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폭약류의 철도수송에 따른 리스크 평가

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The Risk Analysis for the Rail Transport of Explosives

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요 약

이 논문은 철도를 이용한 폭약류의 운송 시 사고위험을 정량적으로 제시하였다. 사고유형은 역내에서의 사고와 수송 중의 사고로 분류하였다. 그리고 각각의 유형에 따라 열차의 탈선사고와 충돌사고의 빈도를 통해 사고빈도의 초기 값을 제시하였으며 ETA(Event Tree Analysis)를 통하여 사고빈도의 결과를 도출하였다. 피해영향평가는 TNT Equivalent method과 Probit analysis method를 이용하였다. 리스크 평가 결과 인구밀도가 높은 지역을 통과하는 폭약류의 철도운송은 사고발생시 높은 인명피해를 야기 시킬 수 있는 것으로 나타났다. 특히 유류와 복합된 사고의 경우 대형 폭발사고로 이어질 리스크를 가진 것으로 예측되었다. 결론적으로 폭약류의 위험물 수송 시 인구밀도가 높아 피해영향이 높은 지역의 경유를 줄이고 또한 리스크를 경감시킬 수 있는 대책을 강구해 위험요소와 사고빈도를 줄 일 필요성이 있을 것이다.

Abstract - This study presented quantitative risk analysis in case of transporting explosive materials by railway. Accident types were classified into accidents of in station and in transit. And the study presented an initial value of accident frequency through derailment accident and crushing one according to each type, and drew the results of accident frequency through event tree analysis. Damage impact evaluation used TNT equivalent method and probit analysis method. As the result of risk evaluation, railway transportation of explosive materials passing through areas which are high in population density is appeared to be able to cause a large number of personnel injury when occurring accidents. Specially, the accident of explosive transportation combined with petroleum was forecasted as easily resulting in large explosive accident. Consequently, there is a necessity to reduce consequences by decreasing passage through areas where are high in population density, and take measures for lessening the risks in case of transporting dangerous explosive materials.

Key words : railroad transportation, explosives, quantitative analysis

I. INTRODUCTION

In many developed countries, a large share of the transportation of hazardous materials is performed by railroad, and transportation load has also gradually increased with the economic growth of such countries. With the continuing interest and demand for increased safety, systems to effectively prevent and protect against accidents in the transport of hazardous materials have been established and kept up-to-date, not only in the rules related to transportation safety, but also in practical safety measures. In this environment, the safety system

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for the rail transport of hazardous materials in South Korea should be updated to correspond with the safety level of other developed countries, as the railroad is expected to be required to cope with a tremendous transportation load in the near future. Before updating the safety system for rail transport, including the transport of hazardous material, a risk analysis of hazardous material rail transport is performed. In this study, a quantitative risk analysis, including frequency analysis and consequence analysis, is carried out for the rail transport of hazardous material, specifically explosives, to estimate the effect of accidents.

II. PRELIMINARY HAZARD ANALYSIS

2.1. Population density and railroad line

There are various rail transport routes for explosives. In this study, one rail route was chosen, which starts in the North Gyeonggi area and proceeds to the North Chungnam area. This was selected because it passes through a region with a high population density. The population density was estimated along selected railroad routes 1 through 4 using Table 1, which shows the detailed population information[1].

2.2. Accident phases, in transit and in station

Typical accident phases in rail transport are listed in Table 3, both in transit and in station. Based on the accident phase, frequency analysis and consequence analysis were estimated[3].

According to the law related to explosives railroad transportation, the layout for a loaded rail boxcar was shown in Figure 1.

Table 1. Population density

Region	No	Population Density [Man/km^2]	Distance [km]	Number of people [Man]
North Gyeonggi	1	4902.1	32.2	631,377
Seoul	2	19592.9	31.2	2,445,200
South Gyeonggi	3	6125.9	58.1	1,423,659
North Chungnam	4	801.1	9.4	30,121

Table 2. Recommended population density[2]

	Density [man/mile^2]	Description
Remote	20	No metropolitan area with scattered housing; farms
Rural	100	Small village or town; recreation area
Suburban	1000	Typical suburbs; mixed used area
Urban	3000	Small city; densely populated suburbs; congested commercial area
Extremely High	10,000	Very dense city area

Table 3. Accident phases in railroad transportation

a) Accident in railroad station
- Collision with other train in station - Derailment in station - Fire in station - Loading and Unloading
b) Accident in transit
- Collision with other train - Derailment - Crossing accident

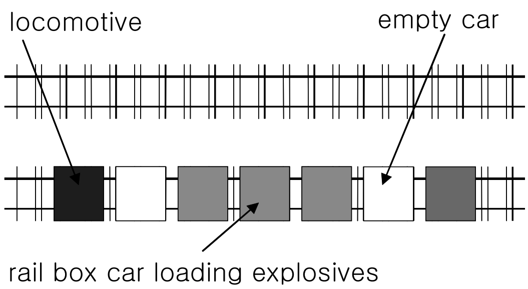

Fig. 1. Layout for loaded rail box car.

