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# Effects of the tunnel length and gradient in the quantitative fire risk assessment of railway tunnels

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ABSTRACT

*Quantitative fire risk assessment (QRA) is a method to design the accident scenarios, estimate the accident probability and thus quantify the degree of risk. QRA is affected significantly by tunnel specifications, fire characteristics, ventilation method, normal ventilation and smoke control methods and the other factors. In this paper, ventilation velocity and relationship between the ventilation and evacuation directions were selected to study their effects on the fire risk assessment in the tunnels of 18-26 km long and 5-25% grade. The results show that in a double track tunnel with the cross sectional area of 97m², it is most effective to evacuate in the opposite direction of the ventilation regardless of the fire location. In addition, when the mechanical ventilation is applied for the fire control, the risk index decreases by up to 10% compared to the case only with the natural ventilation.*



## 1. Introduction

Although traveling by rail is statistically known to be safer than traveling by car or plane, there will be damages and casualties in case of fire due to exposure to the toxic gases and heat generated from the fire. Fire accidents in railway tunnels with limited ventilation are likely to develop into catastrophic disasters because a large group of people are located in small congested space.

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In accordance with South Korean and international standards and relevant regulations, disaster prevention facilities are required to install in railway tunnels for fire safety. In South Korea, according to the Railway Facility Technical Safety Standards (Ministry of Land, 2013), safety evaluation by quantitative methods is mandatory for tunnels longer than 1km, and based on the assessment results, disaster prevention facility installation will be decided. Thus, the quantitative safety evaluation standards were established, and the site for the first application was Honam High Speed Railway (Yoo, 2010).

Quantitative risk assessment of the tunnel fires involves several stages of works including fire scenarios design, accident frequency estimation and fatalities/damage quantification. The assessment consequence and frequency are displayed on an F/N curve where frequency (F) of accident having N or more fatalities is plotted against N with log-log axes. F/N curve is then compared with the societal risk criteria. This curve is used as a decision making tool for assessing the adequacy of the emergency facility. The sequence of quantitative risk assessment procedures is summarized in Figure 1.

Quantitative risk assessment is influenced not only by the frequency of accidents but also by tunnel specifications (i.e., the tunnel length, gradient, cross-sectional area), fire characteristics (i.e., fire intensity and growth curve), use of ventilation, and the evacuation and ventilation directions.

In particular, if a fire occurs in the central carriage of the train and the ventilation system is on, evacuees running away from the fire source are likely to be exposed to smoke and toxic gases dispersed in the same direction by the mechanical ventilation system.

This paper evaluates the effects of main parameters affecting the quantitative risk assessment: those include the tunnel length and gradient, smoke control and the ventilation and evacuation directions.

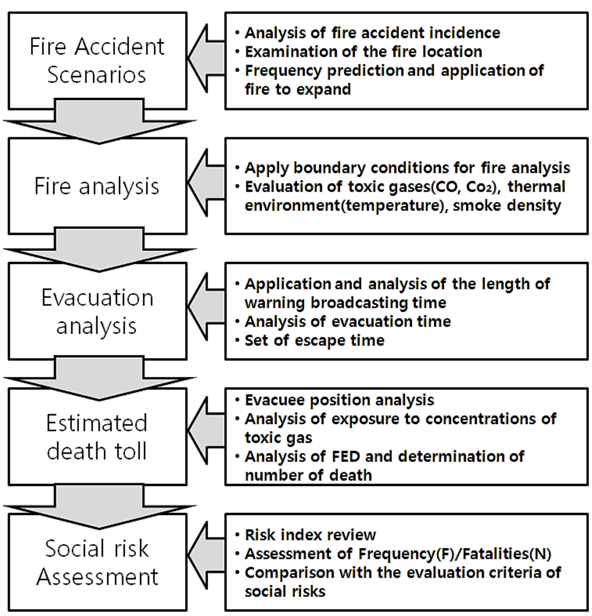



*Figure 1. Quantity risk assessment procedures.*

## 2. Risk assessment model

This study aims at evaluating how several parameters related to the tunnel specifications and emergency ventilation methods affect the quantitative risk assessment. A series of the analysis were carried out for different tunnel lengths; that is, 2, 3, 4, 5, and 6 km. The gradient also varied for the assessment; 5, 15, and 25%. The procedures in Figure 1 were applied step-by-step for the risk assessment.

