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The integrated strategies for fire safety of long road tunnels in Taiwan

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Abstract

The Guanyinshan Tunnel opened in 2009 allowed passages of large chemical tankers. To ensure public safety, subsequent researches on fire safety design in a road tunnel in which dangerous goods are allowed to travel through were performed. The research results then led to the debate of effectiveness of the tunnel fire safety and to a consensus on the need for installation of water-based firefighting system (WFS) in the tunnels of Suhua Highway Improvement Project. The evolution of integrated fire safety management and design in long road tunnels has positively impact the fire safety industry, academia and transportation in Taiwan. This study proposes a new integrated fire safety strategy for long road tunnel in Taiwan based on the simulation inference of fire scenarios, design specifications, and project management in Japan and European. In this study, two-bus fire scenario in a road tunnel are analyzed using the fire dynamic simulators (FDS) program and a safety assessment method is developed for human evacuation and rescue operations in a road tunnel fire. A time constraint of 7 minutes for firefighters to engage in firefighting activities is determined on full scale experimental results and simulation results. Based on the assessment and field survey results, an appropriate firefighting scheme can consequently be determined. The results of this study serve as a useful information for road tunnel fire safety design and strategy of emergency response management.

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Keywords: Tunnel fire; Fire scenario analysis; Fire rescue availability; Integrated fire safety management

1. Introduction

A tunnel is constructed to fulfill societal expectation of economic development by providing a faster access route through mountainous areas or crossing waterways. However, the public often focuses only on this advantage and overlooks safety issues such as fire safety issues. Many catastrophic fires have occurred in the past as a result of the public's negligence on this subject. From 1999 to 2001, catastrophic tunnel fires in Europe, including the Mont Blanc Tunnel fire, the Tauern Tunnel and the Gotthard Tunnel fire, led to numerous casualties, collapsed of tunnel structures and closure of tunnels for extended periods. Recent (2006 to 2007) fires in the Viamala Tunnel in Switzerland, the Burnley Tunnel in Melbourne and the Santa Clarita Tunnel in California also resulted in a number of deaths. These incidents have heightened awareness of tunnel fire safety, which is a significant challenge for fire safety engineers and tunnel operators. Since then, many tunnel fire research projects have been conducted worldwide either by experimental work or by numerical analysis focusing on the tunnel fire safety issues

Taiwan is a mountainous country; approximately two thirds of the lands are covered by steep mountains. Due to the requirements of economic, transportation and tourism developments along the countryside, long road tunnels have been

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built and a new highway project is planning to be built. This study presents the evolution of fire safety design and emergency response management for long road tunnels in Taiwan base on the results from the Runehamar Tunnel fire tests.

2. Development of road tunnel fire safety in Taiwan

2.1. History of road tunnel safety design in Taiwan

Previously, there were no specific fire safety design standards for road tunnels in Taiwan. Road tunnel fire safety facilities in Taiwan included only basic equipment, such as dry chemical fire extinguishers, evacuation signs, fire hydrants, and fire detection system. Following consultation with overseas experts and compliance with PIARC standards, the transportation management authority in Taiwan began to focus on smoke exhaust system design and escape route design. Nevertheless, fire safety facilities and their installation in tunnels lacked strict verification processes.

During that period, the Taiwan Government and the public focused only on how fast a tunnel could be opened. A tunnel was ready to open as long as the Department of Transportation and Communications approved emergency response plan of a tunnel without a systematic and strict verification procedure. Therefore, over an extended period, fire safety objectives regarding road tunnel in Taiwan were ambiguous, with limited discussion on fire scenarios and corresponding design fires during the tunnel design stage.

Since its establishment in 2000, Taiwan's National Disaster Prevention and Protection Response Committee (NDPRC) proposed that a stakeholder joint verification committee should be required to approve emergency response plans for long road tunnels. The stakeholders include transportation authorities, police departments, fire departments, hospitals, environmental protection authorities and experts, as shown in Fig. 1. From this period onward, considerable discussion has concentrated on road tunnel design fire, human evacuation and rescue activities.

