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Safety of Train Passengers in a Tunnel

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Abstract

Along with the opening of the high speed railroad in 2004, the number of long tunnels constructed is increasing and will be continued. In this respect, the fire inside the tunnels is a main cause of drastic damages to both facilities and lives of passengers on board, especially more severe consequences are expected if the fire occurs on a train in urban area. Even though, the threat to human lives due to the increasing number of long tunnels and increasing train operation times inside such tunnels is getting bigger, the studies to measure safety of the tunnel and to enhance the safety of passengers have not been carried out enough in Korea. Therefore, in this paper, we will use the probabilistic method to predict the average number of deaths of passengers in case of fire on a train in tunnel, and show the potential risk to passengers which can be a guide for safer design of tunnels to be constructed.

Key words : Risk analysis, F/N Curve, tunnel fire, passenger evacuation scenario

1. Introduction

The rail-tunnels for high speed trains have been increased in length as well as in number. Among the total tunnels in Korea, 125 tunnels are longer than 500m in length and only 4 of the total tunnels have emergency exit, which means that in case of emergency such as a fire on a train running inside a tunnel, passengers are supposed to get off the train (if the attempts to extinguish the fire failed) and escape through the emergency exits. However, for the tunnels without such exits, passengers should walk to the end of the tunnel using the emergency walkways provided on both sides of the tunnel.

Considering relatively long tunnel without any fire fighting system inside, the toxic materials and smoke as well as the fire itself can be a deadly threat to the passengers trying to escape the tunnel. For the tunnels equipped with ventilation system, emergency cross passages, sprinklers and other safety systems the passengers will escape more easily resulting in less casualties in number than for the ones without such systems. In Korea, most of the tunnels being used have no such safety systems which have great potential for catastrophe in case of fire inside a tunnel.

The subway arson in Dae-Goo in 2003, sent the wake up call to public as well as the rail authorities on the danger of fire and the issue on rail transport safety is gaining more attention than ever. Accordingly, researches

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on fire in long tunnels have been carried out actively and in this study, as a part of the rail safety, we perform a quantitative risk analysis to predict the number of deaths of passengers in case of fire on a train inside a tunnel with and without fire safety system, analyze the effects of such safety system, and provide strategies to enhance the safety level in terms of how to design or construct future tunnels to decrease the number of deaths.

The matters of safety of passengers on board have been studied by many researchers, especially in Europe. Molag, M & Sluis. L [1] shows the quantitative risk analysis model of the Green Heart bored tunnel and represents the risk on a graph called F-N curve. Molag, et al. [2] describes the development of realistic fire scenarios for a train fire in tunnels. Matthew.S, et al. [3] discusses the applications and limitations of various methods for tunnel fire safety assessment which are affected by length, height, slope, cross sectional area and ventilation.

In this study, we consider a tunnel commonly being used for operation in Korea and provide all the possible fire related scenarios when a fire occurs inside a tunnel in section 2 and analyze the results along with key factors affecting the deaths of passengers in section 3. Concluding remarks and future research directions will be briefly discussed in section 4.

2. Quantitative risk analysis

2.1. Possible scenarios in case of fire

In this section, we provide all the possible scenarios following the initial fire on a train to calculate the death for each scenario through assumptions on tunnel, train, fire size, smoke traveling speed, and passenger evacuation speed.

<Assumptions>

(1) Tunnel characteristics

The lengths of a tunnel ranges from 1km to 3 km and fire safety systems are emergency ventilation system, emergency light, emergency guiding light, and emergency walkway. We assume that the ventilation system can reduce the smoke speed by 0.3m/s.

(2) Train characteristics

The train we investigate is KTX high speed train currently in use on Seoul-Pusan line with 20 cars (including 2 power cars) carrying 900 passengers. The length of the train is 388m, and each car has 2 exit doors on both sides and equipped with a fire detector to detect fire when a fire occurs on a train.

(3) Fire size and flash over time

The initial fire takes place in locomotive and the train is assumed to stop in 5 minutes after the fire breaks out. Fire size will be 5MW, 10MW, and 20MW and other assumptions are as follows.