### *2.1. Fire accident scenarios*

Fire accident scenarios were designed using the Event Tree technique, as shown in Figure 2. The fire occurrence in a twin-tube tunnel can be classified into two categories; left and right. And its location in a tube can be entrance portal, middle point, or exit portal. In addition, the railroad car with fire may be located in the front, middle or rear part. The frequency of fire occurrences in tunnels was investigated using the reports on number of fires in rail car by the Transportation Safety Authority, and the fire accidents rate was found to be 0.007events/106 tr/km.

In the event of fire outside a moving train, the operation manual states that the train must continue on and escape the tunnel. Therefore, the possibility that the train stops inside the tunnel is very low. This study assumed that the probability of the train escaping the tunnel without stopping is 95%.

In addition, based in the existing studies, we considered that if a fire occurs on a train, there would be a 90% probability that either the fire is minor or is in the initial phase (Kees Both, 2004).

The train line between Suseo and Pyeongtaek, South Korea, recently completed, was used for this research; its operation plan is shown in Table 1.

*Table 1. Train operation plan.*

| Division | Coach | Number of service | No of Passenger |
|---|---|---|---|
| KTX10 | 10 | 16 train/one way per day | 363 |
| KTX20 | 20 | 32 train/one way per day | 935 |
| MTX | 8 | 136 train/one way | 984 |

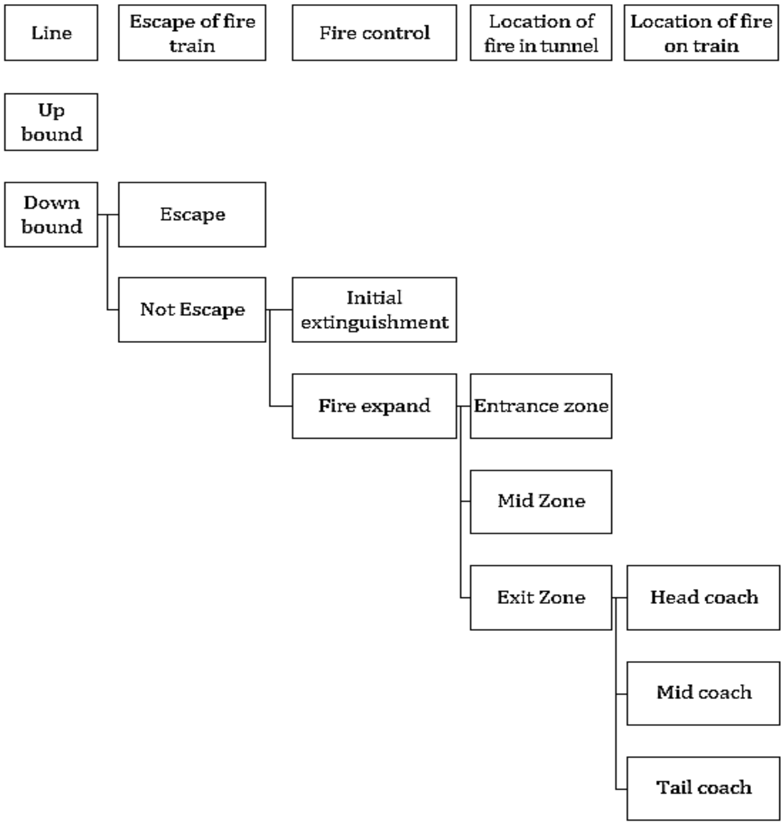



*Figure 2. Fire accident scenarios.*

*Table 2. Fire accident incidence and return year.*

| Scenario | Fire Accident Incidence (events/$10^6$ tr · km) | Frequency per year | Return year |
|---|---|---|---|
| Fire accident | 1.20E-2 | 2.80E-4 | 3,567 |
| Train escapes (95%) | 1.14E-2 | 1.33E-4 | 7,510 |
| Train does not escape (5%) | 6.00E-4 | 7.00E-6 | 142,694 |
| Fire controlled (90%) | 5.40E-4 | 6.30E-6 | 158,549 |
| Fire expand (10%) | 6.00E-5 | 7.00E-7 | 1,426,940 |

The frequency of accidents and the return period based on the fire accident scenarios are listed in Table 2.

