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A Case Study of Safety Evaluation Using Probabilistic Analysis Techniques - Application to the Survival Rate of Passengers in Tunnel Fire -

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Abstract: A deterministic analysis that assumes a physical quantity including variance as a representative value, such as an average value, is inevitably conservative when compared to a phenomenon that actually causes damage. In addition, if there are not enough data available, conservatively selected values may not predict actual damage. Probabilist evaluation techniques can be applied efficiently because they predict unmeasured data through statistical analysis of existing measured data even if there is no actual measured data. Therefore, this paper aims to confirm the validity of the method through a case study using the probabilistic analysis method. The currently used scenario for predicting the risk of a tunnel fire accident contains many uncertainties such as the tunnel length, passenger occupancy rate, and the propagation time of a train fire, so conservative assumptions are used. In the existing studies, it is difficult to quantitatively evaluate each variable, so sufficient research has not been conducted, especially in terms of not clearly presenting the risk assessment results for the influencing factors because the uncertainty of the data is not taken into account. However, it is judged effectively to represent most of the variables predicting the survival rate of passengers in a tunnel fire as a probability distribution including variance. This study aims to investigate the risk assessment of tunnel fires in railway systems. In this regard, various accident scenarios were assumed by using a probabilistic approach to consider the uncertainty in the event of a fire, and then the survival rate of passengers under conditions affecting the accident scenario was predicted. The effects of factors on survival of passengers in tunnel fires were also analyzed. As a result, it was found that smoke propagation speed, fire detection time, and emergency support arrival time have a great effect on the passenger's survival rate.

Keywords: Determinisitc Method, Probablistic Method, Probability Density Function, Monte-Carlo Simulation, Risk Assessment, Survival Rate

1. Introduction

In the case of a train fire, many passengers may be exposed to it, so there is a high possibility that it

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will develop into a large fire accident. In Korea, the Standards for Safety Technology for Railroad Facilities stipulated that there should be a conduct of fire safety evaluation for tunnels over one kilometer in length[1]. This is to introduce a performance-oriented design technique for disaster prevention facilities in railway tunnels to quantitatively evaluate the risk of installing disaster prevention facilities in railway tunnels and to determine whether to install the facilities. Besides NFPA[2], many foreign research institutes such as BHRG, ITC, and APTA are also conducting research on fire safety in tunnel sections[3].

In particular, to identify factors that have the greatest impact on human safety, quantitative risk assessment is performed to determine whether disaster prevention facilities are installed. Quantitative risk assessment for train fires in tunnels creates fire scenarios and calculates the number of fatalities and economic costs based on the accident frequency and accident results for each scenario. In addition, it was mainly introduced in European countries to predict the level of risk by multiplying them and evaluate the appropriateness of the level of risk such as social risk evaluation criteria[2].

With in Korea, the accident scenario is presented in the “Railway Tunnel Fire Safety Assessment Manual” by considering the location of the fire train, the location of the fire, the evacuation time delay, the operation of the smoke exhaust system, and the expansion of the fire[4].

Factors that have a major influence on the risk assessment results in a fire scenario are the delay in evacuation time, the probability of fire spread, the probability of stopping a train fire in the tunnel, and the correlation between the operation of the ventilation system and the direction of evacuation. Yoo et al.[5] analyzed the evacuation characteristics according to the ventilation wind speed and evacuation direction.

In addition, Park[6] reviewed the appropriateness of application standards by synthesizing the analysis results of model tunnels through quantitative risk analysis on railroad tunnel fires and comparing them with domestic and foreign standards related to evacuation promotion facilities. In addition, a methodology for predicting the number of fatalities and possible fire spread scenarios in the event of a train fire in a tunnel through the analysis of passenger safety in railway tunnel fire accidents using simulation[7] has also been presented. Also, a systematic risk assessment case study for fire accidents was conducted through a fire accident risk analysis study in railway tunnels and underground sections[8]. However, since it is difficult to evaluate quantitatively each variable in existing studies, sufficient research has not been conducted, such as not clearly presenting the risk assessment results for influencing factors because data uncertainty is not considered.

Therefore, in this study, the risk assessment of tunnel fires in railway systems was studied, and the effect of factors on the survival of passengers in tunnel fires was analyzed.

