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Development of the Strategic Reliability Evaluation Method for the Entire Railway System



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JR East has been implementing a wide variety of measures in the field of cars, equipment, and sales in order to improve safe and stable transportation services. As a result, safety and reliability have been steadily improving in each field. The railway system, however, has become sophisticated and complicated due to recent technological renovation and diversification of needs. Thus, implementation of more effective measures requires an integrated index for correctly understanding the weaknesses of the entire railway system and also for deciding where measures such as capital investment should be focused. In this study, we treat all areas of JR East business as one system and comprehensively evaluate this system in terms of safety and stable transportation. We have already established the basic model, and its effectiveness has been confirmed. In this paper, an overview of the basic model and the current approach are introduced.

● Keyword : reliability, safety, risk, evaluation

1 Introduction

As represented by technological trends in recent years and diversification of needs, the environment of the railway business is constantly changing. In response to such changes, JR East has been implementing a wide variety of measures in the field of cars, equipment, and sales in order to improve safe and stable transportation services. As a result, safety and reliability have been steadily improving in each field. In order to further improve the services, an integrated index is necessary for correctly understanding the weaknesses of the entire railway system, for deciding where measures such as capital investment should be focused, and for estimating how much safety and stability improvement we can expect from the various measures.

With the abovementioned issues in the background, in this study, we comprehensively evaluate the entire railway system in terms of safety and stable transportation to decide priorities among various measures such as capital investment and also to establish a reliability evaluation method which is believed to be effective in examining the effect of such measures. We have already established the basic model, and its effectiveness has been confirmed. We are currently working on issues inherent to this basic model.

This paper introduces the established basic model and our current activities. Note that the numerical values and graphs used in this paper are reference data to support better understanding of the subject and are fictional.

2 Approach to the reliability evaluation method

2.1 Definition of "reliability" for this study

In this study, we defined "reliability" as what passengers expect from JR East. To date, we have viewed our improvement measures such as capital investment in terms of the percentage of decrease in accidents or transportation disruption ("accidents," hereinafter) as a result of implementation of these measures. From this point forward, we must view the implementation of these measures from the passenger's point of view and consider how much these measures can fulfill passengers' expectations.

What passengers expect from JR East is safety and stable transportation. Therefore, in this study, we review the safety and stability of transportation as components of reliability, and then evaluate each of them.

2.2 International safety standards

When discussing safety issues, it is necessary to understand related international standards or specifications. Here, a brief explanation of international trends regarding safety will be provided.

A large number of international standards or specifications have been established by the International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC). In order to ensure consistency among these standards or specifications, ISO / IEC Guide 51 was created in 1990, which was then revised in 1992.

According to Guide 51, "safety" is defined as "release from unacceptable risks." Also, terms such as "risk" are defined as follows:

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(1) risk: combination of harm probability and gravity of the harm

(2) harm: physical or health disturbance affecting human bodies, or damage to assets or environment

(3) tolerable risk: acceptable risks under certain conditions based on the prevailing concept of social values

Before revision, ISO / IEC Guide 51 defined "harm" as "damage (to people) or health disturbance." Its definition, however, largely changed after the revision in February 1999; in response to increasing awareness of environmental issues, descriptions regarding assets and environment were added to the definition.

This revision became the major turning point for approach to safety. Simple system stoppage is no longer considered safe. Improvement of the system operating ratio by making the system redundant or by improving the fault diagnosis function, and also reduction of risks by prompt recovery from failures are now required.

2.3 Target setting

The goal of this study is to evaluate risks for entire railway systems in the areas where JR East conducts business operations as shown in Figure 1. Here, "risk" is defined as events that damage safety (death or injuries of passengers or death of JR East employees) or transportation stability (delay in passenger transportation).

Fig 1: Areas subject to JR East business operation

The model, as seen in Figure 2, has a configuration in which two evaluation values, one for safety and the other for transportation stability, are output in response to the input of various types of conditions. Our mission is to establish a model that can incorporate changes in train operation diagrams, abolition or integration of various types of equipment, and fluctuation in the number of passengers into evaluation values, and that can examine the effectiveness of measures against accidents.