## 2.2. Fire analysis model

Fire Dynamics Simulator (FDS) was used as the analysis model, while the fire growth curve for trains in Figure 3 provided by the Korea Railroad Research Institute was adopted (Korea Railroad Research Institute, 2014). The maximum heat release rate was assumed to be 15 MW for a fire in KTXII (KTX10, KTX20) and 20 MW for MTX. In addition, it was assumed that the fire would continue and spread to adjacent rail cars. 0.132 kg/kg fuel and 0.161 kg/kg fuel were the input data for the generation rates of CO and soot, respectively (Tunneling and Underground Space Association, 2009).

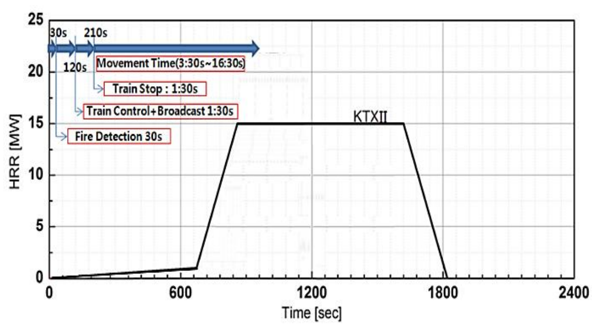



*Figure 3. Fire strength of train.*

### *2.3. Evacuation analysis and fatality estimation*

In this analysis, it was assumed that passengers would begin evacuation immediately after the warning broadcast. We assumed that they could listen to the first broadcast four minutes after the fire break-out. Using Simulex (IEX, 2004), it was found that it would take be 5~140 s for all passengers to evacuate the train. The amount of toxic pollutants released into the harmful environment while the passengers are evacuating is quantified using the Fractional Effect Dose (FED) in Equation 1. If the resulting FED value exceeds the limit, it implies that there are casualties. The number of casualties can be estimated according to the FED value (SFPE, 2003). The evacuation analysis program calculates factors such as location of the evacuees, evacuation speed, and exposure degree to the hazardous environment using the FED (Fractional Effect Dose). Data about the hazardous environment that the evacuees are exposed to include the CO, $CO_2$, and soot concentrations at breathing height, the low oxygen lapse rate and the radiation intensity fire. This database also included the time and the evacuee's locations. FED is defined as the cumulative dose level of the lethal toxic gases that the evacuee breathes, and can be calculated through Equation (1).

$$FED = (F_{ICO} + F_{IHCN}) \times V_{CO_2} + F_{IO} + F_{IHeat} + F_{IRAD} \qquad (1)$$

Where:

$$F_{ICO} = \frac{\%COHb}{D} = \frac{8.2925 \times 10^{-4}(ppmCO)^{1.036}t}{D}$$

$$F_{IO_2} = \frac{t}{e^{8.13-0.54(20.9-\%O_{(2)})}}$$

$$V_{CO_2} = \frac{e^{0.2496\%CO_2+1.9086}}{6.8}$$

$$F_{ICO_2} = \frac{t}{e^{(6.1623-0.5189\%CO_{(2)})}}$$

$$F_{IHEAT} = \frac{t}{e^{5.1849-0.0273T}}$$

$$F_{IRAD} = \frac{q\,''^{1.33}}{1.33}\,t$$

### *2.4. Ventilation and evacuation directions*

In case of a train fire within a tunnel, the smoke control direction by the mechanical ventilation and the evacuees' movement direction have significant impacts on the safety particularly when evacuees cannot realize the situation correctly. Therefore, we analyzed the effects of the direction and method of ventilation, and the evacuation direction on the level of risk. The scenario shown in Figure 4 was designed to take into consideration of the effects of the aforementioned factors on the risk.

The branching ratios in the scenario are listed in Table 3; the branching ratios for smoke control by the mechanical ventilation were set identically for each direction.

