Full-automatic Operation System for Nanakuma Line Subway in Fukuoka

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OVERVIEW: The Fukuoka City Transportation Bureau's Nanakuma Line Subway, constructed to relieve chronic congestion in the southwest section of Fukuoka, Japan, to provide an efficient and convenient public transportation system, and to further promote well-balanced urban development, went into service on February 3, 2005. Existing lines built over the past 20 years have been the driver-only operation type, but with this line for the first time in Japan a full-automatic operation system was applied to a subway line, a system that supports "the Fukuoka plan," flexibility for diversity of train crew personnel employment.(1) Implementing full-automatic operation on a subway involves much more than simply automating the navigation of the train per se, for it requires careful consideration of the security and riding comfort of passengers while ensuring their safety in the face of various abnormal events that might occur. Building on the company's accumulated technical expertise with driver-only operating systems, Hitachi was brought in early to participate in the development of a subway full-automatic operation system that is safe and efficient, and charged with the development of two key systems that are at the heart of the full-automatic operation system: the traffic control system and the train system.

INTRODUCTION

CONSTRUCTED by the Fukuoka City Transportation Bureau as the optimum solution to alleviate the chronic congestion in the southwest quarter of the city, the Nanakuma Line Subway takes about 24 minutes from the Hashimoto Station at one end of the line to the Tenjin-minami Station at the other end. The line connects a total of 16 stations that are relatively short-spaced an average of 800 meters apart. The most intriguing aspect of the new line is that it is the first

Fig. 1—Fukuoka City Transportation Bureau's Nanakuma Line Traffic Control System and Series 3000 Train.
The traffic control system and Series 3000 train designed and manufactured by Hitachi are the heart of the new full-automatic operation system, the first time this kind of system has been applied to a subway in Japan.

subway built in Japan using a full-automatic operation system that achieves an efficient and highly convenient transportation facility while at the same time absolutely ensuring rider safety.

Safe operation of a subway full-automatic operation system certainly involves much more than simply automating the navigation of the train per se; it requires the ability to deal smoothly and efficiently with passengers, and especially to ensure passenger safety in the face of potential abnormal events that could occur when the train is operating. After painstaking investigation in collaboration with the Fukuoka City Transportation Bureau, Hitachi designed and manufactured the first full-automatic operation system for subways developed in Japan. This paper will present an overview of the new Nanakuma Line full-automatic operation system run by the Fukuoka City Transportation Bureau, with emphasis on the traffic control system and the train system that Hitachi was charged with designing and manufacturing.

TABLE 1. Basic Functional Requirements for Full-automatic Operation Subway
Basic functional requirements for a full-automatic operation subway are listed.

Basic functional requirements
(1) Methods to prevent trains from stopping between stations, or when stopped, to proceed to the next station.
(2) Redundant systems and equipment directly involved in running the train, so functionality is not interrupted even if one system or equipment unit fails.
(3) Even in the event of loss of auxiliary power such as when the train is stopped between stations because the overhead power lines lose power, key functions including operation functions, contact with the operation control center, and functions putting passengers at ease shall not be lost.
(4) Redundant implementation of key track-side safety equipment, fail-safe configuration of system as a whole.
(5) System to deal with train abnormal events including rapid evacuation guidance and other measures.

FUNCTIONS REQUIRED FOR SUBWAY FULL-AUTOMATIC OPERATION(2)

Prior to Nanakuma Line, no subway line had been constructed in Japan with full-automatic operation capability. One reason is that subways travel through tunnels, and it is assumed that if the train breaks down between stations, it would be very difficult to evacuate the passengers. Highlighting the unique conditions of subways, the following three conditions must be addressed to ensure safe operation of trains:

(1) No stopping of the train between stations
(2) Doing nothing that would arouse uneasiness among passengers
(3) Assurance of operating safety

Table 1 lists the basic functions required for a subway full-automatic operation system to satisfy these three basic conditions.

NANAKUMA LINE FULL-AUTOMATIC OPERATION SYSTEM

Overview of Full-automatic Operation System

In the automatic operation system, the various train operation and risk avoidance tasks that are normally done by the driver in a driver-only operation train based on the ATO (automatic train operation) system must be done either automatically or as a remote operation. To achieve this requires

(1) tight integration between various track-side and on-board systems,
(2) two-way data transmission capabilities between the track and on-board systems, and
(3) implementation as a total system (see Fig. 2).

