvement of emergency signal recognition
  By changing the emergency signal at level crossing obstructions to an audible warning signal inside the cab, the system reduces the risk of overlooking or delaying recognition without being affected by poor visibility due to vegetation, fog, or other factors.
- Prevention of no-barrier due to sensor non-detection
  Since the system does not use conventional track circuit type sensors for warnings, it is possible to prevent unstable events due to detection errors such as non-short-circuit.

The introduction of the system will reduce the number of ground facilities, but will require the installation of new on-board device. The life-cycle costs calculated from the installation and maintenance costs on the Hachiko Line were estimated, and it is possible to reduce the life-cycle costs related to level crossing warning control and protective control at level crossing obstruction and obstruction protection by 20–30%, even taking into account the increased costs related to on-board device.

3 CONTROL METHODS AND SAFETY CONCEPTS

Since this system utilizes mobile communications and GNSS for high-risk control of level crossing control and protective control at obstruction, where hazardous events may occur, it is important to analyse safety and control methods based on this analysis. Safety analysis was conducted for the following non-safety events: no warning, insufficient warning time, and failure to send/receive an emergency signal. Hazards were identified and countermeasures were taken using STAMP analysis, an analysis method used to identify non-safety events in the control process, and FTA analysis, an analysis method used to analyse the causes of non-safety events and consider countermeasures [1]. By combining STAMP analysis and FTA analysis, countermeasures were comprehensively examined against non-safety events. This section outlines the basic functions studied based on the analysis and describes how to ensure safety.

3.1 Information transmission

In this system, each device is controlled by exchanging information between the control server and each device via a mobile network. Since the mobile networks utilize other companies' resources and public radio waves, they may be affected by stability due to factors over which we have no control. The mobile networks of two telecommunication companies are used together, and the same information is sent to both lines at the same time, with the first-arrived information being used to ensure stability. The control server sends a polling message to each device every second, and each device exchanges information by sending back an answer message to the control server. If the control server and each device cannot receive a message for three consecutive cycles, the mobile network is assumed to be disconnected and the safety-side operation is performed. As described in Sections 3.3 or 3.4, the safety-side operation at the level crossing device is to warn at the scheduled warning time, and the safety-side operation at the on-board device is immediate stop control. This system is designed to ensure safety even in the event of a mobile network breakdown.

3.2 Train localization

Level crossing waning control is based on the train position calculated by on-board device. The on-board device determines the train position by calculating the distance travelled based on GNSS speed information and adding it to the previous position. Whether GNSS can be valid or not is determined by performing various tests using input information from two antennas installed on the car. This test eliminates incorrect data from the GNSS. As a backup in case GNSS is not available due to structures or other surrounding environments, continuity is ensured by calculating the distance travelled from the speed information obtained from the speed generator as shown in Fig. 3. Position-corrected balises are installed between the rails to correct the position as an absolute position at the time of passage. The train position in the system is added to the train length as a correction value for the error assumed for the distance travelled, thus covering the error included in the GNSS or TG speed information. Each on-board device transmits its own train position to the central unit via a cellular phone line every second, and the central unit manages the position of each train for control.

3.3 Level crossing warning control

Fig. 4 shows an overview of control at the start of a level crossing warning. Level crossing waning start control is performed according to the scheduled alarm time calculated from train

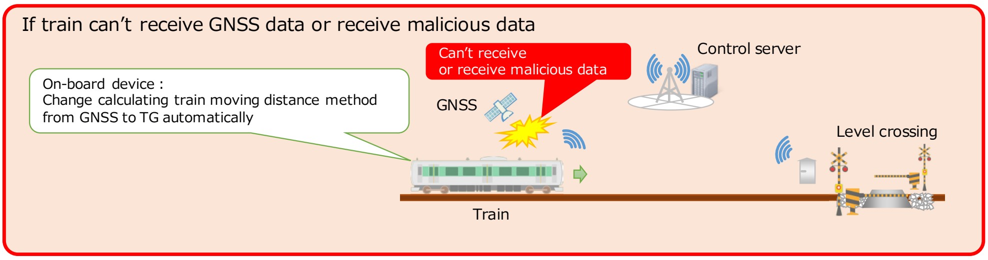

Figure 3: Behaviour when GNSS is not available.