III. FREQUENCY ANALYSIS

The accident frequency of accident phases in transit and in station was shown in Table 4. Probabilities of each accident event were presented by ETA from Figures 2 to 5.

3.1. Frequency analysis in station

The accident frequency rate for hazardous material transport in a railroad station is 6×10^{-6} per car visit, as determined by the U.S. FRA (Federal Railroad Association)[5]. The amount of explosives transported from the North Gyeonggi area to the North Chungnam area via railroad carrier is about 11,814 tons per year. The explosives that can be transferred at once amount to 200 tons. Thus, there are 59 trains bearing explosives that travel on this route per year. The Accident frequency for hazardous transportation in station is 3.54×10^{-4} per year.

Generally, accidents result from derailment 81.8 percent of the time, and from other collisions 18.2 percent of the time. (Fischer et al., 1987) Probabilities of each accident event were assumed by ETA from the rates.

3.2. Frequency analysis in transit

Accident frequency rate concerning hazardous material transportation in transit is 2×10^{-7} per loaded car mile U.S. FRA (Federal Railroad Association) offered[5]. The distance between North Gyeonggi area and North Chungnam area is 130.9km, thus accident frequency in transit is 1.6×10^{-5} per year.

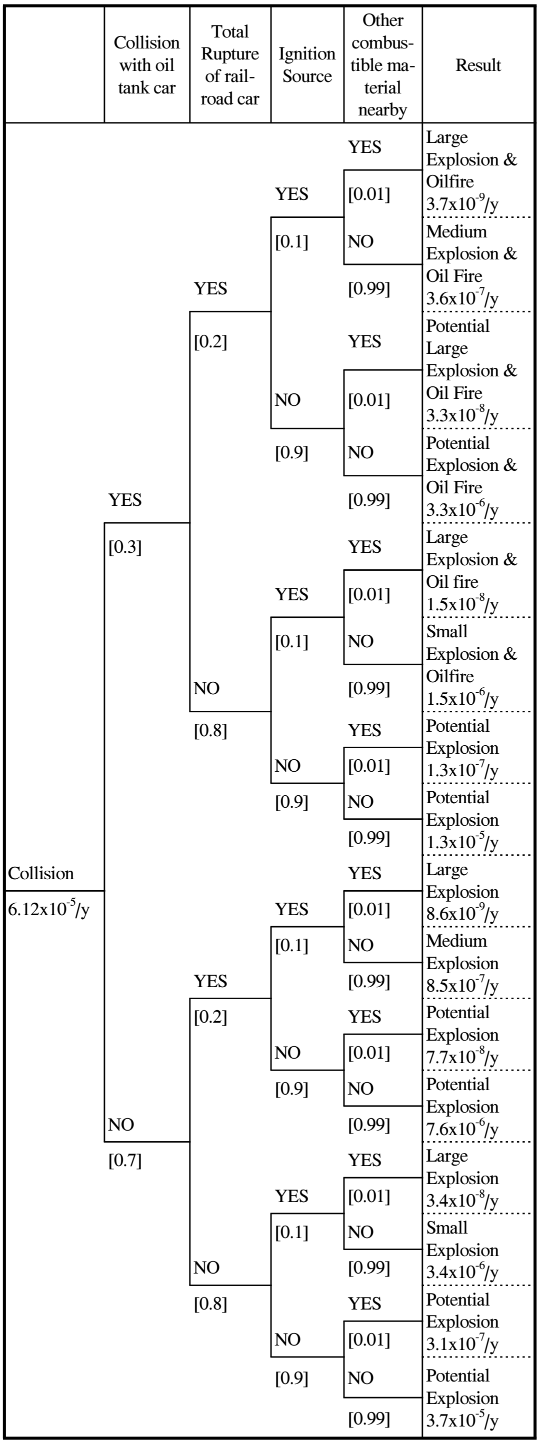

Fig. 2. Event Tree Analysis by collision in station.