The full-automatic operation system functions are supported by track-side equipment [traffic control system, interlocking platform door (gate), ATO, train radio equipment, etc.] by on-board equipment [ATO, train radio equipment, train monitoring system series that provides information to the train crew, etc.], and two-way data transmission between track-side and on-board systems is supported by the train radio equipment (all lines) and ATO antennas (deployed in stations).

For dealing with equipment failures and other abnormal events, the train system constantly monitors the state of the equipment and features obstacle detecting, derailment detecting, and various other detecting devices. This monitoring data and other information is transmitted in real time via a radio link to the operation control center, where a decision is made on how best to act on the information. Logging capabilities have also been upgraded, so all the I/O (input/output) from the various systems and equipment (including train operations) are recorded, data that becomes very useful for troubleshooting when problems occur. Passenger safety is markedly improved with interlocking platform doors that effectively prevent passengers from falling off the platform. Inside the trains, passenger information displays and broadcast content have been upgraded, and an emergency intercom system enables passengers

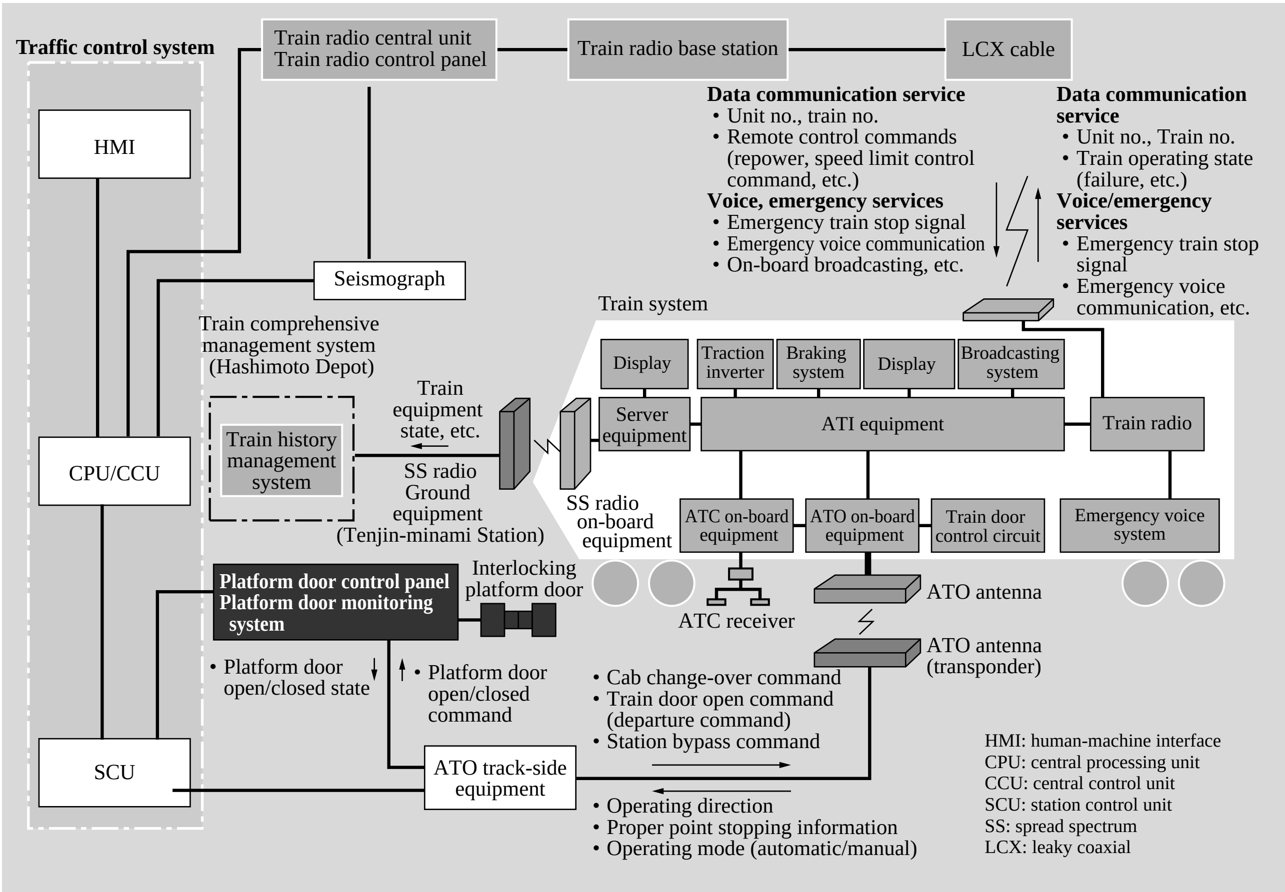

Fig. 2—Schematic Overview of Subway Full-automatic Operation System.
Traffic control system, train system, interlocking platform door, and other related equipment are functionally integrated.

to directly contact the operation control center in case of an emergency.

System and Train Features

System features

Table 2 lists the main systems and functions supporting the full-automatic operation system. The traffic control system consists of the CPU, the CCU, and the SCU, which are all implemented redundantly. In other words, it is configured so that, even if one system fails, the traffic control system switches over to the redundant backup system and the automatic operation continues without interruption. Train control response has also been significantly improved with a centralized system configuration—main functions including train timetable management, train tracking, route control, and passenger information—and distributed systems deployed in each station that receive signals from ATO track-side equipment and interlocking platform doors and are governed by the automatic operation. Status of trains is continually monitored by the train radio central equipment over a

TABLE 2. System Configuration and Functions for Full-automatic Operation
Table lists basic equipment, configuration, and functions needed to support the full-automatic operation system.

Unit name	System configuration, function for full-automatic operation
