Sensitivity Analysis of Safety Measures for Railway Tunnel Fire Accident

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Abstract:
After the subway train fire accident at Daegu in 2002, Korean government set up the first Integrated Railway Safety Plan (2006-2010) in 2006. The targets of this plan are 40% reduction of accident fatalities and the prevention of major accident. Among total 77 action items, included in this plan, 13 action items, such as the installation of emergency exit tunnel and the replacement of train interior materials with inflammable materials are directly related to the fire safety improvement. Furthermore, 10 action items are indirectly related to the fire safety such as the training and the education of staffs on the emergency response, the competency management for safety critical workers, and the fire risk assessment on subway trains.

Since many fire safety improvement alternative measures can be applied in our railway systems, the effect of the each safety measure must be quantified prior to the safety investment. Fire accidents not only rarely occur but also contain so many uncertainties such as human responses, smoke spread speeds, physical conditions of fire and etc. Since there had been no report of fatalities caused by train fire accidents before the huge accident in Daegu, it is difficult to analyze on safety measures quantitatively based on such an accident history.

Considering the uncertainties of many input parameters to the analysis, a probabilistic approach is necessary. In this study, a probabilistic risk assessment has been carried out considering key factors such as physical conditions of a fire accident, human responses on fire, and the sensitivity of each key parameter has been derived. Prior to the probabilistic risk assessment, a deterministic risk model was constructed based on the system safety method such as fault tree and event tree. Among various probabilistic approaches, the Monte Carlo simulation has been applied in this study. The probabilistic risk assessment has been carried out with the following sequence: 1) the derivation of probability distributions for safety assessment factors, 2) the sampling of probability variables, 3) the consideration of safety measures, 4) safety assessments, 5) Monte Carlo simulation, and 6) the statistical processing and the sensitivity analysis for assessment results. To quantify human factors, HEART (Human Error Assessment and Reduction Techniques) have been applied. The effect of new safety measure can be quantified by comparing existing risk with modified risk with new safety measure. As a result, the estimation method has been proposed and a case study for the quantitative effect estimation of safety measures has been done.

1. Introduction
In order to reduce the accident and fatality up to 40%, railway safety specialists who were gathered from the government, railway companies (including infrastructure managers), research institute, and transportation safety authority derived railway safety issue and safety measures in 2005 [1]. They derived 77 safety projects in 6 fields (staff, infrastructure, rolling stock, safety management system, accident investigation, and R&D in safety system). Among these safety measures, some of safety measures are finished already such as the replacement of interior materials with inflammable material in rolling stock, preparation of rolling stock safety standard, competency management for safety critical workers. But many of safety measures will be finished by 2010. Due to these safety measures, accident fatalities have been reduced according to the planned target. There was no major accident fatality, but some critical accidents happened. Some accidents could cause disastrous fatalities such as the passenger train fire in tunnel, and the passenger train collision in the platform. Investigation results showed that driver's improper response was the main cause and some of safety measures were not effective in case of that accident especially for the cause of train fire accident [2].

Many of fire safety measures focus on building physical barriers such as fire detection & alarm system, interior material change with inflammable material and smoke control equipment. For the effective application of many fire safety measures, sensitivity analysis of each safety measure is required. But in the previous studies [3~5] human factors were not considered due to the lack of human factors data, so effects of safety measures were overestimated. To consider the human reliability in sensitivity analysis, HEART [6, 7] analysis results are reflected in fault tree and event tree of train fire accident...
scenario. As fire accidents have so many uncertainties and rarely happen, thus it is difficult to estimate consequence of train fire accident. For this, Monte Carlo simulation is applied for the consideration of uncertainties. For the application of this sensitivity analysis model, many iterative calculations and expert judgments are required. Thus, in-house codes are developed to apply this model effectively.

2. Scenario for train fire accident

Accident statistics show that majority of train fire accidents are caused by arson and rolling stock problem caused by driver or maintenance personnel's mistake. Among the many train fire accidents, only the accident happened in the tunnel occur fatalities, so train fire accident scenario is focused on tunnel. Hazardous events for tunnel fire accident are classified into prevention of incidents and mitigation of impact. Many of safety measures to prevent fire incidents are finished, and safety measures to mitigate accident consequence are progressed. This is because accident response related works depend on the human factors and include many uncertainties, which are difficult to estimate reliable effects.