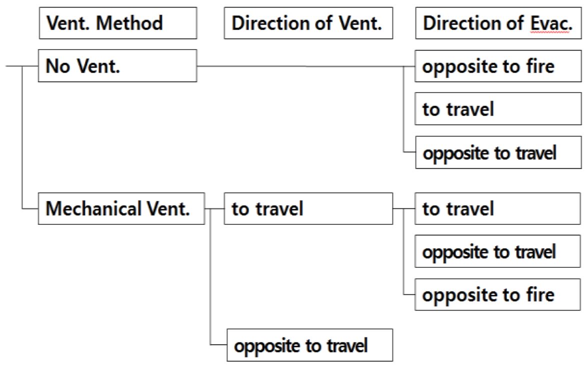



*Figure 4. Scenario according to ventilation and evacuation direction.*

*Table 3. Scenario branching ratios according to ventilation and evacuation direction.*

| Ventilation scenario | V000 | V010 | V050 | V090 | V100 |
|---|---|---|---|---|---|
| No ventilation | 100% | 90% | 50% | 10% | 0% |
| Mechanical ventilation | 0% | 10% | 50% | 90% | 100% |
| Evacuation scenario | E100 | E090 | E050 | E010 | |
| Opposite ventilation direction | 100% | 90% | 50% | 10% | |
| Away from fire | 0% | 10% | 50% | 90% | |

## 3. Analysis results

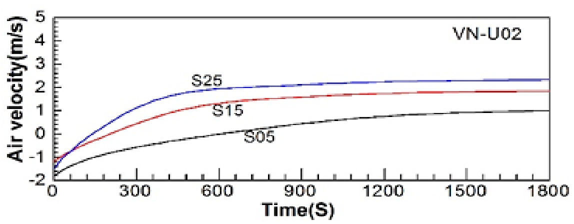
### *3.1 Effects of the wind velocity*

The ventilation velocity in the tunnel has the largest influence on the fire simulation. However, since it is realistically impossible to conduct a 3D ventilation simulation using FDS, the SES (Subway Environmental Simulator) was applied for the analysis of the tunnel airflow velocity during a fire. Figure 4 shows the ventilation air flow velocity during a fire.

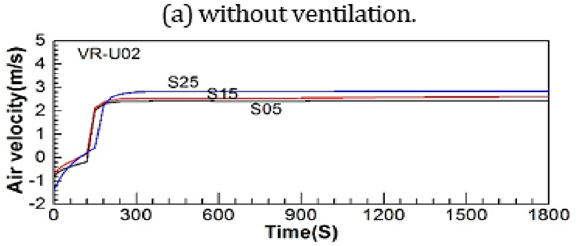
Figure 5(a) shows the changes in the air flow velocity by gradients after the train stops on the downward slope and it is assumed that there is no mechanical ventilation. The train was assumed to run in the opposite direction from the exit to the entrance until it stops at the center of the 6 km-long tunnel. As seen in Figure 5, the airflow initially travels in the same as the train. However, over time, the airflow direction changes to the positive direction, mainly due to the thermal buoyancy force. The airflow velocity reaches steady state after 600-900s. As expected, the airflow velocity increases as the gradient increases; on the slopes of 5, 15, 25%, the airflow velocities were stabilized at 1.1, 1.93 and 2.42m/s.

Figure 5 (b) shows the case where the direction of the smoke control ventilation direction is opposite to the train operation, while Figure 5 (c) the smoke control ventilation and the train operation are in the same direction. When the train is running, the air flows in the same direction as the air due to the piston effect caused by the moving train. And after 60s of the fan operation, the air flow velocity reaches steady state and approach a target velocity designed for the smoke control. According to the Railway Safety Technique Standard of South Korea (Ministry of Land, 2013), the smoke control velocity by ventilation which is referred to as the critical velocity should be higher than 2.5m/s. The transient stage created by turning on the fan and stopping the train lasted only 240s until the steady state is reached.