Table 1. Fire size, flash-over time, and smoke speed

Fire size	flash-over time	Smoke speed(m/s)	
		Ventilation not working	Ventilation working
5MW	1600 sec	1.3	1.0
10MW	800 sec	1.6	1.3
20MW	240 sec	1.9	1.6

Referring to Table 1, the toxic smoke leading to death of a passenger will start spreading 800 seconds after the occurrence of the initial fire with the fire size growing to 10MW and the smoke speed is 1.3m/s if ventilation system works properly, and 1.6 m/s if it fails working. Note that if the fire size is 20MW, the smoke is assumed to spread at the moment the train stops.

2.2. Construction of passenger evacuation scenarios

The risk analysis is performed in the case when the train is stopped inside a tunnel by some reasons such as miscalculation of distance to stop, malfunction of brake system or other uncontrollable situations. If the fire is detected by the detector inside the train and extinguished at early stage, the fire will not develop further. However, if the attempts to put out the fire fail, it will grow to different sizes depending on the environments around the fire.

For our research, we selected 3 different sizes: 5MW (size of burning 1/2 the car), 10MW(size of burning 1 car), and 20MW(size of burning 2 cars) with possibility (probability) of 0.4, 0.4, and 0.2, respectively. The train is assumed to stop in the middle of the tunnel and passengers after getting off the train start evacuation through the emergency walkway in the opposite direction of fire. Since the walking speed of passengers along with the smoke spread speed is a key factor to calculating the number of survivals, we use two common walking speeds for our analysis, 1m/s and 0.7m/s depending on the brightness of walkway. Also, the distance between passengers is assumed to be 1m and each passenger walks in a (single) row.

The following Table 2 shows probabilities for ensuing events after the fire starts.

Table 2. Probabilities for each event

	Fire detector		Fire suppression		Fire size			Ventilation system	
Fire	Suc-cess	Fa-il	Suc-cess	Fa-il	5 MW	10 MW	20 MW	Suc-cess	Fa-il
	0.9	0.1	0.8	0.2	0.4	0.4	0.2	0.9	0.1

We can construct passenger evacuation scenarios combining the events in sequential order as in Table 2, which is demonstrated in Table 3 showing 14 such cases. The last column of Table 3 indicates the probability of occurrence of each scenario which is obtained by multiplying individual probabilities for events contained in each scenario.

Table 3. Passenger evacuation scenarios

Fire	Fire detector	Supp-ression	Fire size	Ven-tilation	Pro-bability	
		Success			P1	0.72
	Success	0.8	5MW	Success 0.9	P2	0.0648
	0.9		0.4	Fail 0.1	P3	0.0072
		Fail	10MW	Success 0.9	P4	0.0648
		0.2	0.4	Fail 0.1	P5	0.0072
			20MW	Success 0.9	P6	0.0324
			0.2	Fail 0.1	P7	0.0036
		Success			P8	0.02
	Fail	0.2	5MW	Success 0.9	P9	0.0288
	0.1		0.4	Fail 0.1	P10	0.0032
		Fail	10MW	Success 0.9	P11	0.0288
		0.8	0.4	Fail 0.1	P12	0.0032
			20MW	Success 0.9	P13	0.0144
			0.2	Fail 0.1	P14	0.0016

Fig.1 shows the train stopped in a tunnel and passenger evacuation direction for evacuation.

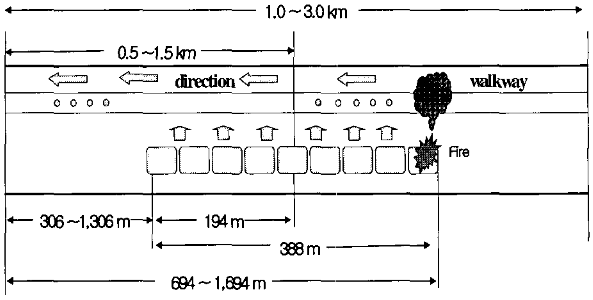

Fig. 1. Passenger evacuation scenario

3. Results

3.1. Number of deaths for each scenario

Major causes of passenger death are toxic smoke containing hazardous materials such as carbon monoxide (CO), carbon dioxide (CO_2) and heat. For simplicity, we assume that passenger will die at the moment the smoke reaches the passenger and the number of deaths can be calculated from the following simple comparison rule:

If ETi < ST, then the passenger will survive, where ETi is evacuation time of a passenger i until the end of the tunnel and ST is smoke spread time to reach the end of the tunnel.