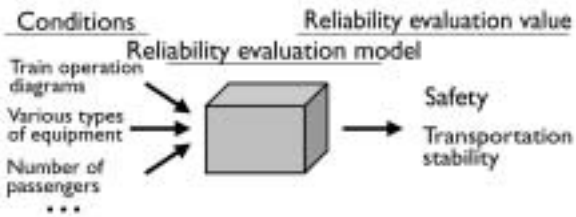


Fig 2: Image of how the reliability evaluation model works

3 Creation of the reliability evaluation model

3.1 The basic model

A general risk assessment method is used in evaluation. In risk assessment, in general, risk can be expressed as follows:

Risk = frequency of occurrence × magnitude of influence

Using this equation, we have defined scenarios containing risks, obtained frequency of occurrence and magnitude of influence for all these scenarios in each area of JR East business operations, and regarded the resulting integrated values as reliability evaluation values.

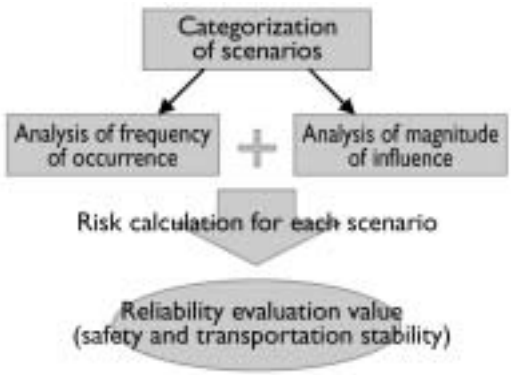


Fig 3 shows the flow of evaluation, and a description of each operation will be provided below.

(1) Categorization of scenarios

First scenarios containing risks must be categorized. In this evaluation method, events that damage safety and transportation stability are defined as "risks."

To be specific, scenarios are categorized based on the categorization system used in the train operating accident database that JR East uses to collect information. This database is used to collect and accumulate information each time an accident occurs within the area under JR East's management in order to prevent recurrence of similar accidents. Data from April 1, 1987 (when JR East was founded) and on has been stored in this database. Scenarios are roughly divided into train operating accidents and transportation disturbances. Train operating accidents include six types specified by the ministry ordinance, as seen in Figure 4. Transportation disturbances are defined as events, other than train operating accidents, which cause disturbances in transportation. JR East defines 40 types as examples of transportation disturbances.

For this study, we further subdivided the categorization system described above. As we made subdivisions, from the standpoint of safety and transportation stability, we checked whether or not each category contains factors for very different influences. If factors contributing to different influences are included in a category, this category was further subdivided. As a result, we created approximately 450 scenarios for train operating accidents and transportation disturbances.

Fig 4: Accident categorization used in reports

(2) Frequency analysis

The objective of this study is to appropriately evaluate the entire railway system and to understand the effectiveness of each measure beforehand such that the effectiveness can be used when making decisions about capital investment. Many of the measures are created and implemented in order to reduce the number of factors that contribute to occurrence of scenarios with high occurrence frequency by improving equipment functionality or by terminating the use of such equipment. Therefore, the mechanism of occurrence of each scenario must be taken into consideration and also numerical values such as "number of times" or "length" which serve as components of the factors contributing to occurrence of the scenarios must be included in calculations when defining "occurrence frequency" of the scenarios.

Meanwhile, accidents are the results of complicated combinations of various factors such as the number of trains, the number of passengers, safety equipment, surrounding environment, and human factors; therefore, it is impossible to appropriately incorporate all of them into the accident occurrence frequency. Thus, from the multiple factors, we first select one situation (single factor or, it could be a combination of multiple factors) having the strongest relationship with scenario occurrence and then regard it as the main factor. We then use this main factor to define the scenario occurrence frequency. Here, each numerical value that constitutes the major factor is called a "radix," and each past scenario occurrence is divided by this radix to obtain the occurrence frequency of each event.