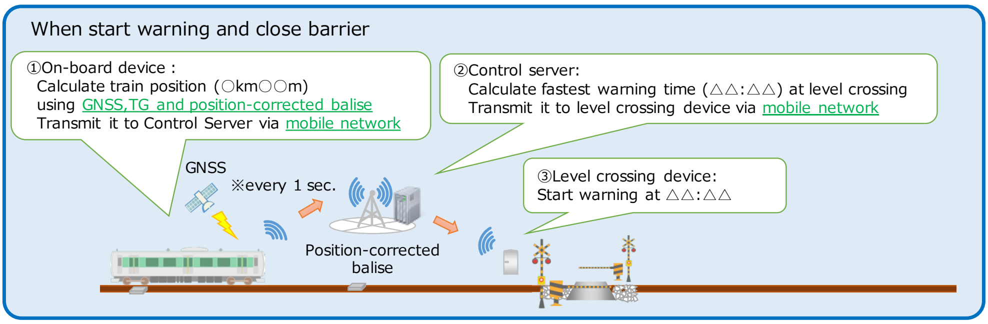

Figure 4: Level crossing warning control (start warning and close barriers).

positions by the control server. The scheduled warning time is the time that the control server calculates based on the train position and the starting position of the level crossing warning in the DB, and is the time that the train would reach the starting position of the warning if it travelled at the maximum speed of the line. The central unit transmits the calculated scheduled warning time to the level crossing device via mobile network, and the level crossing device that receives the information starts warning and closes the barriers when the scheduled warning start time arrives.

If the mobile network between the control server and the on-board device or between the control server and the level crossing device is disconnected and the scheduled warning time is no longer updated, the level crossing device will start warning when the last received scheduled warning time is reached. This ensures that even if the mobile network is interrupted, the level crossing can start warning before the train arrives, so that no interruption or insufficient warning time can occur. Furthermore, trains are prevented from approaching level crossings for which the scheduled warning time has not been set. For example, an indication of progress on the departure signal at the station is issued only when the warning time is set for all level crossing, thereby avoiding the danger of omission of time settings. In addition, the central unit constantly monitors the level crossing warning status, and when a train approaches a level crossing that has not been warned, it transmits information to the on-board device and controls braking to prevent no-barrier.

Fig. 5 shows an overview of the control at the end of the level crossing warning. In the level crossing warning control, the control server determines that the train has moved through the level crossing based on the train position and the location of the level crossing in the DB, and sends an instruction to the level crossing device to terminate warning.

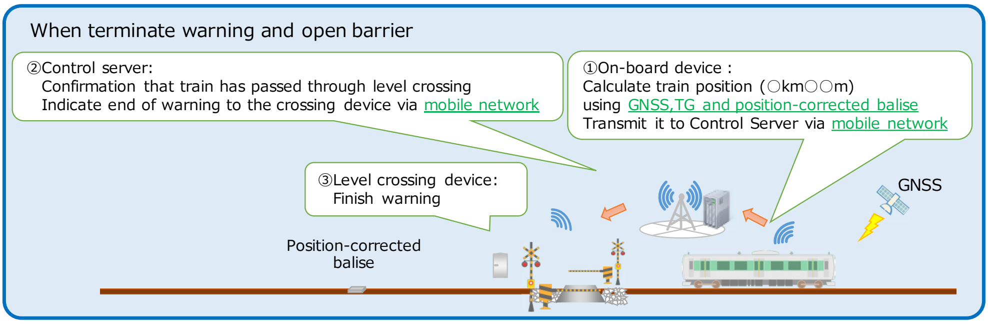

Figure 5: Level crossing warning control (terminate warning and open barriers).

