Feature

Railway Safety for the 21st Century

Minoru Arai

First, what is the positioning of safety in the railway business? Of course, safety is of the utmost importance and even one passenger or staff fatality is one too many. Unfortunately, in the 15 years since JR East was established following the privatization of JNR, we have had accidents like that on 5 December 1988 when a train collision near Higashi Nakano caused the death of one passenger. Notwithstanding this, even if we exclude the huge number of passenger-km travelled on our shinkansen, in comparison to other transport businesses, we have an extremely good safety record that is also much better than the huge number of road casualties.

Figure 1 shows a clear downward trend in JR East's accident rate since 1987. Considering that the number of train-km operated each day by JR East has risen by 15% in the last 15 years since privatization while the number of accidents has dropped by 67%, we can say that there has been a dramatic improvement in railway safety. JR East gives absolute top priority to safety and is constantly investing in safety while continually updating its safety planning. However, looking at the absolute number of accidents that still occur, I think there is still a clear need for reducing accident risks even further. Most of the accidents on JR East's tracks are either disaster related due to the high incidence of typhoons and earthquakes or are caused by failures in infrastructure or human error. To reduce accidents caused by natural disasters, a number of disaster prevention alarm systems have been introduced across the network since 1990. A typical example is the installation of earthquake accelerometers that can detect the primary waves from an earthquake and shutdown the railway electric power system, stop trains, etc. Recently, there has been a trend towards more instances of localized flooding in Japan with sudden downpours exceeding 100 mm/h. These types of cloudburst can quickly wash away track ballast or cause mudslides that easily derail trains.

Figure 2 shows the incidence of major earthquakes exceeding magnitude 7 near Japan during the last 100 years. The JR East operations area is on the Pacific coast of Japan, which tends to suffer the greatest incidence of major earthquakes due to its proximity to major tectonic plates moving against each other. Since natural disasters can cause major rail accidents, a large part of our R&D is into methods for assessing the mechanisms causing natural disasters. My personal belief is that this type of work will become more important as global climate change exerts even greater impact on Japan's weather patterns.

Next, I want to mention level crossing accidents causing derailments, which have been responsible for many fatalities in the long history of railways worldwide. Another area where increasing safety is of utmost importance is at the station platform, which must be both safe yet barrier-free.

Most train collisions, which occur rarely in Japan, may cause great damage and high loss of life. Since 1987, both JR East and other railway operators have experienced major train collisions. In many cases, such collisions are due to the train driver not observing the correct signal aspect for one reason or another. Our company has been tackling this problem by researching countermeasures using both hardware and software solutions. In particular, we have put a great deal of effort into automatic train stop and protection systems such as ATP-S, which monitors train speeds and applies brakes automatically. In terms of track-km, such systems are now installed on 23% of conventional narrow-gauge lines on the JR East network, but this figure rises to 90% in terms of passenger-km.

Train derailments, most of which are caused by natural disaster or level-crossing accidents, tend to decrease. However, more countermeasures are still necessary. Although passenger safety is of the utmost importance to JR East, another extremely important theme is assuring the safety of employees both within JR East and in the JR group of companies. Since 1987, the

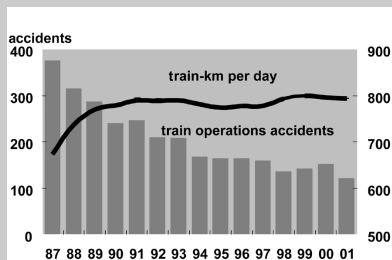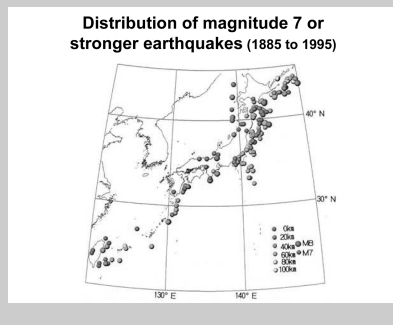**Figure 1 Current Safety Status of JR East**