Since it is possible to believe that the main factor of a train operating accident is a transportation disturbance, the number of transportation disturbance evaluations already made will be the radix for the train operating accident. With this method, it is possible to make an evaluation in which the number of train operating accidents caused by transportation disturbances decreases when the occurrence of transportation disturbances becomes less frequent as a result of implementation of measures.

$$\text{Transportation disturbance : Frequency of occurrence} = \frac{\text{Past scenario occurrence}}{\text{Radix}}$$

$$\text{Train operating accident : Frequency of occurrence} = \frac{\text{Past scenario occurrence}}{\text{Number of related transportation disturbance evaluations}}$$

Here, we will provide a detailed illustration of frequency analysis by using an example scenario of "violation of an entry signal within the ATS-Sn section." "Violation of signal" means that the train operator does not stop the train at a stop signal, and this may lead to serious accidents such as train collisions. To prevent such accidents, safety

equipment such as ATS is installed. Frequency of scenario occurrence varies with the type of installed safety equipment, and the effect of the scenario occurrence varies depending on which signal is violated. Therefore, it is necessary to include the type of safety equipment and the type of signal in the scenario.

Violation of a signal is caused by the train operator's failure to check the stop signal. Thus, the main factor can be "the number of times the train operator checks the stop signal." However, since operation of the stop signal depends on the preceding train, it is difficult to count such a number. If it is hypothesized that "if the number of times the train operator checks the signal increases, the number of times he/she checks the stop signal and also the number to times he/she misjudges the stop signal increase," then it is possible to regard "the number of times the train operator checks the signal" as the radix.

For example, the number of times a train operator checks the signal at Sendai station on the Tohoku line can be obtained by multiplying the number of signals by the number of trains. Since the Senzan line and Senseki line also serve Sendai station, the calculation must be conducted for both lines. Similarly, the same calculation must be conducted for all the possible combination of lines and stations (approximately 2,100), and the grand total of the calculation results will be the "the number of times the train operator checks the stop signal" in the case of JR East, and this number is regarded as the radix. Assuming that this number amounts to 200 million times / year, and that signals are violated 10 times in a year, the frequency can be obtained as follows:

$$\text{Frequency} = \frac{10}{0.2\times10^{9}} = 0.5\times10^{-7}\ (\text{incidents / times})$$

Furthermore, frequency of scenario occurrence for each station can be calculated by multiplying the frequency by the numerical value that the radix is based on for each station. By tabulating the results and

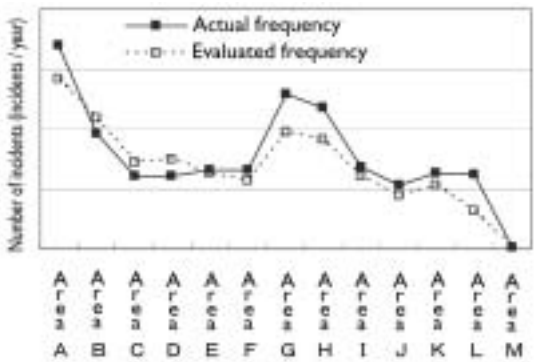


Fig 5: Comparison between the evaluated frequency and the actual frequency by using the radix

comparing them against the actual occurrence values of a certain area as seen in Figure 5, it is possible to validate the radix.

(3) Analysis of magnitude of influence

Magnitude of influence must be analyzed for safety and for transportation stability.

○Safety

Influence of safety includes the following, taking into consideration injuries and death of JR East passengers and employees:

Passengers: injuries or death in the trains or on / off the platforms (excluding suicides)

Employees: injuries or death resulting from train operating accidents

Magnitude of the influence is defined as the average value of past occurrence of each scenario.

$$\text{Influence of safety (man)} = \int(\text{Scenario})$$

○Transportation stability

Influence of transportation stability is expressed by the level of inconvenience imposed on the passengers, and is defined as the total duration of extra time (man-minutes) that passengers must wait on the train or platform. Specifically, a function with the size of scenario (train operation downtime) and the location of occurrence (line and station names) as parameters is developed and used in evaluation.

The "line and station name" parameter is associated with each of the JR East track sections, divided into 200 in advance, and for each of them data on the average train operation interval, the number of on-board passengers, and the number of passengers getting on and off is obtained. Then the "train operation downtime" parameter, or a parameter that indicates the size of influence, is added to the abovementioned data to establish the function. By using this function, the influence of transportation stability, which indicates the accumulated extra wait time imposed on the passengers, is calculated. Explanation of the calculation method is omitted in this paper due to its complexity, but its important point is that the differences of scenario sizes or locations of occurrence are all incorporated in the parameters and the influence is modeled by using one function.

$$\text{Influence of transportation stability (man-minutes)} = \int\left(\begin{array}{l}\text{train operation downtime,}\\ \text{line and station name}\end{array}\right)$$

As described later, the influence calculation method of the basic model is problematic in that the time of occurrence is not taken into

consideration when evaluation is made.