Traffic control system	• Key equipment: redundant configuration • Train door close command (departure command) • Cab change-over command • Station bypass command • Force door open command • 15 km/h release command function • Repower command function • 15 km/h command function • Front emergency egress door unlock command • Emergency brake maintain/release command function • Force stop command function • Abnormal situation on-board announcement command • Air conditioner operation command function • Train failure state monitoring
Interlocking platform door	• Train and platform door interlock open/close function • Detect abnormality, automatic reopen/reclose function

TABLE 3. Train Equipment Configuration and Functions for Full-automatic Operation
Table lists basic train equipment configuration and functions needed to support the full-automatic operation system.

Unit name	Train equipment configuration and functions for full-automatic operation
ATC equipment	• Redundant implementation of receiver and control unit • Battery backup
ATO equipment	• Redundant implementation of receiver and control unit • Battery backup • Automatic departure with departure command from ATO antenna (transponder) • Automatic forward inching • Repower • Alert when train stopped between stations and report its location • Backup function when train misses mark on track • Station bypass • Speed limit control (when traction inverter fails, in the event of earthquakes)
Train monitoring system	• Main communication line: redundant system • Battery backup
Train radio (voice/emergency systems)	• Main communication line: redundant system • Battery backup • Emergency signal initiation • Emergency brake command when emergency signal is received • Emergency voice communication • Train failure state reports (data communication service backup)
Train radio (data communication service)	• Main equipment: redundant configuration • Battery backup • Emergency signal output function • Remote control command output function from operation control center (repower command, speed limit control to 15 km/h command, front emergency egress door unlock command, etc.) • Train failure state reports
Train door control equipment	• Train door interlock open/close interlocked with platform door • Door obstruction detection, automatic open/close • Side door, front emergency egress door open detection during automatic operation
Others	• Cab automatic change-over circuit • Obstacle detecting device • Derailment detecting device • On-board broadcasting, display equipment (guidance in abnormal case) • Traction inverter (automatic fault reset, unit release function)

radio connection, so if a problem occurs or any equipment fails, this information is immediately conveyed to the central dispatcher for fast remedial action. In addition, the automatic operation system takes some of the burden off the central dispatcher so he/she can respond and make decisions more quickly, and efforts have been made to make the HMI display content and operability as user friendly as possible.