The following Table 4 shows the number of deaths in a tunnel when the ventilations system fails to work.

Table 4. Number of deaths with ventilation system failed

Unit : person

Walking speed / Tunnel length	1m/s			0.7m/s		
	5MW	10MW	20MW	5MW	10MW	20MW
1.0km	0	272	840	0	570	900
1.5km	0	365	900	37	693	900
2.0km	0	459	900	153	833	900
2.5km	0	557	900	268	900	900
3.0km	0	647	900	383	900	900

Table 5 shows the number of deaths when the ventilation system works, which means the smoke spread speed is reduced by 0.3m/s.

Table 5. Number of deaths with ventilation system worked

unit : person

Walking speed / Tunnel length	1m/s			0.7m/s		
	5MW	10MW	20MW	5MW	10MW	20MW
1.0km	0	172	772	0	482	900
1.5km	0	229	865	0	598	900
2.0km	0	287	900	0	713	900
2.5km	0	345	900	35	828	900
3.0km	0	402	900	110	900	900

<Interpretation of the results>

(1) The effects of fire size on passenger deaths

In case the fire grows to the size of 5MW as the Tables 4 and 5 show, there is no deaths when the walking speed is set to 1m/s regardless of condition of the ventilation system.

However, the death toll of passengers increased to 383 for 3km tunnels if the walking speed is reduced to 0.7m/s and the ventilation system failed to work, whereas the number of deaths decreased to 110 when the ventilation system worked.

For the fire size of 10MW, unlike the case of 5MW, many passengers lose their lives depending on the length of the tunnel, the walking speed, and the condition of ventilation system. For the worst case of 20MW of fire size, all the passengers will die if the tunnel length is 2 km or longer regardless of ventilation system and the walking speed.

(2) The effects of walking speed on passenger deaths

For 5 MW, passenger death occurs in the tunnel with the length of 2.5km and longer when the walking speed is reduced to 0.7m/s even when the ventilation system works, which implies that the brightness of emergency walkway is a major factor for passenger safety as well as the ventilation system.

(3) The effect of tunnel length on passenger deaths

If the tunnel length is relatively short, ventilation system may not be necessary, however, the longer a tunnel is the more time it takes for evacuation and accordingly safety system should be provided.

(4) The effects of ventilation system on passenger deaths

The ventilation system is mainly used to reduce the smoke speed coming toward passenger and the condition of the ventilation equipment (working or not working) makes huge difference in the number of deaths during evacuation process. As indicated in (1), the ventilation system (depending on its capacity) to prevent the smoke from spreading fast through the tunnel can dramatically reduce the death toll.

3.2. The average number of deaths

The average number of deaths can be denoted and calculated by $E(X) = \Sigma x_i P(x_i)$, where xi is the number of death for scenario i and $P(x_i)$is the probability of that scenario. The following Table 6 represents the $E(X) = 59.4256$ when the tunnel length is 1.0km, and the walking speed is 1m/s.

Table 6. Average number of deaths(walking speed : 1m/s, tunnel length : 1.0km)

Length	$P(x_i)$		x_i	x_i $P(x_i)$
1.0km	P_1	0.72	0	0
	P_2	0.0648	0	0
	P_3	0.0072	0	0
	P_4	0.0648	172	11.1456
	P_5	0.0072	272	1.9584
	P_6	0.0324	772	25.0128
	P_7	0.0036	840	3.024
	P_8	0.02	0	0
	P_9	0.0288	0	0
	P_{10}	0.0032	0	0
	P_{11}	0.0288	172	4.9536
	P_{12}	0.0032	272	0.8704
	P_{13}	0.0144	772	11.1168
	P_{14}	0.0016	840	1.344
		$\Sigma P(x_i) = 1$		$E(X)=59.4256$

With similar way, we can calculate E(X) with different tunnel lengths and walking speeds as shown in Table 7, where the E(X) is an increasing function of tunnel length and a decreasing function of walking speed.