2.1 Construction of event tree and fault tree

Many safety measures have been published in many standards and study. Recently constructed high speed train and metro line have reliable safety system to protect train fire, but conventional lines, which takes greater part of railroad length in Korea, has plan for safety investment. Passenger train on the conventional line is selected for case study. Event tree is shown in Figure 1 for conventional line train fire caused by rolling stock problem such as engine or electrical equipment failure. During the analysis each probabilities of occurrence are determined by the fault tree. Fault tree for the each branch of event tree are shown in Figures 2~4.

2.2 Determination of passenger fatality

Based on the fault tree and event tree, factors affecting passenger's life are determined and factors are classified into two categories [3]. One is “available time to passenger” and the other is “required time to escape from tunnel”. Some factors such as types of rolling stock, dimensions of tunnel, and communication system are related with both time sets. In this study, following factors are considered in the analysis.

1) Factors affecting passenger’s survival time
   - Type of train(size of fire, fire detector type, interior material)
   - Fire suppression equipment (extinguisher, spring cooler)
   - Ventilation system (installation interval, capacity): Conventional lines have no ventilation system and it is difficult to install current condition due to the electrification in the ceiling.
   - Physical condition of tunnel (cross section of tunnel, single or double track)
   - Driver’s experience and training level

2) Factors affecting passenger’s evacuation time
   - Type of train(number of passenger on board, number of exit in train)
   - Physical condition of tunnel (cross section of tunnel, single or double track, escape route, length, train stop position, illumination, monitoring system)
   - Fire suppression equipment (extinguisher, spring cooler)
   - Driver’s response (fire detection, decision, communication, operation)
   - Emergency response time (tER)

Passenger fatality is determined by comparing passenger survival time and passenger evacuation time. If passenger evacuation time is longer than the survival time, fatality will occurs. Required time to passengers (tR) is determined using the following equation.

\[
t_R = t_D + t_{ER} + \frac{S}{V_1} \frac{1}{V_2/V_1 + 1} - t_2
\]  
(1)
where $t_d$ is detection time, $t_2$ is emergency rescue arrival time, $S$ is escape length, $V_1$ is passenger evacuation speed, and $V_2$ is emergency rescue moving speed.

So many uncertainties made it difficult to determine consequence of accident in event tree. In Figure 1 consequence of damage 1-8 varies from input data assumption. In order to solve this problem a probabilistic method is applied and this method is explained in the following section 3.

Figure 1: Train fire event tree cause by rolling stock problem

Figure 2: Fault tree for fire detection

Figure 3: Fault tree for tunnel evacuation

Figure 4: Fault tree for fire suppression, driver's emergency response and rolling stock evacuation
2.3 Human reliability analysis

HEART is applied for the quantitative estimation of driver's reliability. It is applied from 8 kinds of generic task type (GET) and 16 performance shaping factors. Generic task type is similar with RSSB research [7,8], and performance shaping factors (PSF) are determined by expert judgement and other research results in nuclear industry in Korea [9]. Human error probability (HEP) is determined by equation (2).

\[
HEP = GEP \times \Pi [R_i \times (W_i - 1) + 1]
\]  

where \( R_i \) is effect of PSF, which varies from 0 to 1, \( W_i \) is a weighting factor of PSF. HEP values vary form \( 1.0 \times 10^{-3} \) to \( 4.0 \times 10^{-1} \), and this values are reflected in fault trees in Figures 2~4.

3. Accident consequence estimation

For the consideration of uncertainty, a probabilistic method with developed code is applied. Probability density function (PDF) for some probabilistic variable is derived from accident data, expert judgments and testing results. Sensitivities or effects of safety measures can be considered as input data distribution. For example installation of fire detector reduces the mean value and standard deviation of fire detection time.