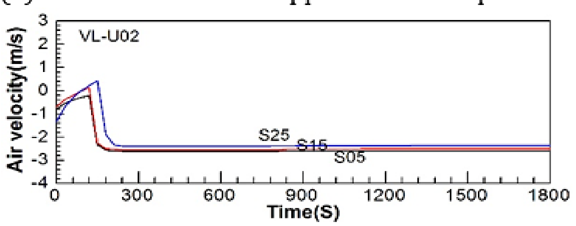
When no mechanical ventilation is applied, the airflow velocity in the tunnel is significantly affected by the tunnel gradient. It takes more than 600 s to reach steady state. With mechanical ventilation on, the airflow velocity reaches steady state quickly after turning on the fan. These imply that the risk is not affected by the tunnel gradient if the mechanical ventilation is applied.




(a) without ventilation.




(b) ventilation direction: opposite to train operation.




(c) ventilation direction: direction of train.

*Figure 5. Wind velocity in tunnel in case of a fire.*

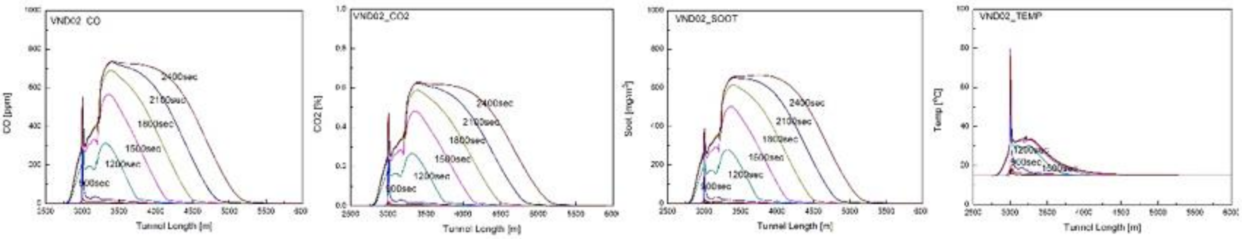
### *3.2. Fire simulation*

In this study, a series of the fire simulation by tunnel length and gradient were carried out under the various conditions of tunnel lengths and gradients. Figure 6 shows the average concentrations of CO, $CO_2$, and soot, and the temperatures at the height of the respiratory line when the tunnel length and the gradient are 6 km and 5%, respectively.

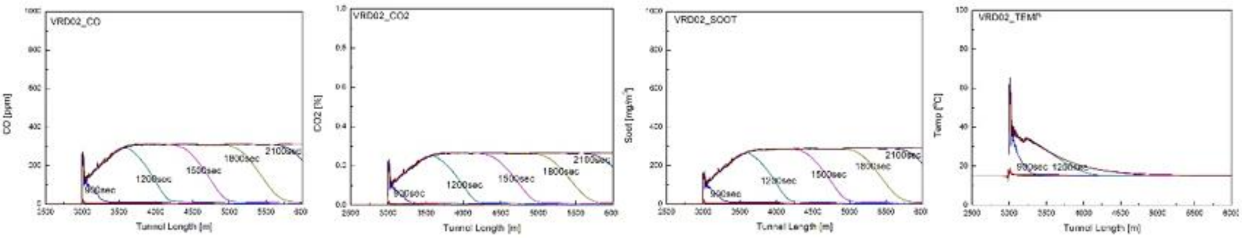
Figure 6(a) shows the cases only with the natural ventilation. The airflow velocity is low and therefore smoke spreads slowly downstream of the fire location. Some time later toxic gas concentration and temperature reach steady state; the average concentrations of soot, CO2, and CO reach 660 mg/m3, 0.6% and 700 ppm, and the temperature 80°C. The temperature is less than 40°C except the vicinity of the fire. Therefore temperature is found to be insignificant effects on the evacuation environment.

Figure 6 (b) and (c) show the case of mechanical ventilation. The concentrations of toxic pollutants gradually increase and reach steady state. In the case of positive ventilation direction, the stabilized concentrations of soot, $CO_2$ and CO are 290 mg/m3, 0.26%, and 300 ppm, respectively. In the case of negative ventilation direction, they are 275 mg/m3, 0.25% and 290 ppm, respectively.