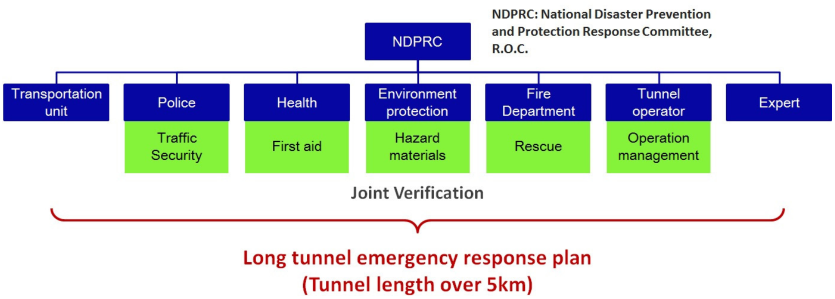


Fig. 1. Stakeholders of long tunnel in Taiwan.

2.2. Fire safety management system for existing tunnels

2.2.1. Hsuehshan tunnel

Opened in 2006 as the second longest tunnel in Asia with a total length of 12.9 km, the Hsuehshan Tunnel is a two-bored tunnel with two lanes in each unidirectional tunnel. The design fire for smoke exhaust system design is set at 30 MW. The Hsuehshan Tunnel connects New Taipei City to Ilan County in northeastern Taiwan, reducing the travel time from more than two hours to only forty minutes. Therefore, following its opening, the tunnel drew a greater than expected traffic load, especially during the holidays. To ensure the user safety through the Hsuenhshan Tunnel, the tunnel management authorities stringently enforce traffic regulations to decrease the likelihood of accidents However, the measures to improve tunnel safety also led to bottlenecks effects inside the tunnel and congest traffic outside the tunnel.

Many multidisciplinary experts have closely monitored safety concerns of the Hsuehshan Tunnel, as evidenced by numerous discussions on fire scenarios and safety strategies. To increase the transportation safety of Hsuehshan Tunnel, the governmental authority has established three stages to allow different vehicles (cars, buses and trucks) to pass through the tunnel. Each stage must comply with different operational requirements. Currently, only small vehicles and buses are allowed to pass through the tunnel.

While several full scale tunnel experimental results and European Union studies have demonstrated that water-based firefighting system (WFS) can sufficiently control the spread of fire and provide an allowable environment for evacuation, many tunnel fire safety experts in Taiwan still remain hesitant towards installing WFS inside road tunnels.

2.2.2. Guanyinshan Tunnel

The Guanyinshan Tunnel is of 2.5 km in length, consists of two unidirectional tubes. It is the main route that connects Taipei Port with New Taipei City, and large numbers of tanker trucks and heavy goods vehicles have been passing through it daily since its opening in 2009 A the same time, the fire safety of Guanyinshan Tunnel poses as an enormous challenge for the tunnel manager and the local government.

Taiwan's transportation management units originally allowed all vehicles to pass through the Guanyinshan Tunnel including tanker trucks, HGVs, buses and small vehicles. However, the decision was overturned due to doubts and questions from experts regarding the Guanyinshan Tunnel safety on the fact that Guanyinshan Tunnel's original design fire was only 30MW and lacks of many emergency response and rescue ability.

Due to considerations on the potential high risks of allowing tank trucks to travel through the Guanyinshan Tunnel, the Taiwan Government prohibited tanker trucks from entering the tunnel. However, local residents protested against this governmental policy over their concerns on the fact that tanker trucks travelling along the local road would create much more pollution and will pose as a dangerous threat to local inhabitants. Oil manufacturers also express dismay of inconvenience that would be created if the crude petrol could not be transported from the Taipei Port through the Guanyinshan Tunnel. In order to appease public protest, the Taiwan Government conditionally approved the trucks with transporting of dangerous goods to pass through the tunnel in 2009. The conditional approval included three requirements, including application ahead of time, stationing guard cars in front and behind the vehicle in the Guanyinshan Tunnel, and limited access time from 9 AM to 4 PM, Mondays to Fridays.