Train features

The main train equipment and function supporting the automatic operation system are listed in Table 3. To ensure that trains never have to stop between stations, all the equipment directly involved in running the train are implemented as redundant system or a backup unit is provided, so if one unit fails, the function continues without interruption. Even if the overhead power line and other auxiliary power equipment fails, backup power is provided by on-board batteries, so operation function, ability to communicate with the operation control center, and functions for making passengers feel more at ease are not disrupted. In other words, even if the overhead power line fails, a passenger can press the emergency intercom button inside the train and speak directly with the operation control center.

Status of on-board equipment is constantly monitored, so if a problem develops, this information is immediately conveyed to the operation control center by radio where they can decide what to do based on the information. In addition, train equipment status data (including failures and dynamic monitoring data) recorded by the train monitoring systems is sent to the Hashimoto Depot via SS (spread spectrum) radio equipment that is deployed on the train and at the Tenjin-minami Station terminal. Finally, there is no partition between the cab and the saloon in the train. This lessens the feeling of confinement inside the train and also gives passengers a sense of security to be able to directly see a train crew.

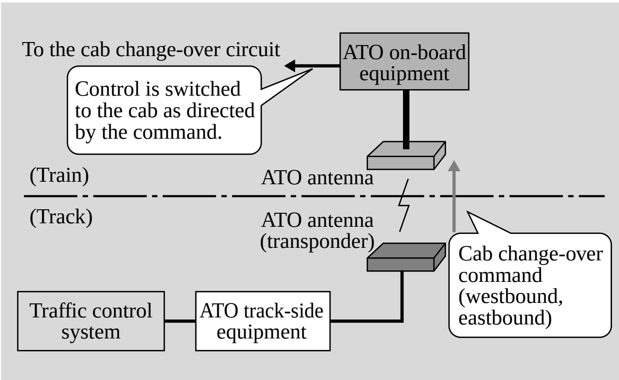

Fig. 3—Schematic of Cab Automatic Change-over Control.
The automatic cab change-over control is mediated through the ATO antenna.

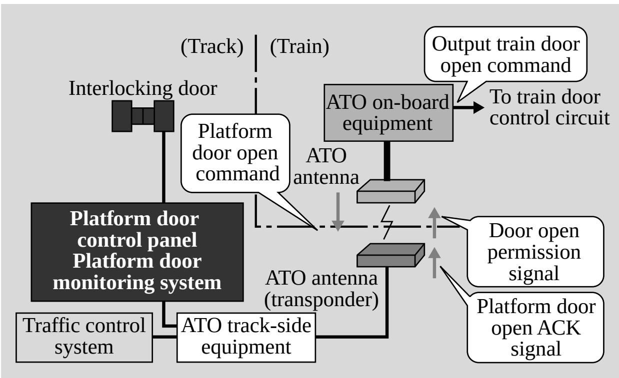

Fig. 4—Schematic of the Automatic Door Open Control.
The automatic door open control is mediated through the ATO antenna.

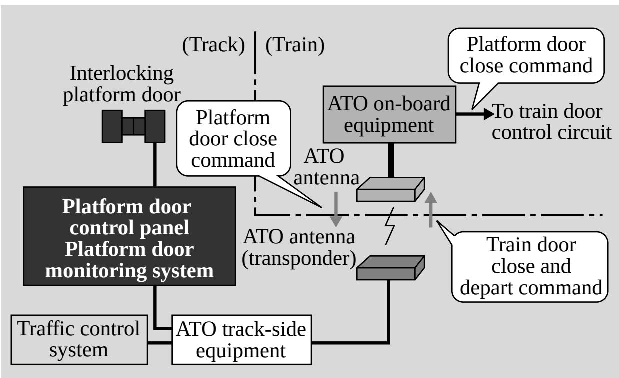

Fig. 5—Schematic of Door Close Control and Automatic Depart Control.
The automatic door close control is mediated through the ATO antenna.

Interaction between Track-side and On-board Systems[3]

Basic functions

(1) Automatic cab change-over control

When the train receives the cab change-over command (i.e. when the train reverses direction) from the traffic control system, this drives the operation direction change-over relay on the train, which automatically switches the traveling direction of the train. This saves considerable time and labor at the two terminal stations at either end of the line (see Fig. 3).

(2) Automatic door open control

(a) When the train stops in the proper position in a station and receives a door open permission signal, the platform door open command is sent.