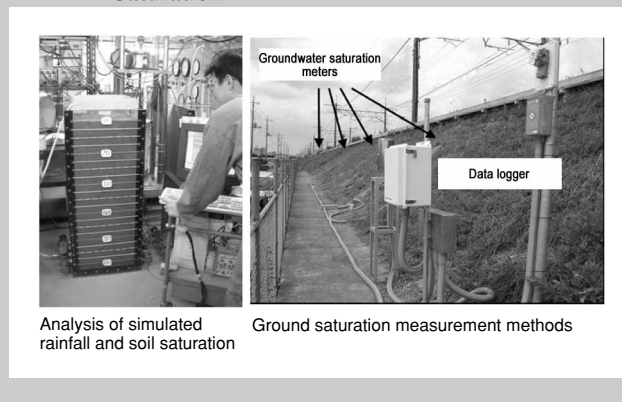**Figure 2 Major Earthquakes near Japan**

Rockfall blocking track   (JR East)

Figure 3   Predicting Torrential Rainfall

New rules for operating in heavy rain
Rain countermeasure for slopes → Groundwater saturation methods

Mudslide on Tohoku main line in August 1998

Figure 4   Rainfall Disaster Prediction and Ground Saturation

Groundwater saturation meters

Data logger

Analysis of simulated rainfall and soil saturation

Ground saturation measurement methods

number of employee fatalities has been on a downward trend but there are still several every year. In particular, there are too many instances of track maintenance workers being struck by passing trains and we are researching better ways to prevent this happening in future.

So far I have described the necessity to approach risk reduction from the aspect of human factors. In recent years, due to the systematization of railways, there has been widespread reduction in the need to rely upon human consciousness in ensuring safety. However, human-factors will always play a role in railway safety and it will still be necessary to give importance to this in the future. So far, I have outlined JR East's basic concept of safety-related research, but what exactly are we doing in concrete terms to reduce accidents, and eliminate passenger and employee fatalities? The next part of this article explains our work in five specific fields. The first is about preventing natural disasters. Natural disasters run the whole

gamut of events from torrential rain earthquakes, typhoons, mudslides, landslides, avalanches, etc. Since they are so varied in nature, it is important to establish operation rules based on the specific nature of the threat and also to accurately assess the risk of the event occurring. This requires both time and locality prediction techniques.

First, I would like to explain our research into groundwater saturation analysis for preventing flooding and mudslide disasters. The safety of grades, cuttings and embankments is not simply related to the amount of rainfall but is also strongly correlated with the saturation of the ground by water. However, there are several problems to be overcome in using groundwater analysis to forecast the risk of mudslides. Currently, we are progressing with establishing operations standards based on an exponential rain index that takes into consideration the rainfall and its passage into the water table, etc.

We are also researching methods for establishing operation regulations based on the groundwater saturation levels following heavy rainfall (Fig. 3). Some of the details are explained below.

How does a mudslide actually occur following heavy rain? Put simply, at the microscopic level, the water molecules reduce the molecular attraction between mud particles and also increase the ground weight, resulting in an increased risk of a mudslide down a gradient.

We undertook some research to examine how mudslides actually occur using a sprinkler system to saturate ground and trigger a small-scale slide. We also undertook research into predicting slides and how to recover from them as quickly as possible. Figure 4 shows our two-pronged approach. In the first case, we simulated how rainfall saturates soil; in the second case, we examined actual groundwater on a railway embankment. We found that when water was supplied from the top of the slope, the ground tended to slip down from the front surface. Also, the ground dried slowly after the water dispersal stopped. In comparing the test results with groundwater saturation levels in embankments and natural slopes, we found an extremely diverse range of rainfall patterns. In addition, the changes in the ground structure were also diverse. As a result, we realized that the changes in the groundwater saturation levels differ according to rainfall pattern and ground

Level-crossing accident...

and platform safety   (JR East)