Although the Taiwan Government made many requirements and limitations in terms of the traffic, the Guanyinshan Tunnel still has the highest fire risks in terms of the possibility of tanker truck fires. The Taiwan Government is now thinking about how to improve fire safety in existing tunnels in terms of the possibility of the Guanyinshan Tunnel. How to allow every kind of vehicles, including heavy goods vehicles and tanker trucks to pass through tunnels safely, discussions on fire performance design for road tunnels are starting to be held.

2.3. Fire safety design for new tunnels

Tunnel stakeholders, including transportation management authorities, tunnel managers, constructors, fire departments, research institutes and experts have been actively discussing the feasibility of water-based firefighting system (WFS) in road tunnels. The SFPE Taiwan Chapter has strived to increase road tunnel safety awareness by inviting many overseas experts to share their experiences with road tunnel safety management systems and expertise in installing WFS in road tunnels. Most tunnel stakeholders have gradually accepted the notion that installation of WFS can improve overall road tunnel safety. In 2010, the Ministry of Transportation in Taiwan enacted a standard for road tunnel fire safety equipment, which requires that tunnels longer than 3 km must be installed the WFS, profoundly impacting the construction and fire safety design of future tunnels [1].

3. Fire Safety Performance-Based Design of a New East Coast Highway

Other than transportation via railway, the Suhua Highway is the most convenient main route connecting northern and eastern Taiwan. However, it is often shut down by torrential rain during typhoon seasons. The Taiwan government is thus expediting a project which is aimed at improving the original Suhua Highway where landslides frequently occurred during the rainy season.

3.1. Suhua Highway improvement project

The project includes improving three dangerous sections of the road among Suao and Dongao, Nanao and Heping, and Hechung and Dachingshui. The new road will be built along with eight tunnels and twelve bridges. Five of the eight tunnels are longer than 3km including the Dongao Tunnel, Guanyin Tunnel, Gufeng Tunnel, Chung-jen Tunnel and Jen-shui Tunnel as shown in Fig. 2. In the Nanao and Heping section, the Guanyin Tunnel and Gufeng Tunnel are connected by a 60 meter bridge allowing these two tunnels to be regarded as one tunnel with total length is 13 km. Most of the tunnels consist of two unidirectional tubes except for the Jen-shui Tunnel.

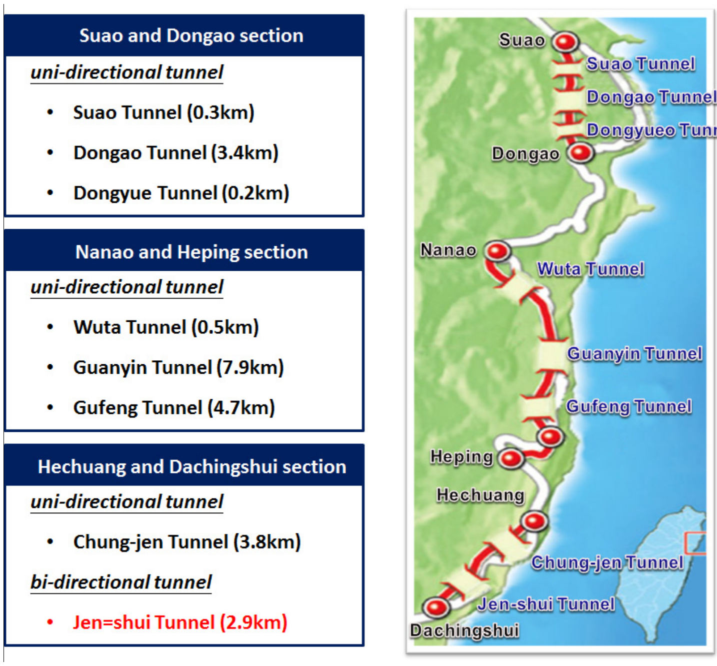
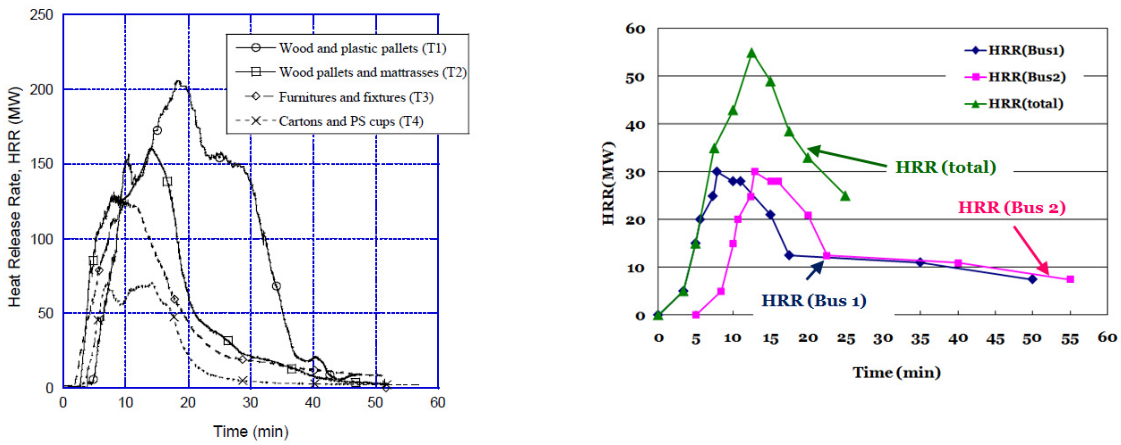