(b) When the train receives a platform door open ACK (acknowledgement) signal, a train door open circuit is formed and the car doors open (see Fig. 4).

(3) Automatic door close control, automatic depart control

(a) At a brief fixed interval before the train departs, the traffic control system outputs a train door close and depart command.

(b) When the train receives this command, the open train doors are closed, and at the same time, a platform door close command is sent to the track side (the station).

(c) Following a brief fixed interval after the train doors and platform doors are completely closed, the train automatically departs from the station (see Fig. 5).

Functions for dealing with abnormal events

Safe automatic operation of a subway requires capabilities for dealing smoothly and efficiently with passengers to ensure their absolute safety in the face of potential abnormal events. Here we will highlight some of the key functions for dealing with abnormal events.

(1) Onboard equipment failure → Redundant equipment failure transmission paths

It is necessary to notify the operation control center if on-board equipment fails or an abnormal event occurs. However, if there is only one transmission path, the ability to monitor train data is lost if the equipment fails on that one path, so redundant transmission paths are essential (see Table. 4).

(2) Train stopping between stations → Repower function

If for some reason a train being operated by automatic control stops between stations, it is

TABLE 4. Overview of Redundant Train Equipment Fault Transmission Path
Transmission path for transmitting train failure and abnormal data is implemented redundantly.

Transmission path	Transmission information
Train monitoring system → Train radio (data communication service) → Train radio track-side station	Train failure information, train state information
Train monitoring system → Train radio (voice/emergency services) → Train radio track-side station	Train failure information (backup when data communication service fails)
Train equipment/train circuits → Train radio (data communication service, voice/emergency services) → Train radio track-side station	Train failure information (backup when train monitoring system experiences a major trouble)
ATO on-board equipment → ATO track-side equipment	Train state information, train monitoring system major trouble Train radio major trouble (backup when train monitoring system or train radio experiences a major trouble)

necessary if at all possible for the train to proceed to the next station.

(a) The train sends a train stopped between stations message via the train's radio to the operation control center.

(b) After the operation control center verifies the state of the failed on-board equipment and that it is safe to proceed, the traffic control system sends a repower command to the train using the train's radio.

(c) When the train receives this command and conditions are safe for repowering, the train automatically repowers and departs (see Fig. 6.)

(3) Station fires → Station bypass

Obviously passengers cannot be allowed to get off the train at a station where there is a fire, so the train must be capable of proceeding to the next station without opening the doors.

(a) The operation control center sends a station bypass command to the traffic control system, which then transmits the command to the station ATO antenna.

(b) A train receiving this message when it is stopped at a station, immediately departs and automatically proceeds to the next station without opening its doors (see Fig. 7).

(4) Earthquakes → Speed limit control 15-km/h, force stop function

If an earthquake occurs, trains may have to operate at a slow speed or stop altogether to avoid danger and risk to passengers.

(a) Class 4 earthquakes

(i) If seismographs detect a class 4 earthquake, the traffic control system sends a speed limit control to 15-km/h command to trains by train radio.

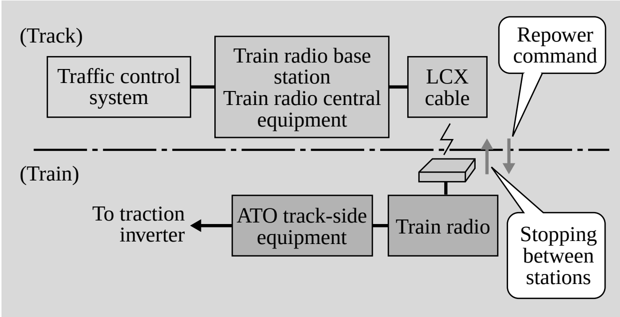

Fig. 6—Schematic of Repowering.
Repower command is transmitted to the train via train radio (data communication service).

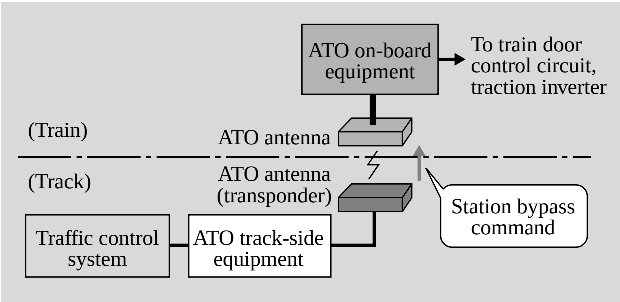

Fig. 7—Schematic of Station Bypass.
Station bypass command is transmitted to the train by the ATO antenna.