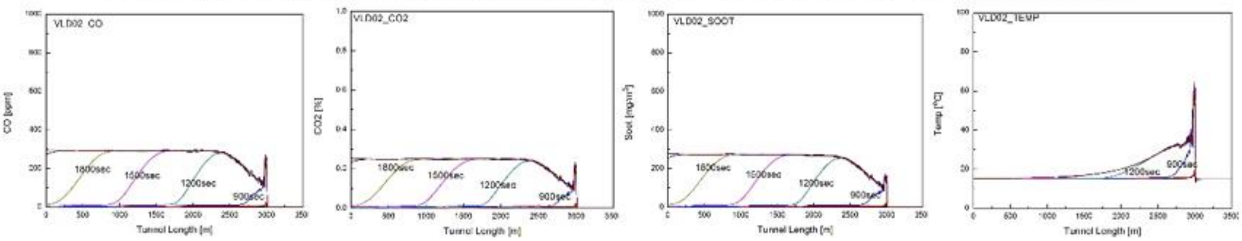
Thus, the results show that application of the mechanical ventilation can lower the pollutants level significantly compared to the case with the



(a) With the natural ventilation(tunnel length : 6km, fire site : at the center)



(b) With the mechanical ventilation (positive smoke control direction, tunnel length : 6km, fire site : at the center)



(c) With the mechanical ventilation (negative smoke control direction, tunnel length : 6km, fire site : at the center)

*Figure 6. CO, $CO_2$, Soot concentration and temperature distribution.*

natural ventilation. However, comparison between the two cases of the mechanical ventilations, one with positive direction and the other with the negative direction, lead to very similar results. The concentration of the toxic gases is inversely proportional to flow velocity according to the diffusion theory. Therefore, when the airflow velocity in the tunnel is set to 2.5m/s by the mechanical ventilation, then the concentrations of toxic pollutants remain same regardless of the ventilation direction. This is why the two cases with the mechanical ventilation show the same results.

Figure 7 compares the concentrations of toxic pollutants by tunnel gradients. As the gradient increases, the concentrations of all toxic pollutants decrease. This is due to the increased airflow velocity in the steeper tunnels. Consequently, the risk level seems to be lowered with higher tunnel gradient. This is not always the case. In steeper tunnels showing higher airflow velocity, smoke will propagate faster and the evacuees will be exposed sooner. This indicates that increasing risk with higher gradient is in complete contrast to the previous results showing lower risk with lower concentration.

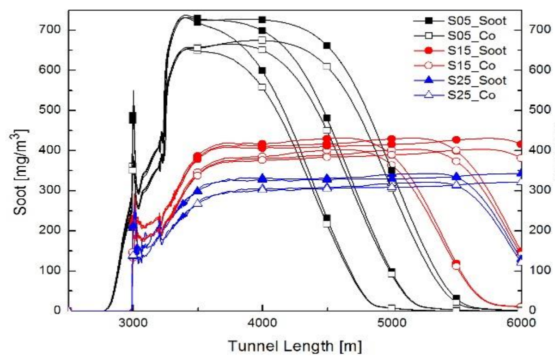


*Figure 7. Concentration of hazardous substances according to slope.*

### 3.3. Risk assessment

#### *3.3.1. Effect of tunnel length and gradient*

Figure 8 shows the F/N (Frequency/Number of Fatalities) curve by tunnel length at the gradient of 25%. And the ventilation scenario is V090 which corresponds to the case of the natural ventilation 10% plus the mechanical ventilation