Fig. 2. Suhua Highway.

3.2. Assumption of fire scenarios

The Suhua Highway is the only route connecting northern and eastern Taiwan, explaining the need to allow trucks and tour buses to pass through its tunnels. Therefore, fire safety design for the Suhua Highway tunnels must incorporate possible fire scenarios of truck and bus fires. Heat Release Rate (HRR) measurements from the Runehamar Tunnel fire tests [2] were selected as the heat source in the performance-based fire safety design of Suhua Highway tunnels. Notably, the tunnels design incorporates a HRR curve [3] in which a two-bus collision fire scenario is obtained by numerical simulation. Fig. 3 displays the heat release rate curves of the above mentioned truck fires and two-bus fire individually.



(a) HRR curve of truck fires (Runehamar Tunnel fire tests) [2]

(b) HRR curve of two-bus fires (CFD simulation) [3]

Fig. 3. HRR curves of Runehamar Tunnel fire tests and two-bus fire simulation.

3.3. Analysis of the environment in road tunnel during fires

Table 1 lists the safety criteria of hazard factors for life safety and fire control in tunnel fires. The time constraints for fire-fighting activities inside tunnels are dominated by two factors: the time interval that fire fighter can perform firefighting activities safely and the time before rapid fire spread from one vehicle to another.

The effective range of firefighting using fire hose is 20 meters. Therefore, the radiation levels at 20 m upstream fire determining whether or not the fire brigade can perform firefighting activities safely. Experimental results from Runehamar Tunnel Fire indicated that fire fighters in protection clothing have a limit of approximately 5 kW/m^2 in exposure, above which, they will have difficulty in working and eventually start to feel pain after about 5 minutes [4]. However, for a firefighter to withstand the work environment for 20 minutes, radiation heat must not exceed 2 kW/m^2 [5]. With respect to the radiation level of fire spread from one vehicle to another, most of the materials will be ignited when the radiant intensity reaches 12.5 kW/m^2 [6]. Overall, the time constraint for fire-fighting activities can be determined by using the above safety criteria to address fire brigade safety concerns and prevent a fire from spreading in a tunnel fire.

Table 1. The safety criteria of hazard factors for life safety and fire control in tunnel fire

Assessment Category	Parameter	The safety criteria
Structure explosion (Spalling of concrete)	Temperature	500 °C
Life safety of tunnel users (Evacuation Environment)	Temperature	60 °C
	Visibility	10 m
	CO concentration	800 ppm
Life safety of fire fighters (Fire-fighting Environment)	Radiant Heat Flux	5 kW/m^2
Fire spread in Traffic jam	Radiant Heat Flux	12.5 kW/m^2

3.3.1. Runehamar Tunnel fire test [4, 7]

The measurements during the Runehamar Tunnel test, presented in Fig. 4, showing that the radiation flux at 20 m upstream of fire are below the critical level of 5 kW/m^2 for the truck fire scenarios. This means that the fire brigade can approach the burning trucks up to 20 meters and attacks the fire. In Fig. 5, the radiation flux curves at a distance of 5 m upstream of the fire exceeding the critical value of 12.5 kW/m^2 within approximately 7 to 10 minutes.