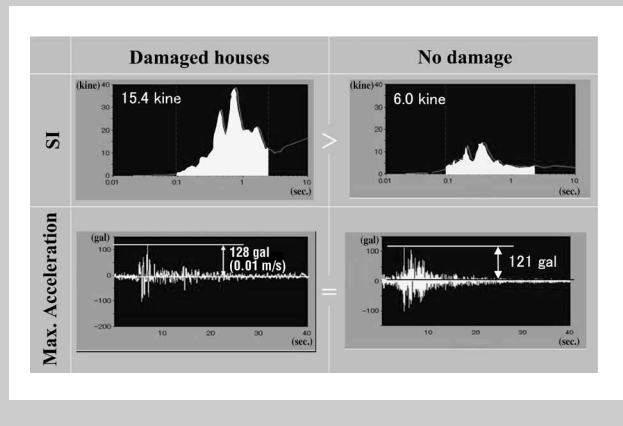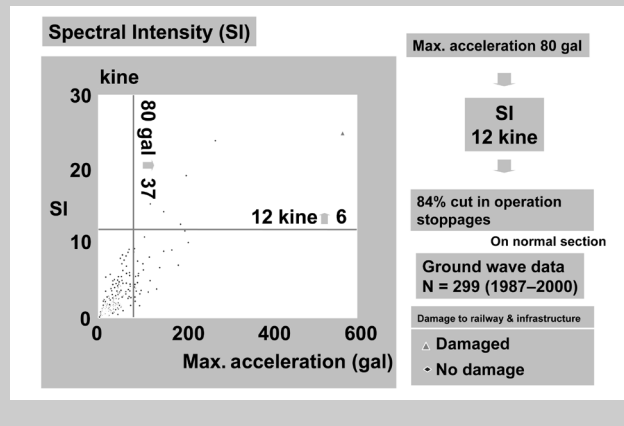**Figure 5   Comparison of Spectral Intensity and Max. Acceleration**

Figure 6   Earthquake Damage Prediction

structure, which helped in establishing methods for inspecting water flow in soil and regulations limiting operations in terms of groundwater saturation observations. In the future, we're looking at ways of improving rainfall indices based on the proportion of the current rainfall and a groundwater index. We are also looking at researching new regulations for operations in heavy rain. Other areas include stability analysis of slopes, etc., evaluating the effectiveness of civil engineering works to prevent ground slip, and establishment of methods for evaluating rainfall countermeasures on slopes.

Next, I want to explain damage to structures caused by earthquakes. In simple terms, each structure has a unique frequency; taller buildings have shorter frequencies while low buildings have longer frequencies. The degree of damage sustained by a building in an earthquake is greater when the unique frequency of the structure matches the frequency of the ground vibration caused by the earthquake. Conversely, if the unique frequency of the structure does not match the ground frequency, the structure will not be damaged; in other words, damage occurs when the structure vibrates at a frequency exceeding its ability to withstand vibration.

As a consequence, structural damage is not simply related to the strength of the earthquake—there is also a relationship

with the earthquake frequency. Until now, the rules governing suspension of railway operations in an earthquake were based only on an index related to the maximum ground acceleration caused by the quake. However, the spectral intensity (SI) is an index that takes into account the acceleration of the structure caused by the earthquake and the frequency of the vibration. The SI is more correlated with damage to the structure caused by the earthquake than the maximum acceleration because it considers both the strength of the vibration of the structure caused by the earthquake and the frequency of the vibration. Figure 5 shows the SI and maximum acceleration of two earthquakes that did and did not cause damage to houses. Although the maximum acceleration of both earthquakes was broadly the same, the SI of the earthquake that caused damage was much larger.

Why does this difference occur? The lower value shows the evaluation including short frequency components that do not cause damage to structures while the upper SI evaluates spectral components causing damage to the structure. From this, we can see that SI is more highly correlated with earthquake damage than maximum acceleration.