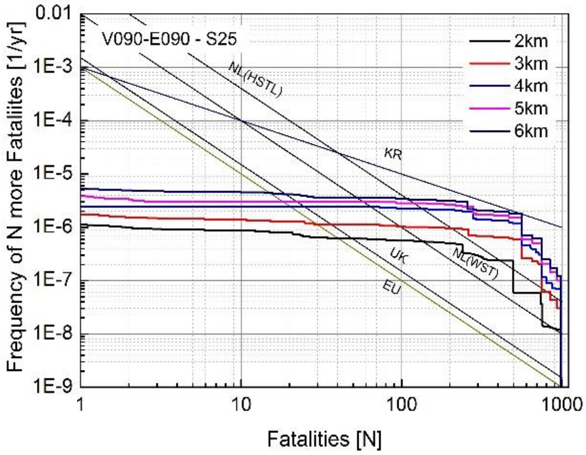



*Figure 8. F/N diagram by tunnel length.*

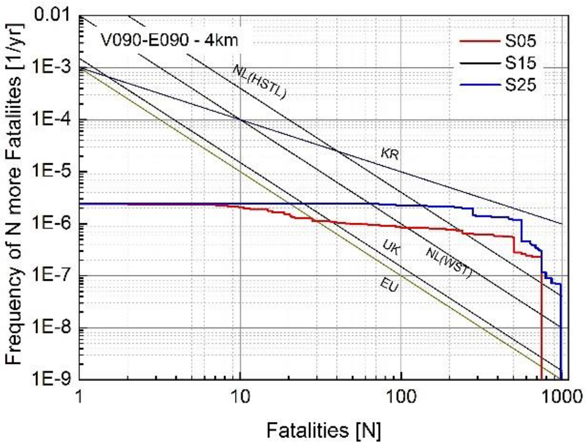



*Figure 9. F/N diagram for tunnel slope.*

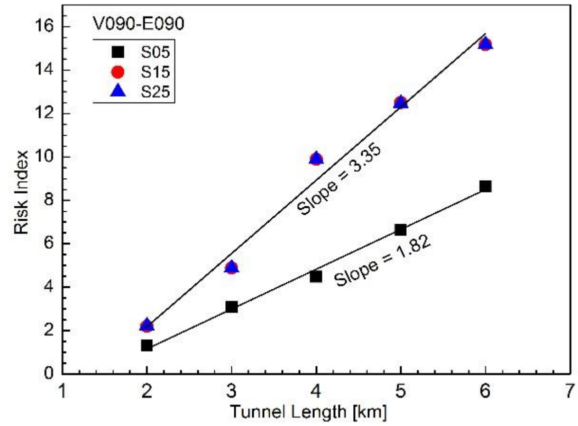



*Figure 10. Comparison of Risk Indices (V090-E090).*

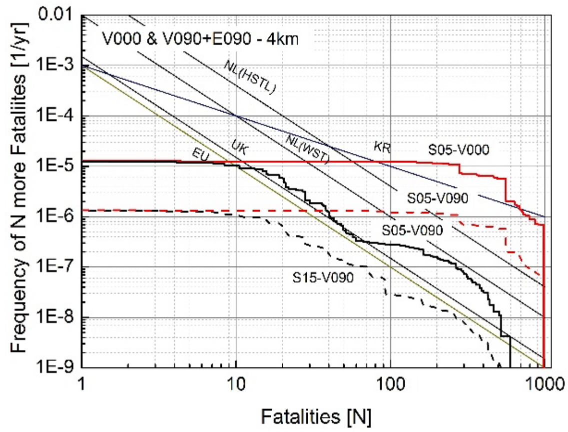



*Figure 11. Comparison between use of natural ventilation and mechanical ventilation methods (Length: 4 km, Gradient: 5%, 15%).*

90%, and the evacuation scenario is E090 corresponding to the case of Opposite ventilation direction 90% plus Away from fire 10%. As shown in Figure 8, risk increases with the tunnel length.

Figure 9 shows the F/N curve when the tunnel is 4 km long and its gradient is 5, 15, and 25%, respectively. In this case, when the gradient is 15% and 20%, the risk is almost identical, but when the gradient is 5%, the risk is relatively low.

Figure 10 shows the changes in the Risk Index (RI) by varying the tunnel length and gradient at the same time. The RI can be calculated using Equation (2), and it refers to the number of fatalities per year.

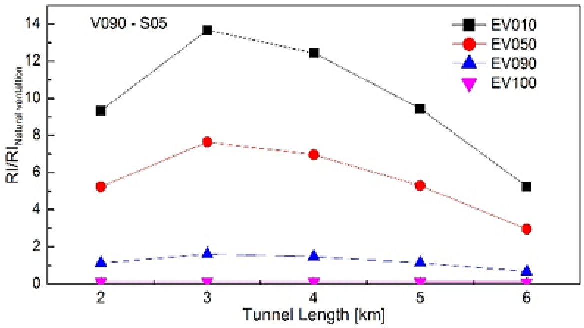
$$Risk\ Index = \sum frequency \times fatalities \quad (2)$$

The RI is lowest when the gradient is 5‰, and is almost the same for 15% and 25%. The increasing slope of the RI based on an extended increase is 1.82 (for 5‰) and 3.35 (for 15, 25‰) for each gradient.