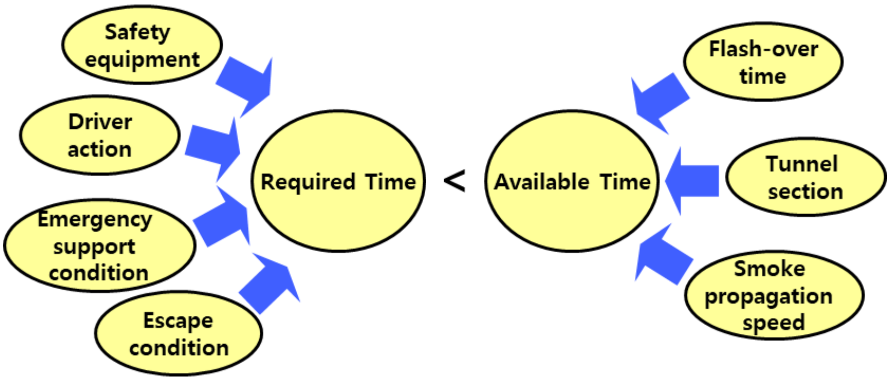
2. Probabilistic Technique

2.1 Selection of Probability Variables

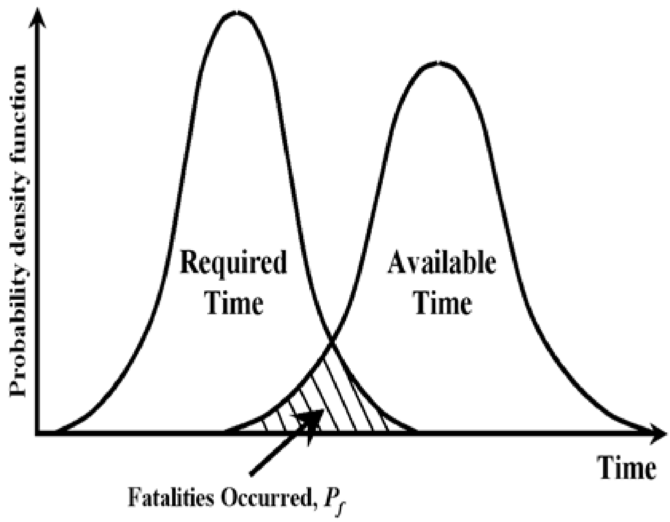
In the probabilistic methodology, a probability variable is an input variable to consider variance, and a measured quantity with uncertainty is mainly included here. Representative probability variables include tunnel length, train stop position, passenger escape speed, fire detection time, emergency assistance arrival time, and smoke propagation speed. Analysis can be performed by considering all input variables including variance as probability variables, but only the main input variables are considered as probability variables in consideration of the reliability and efficiency of the calculation. In addition, the effect of each probability variable on the overall passenger survival rate can be quantitatively evaluated through sensitivity analysis of each probability variable.

Random variables can be divided into continuous random variables having continuous values and discrete random variables having discrete values. Physical quantities such as emergency support conditions and driver action can be viewed as continuous random variables, while flash-over time and escape conditions can be viewed as discrete random variables.

When the random variable increases, it is impossible to construct an equation and derive a solution using a numerical analysis or a method using a reliability index. Analysis using simulation leads to an increase in the number of iterations, which takes a lot of time for calculation and result processing. In general, for a prediction with a probability of 0.001, 10,000 iterations, which are ten times the reciprocal of the probability, are required. However, if the random variable increases, more iterations must be performed to obtain a reliable probability, and it takes a lot of time to predict the probability. In this case, it is possible to increase the efficiency by assuming the discrete random variable as a fixed value and then limiting the analysis to each possible case. In addition, if a sensitivity analysis is performed on a continuous random variable, the probability can be predicted efficiently. Factors affecting the survival rate of passengers in a tunnel fire accident are diverse as shown in [Fig. 1], and if these factors are broadly classified, they can be divided into factors that improve the survival rate of passengers and factors that improve the mortality of passengers. In this study, the required time (RT) and the available time (AT) for the survival and evacuation of passengers were set as criteria for determining the survival of passengers. These variables RT and AT are not determined as a single value, but can be expressed as a probability distribution as shown in [Fig. 2] according to the characteristics of the influencing factors. It can be said that the analysis using the probability distribution is more appropriate than the general analysis assuming a single value for all factors including uncertainty.