(ii) When it receives this command, the train automatically slows to a speed of 15 km/h and continues operating.

(iii) To cancel the speed limit control to 15-km/h command, the operation control center sends a speed limit control to 15-km/h release command to the traffic control system which is output by the ATO antenna.

(iv) When a train stopped in a station receives this command, the speed limit control to 15-km/h

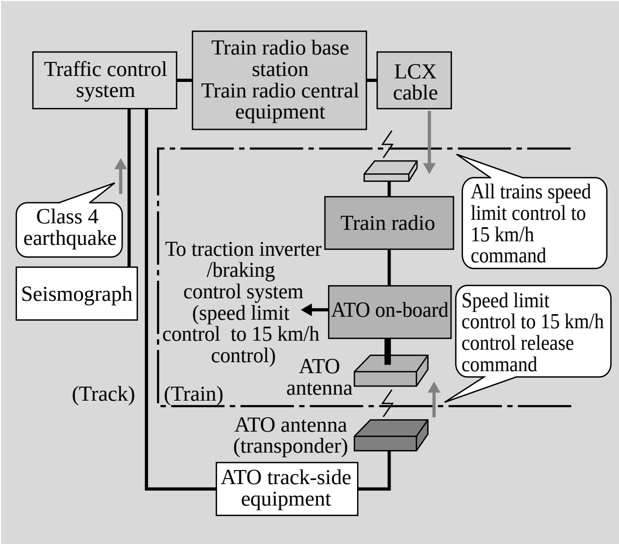

Fig. 8—Schematic of Speed Limit Control to 15 km/h (Class 4 Earthquake).
When a class 4 earthquake is detected by a seismograph, the traffic control system outputs a speed reduction command. The speed limit control to 15 km/h command is transmitted to the train by the train radio equipment (data communication service).

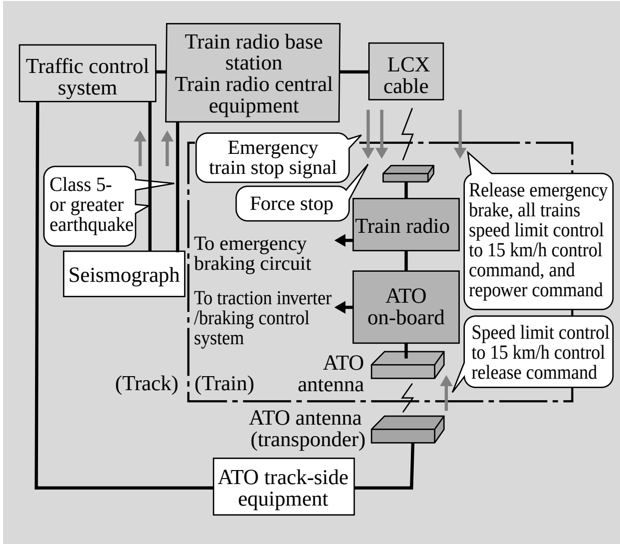

Fig. 9—Schematic of Force Stop (Class 5- or Stronger Earthquake).
When a class 5- or above earthquake is detected by a seismograph, an emergency train stop signal (voice communication service) and force train stop command (data communication service) is transmitted to the train by the train radio system, and the train makes an emergency stop.

command is cancelled and the train automatically resumes its normal speed profile (see Fig. 8).

(b) Class 5- or higher earthquakes

(i) If seismographs detect a class 5 or higher earthquake, the train radio central equipment sends an emergency stop signal to the train.

(ii) At the same time, the traffic control system sends a force stop command (as a backup for the train emergency stop signal), via the data communication system.

(iii) Trains receiving either an emergency stop signal or a force stop command, apply the emergency brake and come to a stop.

(iv) In order for a train to resume operation, it must receive an emergency brake release command, and all trains speed limit control to 15 km/h command or a repower command from the traffic control system via the train radio (data communication service) after the operation control center has verified it is safe to proceed.