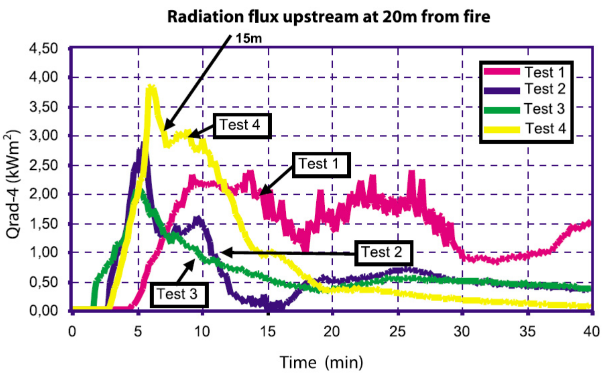


Fig. 4. Radiation flux upstream at 20 m from the fire for Runehamar tunnel fire tests. [4].

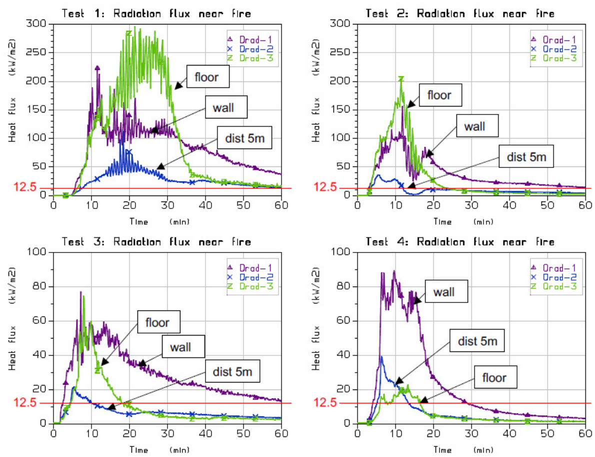


Fig. 5. Radiation flux curves and risk of fire spread for Runehamar tunnel fire tests. [7].

3.3.2. Two-bus fire by CFD simulation [3]

Figures 6 and 7 are the CFD simulation results of a two-bus fire in a long road tunnel in Taiwan. Fig. 6 indicates that the radiant flux at 20 m downstream of a fire reaches in 5 kW/m^2 about 6.6 minutes after ignition. Fig. 7 displays the radiant flux at 5 meters downstream from the fire, 7 minutes from ignition and no water-based firefighting system is activated during a tunnel fire.

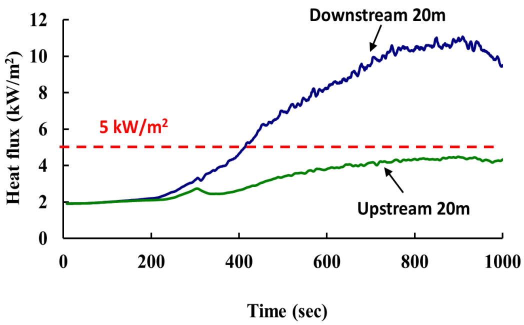


Fig. 6. Radiation flux at 20 m from the fire for two-bus fire.

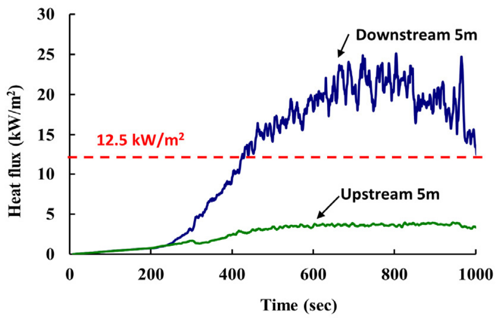


Fig. 7. Radiation flux at 5 m from the fire and risk of fire spread for two-bus fire.