[Fig. 1] Major Factors for Passenger Survival



[Fig. 2] Survival Probability under Tunnel Fire[9]

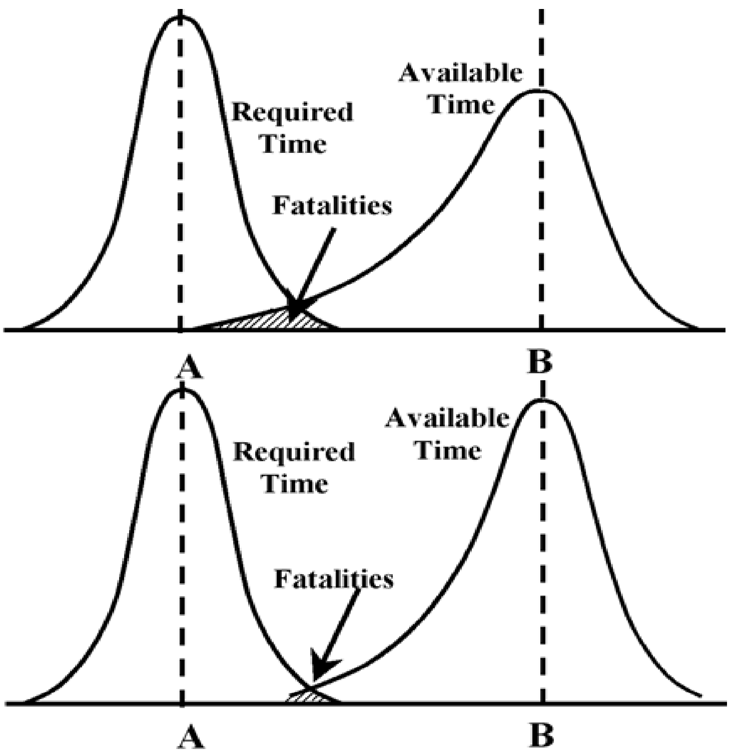
The measure of safety in probabilistic interpretation, that is, probabilistically "safe", is reliability, which is expressed as the probability that RT is less than AT.

$$R = P(RT < AT) = 1 - P_f \quad (1)$$

where P_f is the probability that death will occur. If the RT required for evacuation and the AT given to passengers are distributed probabilistically, they can be regarded as random variables and expressed as probability density functions *f(RT)* and *f(AT)*, respectively. Therefore, the probability of death is expressed as the following equation[9].

$$P_f(RT > AT) = \int_0^{\infty} (\int_{AT}^{\infty} f(RT) d(RT) f(AT) dAT \quad (2)$$

Schematic representation of the above equation corresponds to the shaded area in [Fig. 2]. The reason that the uncertainty and variance of the input data must be taken into account when calculating the mortality probability is that, as shown in [Fig. 3], different mortality rates are sometimes calculated even with the same average value depending on the data. Therefore, since many factors are probabilistically distributed as the factors governing the actual phenomenon, using an analysis method such as Monte Carlo simulation can more rationally evaluate risk phenomena including stochastic factors.



[Fig. 3] Different Death Probability at the Same Average[9]

2.2 Input Date Considering Variance

For probabilistic analysis, random variables considering the variance of input data should be selected and evaluated according to the distribution of these variables. In this section, the derivation process of the probability density function and the probability density function for the selection of the necessary random variables and the expression of distribution characteristics has been described.

2.2.1 Input of Probability Variables

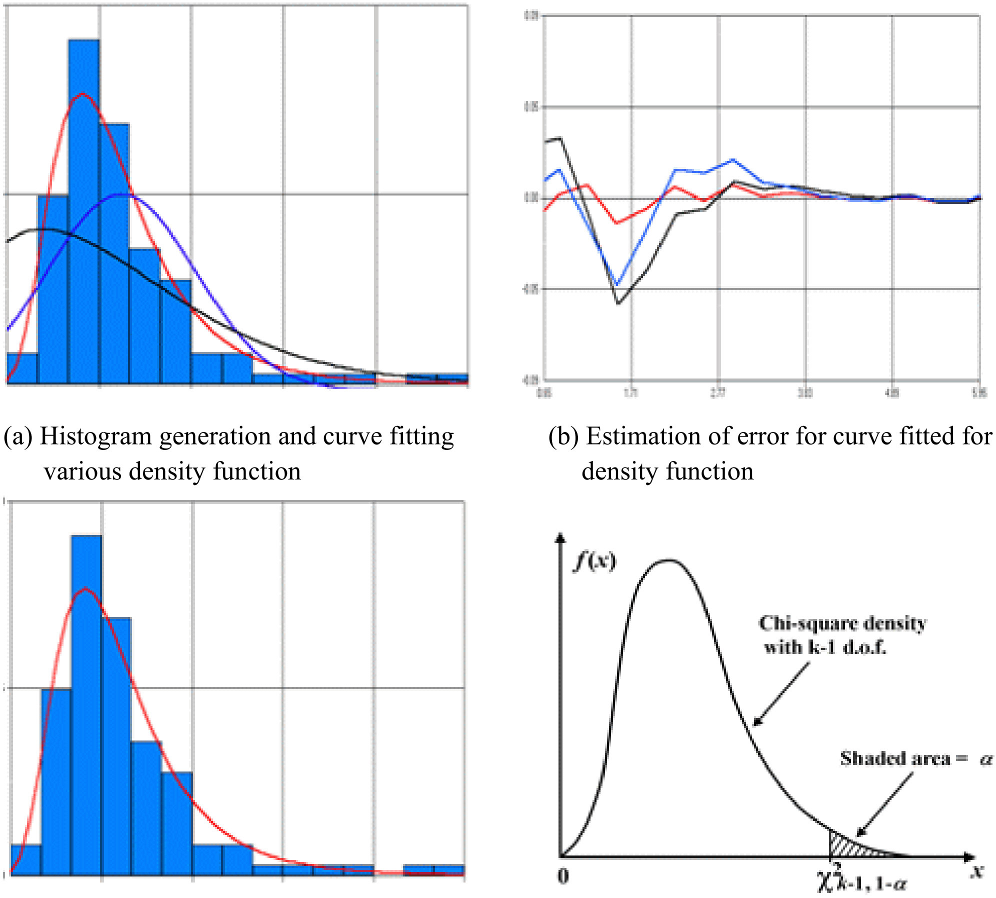
As a data input method considering variance, there is a method using the probability density derived through trend analysis of the input data and a method using the actual data directly.