Table.7. E(X) with different lengths and speeds

Unit : person

Tunnel length \ Walking speed	1m/s	0.7m/s
1.0km	59.4256	97.8432
1.5km	70.3924	110.3648
2.0km	78.4368	123.7912
2.5km	84.8848	139.724
3.0km	91.156	158.8808

3.3. Presentation of the passenger risk with F/N curve

The F/N curve is used to show the risk of the initial fire on a two dimensional plane, where horizontal axis represents the number of deaths for each scenario and the vertical axis represents the corresponding complementary cumulative probability (or frequency).

The F/N curve has been applied to a variety of areas such as nuclear facility, hazardous material transport, harbor management, and many other risky industries to identify the risk level (see Fig. 2 and 3).

Fig. 2 represents the F/N curve with the walking speed of 1m/s and tunnel length of 3.0km.

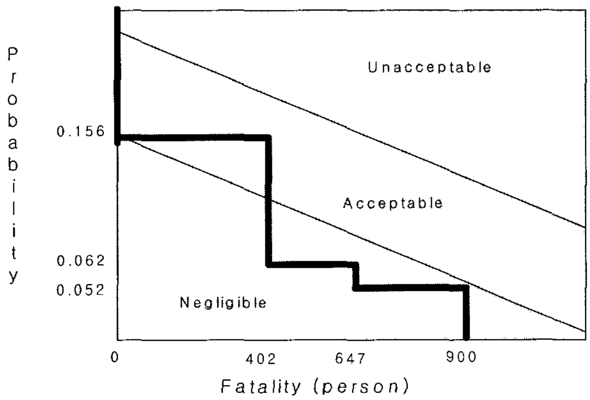

Fig. 2. F/N curve
(walking speed : 1.0m/s, length : 3.0km)

For the study, the F/N curve consists of three separate areas: upper, middle and lower each of which is called unacceptable, acceptable and negligible region, respectively.

The risk initiated from the fire is graphed by the blacked lined step wise function. If all the lines are below the upper region, then the risk is assumed to be acceptable. However as the Fig. 3 indicates, if there exists a line segment which lies in the upper region the risk is assumed to be high at that point and proper actions to reduce the risk level to middle or lower level should be taken.

Fig. 3 represents the F/N curve with the walking speed of 0.7m/s and tunnel length of 3.0km.

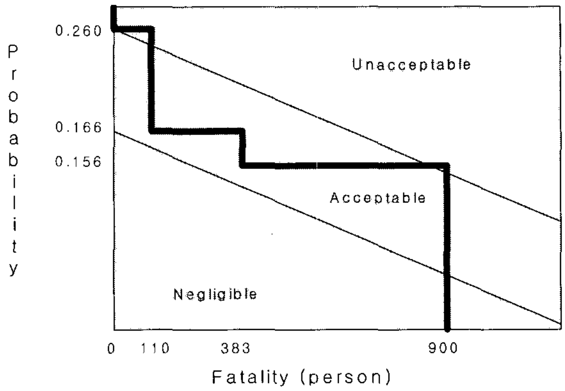

Fig. 3. F/N curve
(walking speed : 0.7 m/s, length : 3.0km)

As shown in Fig. 3, the line segments with fatalities of 110 and 900 are lying in the upper region implying that the corresponding probabilities 0.260 and 0.156 are high and, the decision maker should apply more safety system to lower the probabilities of such risks.

4. Concluding remarks and future research

In this study, we established a basic model for calculating the number of deaths for each possible scenario considering 4 events, i.e. fire detector, fire suppression, fire size, and ventilation system in the order of occurrence starting from the fire on a train inside a tunnel. We also showed the risk level through the F/N curve with which the decision maker will take necessary measures to reduce the potential risk for safer train transport.

The probabilities for each event and the values for assumptions are randomly chosen due to insufficient information and data. For more accurate calculation of the risk, however, the model should be expanded by putting more events such as, emergency passage exit, the location of the train stopped in the tunnel, irrational human behaviors in emergency, and so on. The treatment of uncertainty of probability for each event varying from the lowest possible value to the highest possible value of occurrence should also be performed to reflect realistic situations for further research.

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