3.3.3. The time constraints for executing firefighting activities

By considering the above two factors (firefighter safety and fire spread) and evaluation of time-dependent radiant intensity curves downstream and upstream from a fire, the tunnel managers can evaluate the time constraint for firefighters to combat the fire safely and prevent the fire from spread within a tunnel. Figs. 4 to 7 indicate that the time constraint for executing fire-fighting activities is 7 minutes after ignition. This information is important when evaluating whether local fire brigades can arrive at the fire site in time to control the fire. It is recommended that one of the two choices, designated fire brigade or WFS, should be incorporated in the fire service plans for long tunnels.

3.4. Evaluation of fire-fighting capacities

Based on a field survey study, Table 2 presents the time required for fire brigades near the Suhua Highway tunnels to reach the tunnel under different traffic conditions. This table reveals that most of the fire brigades cannot reach a tunnel within 7 minutes, regardless of whether under normal traffic condition or during traffic congestion, with the latter lengthening the arrival time to the tunnel by more than 10 minutes. Obviously, the time required for fire brigades reach to the tunnel exceeds the time constraint of 7 minutes. Additionally, these fire brigades are often not experienced firefighters and lack appropriate equipment to perform firefighting and rescue duties in tunnel fires.

Table 2. Travel time of the fire brigades arrived neighboring long tunnels of Suhua Highway

City	Fire brigades (start)	Long Tunnels (end)	Distance (km)	Travel time (min)	
				Normal traffic	Traffic jam
Yilan	Suao fire brigade	Dongao Tunnel	6.09	7	14
	Nanao fire brigade		13.84	15	31
Yilan	Suao fire brigade	Guanyin Tunnel and Gufeng Tunnel	25.54	28	57
	Nanao fire brigade		10.07	11	22
Hualien	Heping fire brigade	Chung-jen Tunnel	5.99	7	14
	Hsin-hsiu fire brigade		20.28	23	45
Hualien	Heping fire brigade	Jen-shui Tunnel	21.52	24	48
	Hsin-hsiu fire brigade		15.24	17	34

3.5. Evaluation of fire-fighting schemes

The evaluation of the fire-fighting schemes of tunnel fire rescue are shown below in Table 3, including tunnel portal fire brigade, self-defense fire brigade, and local fire brigade for the tunnels of Suhua Highway. The tunnel portal fire brigades and self-defense fire brigades are located either at the tunnel portal or inside the tunnel. Such locations allow the brigade members to respond immediately once fire occurs in a tunnel and communicate conveniently with the tunnel control center. Tunnel portal fire brigades are composed of professionally trained firefighters that can handle tunnel fires efficiently but they such brigades are expensive to maintain. On the other hand, self-defense fire brigades in charge of fire extinguishment during the initial stage of tunnel fire, traffic control and traffic accident management. have a relatively cost but often fail when handling large vehicles fires since they normally consist of general staff but without professional fire fighters. Local fire brigades are the most well trained out of the three but requires a longer travel time, often exceeding the given time constraint, to reach the scene of fire.

Table 3. Evaluation of the fire-fighting schemes of tunnel fire rescue

Item	Tunnel portal fire brigades	Self-defense fire brigade	Local fire brigades
Employee	fire fighters	general staff	fire fighters
Capabilities on Tunnel fire rescue	YES	NO (only in charge of extinguishment during initial stage)	NO (lack tunnel fire rescue experience and training)
Location	Tunnel portal	Tunnel portal and inside the tunnel	Nearby areas
Communication with control centre	convenient	convenient	inconvenient
Defect	• High human resource cost	• Incapable of facing fire involving large vehicles	• lack sufficient firefighters • Many duties • A long distance from fire brigades to tunnels

4. Water-based firefighting system (WFS)

Previously, there was lack of a global consensus on the use and effectiveness of WFS in road tunnels. Following the Mont Blanc Tunnel Fire, the European Union conducted several full scale tunnel fire experiments. Their results show that WFS is an effective method of fire protection for both tunnel users and fire fighters and can adequately control a road tunnel fire by limiting the spread of a fire. Fire tests of the UPTUN project demonstrated that steam only forms near a fire and that cooling effect of WFScan help with maintaining a survivable a tunnel environment. The UPTUN project results indicate that the WFS is not only valued as a first choice to enable evacuation of tunnel users but also to enable emergency services to enter the tunnel [8]. Additionally, an increasing number of international tunnel associations and organizations such as NFPA502 [9], AFAC (Australian Fire Authorities Council) [10], PIARC [11] favor installing WFS inside tunnels. To avoid catastrophic tunnel fires, an increasing number of countries have installed WFS inside tunnels, including France, Germany, Japan, Norway and Netherlands.