When using probability density function, it takes time to derive the probability density function through input data analysis and to verify the reliability of the derived function. However, it is mainly used in probabilistic soundness evaluation because it is possible to predict extreme data that are not included in the range of given data. In addition, it is convenient to refer to the probability distribution included in the results of other researchers, and only major values, such as mean and standard deviation, are required for interpretation.

However, depending on the curve fitting method used in derivation of the probability density function, different probability density functions can be derived for the same data and can be applied only when the number of input data is large.

With actual data, it can be used efficiently efficiently when the reliability of the input data is high, and it is easy to use because it does not take time to analyze the input data. However, it is difficult to apply to the evaluation of factors affecting the survival of passengers, such as tunnel fire, because it is impossible to simulate extreme situations outside the range of input data.

2.2.2 Induction of Probability Density Function[9]



(a) Histogram generation and curve fitting various density function

(b) Estimation of error for curve fitted for density function

(c) Determination of best fitted density function

(d) Goodness of fit test

[Fig. 4] Inductive Process of Probability Density Function

The derivation process of the probability density function includes a method using a histogram and a method using probability paper[10]. The method using the histogram used in this study is described below.

1) To derive the probability density function, first divide the input data into several sections and create a histogram as shown in [Fig. 4] (a). For example, when deriving a probability density function for variable 1, the axis in the figure is variable 1. In this case, the minimum value is 0 and the maximum value is 1, and the axis is the frequency of occurrence.

2) A plurality of probability density functions assumed to predict the distribution of the histogram are shown together with the histogram.

3) Calculate the error between the distribution obtained by the curve junction of the created histogram and the assumed probability density function, respectively. The calculated error for each assumed distribution is shown in [Fig. 4] (b).

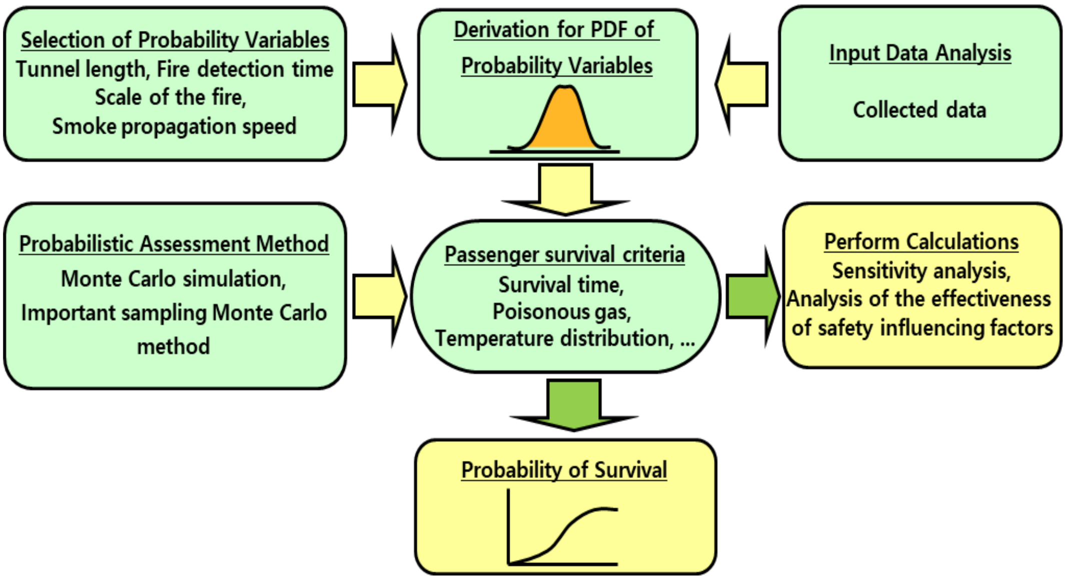
4) Select the probability density function to be used for analysis, considering the error calculated above. When selecting the probability density function, it is possible to refer to the error in the main area of interest of the random variable, the overall error, and the research contents of existing researchers.