Lastly, what would be the effect of using SI on railway operations? Figure 6 shows the incidence of railway operations stopped on normal sections of

conventional narrow-gauge lines when the maximum acceleration exceeded 80 gal. If we use the same method but use SI instead of maximum acceleration, we obtain a value of 12 kine. If we use this value as the reference, when we look at the number of times that past earthquakes have caused operations stoppages, we find that the incidence is 37 times for maximum acceleration and six times for SI. In other words, using SI as an index for stopping operations during earthquakes results in 84% fewer stoppages. Moreover, if we look at the single instance of an earthquake that did cause damage to railway structures (triangle at top right of Fig. 6), we find that the SI index would also have resulted in operations being stopped.

What about wind prediction? We have developed a method for stopping operations based on predicted wind speed. Currently, operations on narrow-gauge lines are stopped when wind speeds exceed 30 m/s and there are some special locations where the wind speed regulation is as low as 25 m/s. The rule is that operations must not be restarted until a period of 30 minutes has passed since the last wind speed measurement exceeding the 30 (or 25) m/s speed limit. In the newly developed method, analysis of past wind speeds is used to predict future wind speeds and these predicted speeds are used as the basis of the operations stop rule. This method achieves the same safety level as

Figure 7   Slope Safety Evaluation

Remote land form sensing

Visible light   3D imaging with laser

GIS   Real-time potential disaster location evaluation

Rainfall history   Disaster history

Earthquake history

Rainfall (mm/h)

Long-term heavy rain   Time
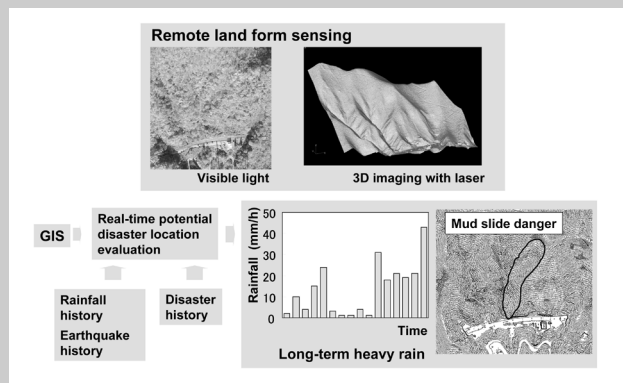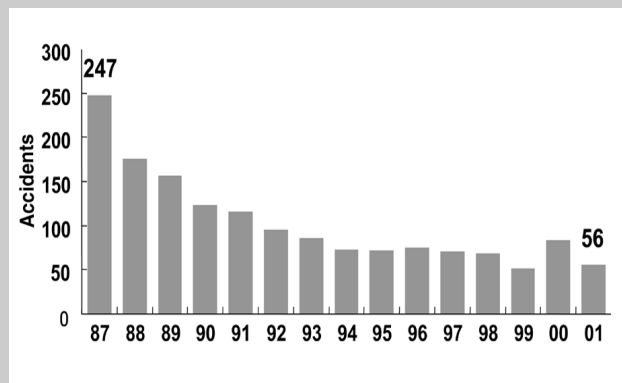
Mud slide danger

Figure 8   Level-crossing Accidents

the previous method but also reduces operations stoppage times by 20% to 50%. What about locality prediction? We have developed a number of technologies for use in predicting localities that might be most susceptible to flooding or earthquakes. One method being developed quantifies parameters such as the gradient of slopes at high risk of mudslides, etc. In addition, advances in remote-sensing technologies, such as high-resolution photography using visible light and detailed 3D imaging using laser measurements can simplify the work of surveying slope gradients and lengths and also in measuring and mapping topography. New data analysis techniques that integrate parameters such as past groundwater saturation levels, previous earthquakes, rainfall, etc., can all help in predicting future risks. Recently developed technologies such as the Geographical Information System (GIS) may also soon be linked in real-time with other information and imaging systems to provide disaster assessment systems for high-risk locations (Fig. 7). We are currently trying to develop a system that can pinpoint the locations with the highest risk in real time based on parameters such as rainfall patterns and earthquake characteristics.

Another hot R&D topic is prevention of level-crossing accidents. Figure 8 shows the incidence of these accidents since 1987. Although there has been a good drop over the last 15 years, the figure has still not reached zero.