(4) Risk calculation

As seen in Figure 6, risk is calculated for each location using a station or the section of track between stations as the minimum unit, and evaluation values are then obtained as a result of three-dimensional tabulation of the calculation results for areas (certain line districts) and scenarios subject to comparison. Flow of the risk calculation is as follows:

① For each scenario, calculate the occurrence frequency (incidents / year) for each location based on the radix.

② For each scenario, calculate the reliability evaluation values (for safety and for transportation stability) by multiplying the occurrence frequency (incidents / year) by the influence.

③ Tabulate the calculation results for each comparison target to obtain the following reliability evaluation values:

・Safety evaluation value

・Transportation stability evaluation value

$$\text{Reliability evaluation} = \sum_{\text{Area}} \sum_{\text{Scenario}} (\text{Evaluation value for each location})$$

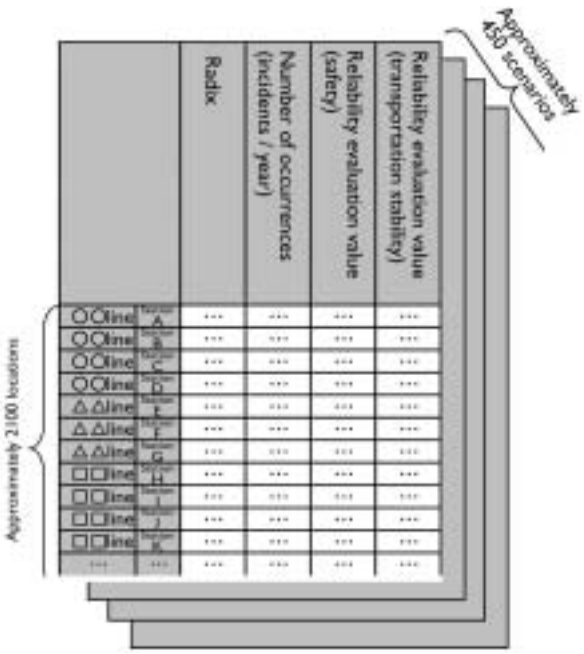


Fig 6: Image of risk calculation

(5) Examples of model usage

This section introduces a few examples of how the model established above can be used.

First, this model can be used to understand the actual situation. For example, in the graph in Figure 7, JR East's transportation stability evaluation values are divided for particular areas and then similar scenarios are grouped. Since the evaluation values are risk estimations, large values mean that the necessity for establishing measures for that location should be considered. JR East's business territory is managed by a set of 12 branches. If each area is expressed as a branch, it will become possible to understand which branches and which scenarios are JR East's weak points. Also, if each area is expressed as a line district managed by a corresponding branch, then it is possible to quantitatively understand which measures individual branches should focus on; therefore, this model can be used to narrow down the choices of measures.

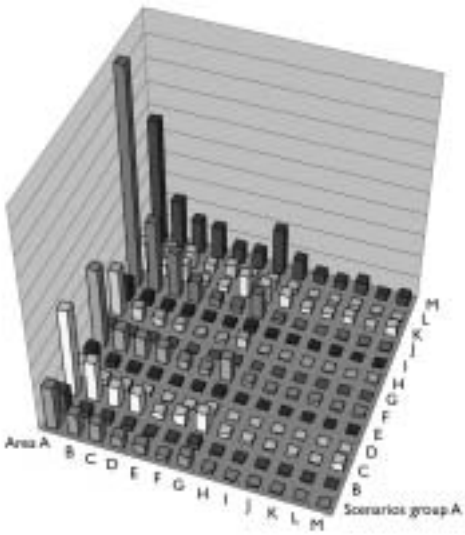


Fig 7: Transportation stability evaluation value for each area-scenario group combination

Second, this model can be used to compare measures. For example, assume that a few areas have been selected as areas requiring measures based on the understanding of the current situation, and also that it has become clear that it is necessary to focus on crossing accident measures and disaster prevention measures. If different numbers are input into the basic model and calculations are made for crossing accident measure X and disaster prevention measure Y, and if, as a result of such calculations, the effectiveness of the measures compared to the evaluation values of the entire company before changing measures is as shown in Table 1 and if the cost of implementing disaster prevention measure Y is three times as much as the cost of implementing crossing accident measure X, then we can determine that crossing accident measure X has higher cost effectiveness for both safety and transportation stability.