5) As shown in [Fig. 4] (d), it is determined whether the obtained distribution is suitable or not, and if it has reasonable reliability, it is adopted as a probability distribution. The Chi-Square method, the Kolmogorov Simirnov method, and the Poisson Process Test[11] are used to determine the suitability. These discriminant methods are used to determine whether the assumed probability density function satisfies the error range within the confidence interval, and the Chi-Square method is used in this study. By repeating the above process by modifying the section of the divided variable, the probability density function to be used for evaluation can be determined as shown in [Fig. 4] (c).

2.3 Risk Assessment Model[8,9]

As mentioned in the previous section, mathematical analysis methods and methods using simulation are possible to predict the probability of structural failure or death in tunnel fire. For the mathematical analysis method, an optimization method or a formula expansion method can be used by constructing a joint probability density function or a limit state equation composed of random variables. However, in the analysis using simulation, the system configuration is required with many iterative calculations, and an example of the evaluation model used in the system configuration is shown below.

1) For probabilistic analysis, random variables are selected to consider variance or uncertainty.
2) Derive a probability density function through data analysis of random variables or use it as input data for deterministic analysis by constructing a database.
3) Introduce probabilistic evaluation methods, such as Monte Carlo simulation techniques, to determine the survival criteria of passengers.
4) Analyze the effect of sensitivity analysis or safety influencing factors.
5) Perform the above steps 1) to 4) as many times as the set number of repetitions to calculate the number of surviving or dead samples among all extracted samples.
6) It is possible to calculate the survival probability from the above results. A schematic flowchart of the above evaluation model is shown in [Fig. 5].



[Fig. 5] Schematic Diagram of the Risk Assessment Model[9]

3. Factors Affecting the Survival of Passengers in Tunnel Fire

Factors affecting the survival rate of passengers in tunnel fire accidents are diverse as mentioned in Chapter 2, and if these factors are broadly classified, they can be divided into factors that improve the survival rate of passengers and factors that improve the mortality of passengers. In this study, the time required for passenger survival and escape, (RT) and the time given to the passenger, (AT) were set as criteria for determining the passenger's survival.

Of the two variables (AT and RT) that determine whether a passenger survives, the time required for a passenger's evacuation is determined by the following factors:

1) detection time of a fire in the train, 2) escape distance (determined by the length of the tunnel, train stopping position, and tunnel gradient), 3) escape of passengers (determined by the floor condition of the escape route in the tunnel, lighting and smoke condidiotns, and passenger density), 4) arrival time of emergency assistance, etc. Also, the time required for a passenger's survival, i.e., the time limit for escaping the tunnel, is determined by the following factors:

1) time of fire flash-over (determinable from fire scale), 2) smoke propagation and smoke layer descent speed

However, these two variables, AT and RT, can be expressed as probability distributions according to the distribution characteristics of influence factors rather than being determined as a single value. In addition, when analyzing a specific tunnel, the shape of the tunnel section, the presence or absence of an escape route, the effect of the season, and the effect of the longitudinal curve of the tunnel can be considered.

In this paper, the above factors were not considered in order to perform the risk assessment method and overall risk prediction. Many of the factors mentioned above are all values including uncertainty, and it is more reasonable to use probability distribution than to general analysis assuming a single value. The safety influencing factors of tunnel fires and the details of accident scenarios for setting them are described below.

3.1 Tunnel Length and Train Stop Location

When a train stops in a tunnel without an evacuation tunnel or smoke exhaust system, such as in Korea, the worst-case accident scenario can be seen as a case in which the train stops in the middle of the tunnel. For example, when a train stops in the center of a tunnel with a length of one kilometer, the evacuation distance of passengers can be calculated as 500 m. The length of the tunnel subject to tunnel fire safety evaluation suggested in NFPA 130 is 300 m or more. As a result of analyzing domestic general and high-speed rail tunnels with a length of 300 m or more, it was found to be a log-normal distribution with an average of 1,100 m and a standard deviation of 2.59. The case study in this paper intends to interpret the case where the tunnel length is 6 km and there is no evacuation tunnel.