3.4 Protective control at level crossing obstructions

Fig. 6 shows an overview of protective control at a level crossing disturbance. When a level crossing is disturbed and an emergency button is pressed or an obstacle is detected by the obstacle detection device, the level crossing device transmits the emergency information to the control server via mobile network. The control server transmits the emergency information to the on-board device of the train approaching the level crossing where the obstruction occurred. When the on-board device receives the emergency information, it outputs an alarm sound as an emergency signal to warn the driver of the danger. When the driver recognizes the alarm sound, he or she immediately makes arrangements to stop the train. When the on-board device receives the emergency information, it outputs a speed profile that enables the driver to stop before the level crossing. This enables the system to automatically apply the brakes even in the unlikely event that the driver's stopping arrangements are delayed, thereby preventing entry into the obstruction level crossing.

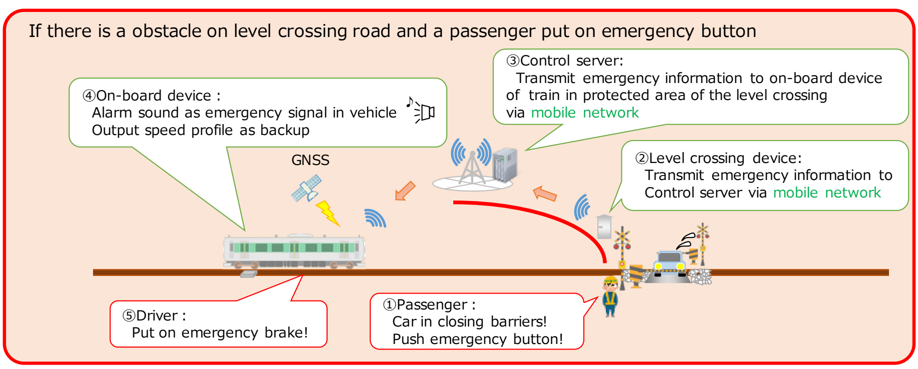

Figure 6: Protective control at level crossing obstructions.

If the communication between the control server and the level crossing device is disconnected, the system assumes that an obstruction is occurring at the crossing and transmits the emergency information to the on-board unit of the approaching train. If communication between the control server and on-board units is disconnected, emergency braking is applied to the train when communication is disabled for three times. This prevents the risk of failure of the obstacle protection due to communication breakdown.

4 TESTING FOR SYSTEM VERIFICATION

A prototype was developed and tested to verify the practicality of the functions of the devised system and the usefulness of the mobile network and GNSS. We conducted a test in the factory and a running test on the test line in advance, followed by a running test on the commercial line to confirm functions and verify data in the commercial environment. The running test in a commercial line on the Hachiko Line were conducted from September 2020 to January 2021. This running test consisted of monitored runs (39 daytime runs, approx.6,000 km) to verify the stability of the mobile network, communication delays, and position detection accuracy when utilizing GNSS, and night time controlled runs (25 night time runs, approx.500 km) to verify basic system functions and safety operation in case of failure. Level crossing devices were installed at two crossings, station devices were installed at two stations (Yorii station and Ogawamachi station), and two test trains were equipped with on-board devices. An overview of the running test is shown in Fig. 7.

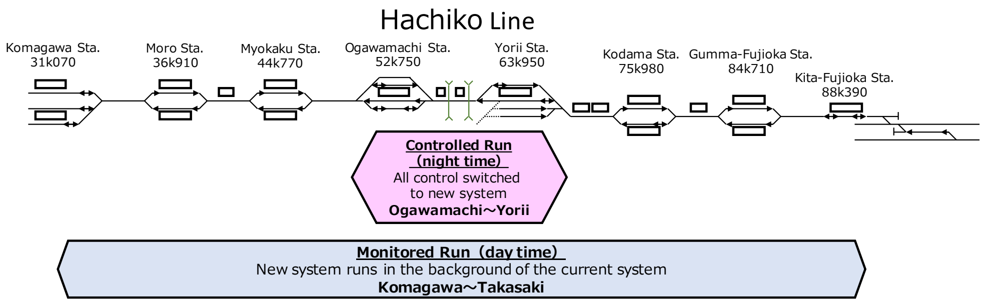

Figure 7: Overview of the running test in Hachiko Line.