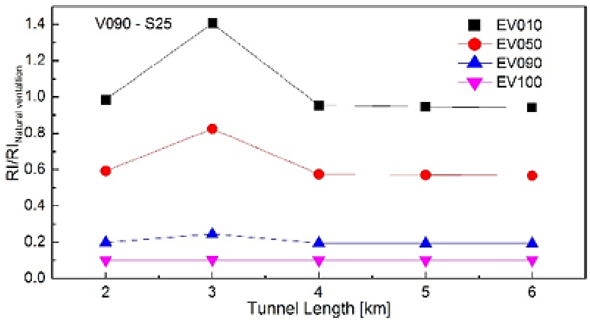
### *3.3.2. Effects of the ventilation and evacuation directions*

In Figure 10 and 11, the results from the assessment of the natural and mechanical ventilation methods in a 4km-long tunnel with the gradients of 5 and 15% are plotted. They are the F/N curves for V000+E090 corresponding to the case of the natural ventilation and evacuating Away from fire 90% in the same direction 10% and V090+E090 corresponding to the case of the mechanical ventilation 90% and the natural ventilation 10%.

As shown Figure 11, when mechanical ventilation was used, the risk was decreased by up to 10%. Figure 12(a) and (b) shows the comparison between the Risk Index ratio ($RI/RI_{no\ ventilation}$) of the mechanical ventilation to the natural ventilation by the evacuation direction. In Figure 12, V090 is the scenario with the mechanical ventilation 90% and the natural




(a) slope 5‰




(b) Slope 25‰

*Figure 12. Comparison of Risk Indices.*

ventilation 10%. The gradients studied are 5% and 25%.

In the case of 5% gradient, the Risk Index are lower for E100 and E090, but E050 and E010 show significantly higher RI's depending on the tunnel length. In the case of 25% gradient, application of the mechanical ventilation lowers the risk regardless of the evacuation methods.

All these results imply that it is imperative to perform the quantitative risk assessment when the mechanical ventilation facilities and the ventilation schemes are under consideration.

## 4. Conclusions

In this study, the effects of the ventilation method and the ventilation and evacuation directions on quantitative safety assessment were evaluated for a double track tunnel with cross-sectional area of 97 m2, length of 2, 3, 4, 5, and 6 km, and gradient of 5, 15, and 25%. The results are summarized as follows:

1. The toxic pollutants concentrations in case of a fire in tunnels are dependent on the airflow velocity. When the velocity is kept at a constant critical velocity by the mechanical ventilation system, the concentrations will reach steady state. In this study, the fire intensity of 15 MW was assumed with the air velocity of about 2.5 m/s. When it reaches steady state, CO and soot concentrations are 300 ppm and 275–290 mg/m$^2$, respectively

2. When the tunnel depends only on the natural ventilation, the airflow velocity will rely on the tunnel gradient. The velocity will increase with the gradient, while the toxic pollutants concentrations will decrease.

3. As the tunnel length increases, the RI increases linearly. However, there is insignificant difference in risk for the gradient higher than 15%. The increasing rate of RI is 1.82 for the gradients of 5% and 15%, while it is 3.35 for 25%.

4. When the mechanical ventilation is applied, it seems to be safer to evacuate against the airflow. In this case, the RI decreases by 10% compared to the case of the natural ventilation.

5. The effects of the mechanical ventilation are significantly different depending on the evacuation method and the tunnel gradient. When the gradient is 5%, there is no difference in the risk even with the mechanical ventilation, except in the ideal case where evacuees are moving against the airflow. But when the airflow created by the buoyancy force of a fire is similar to the airflow velocity by the mechanical ventilation system, the control effects by mechanical ventilation are relatively larger under all conditions. Thus, when the tunnel gradient is low, the ventilation effects should be verified by the quantitative risk assessment method.

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