Looking at the types of accident, 66%

involve automobiles and about half of these accidents are caused by attempting to cross just as a train approaches. In most of these cases, the car driver has ignored the warning bells and barriers. In the other half of the cases, the vehicle has become stuck on the crossing for one reason or another after the barriers have come down. We are looking at ways to prevent both these types of accident by providing drivers with more up-to-date information on the location of an approaching train before they attempt to cross the track. One possibility is to link train position location systems to the increasingly popular car navigation systems to provide the driver with an in-car audible warning of a train approaching a crossing and perhaps to prevent an attempted crossing at the wrong time by automatically applying the car brakes. To prevent the type of accident where a vehicle becomes trapped between the crossing barriers due to a breakdown, etc., we have been actively installing vehicle detectors on crossings and this is one reason why the number of these accidents has dropped so markedly over the years. In the future, we are hoping to cut the number of accidents even further and reduce costs as well by using the latest data processing and information technologies such as stereo cameras and image processing systems installed on crossings.

Platform accidents are another safety issue that we are looking closely at. Excluding suicides, passengers can be hurt through

accidentally coming into contact with trains in a number of ways. The number of platform accidents has almost halved since 1987 but looking at the types of accident, about 60% occur on the platform and the majority of these are within the metropolitan area. To prevent accidents, we have taken a variety of countermeasures, including installation of emergency stop buttons on platform pillars. In the event of an accident such as somebody falling off the platform onto the tracks, a member of the public or station staff can bring all trains to a halt by pressing any emergency stop button.

To prevent the types of accidents where passengers mistakenly step off the platform between two stopped carriages or simply fall off the platform, we are also researching stereo cameras and image processing systems that would detect these events automatically and activate the emergency stop system. Use of stereo imaging systems installed above the platform would help prevent detection errors caused by shadows.

Some subway operators in metropolitan Tokyo have installed platform doors but although some of our stations in the metropolitan area are very crowded, it would be very difficult to install standardized off-the-peg platform doors due to the diversity of door designs on JR East's rolling stock used in the region. Furthermore, platform populations will be dropping due to the declining birth rate so we are trying to develop a flexible
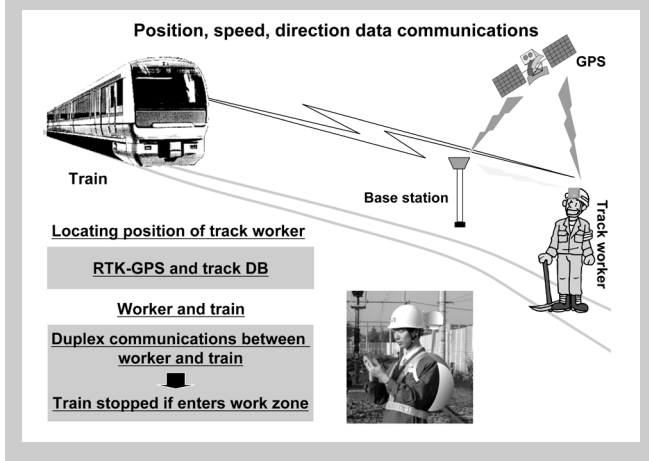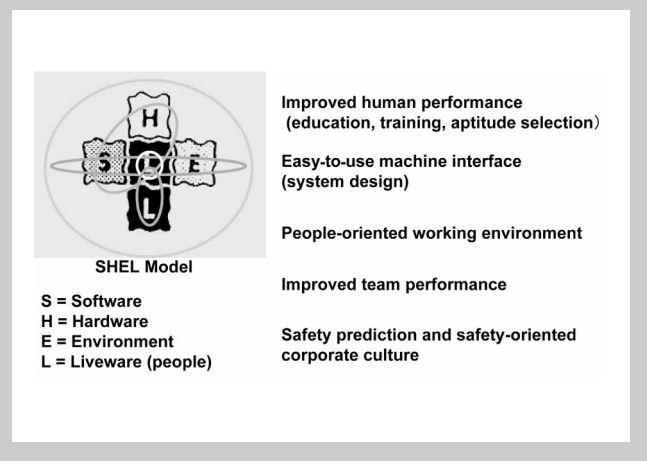
Figure 9   Future Track Worker Protection System