5 VERIFICATION RESULTS

5.1 Functional verification

It was confirmed that there were no problems with the basic control functions and the functions to ensure safety in the event of an abnormality by all tests. In the functional verification test, to confirm the safety of the system, it was verified that safety side operations such as emergency stop of trains and blocking of level crossings work in situations where GNSS and mobile networks are not available or when device malfunctions.

5.2 Reliability of mobile networks

The data to be verified was the data transmitted and received by the control server to and from each device in one-second cycles, and the transmission delay and transmission loss were combined to obtain the transmission error rate. Transmission delay occurs when the response time exceeds the time allowed by the system, and 600 ms is used as the threshold value in this test. Transmission loss is considered to occur when there is no response from each device to a transmission from the control server. Table 1 shows the probability of a single transmission error between the control server and ground equipment (level crossing devices and Interface devices with interlocking device) and between the control server and on-board devices, as well as the probability of three consecutive errors that cause the system to operate on the safe side. A frequency of 1.0×10^{-5}/h, which is the frequency of occurrence once every 10 years, was used as the evaluated value of the transmission error rate. If only one company's mobile network is used for both ground devices and on-board devices, the evaluated value will not be met, but by using two companies' evaluated value together, a sufficient connection rate below the evaluated value can be ensured. The results indicate the possibility of utilizing mobile networks for information transmission on Hachiko Line. However, it was found that there are some spots with weak signals in some sections, so implementation of countermeasures will be considered in the future.

Table 1: Transmission error rate in running test.

Transmission error rate with control server (/h)		Mobile network (Company A)	Mobile network (Company B)	Combination of two networks
Grand device	Single	8.76×10^{-2}	5.02×10^{-1}	1.22×10^{-5}
	3 consecutive	1.45×10^{-2}	1.17×10^{-1}	4.72×10^{-7}
On-board device	Single	6.53×10^{-1}	3.47×10^{-2}	2.13×10^{-4}
	3 consecutive	1.17	1.02×10^{-1}	9.89×10^{-7}

5.3 Train localization accuracy by utilizing GNSS

The train localization accuracy was verified by comparing the distance travelled by the system with the distance actually measured from the previous ground station when the position-correcting ground station was detected. Table 2 shows the results of train localization accuracy in the running test. The train localization accuracy by utilizing GNSS was found to be 0.18% as an error rate relative to the distance travelled, which is within the2% accuracy assumed at the time of the test, and therefore, the system was found to detect the position with high accuracy as expected. The adoption rate of GNSS in this case was 95%. Since the accuracy of train localization by utilizing GNSS was 0.63% when position detection was performed only by tacho-generator generators, it is possible to perform train localization with higher accuracy by utilizing GNSS. This system ensures safety by extending the train length relative to the distance travelled according to the assumed accuracy. The reliability of the train position is high because the average accuracy is lower than the assumed accuracy, even when three times the standard deviation is taken into account, and this allows the control of level crossings to be achieved with safety ensured. In addition, it was found that GNSS could be used to localize the position without being affected by idling, slipping or changes in wheel diameter. The results indicate that the use of GNSS may be effective.

Table 2: Accuracy of localization in running test.

Localized method	GNSS+TG (GNSS 95% adopted)	TG only
Total distance	3,713 km	4,890 km
Error distance per 1 km	−1.8 ± 2.4 m	6.3 ± 8.5 m
Accuracy	0.18%	0.63%
Assumed accuracy	2.%	4.0%

6 CONCLUSION

This paper proposes a control method and a concept for ensuring safety for a new level crossing control system by utilizing GNSS and mobile networks to reduce maintenance costs at local line sections. In addition, a running test in Hachiko Line using a prototype of the system was conducted to confirm its functionality and to verify the reliability of the mobile line and the accuracy of position detection by utilizing GNSS. The running test result shows that safety and reliability of the system meet the level required for revenue service. We are targeting to start using this system on the Hachiko Line in 2025 as first revenue service. By implementing this system, we are expected to reduce the lifecycle cost of level crossing equipment by about 20%.

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