This study uses CFD modeling to simulate a truck fire in one of the tunnels of the Suhua Highway to investigate the effect of WFS system on human evacuation and environment near the fire site. Several simulation cases shown in Table 4 were simulated using FDS program in this study.

Table 4. Simulation conditions for different fire scenarios [3]

	Ventilation systems	WFS
Case 1	YES	NO
Case 2	NO	YES
Case 3	YES	YES

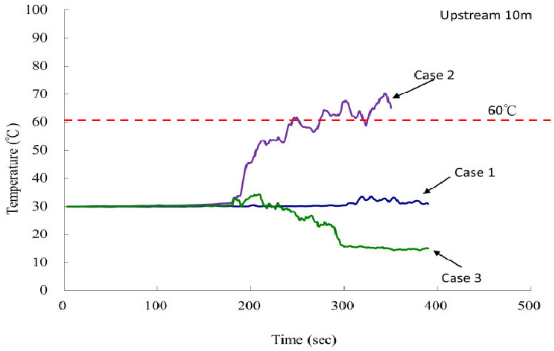
(1) Case 1: Fire scenario with only ventilation system activated. The ventilation systems activated in 30 seconds after the fire is detected.

(2) Case 2: Fire scenario with only WFS activated.
(3) Case 3: Fire scenario with ventilation systems and WFS both activated. To prevent development of a major fire, the time of WFS automatic releasing delay should not exceed 3 minutes [9], therefore this study has set the activation time of WFS to 180 seconds after detecting fire.

4.1. Simulation results and discussions

4.1.1. Tunnel users life safety

To prevent respiratory tract or lung burn by high-temperatures, humans should not be exposed to an environment with temperature higher than 60 °C [12]. Fig. 8 shows the evacuation temperature of the tunnel environment upstream and downstream of fire that is cooled by the ventilation system and WFS (Case 3). If only the ventilation system or WFS is activated, the environment of tunnel will exceed the critical temperature of 60 °C (Case 1 and Case 2).



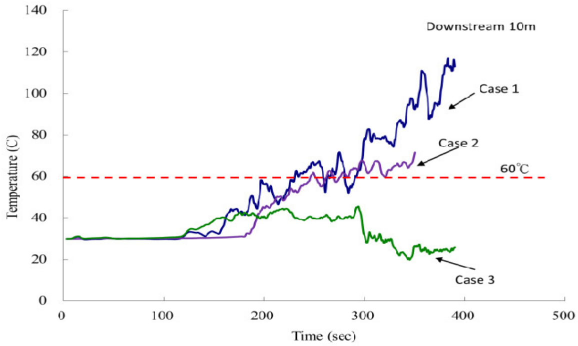


Fig. 8. Temperature curves at up- and downstream 10 m from a fire.

4.1.2. Fire spreading in traffic jam

Figure 9 shows that the vehicle at 1 m upstream from fire will be ignited in the Case 1 where no WFS activation during a tunnel fire. The simulations of Case 2 and Case 3 show that the radiation flux at 1 m upstream from fire drop below the critical level of 12.5 kW/m^2 after the WFS has been activated.

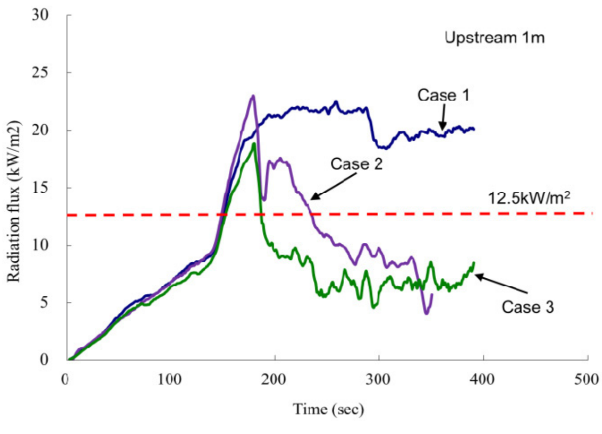


Fig. 9. Radiant heat flux at upstream 1 m from a fire.