Position, speed, direction data communications

GPS

Train

Base station

Track worker

Locating position of track worker

RTK-GPS and track DB

Worker and train

Duplex communications between worker and train

Train stopped if enters work zone

Figure 10 Human Factor Approach

SHEL Model

S = Software
H = Hardware
E = Environment
L = Liveware (people)

Improved human performance
(education, training, aptitude selection)

Easy-to-use machine interface
(system design)

People-oriented working environment

Improved team performance

Safety prediction and safety-oriented
corporate culture

solution for doors that will be adaptable to both current and future problems.

In addition to passengers, we also need to assure the safety of our employees and other staff and I would like to explain one solution that we have developed. Recently, we have seen very rapid development of IT systems based around GPS technology and new developments such as RTK-GPS can pinpoint position with an accuracy of centimeters.

We have been putting a great deal of effort into developing a system based on RTK-GPS to protect track maintenance workers who are at very high daily risk of being struck by trains. The system compares the RTK-GPS data with a track database to locate the worker on the track and then passes this information by duplex wireless communications between the worker and the train. If an approaching train comes too close to the worker on the track, the train is stopped automatically. This approach should offer maintenance workers a high level of safety and we are making progress with the R&D.

RTK-GPS is a high-accuracy GPS system that plots position to within centimetres by comparing the phase level of the GPS waveform at both a base station and a measured position. In addition, we are also thinking about using the VRS method. In this method, when there is some difference between the measured position of a maintenance worker and the distance between the measured position and the

base station, a higher accuracy position measurement is achieved by creating a virtual base station.

As shown in Figure 9, the track database is an important part of the system. Currently, we are considering using the GIS that is conventionally used to create work plans, etc. The GIS uses 1:10,000 scale aerial photographs, so positional data for the required ground station can be obtained without the need for local surveying. When we compare the track database created from the GIS with actually measured data, we can confirm the accuracy. We are currently thinking of using this method to construct the new track database that would be required by our maintenance worker protection system.

Finally, in this article, I would like to explain some of our work from the aspect of human factors. Improvement of railway safety means that we must pay a attention to the human factors in operating railways. Although railways in Japan are becoming systematized, which might be thought to inherently increase safety, to guarantee even higher levels of safety it is important to give consideration to the interaction of people with system interfaces. This concept of understanding human psychology as part of the system is also becoming important in business.

Here, I would like to outline our SHEL model (Fig. 10) of human factors, which focuses on Software, Hardware, Environment, and Liveware (the people

who run the system). To summarize the model, raising safety by eliminating human errors means optimizing the interface between people and machines, people and the environment, and between people. A typical approach to increasing human-error-free performance might be to design machinery and systems to match the characteristics of people while also adopting management systems such as safety prediction and encouraging a corporate culture that puts safety first. JR East is conducting a great deal of research into human factors based on these concepts. I would like to explain our R&D into human factors from the train operation, maintenance and safety management fields. In the train operation field, we developed a driver support system that can support extremely complex works under normal conditions.

In the maintenance field, we are looking at systems for maintenance workers aimed at preventing accidents and cutting the levels of errors. Part of this involves examining how maintenance workers get struck by trains and also development of training methods to prevent such accidents.