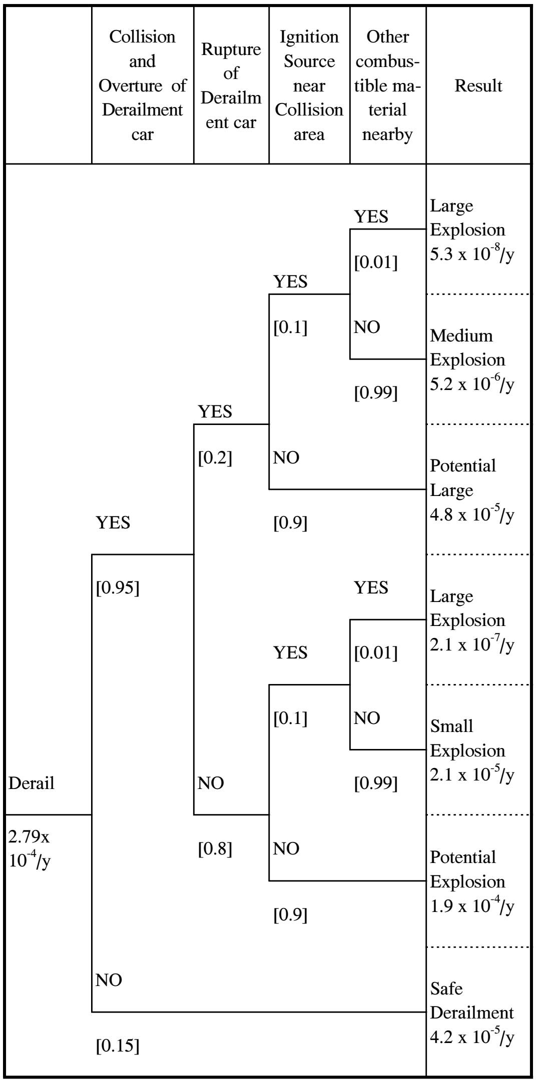

Fig. 3. Event Tree Analysis by derailment in station.

Table 4. Frequency of accident outcome cases

location	Frequency	Accident phases	
In Station	$3.5x10^{-4}$ /year	Derailment [0.82]	$2.79x10^{-4}$/year
		Collision [0.18]	$6.12x10^{-5}$/year
In Transit	$1.6x10^{-5}$ /year	Derailment [0.82]	$1.31x10^{-5}$/year
		Collision [0.18]	$2.88x10^{-6}$/year

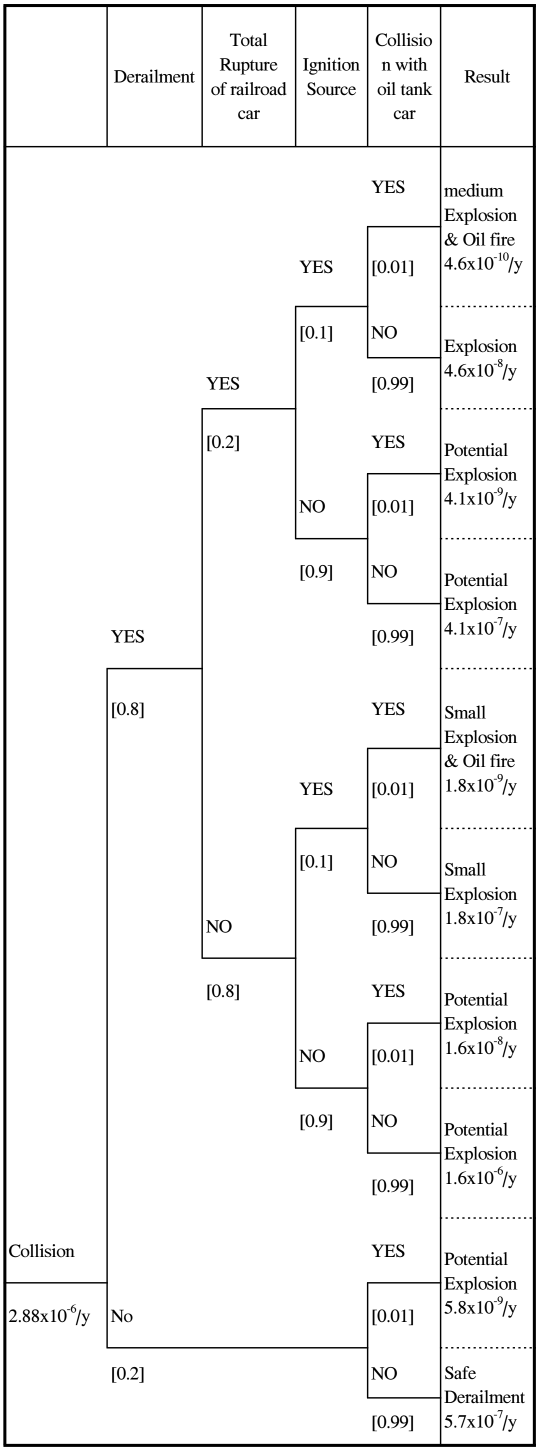

Fig. 4. Event Tree Analysis by collision in transit.