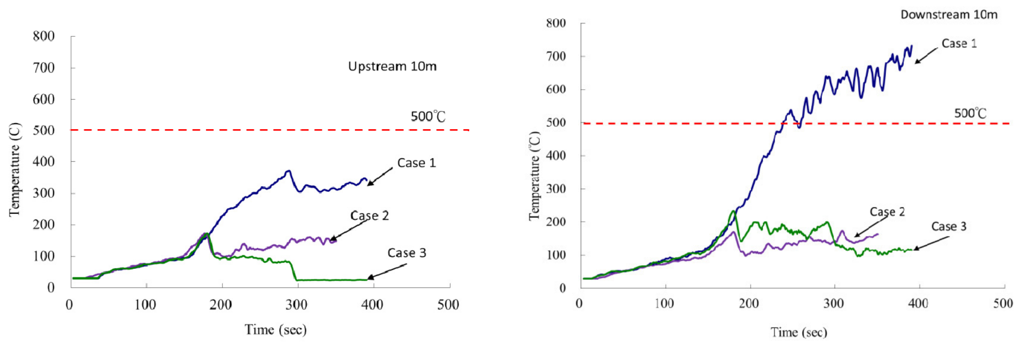


Fig. 10. Exposure temperature underneath tunnel ceiling.

4.1.3. Spalling of tunnel structure

Figure 10 shows the gas temperature below the tunnel ceiling for the three simulations. It is observed that in Case 1 has a possibility of spalling. The temperatures near tunnel ceiling downstream of fire are greater than 500 °C and extremely higher than the other two scenarios. On the other hand, the gas temperatures in Case 2 and Case 3 are reduced significantly, which show the ability of WFS in cooling temperatures near the fire site. Thus it can be concluded that WFS provides an alternative in protecting tunnel structure from spalling.

5. Conclusions

Taiwan has entered an era of long road tunnel transportation since the Hsuehshan Tunnel began operating in 2006. Recent catastrophic tunnel fires in Europe have drawn considerable attentions from the Taiwan Government in regard to fire safety issues in road tunnels.

Fire safety goals for road tunnels should include protection of life, protecting critical infrastructure and property, as well as ensuring business continuity. These safety concerns should be emphasized in a tunnel where vehicles carrying dangerous goods or HGVs are allowed to travel through. Additionally, a truck fire and two-bus fire must be considered when selecting fire scenarios for road tunnels. Evaluated parameters should include spalling of tunnel concrete, life safety, fire rescue capability and fire spread to adjacent vehicles.

Based on reviews of several important researches and tunnel fire experiments, this study determines the standard of a fire brigade rescue capability to be 7 minutes after ignition. This finding implies that a fire brigade must arrive, at a tunnel, and engage in firefighting immediately within 7 minutes. According to the field survey conducted for this study on the firefighting capabilities of fire brigades near the long tunnels of the Suhua Highway in Taiwan most of the fire brigades fail to reach a fire in a tunnel within 7 minutes. However, installing WFS inside road tunnels could extend the rescue time for the fire brigades.

Based on the results of this study, installation of WFS inside tunnels and improving the firefighting capability of local fire brigades in order to upgrade the fire safety systems of Suhua Highway tunnels are strongly recommended. The time duration with activated the WFS and it should be twice as the time requirment for the fire brigades to approach a fire. Therefore, the WFS installed inside the long tunnel should be activated at least for 40 minutes. Doing so can extend the rescue time to 20 minutes for fire brigades.

To ensure road tunnel safety on the Suhua Highway, transportation management authorities, tunnel managers and other stakeholders have finally agreed to install WFS inside Suhua Highway tunnels. This effort represents the first design case for road tunnels installing WFS in Taiwan. However, Taiwan lacks experience in installing WFS in road tunnels and further studies are necessary.

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