In the management field, human-factor research becomes important from the viewpoint of safety prediction and we are looking at development of analysis systems that can collect, correlate, and analyze the causes of accidents and incidents. A lot of work so far has been centred on preventing human errors at

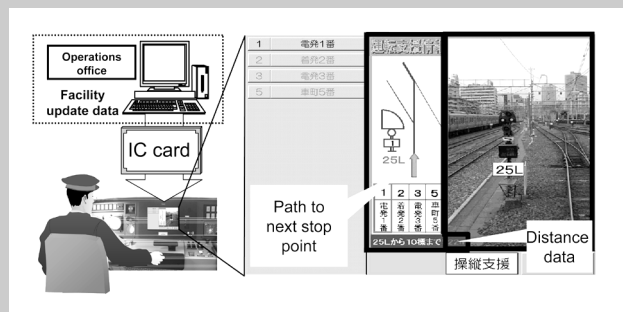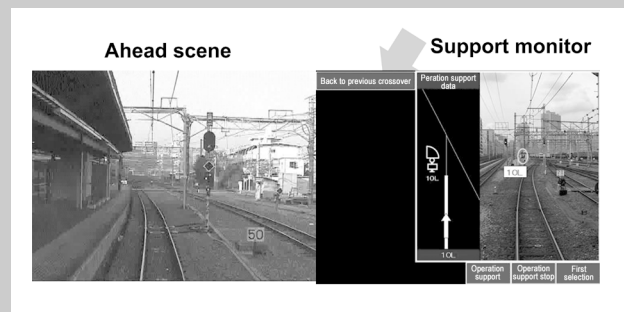**Figure 11 Concept of Driver Support System**

Figure 12 View of Driver Support System

work but similarly a very important theme is how to prevent human errors in maintenance. Sometimes, errors do not lead directly to an accident but instead result in an incident that may be the precursor to a future accident. As a result, we are also looking at systems for analyzing incidents to prevent accidents. Our research themes are focused on both rolling stock and ground infrastructure. One area of particular importance that we are investigating is signal maintenance, which has a direct and immediate impact on operational safety. In the maintenance field, the most common errors are related to work on wiring, and installation of mechanical equipment and mounted parts. In the area of power distribution, the most common errors when undertaking complex work are misunderstandings. This contrasts with errors due to lack of attention when performing simple repetitive tasks. In wiring work, we also often see check errors after the work has been completed. Now I would like to explain some of our research into countering errors due to mistaken understanding and to lack of attention. The first solution is an engineering countermeasure. Put simply this means upgrading working standards with focus on locations where mistakes are easily made. A second solution is to ensure that maintenance workers receive sufficient training on difficult working locations and the need for care. We have spent quite some time researching ways to prevent human error through training, engineering

and management countermeasures such as use of simulation systems to train employees about possible conditions they might encounter.

Train drivers must memorize positions of curves, signals, etc., to drive a train at safe speeds. One unanticipated result of increasing the length of our network by laying new tracks, such as the Shonan Shinjuku Line, for the convenience of passengers was that the longer operations distances greatly increased the need of drivers to maintain their concentration for longer periods of time. In addition, the track structure became much more complex with more signals that needed to be remembered and more possible paths and routes. Clearly, it was very important to prevent drivers missing or misreading signal aspects through lack of concentration. Figures 11 and 12 show our driver support system displaying important information on a monitor on the driver's console to assist him with his work. The development concept was first to display the aspect of ahead signals to prevent signal errors by the driver. In addition, the track layout and distance to the next stop position are also displayed on the monitor to prevent stopping errors.

Figure 12 gives us some idea of what the driver sees in his cab. The image on the right of the figure shows the monitor display; when the driver presses the current position button, the distance and route from the current position to the next signal are displayed. When a signal is passed, a long view to the next signal and route are displayed. As the train gets closer to the next signal, the image changes to that near the signal and a route selection button is displayed. When the train stops and the button to show the path to the next signal is pressed, the route and distance are displayed. This type of operational assistance greatly lightens the driver's burden of repetitive operations. Finally, to summarize the aims of our R&D, we are dedicated to improving railways by researching the latest technologies and expanding our knowledge of their safety applications for the benefit of our customers, employees, and the railway industry as a whole. ■

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Mr Arai was Director of the Safety Research Laboratory in the Research and Development Center of JR East Group. He joined JNR in 1971 after graduating in engineering from Keio University. He has held various posts in the operations and rolling stock departments of JR East. He is now General Manager of Transport Safety Department.