Table 1: Comparison of effectiveness of measures

	Safety	Transportation stability
Crossing accident measure X	0.07% decrease	0.580% decrease
Disaster prevention measure Y	0.15% decrease	0.014% decrease

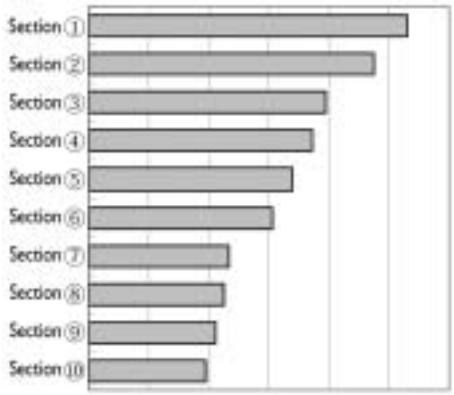


Fig 8: Sections showing high measure effectiveness

Third, this model can be used to search for areas where effectiveness of measures is high. For example, when implementing crossing accident measure X, its implementation may have to be limited to certain locations due to budget constraints. In this case, it is possible to search for areas where implementation of the measures is expected to be effective by first assuming the measure is implemented for all crossings and then by arranging the size of effectiveness as seen in Figure 8.

3.2 Current approach

The basic model is a prototype model, and has the following problems. Currently, we have been working on improvement of this basic model by tackling these problems. Here, description and direction of the resolution of the first of the following problems are presented.

- Consideration of uncertainty
- Definition of potential risks
- Comparison of scenarios having the same risk values but different magnitudes of influence

○ "consideration of uncertainty"

Since accidents occur randomly, there is uncertainty regarding the time of occurrence and also uncertainty of occurrence interval when the occurrence frequency is low. The basic model takes such fluctuations and converts them into an average value when carrying out calculations; therefore, this model is not capable of taking uncertainty into consideration. This may lead to misjudgment when using the model.

Here, consider uncertainty of the time of occurrence. For example, when a car failure occurs, its influence greatly differs depending on the time of occurrence, i.e. rush hour versus quiet times such as early morning, late at night, or the middle of the afternoon. Since the evaluation method of the basic model uses data on daily averages of the number of trains, the number of on-board passengers, and the number of passengers getting on and off, and does not use the "hour" factor, the model may underestimate the influence of the scenario if the evaluated scenario is one that is likely to occur during peak periods. In a similar manner, the influence of the scenario may be overestimated if the evaluated scenario is one that is likely to occur during quiet times. When considering a measure for scenario A and scenario B using the evaluation result of the basic model, there will be concerns as seen in Figure 9.

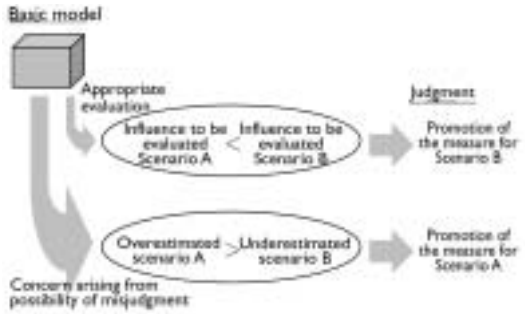


Fig 9: Concerns regarding the basic model

When tendencies of the time of scenario occurrence are examined based on past records, there are distinguishing scenarios (a) through (d) having tendencies shown in Figure 10.