3.1 Probabilistic variable determination

Many references [10,11] are available for many safety measures, but some measures are not practicable. For smoke control system installation of toxic gas evacuation equipment is very difficult due to power supply line in the tunnel ceiling. In some tunnel, emergency exit tunnel can not be installed due to the structural problems. Train driver's performance varies on working conditions so some assumption is required for quantitative analysis. Parameters for the sensitivity analysis are listed in the following

1) Escape distance: derived from tunnel length and train stop position
2) Escape velocity: derived from physical condition of tunnel, escape route condition, number of passenger
3) Emergency rescue system: communication system, monitoring system
4) Smoke spread speed: derived from physical condition of tunnel, smoke control equipment
5) Flash-over time: derived from rolling stock type, fire detection time, driver's response, fire control system

![Figure 5: Flow chart for probabilistic analysis](image)

![Figure 6: Distribution on passenger fatality](image)
3.2 Development of probabilistic analysis code

Monte Carlo simulation is an iterative technique repeating deterministic analysis. Figure 5 illustrates the flow chart of developed code and Figure 6 shows the distribution of required time versus available time in equation (1). Some probabilistic variables are selected according to the employed analysis model. Passenger fatalities are determined as equation (2). In Monte Carlo simulation, the convergence is obtained when number of iterations equals to $10^6$. In order to decrease the random number effect during simulation, five independent simulations are carried and the average value is used as a result.

3.3 Sensitivity analysis

The sensitivity analyses are carried out for the major input parameters that have large variations. Probability density function (PDF) for some probabilistic variables assumed in this study is derived from the design and RAMS data. The probabilistic variables for case study are shown in Table 1 and the sensitivity analyses are explained in the following. During the analysis escape length is assumed in 1500m.

<table>
<thead>
<tr>
<th>Probabilistic variable</th>
<th>PDF type</th>
<th>Mean</th>
<th>S.T.D.</th>
<th>Min. value</th>
<th>Max. value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger escape velocity [m/s]</td>
<td>Normal</td>
<td>0.6</td>
<td>0.4</td>
<td>0.2</td>
<td>4.0</td>
</tr>
<tr>
<td>Smoke spread velocity [m/s]</td>
<td>Normal</td>
<td>1.5</td>
<td>0.3</td>
<td>0.8</td>
<td>3.0</td>
</tr>
<tr>
<td>Fire detection time [s]</td>
<td>Exponential</td>
<td>600</td>
<td>N.A.</td>
<td>60</td>
<td>1,800</td>
</tr>
<tr>
<td>Rescue service arrival time [s]</td>
<td>Log-Normal</td>
<td>900</td>
<td>600</td>
<td>120</td>
<td>3,600</td>
</tr>
<tr>
<td>Fire flash over time [s]</td>
<td>Normal</td>
<td>1,200</td>
<td>300</td>
<td>600</td>
<td>3,600</td>
</tr>
</tbody>
</table>

Table 1: Probabilistic variable assumption for case study

Effects of safety measures are estimated by changing failure probability in fault tree and probability density functions in simulation. A summary of this method considering the effects of safety measures is described in the following.

- Effect of fire detector: decrease of fire detector failure probability in Figure 2 and reduction of mean value for fire detection time in Table 1
- Effect of smoke control equipment: decrease of ventilation control failure probability in Figure 3 and reduction of mean value for smoke spread velocity in Table 1
- Effect of evacuation support equipment: decrease of door failure and evacuation guide support failure probabilities in Figure 3~4. Increase of mean value of passenger escape velocity in Table 1
- Effect of human factors: change of driver’s error probabilities in Figure 2-4

Through event tree and fault tree analysis for the current safety system, probabilities and consequences are determined. As a result, risk for current system is derived. Effect of safety measure can be calculated by comparing existing risk with new risk determined with new safety measure consideration.
3.4 Case study

Many branches in event tree with higher probabilities have no fatality. In the existing system, analysis result shows that more than 90% of accident scenarios produce no fatality, but remaining scenarios produce more than 30 fatalities in case of tunnel fire accident. Case study results are shown in Figure 7 & 8. Figure 7 shows the existing system risk (44 fatalities) and figure 8 shows the new system risk (32 fatalities) with fire detector. So effect of installation of fire detector is 12 fatalities reduction. This effect is only for this tunnel, if the physical conditions of tunnel change another calculation is required. Similar to this, sensitivities can be determined for other safety measure.

4. Results

Sensitivity analysis method for safety measures is proposed in this study, and for the efficient application of this method a probabilistic code is developed. In order to estimate effect of safety measure event tree, fault tree, accident scenario, passenger evacuation model, probabilistic model are also included in this model. A case study has been done for the verification of this model.

References