(v) When a train receives these commands, it automatically resumes operation at a speed of 15 km/h.

(vi) Similarly, when a train stopped at a station receives a speed limit control to 15-km/h release command via the ATO antenna, this cancels the speed limit control to 15-km/h command and the train automatically resumes its normal speed profile (see Fig. 9).

(5) Passenger evacuation → Front emergency egress door unlock function

In the unlikely event that a train is stuck between stations and the passengers have to evacuate the train in the tunnel, the emergency egress doors at the front of the train must be opened.

(a) The evacuation of passengers in an emergency is carried out through emergency egress doors in the front of the train (normally these emergency egress doors are concealed by a locked cover).

(b) The operation control center inputs an unlock front emergency egress door command to the traffic control system, which then outputs the command to the train via the train radio.

(c) When it receives this command, the train unlocks the front emergency egress door and opens the cover.

(d) The front emergency egress door can then be easily opened by manually lifting the handle (see Fig. 10).

FUTURE PROSPECTS

The Nanakuma Line Subway operates with driver-qualified train crews riding in the cab at the front of the train, essentially in the capacity of conductors. The

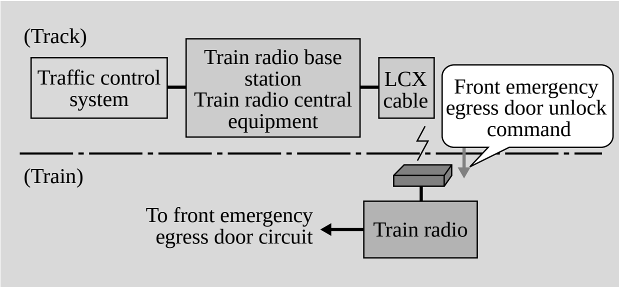

Fig. 10—Schematic of Front Emergency Egress Door Unlock.
In emergencies, the handle cover of the emergency egress door at the front of the train can be unlocked by remote control so passengers can use the door to evacuate the train.

Fukuoka City Transportation Bureau is primarily interested in boosting operating efficiency. They have already made substantial progress in adopted automation technologies ATO systems, converting over from two-person operation to driver-only operation, and by extension one might assume they are moving toward "driverless operation with an attendant crew" in which a crew member is not always present in the driver's cab.(4)

On the other hand, applying driverless operations to subways is fundamentally different from applying that approach to new transportation systems (automated people mover system). This is because passengers feel a certain sense of unease associated with the fact that subways travel underground through tunnels, and assuaging this psychological unease is an important issue.(4) Up to now, the practice of having a train crew (who is usually in a separate cab from the saloon) circulate through the cars has been associated with better passenger service and has helped alleviate the feeling of unease among the riders.

Considering the technical viability of driverless operation of subways, this capability is already feasible by combining on-board video monitoring systems that have been proven with automatic operation systems. Yet there are some other aspects, especially the prospect of dealing with various kinds of abnormal events, that call for further consideration and study.

CONCLUSIONS

This paper presented an overview of the full-automatic operation system that was recently put into service on the Nanakuma Line Subway operated by the Fukuoka City Transportation Bureau. Exploiting the company's proven expertise as a comprehensive railway system integrator in developing everything from rolling stock systems (railcars themselves and electrical components) to advanced track-side systems such as traffic control system and interlocking platform doors, Hitachi will continue to investigate the viability of driverless operation systems.

REFERENCES

(1) K. Yamaguchi, "Fukuoka City Enters Linear Metro Subway Business," *JREA*, Vol. **48**, No. 4, pp. 38-45 (April 2005) in Japanese.
(2) M. Hirashima, "Challenges to Implementation of Driverless Operation," *Rolling Stock & Technology*, No. **86**, pp. 18-26 (June 2003) in Japanese.
(3) S. Inoue et al., "Fukuoka City Transportation Bureau's Driverless Operation System," 41st annual Railroad Cybernetics and Symposium, p. 519, Nov. 2004, in Japanese.
(4) T. Koseki, "Driverless Operation: Prospects and Issues," *Rolling Stock & Technology*, No. **86**, pp. 2-9 (June 2003) in Japanese.

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