3.2 Escape Velocity of Passengers

In order to obtain the time and speed at which the train is dispersed in the event of a fire in the railway tunnel, the following two situations have been studied. It conducted tests and numerical simulation studies of the entire process of the situation in which the fire train continues to operate and the personnel in the cabin are dispersed to adjacent rooms, and the fire train stops and personnel get off and disperse to the emergency rescue area or emergency exit of the tunnel[12]. The results are as follows.

(1) The number of people in the adjacent rooms has a clear limit on the dispersion of people in the fire rooms, but the larger the number of people in the adjacent rooms, the slower the average distribution speed of the people in the fire room, and the longer the people stay and wait in the dispersion process, and the longer the dispersion time.

(2) If the dispersion exit width (3 m) in the tunnel meets the condition that the dispersion of people is not too crowded, the average speed of dispersion of people in the two dispersion routes is basically the same for one dispersion of an emergency rescue and both dispersion of an emergency exit.

(3) Under the condition of opening two exterior doors for each guest room, the two exterior doors located in either direction of the compartment are slower than the occupant dispersion efficiency when located in both directions of the cabin, and the average dispersion rate drops by about 21.6%.

(4) The speed of dissipation for young men and women in the railway tunnel can be set to 1.2 m/s and 1.5 m/s, respectively, and these speeds can be used as a basis for calculating the dispersion speed of others (elderly, children, etc.).

3.3 Visibility & Fire Detection Time

In the case of a fire intensity of 10 MW, the visible distance from the fire area is at least 0.38 m in the vertical cross section, and the smoke from high-temperature areas rises to the tunnel ceiling and spreads along the tunnel wall. There is no diffusion of smoke in the direction[13]. In the case of a fire intensity of 20 MW, when viewed from the vertical cross-section, the visible distance from the fire area is the minimum and it is 0.16 m, and the high-temperature smoke rises to the tunnel ceiling and spreads along the tunnel wall. As a result, a spread of 9 m smoke occurs. According to NFPA 130[2], the visible distance under the conditions of the evacuation route in the tunnel is that a lit sign must be visible at a distance of 9.1 m, and a door or wall must be distinguishable at a distance of 7.1 m. Therefore, it is considered that there will be no hindrance to the evacuation activities of the passengers upstream.

The fire detection time is a very large factor influencing the survival rate of passengers, and if a fire is detected early, a major accident can be prevented. However, since there is no previous study on the fire detection time, this study interpreted the entire time until detection, fire suppression failure, and train escape as a random variable. In the case study, the fire detection time was interpreted assuming a normal distribution with an average of 480 seconds (8 minutes) and a standard deviation of 96 seconds

(20% of the mean).

3.4 Emergency Assistance Arrival Time

For the support of the elderly or the injured, the time for the emergency support team to arrive at the tunnel entrance after a train fire occurred and the time to move from the tunnel entrance to the location of the injured person in the tunnel were added and considered as the arrival time of emergency assistance.

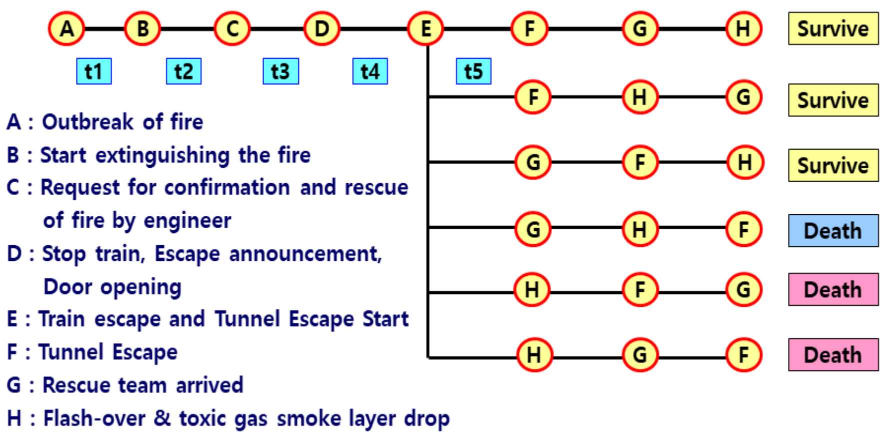
If the flame or smoke does not spread rapidly after a fire, passengers can move, so the arrival time of emergency assistance was decided in consideration of the passengers' movement. In this paper, the arrival time of the emergency support team to the tunnel entrance was assumed to be a log-normal distribution with an average of 900 seconds (15 minutes) and a standard deviation of 600 seconds (10 minutes). And it was calculated as entering at a speed of 2.5 m/s from the tunnel entrance to the location of the injured.