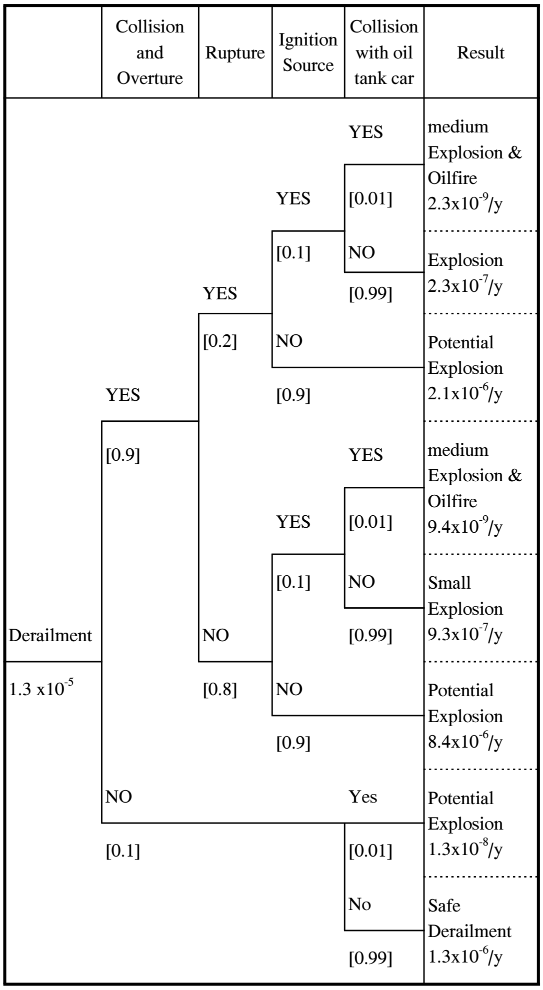

Fig. 5. Event Tree Analysis by derailment in transit.

Ⅳ. CONSEQUENCE ANALYSIS

Accident damages such as large explosions with oil fire (600 tons TNT), medium explosions (200 tons TNT), small explosions (40 tons TNT), etc., are expected. These accident damages are caused by Overpressure and Radiation Heat. Therefore, consequence analysis for the railroad transportation of explosives is performed using the TNT-Equivalent Method:

$$Z = \frac{R}{W^{1/3}} \tag{1}$$

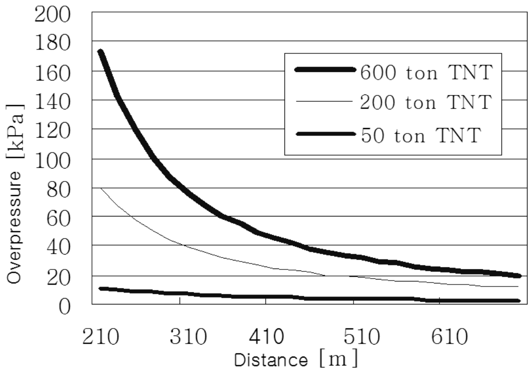

Fig. 6. Overpressure estimation along the distance.

Z : Scaled distance [$m/kg^{1/3}$]
R : Distance to the explosion's center [m]
W : TNT mass [kg]

In addition, TNT Equivalent and Probit analysis method are used in order to analyze for damage of explosives railroad transportation mixed with oil fire. Using Probit presented by Eisengerg et al, eardrum rupture and lung hemorrhage are analyzed when it comes to human damage, building collapse is analyzed when it comes to physical damage. These can be expressed as:

$$Y = -23.8 + 2.92\ln(p^0) \tag{2}$$

$$Y = -77.1 + 6.9\ln(p^0) \tag{3}$$

$$Y = -15.6 + 1.93\ln(p^0) \tag{4}$$

Y : Probit
p^0 : Overpressure [pa] or [N/m^2]

The influence of wind is not considered, as unlike an oil explosion, there is no gas diffusion. It is presumed that 40 tons, 200 tons, and 600 tons of explosives are concerned in explosion in the event of a railroad station accident. Estimated overpressure distribution is shown in Figure 6. The effects of overpressure are so much greater than the damage by thermal radiation that only the damage by overpressure is estimated.

It is presumed that 600 tons of explosives are loaded in the railroad station. In addition, the loadage for conveyance is supposed to be 200 tons, because this is the amount for one-time carrying. This study supposes that the locations are Sung-Hwan station and Ui-Jung-bu station.