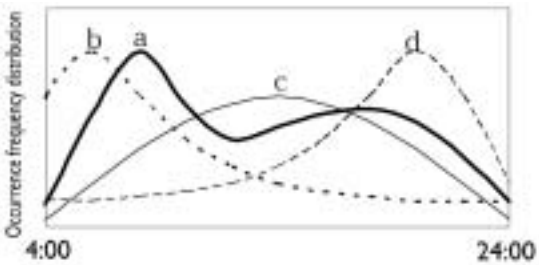


Fig 10: Tendency of time of occurrence for each scenario type

(a) Scenarios related to the number of trains such as car failures and signal violations

(b) Scenarios related to equipment such as split switches and signal equipment

(c) Scenarios related to daytime social activities such as obstruction of crossings and tracks

(d) Railway accidents resulting in injury or death or falling from platforms

Type (a) shows frequency distribution of car failures and other similar events. If car failures occur randomly, then the temporal distribution of failure occurrence is considered to have a correlation with the temporal distribution of the number of trains. The temporal distribution of the number of cars in fact indicates a similar distribution to type (a). From the standpoint of mechanism of failure occurrence, too, it is possible to support the argument that the temporal distribution of car failures is the type (a) distribution.

Despite the fact that the scenarios belonging to type (a), such as car failures and signal violations, are likely to occur during rush hour, the basic model uses average values to calculate the influence of these scenarios; therefore, the influence of these scenarios may be underestimated. Thus, incorporation of uncertainty of time of scenario occurrence is considered to be an issue for consideration.

As a different example, there are also concerns in the cases where scenarios have extremely low occurrence frequency but high magnitude of influence. When a large earthquake, which occurs once every 50 years, is considered, the definition of "once every 50 years" is deduced from an average based on very little data. The actual occurrence frequency of such earthquakes may be once in 25 years or 100 years, instead of once in 50 years. If the interval between these earthquakes is estimated as longer than the actual interval, then its influence may be underestimated. Therefore, incorporation of uncertainty of occurrence interval is considered to be an issue for consideration in the case of scenarios having long intervals and large influence.

Taking these issues into consideration, we are examining the possibility of applying random variables as input values in order to upgrade the basic model to a more practical model. One of the methods to achieve this is the Monte Carlo simulation method. This method takes multiple inputs of random variables and estimates the distribution of output values (refer to the sidebar).

When incorporating the "hour" factor into the influence, it is possible to first decide which type the examined scenario can be categorized as and then apply the random distributions of (a) through (d) shown in Figure 10 as inputs to specify the time of occurrence. For scenarios with extremely low occurrence frequency, too, it is possible to apply the random distributions to the occurrence frequency.

4 Conclusion

In an advanced and complicated railway system, it is important that implementation of measures does not entirely rely on human senses and is instead based on appropriate evaluation (quantification) of these measures. Due to creation of the basic model, it is now possible to evaluate the entire railway system at a certain level by using an integrated index; however, some problems still remain as introduced in this report.

We plan to continue examining these issues in order to further achieve safe and stable transportation services.

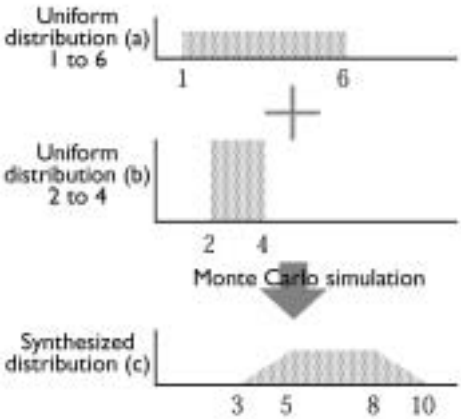
References:

1) Ishizu, Fukuyama, Inuzuka, and Kamase: Research on Railway Reliability; paper from the 40th Railroad Cybernetics Symposium, 2003.
2) Ishizu, Fukuyama, Inuzuka, and Kamase: Research on Railway Reliability; J-Rail, 2003.

The Monte Carlo simulation method

The Monte Carlo simulation method is in general a generic term referring to numerical value simulation using random numbers. In this method, random variables can be used as input data. Values randomly sampled in accordance with the specified probability distribution are used as input values and repeated calculations are conducted. As a result of the calculations, output data can be obtained as probability distributions.

[Example]



There are probably only a few people who can immediately provide a correct answer to the questions "what is the result of synthesis of the uniform distribution (a) and the uniform distribution (b) above" but with the Monte Carlo simulation method, the synthesis result can be easily obtained as a synthesized distribution (c).