3.5 Smoke Propagation Speed

A lot of research is being done on the speed of smoke propagation because it is a toxic gas that is generated by a fire rather than flames caused by fire that threaten the survival of passengers in the tunnel section. The speed of smoke propagation varies depending on the exhaust system of the tunnel, the cross-sectional area of the tunnel, and the size of the fire. In this paper, since the accident scenario is to be interpreted simply, it is assumed that the toxic gas spreads at a constant speed from the accident site to the tunnel entrance. In the case study, 2.5 m/s was assumed.

4. Analysis for Predicting the Survival Rate of Passengers

4.1 Tunnel Fire Scenario



[Fig. 6] Accident Scenario for Passenger Survival[8]

In order for passengers to survive in case of a train fire, as in the scenario shown in [Fig. 6], fire detection, confirmation and report of driving command, failure to extinguish the fire and decision to evacuate the train, broadcast evacuation information and open the door, and walk out of the tunnel process is required. On the other hand, the time given to the passenger can be set until just before the toxic gas generated by the fire is propagated to the passengers' location.

In addition, when emergency assistance arrives, it is assumed that the passengers' tunnel exit speed is increased to 2.0 m/s, and the emergency assistance team is assumed to enter the fire scene from the tunnel entrance at a speed of 2.0 m/s. In the analysis, as shown in [Fig. 6], the case of escaping with the help of emergency assistance and the case of escaping from the tunnel before the arrival of emergency assistance were considered. In both cases, the time given for a passengers' survival is the same, but the time taken for the passengers' escape is considered differently. When emergency assistance is not considered, the escape time is determined by simply dividing the escape distance by the escape speed.

4.2 Simulation Code for Predicting Passenger Survival Rate

By comparing the time it takes for passengers to escape from the train and tunnel with the time given for passenger survival, it is possible to determine whether a passenger survives. As explained in the introduction, these input data contain many uncertainties. Probabilistic techniques applied for this purpose include a method using a reliability index and a method using a Monte Carlo simulation[10][14].

In the method using reliability, a complex joint probability distribution must be integrated, but in many cases integration is impossible, so approximate solutions such as FORM or SORM are sought. However, they could not express the accident scenario as a formula, so in this study, the survival rate of passengers was determined by using the Monte Carlo simulation technique. The Monte Carlo simulation technique is a technique based on iterative random number extraction, and [Fig. 7] shows the simulation procedure to apply it to the prediction of the passenger survival rate in case of a tunnel fire.

The procedure shown in the figure is as follows.

① Selection of random variables and data input

② Selection of fixed variables and data input

③ Random number generation

④ Calculation of evaluation variables (RT, AT),

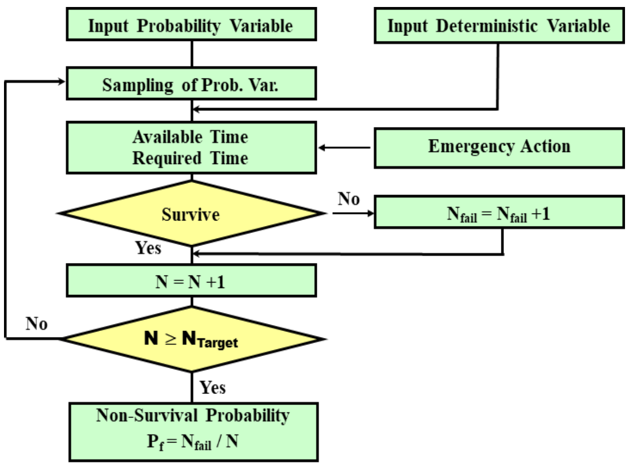
⑤ Determination of passenger survival

⑥ Storage of evaluation results and statistical processing

⑦ Confirmation of simulation conditions

⑧ Process of result processing

In order to apply the Monte Carlo simulation used to predict the survival rate of passengers, many iterative calculations and statistical processing are essential.