V. RISK ANALYSIS

The risk of the rail transport of explosives can be divided into the risk of an accident occurring in stations during loading, unloading and storing, and the risk of an accident occurring on the railroad during transit. The estimated damage derived through the damage analysis method is shown in Table 4.

The radius of an explosion that can cause 80% of lung hemorrhage in the region is 215m when it comes to a large-sized explosion (600 tons TNT), 148m when it comes to a medium-sized explosion (200 tons TNT) and 94m when it comes to a small-sized explosion (50 tons TNT). The individual risk contour of an explosion in a station is shown in Figure 7.

Table 4. Estimated the number of fatality by accident both in railroad station and in transit

Accident in railroad station			
	radius [m]	extent of damage [km^2]	Fatality [Man]
Large Explosion	215	0.145	711
Medium Explosion	148	0.068	337
Small Explosion	94	0.028	136
Accident in transit			
	NO	extent of damage [km^2]	fatality [Man]
Medium Explosion (148m)	1	4.75	23,288
	2	4.62	90,468
	3	8.59	52,667
	4	1.39	1,114
Small Explosion (94m)	1	3.02	14,791
	2	2.92	57,275
	3	5.40	33,451
	4	0.88	707

• Individual Risk

$$IR_{x,y} = \sum_{i=1}^{n} IR_{x,y,i}, \quad IR_{x,y} = f_i p_{f,i} \qquad (5)$$

• Societal Risk

$$\text{Average Rate of Death} \quad ROD = \sum_{i=1}^{n} f_i N_i \qquad (6)$$

f_i : Frequency for incident outcome case [year-1]

N_i : Incident number of fatalities[Man]

Individual risk is defined as the probability per year that anyone person will suffer a detrimental effect as the result of exposure to an activity(Eq. 5). Figures 8 shows the graph for Individual Risk.

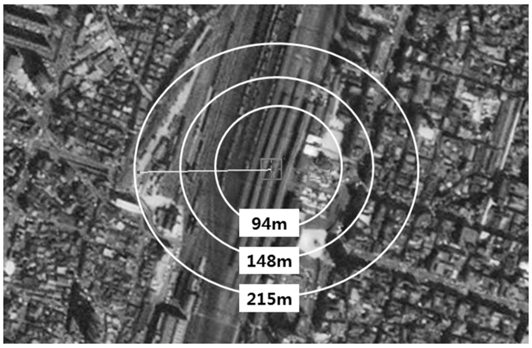

Fig. 7. Individual risk contour plots for lung hemorrhage.

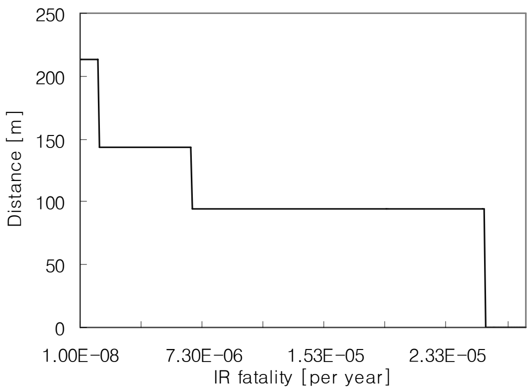

Fig. 8. Individual risk vs. distance in station.

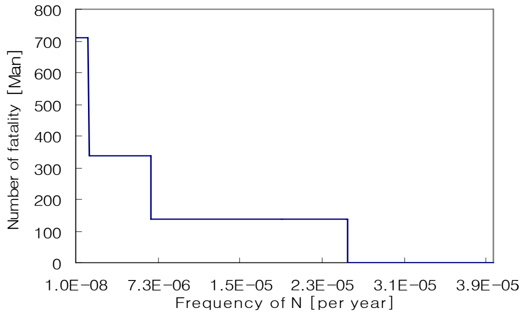

Fig. 9. Total societal risk in station.

Societal Risk is defined as the relationship between the number of fatalities and the chance or likelihood that this number will be exceeded(Eq. 6). Figures 9 shows F-N curve of Societal Risk. It is a graph indicating the cumulative frequency of killing N or more people.

VI. CONCLUSION

The rail transport of explosives through regions with high population density is very dangerous because any accident is likely to cause many people to be injured. In particular, this study shows that an explosives accident mixed with oil fire has a high risk of causing a large-scale explosion. This study does not deal with an emergency response plan for an explosion in a rail station. However, accidents that include explosives and oil are likely to cause many injuries.

In conclusion, we believe that a detour through a region with a low population density is needed for the rail transport of explosives.

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