[Fig. 7] Simulation Flow for Tunnel Fire Accident

4.3 Result of Simulation

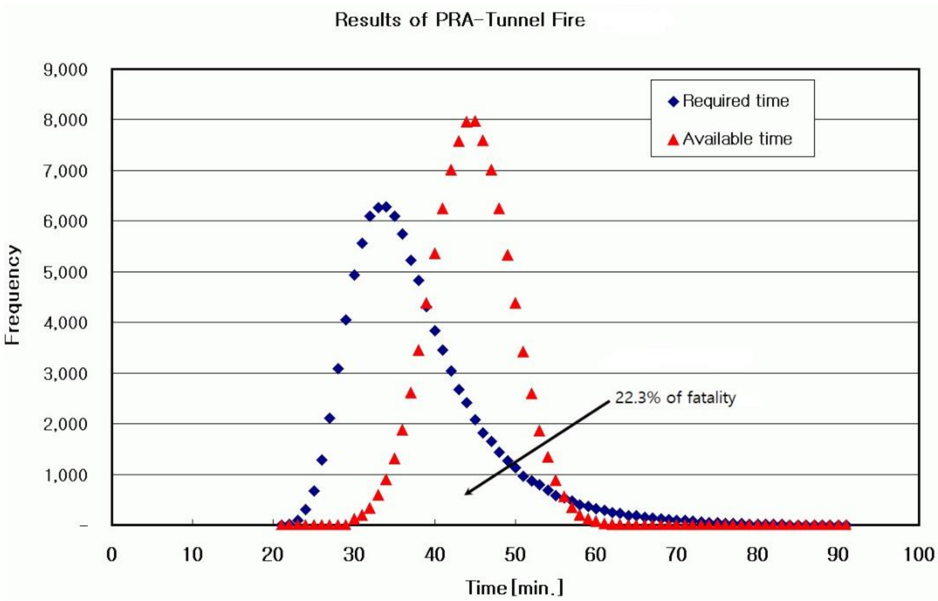
A case study was conducted using the code described in the previous section. The analysis target was a tunnel that could run a 5 km two-way train without smoke facilities, and the value mentioned in Chapter 3 was used for the input value. That is, the passenger's escape speed is normally distributed with an average of 0.6 m/s and a standard deviation of 0.5 m/s, and the fire detection time is normal with an average of 480 seconds (8 minutes) and a standard deviation of 96 seconds (20 % of the average). Distribution, the time the emergency support team arrives at the tunnel entrance is log-normal with an average of 900 seconds (15 minutes) and a standar d deviation of 600 seconds (10 minutes). In addition, it was assumed that the speed of 2.5 m/s from the tunnel entrance to the location of the injured was, and the speed of smoke propagation was 2.0 m/s, respectively.

In the Monte Carlo simulation, in order to reduce the effect of random number generation, 5 independent executions were performed each 100,000 times, and the average value was determined as the survival rate of passengers.

The main interpretation case and passenger mortality (100 % minus passenger survival rate) were calculated. The results for the case where the probability distribution presented above was used and the case where some random variables were analyzed assuming only average values are shown below.

(1) Utilization of given conditions → 22.3 %
(2) Assume that only the passenger escape speed is a random variable → 1.6 %
(3) Assume only the emergency rescue arrival time as a random variable → 15.2 %
(4) Assume only fire flashover time as a random variable → 12.3 %
(5) Assume only fire detection time as a random variable → 0.2 %
(6) Analysis using only the average value of all variables → 0.1 %

The result with a 22.3 % probability of death is shown in [Fig. 8].



[Fig. 8] Result of Fatality

5. Conclusions

In this paper, a study was conducted to predict the safety of passengers in a tunnel fire by using a probabilistic technique, and the following conclusions were drawn. Major influencing factors of risk assessment were derived, and individual characteristics of these factors were analyzed.

It was found that the death rate of passengers according to the escape length was related to the smoke propagation speed and had a great influence on the survival rate of passengers. For example, if the smoke propagation speed is 2.5m/s and the escape speed is 2m/s, the mortality rate is less than 1%, but if the escape speed is 1.5m/s, the mortality rate (15%) has increased sharply.

The fire detection time is a factor that directly affects the given time on the survival of passengers, and it has a great influence on the survival rate of passengers as it is related to the fire flashover time. When the fire detection time was 100 seconds, the passenger mortality rate was 10%, but when the fire detection time was 420 seconds, it increased to 22%.

It was found that the effect of emergency assistance arrival time was related to the escape distance of passengers and had an effect on the mortality rate. For example, when the emergency assistance time was 500 seconds, the mortality rate was as low as 2%, but when it was increased to 900 seconds, the mortality rate also rose sharply to 17%.

In the future, it is thought that a more accurate safety evaluation can be calculated if the disaster prevention facilities of the tunnel are explained in more detail and a simulation model that can analyze the fire characteristics of a long tunnel is used.

6. Acknowledgments

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