Model Analysis of Smoke Control in Long Tunnel: Findings from Hsueh-Shan Tunnel Accident in Taiwan

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Abstract: The common properties of risk in long tunnel fires are high temperature, extreme difficulty of evacuation, rescue urgency and obstacle to rescue operation. Therefore, a complete ventilation design is an indispensable safety measure. Hsueh-Shan Tunnel is the longest in Taiwan, the fifth longest in the world. On May 7, 2012, a serious tunnel fire caused two deaths and numerous victims suffered from smoke inhalation injury. Apart from this, there was smoking entering the cross-passages and shafts which were important for evacuation. In this research, the current ventilation system in Hsueh-Shan Tunnel was simulated with FDS (fire dynamics simulator) software, and the statistics of smoke, visibility and temperature profile were analyzed. The results of this research showed that, with the current ventilation system, the time was shorter and the distance was longer for the smoke spreading windward than in other models. Furthermore, the visibility of windward victims was more affected and the temperature above the fire source was higher than those in other systems. When the wind speed in tunnel is within 2.0~4.0 m/s, the condition for turning off the ventilation fan within 250 m upwind from the fire source can be prominently reduced to 50 m upwind from the fire source. This not only could avoid plume disturbance but also could be maintained. If victims' evacuation should be given the highest priority, it is recommended to straightly activate the maximum power of the fan.

Key words: Long tunnel fires, ventilation system, visibility, plume disturbance, victims' evacuation.

Nomenclature

C	The coefficient for natural convection (empirical constants, $C = 1.43$ on horizontal surface, $C = 0.95$ on vertical surface) (kW/m^2)
C_s	Solids specific heat constant of the material ($\text{kJ/kg}\cdot\text{K}$)
D	Diffusion coefficient (m^2/s)
f	External force vector (excluding gravity) (N/m^3)
g	Acceleration constant equal to Earth's surface gravity (m/s^2)
h	Enthalpy (kJ/kg)
h_i	Enthalpy of the i species (kJ/kg)
ΔH_v	Heat of vaporization (kJ)
I	Radiation intensity (kW/m^2)
I_w	The thermal intensity at the wall (kW/m^2)
I_{bw}	The black body intensity at the wall (kW/m^2)
k	Absorption coefficient ($\text{M}^{-1}\text{cm}^{-1}$)

K	Thermal conductivity; suppression decay factor (kW/mK)
k_s	Solids conductivity of the material (kW/mK)
L	A characteristic distance related to the size of the plate (m)
$\dot{m}$	The mass loss rate of fuel (kg/s)
Pr	Prandtl number ($Pr = 0.7\sim 0.8$ of air and gas)
p	Pressure (N/m^2)
$\dot{q}''$	Heat release rate per unit volume (kW/m^3)
$\dot{q}''$	Convective flux to a solid surface (kW/m^2)
$\dot{q}_c''$	Convective heat fluxes at the surface (kW/m^3)
$\dot{q}_p''$	The energy available for paralyzing fuel (kW/m^3)
$\dot{q}_r''$	Radiative heat fluxes at the surface (kW/m^3)
S	Unit vector in direction of radiation intensity (m)
T	Air temperature ($^{\circ}\text{C}$)
T_s	Temperature of the material ($^{\circ}\text{C}$)
t	Time (s)
U	Dynamic viscosity (m/s)
V	Volume of the enclosure (m^3)
$\dot{W}_i''$	Volume fraction of species i (m^3)
x	Specific heat (kJ/kg)
Y_i	Mass fraction of species i (kg)

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δ	Solids thickness of the material (m)
ε	Emissivity rate (w/s)
ρ	Density (kg/m^3)
λ	Wavelength (μm)
ρ_s	Solids density of the material (kg/m^3)
σ	Stefan-Boltzman constant ($\text{W}\cdot\text{m}^{-2}\text{K}^{-4}$)
Ω	Absolute humidity (g/m^3)

1. Introduction

With the improvement of living standard and development of transportation industry, a variety of tunnels have shown up and fire safety appears as quite an important topic. Road tunnels, with its closed and restricted space, could hardly perform smoke exhaust naturally. Thus the smoke and heat would fill the tunnel without escape, causing high temperature, extreme difficulty in evacuation, rescue operation and smoke spreading. The smoke in a tunnel fire might cause low visibility and casualties due to carbon monoxide inhalation or poisoning. Apart from above-mentioned, the evolved heat from fire would lead to collapse of tunnel structure and damage of equipment, any possible casualties may ensue. Therefore, a complete ventilation design was an indispensable safety measure precaution in long tunnel.

This research adopted smoke control modes of actual operation to analysis the hazard of high fire situation while fire occurred on beginning, middle and final stage in emergency control center of Hsueh-Shan Tunnel. At the present stage, while fire occurred in Hsueh-Shan Tunnel, an existing smoke control strategy has been mainly conducted, which is divided into “evacuation mode” and “exhaust smoke mode”, and “a single hole way” and “two holes—single way”, etc. The actual modes of operation are divided into 28 kinds of evacuation mode and 12 kinds of exhaust smoke modes. This study adopted a single hole way with the original four kinds of evacuation mode and six kinds of exhaust smoke mode as a smoke control optimum design study direction.

This study employed the CFD (computation fluid dynamics) based FDS (fire dynamics simulator) [1]

software, which developed by the U.S. NIST (National Institute of Standards and Technology), to simulate the fire accident smoke exhaust device at the exact time when accident occurs. The FDS is nowadays widely adopted by researchers for tunnel fire scenarios [2-7], which was used to verify tunnel fire in full-scaled and down-sized model. In practice, the results showed consistency in the temperature of jet stream, length of countercurrent smoke layer and critical wind speed with experimental results. Lee [5] and Lotschberg [8] focused on simulating long tunnel fire, while Lin [9] and Kirytopoulos et al. [10] intended to discuss the environment for evacuation in tunnel fire.

Hsueh-Shan Tunnel is currently Taiwan’s longest tunnel, the fifth tunnel in the Asia and the eighth longest highest tunnel. This tunnel is one-way, twin bore and it is approximately 12.9 km long. This research employs the Hsueh-Shan Tunnel as its study subject. Existing researches in tunnel fire simulation are mainly based on uniform speed of exhaust fans or consistent wind speed at the entrances of the tunnel [10]. However, in actual fire scene, exhaust fans on the top of the tunnel will be activated if there is no sufficient ventilation inside the tunnel to ensure certain wind speed. Therefore, in this research, the fans on top of the tunnel were used to stabilize the flow field. Moreover, by analyzing existing evacuation mode and smoke exhaust mode, the results were elucidated in the discussion of fire evacuation environment.

2. Hsueh-Shan Tunnel Fire Accident

The catastrophic tunnel fires since 1999 and a series of fire in some long tunnels in the summer of 2001 triggered extensive discussions and proposals related to tunnel safety in Taiwan [11, 12]. When a fire occurs in a tunnel and in absence of sufficient air supply, large quantities of smoke are generated, filling the vehicles and any space available around them. Unless a strong flow is created and maintained, hot gases and smoke migrate in all directions. Since last two decades, there have been cases of serious long tunnel disasters, such

as Mont Blanc Tunnel in Alps (11.6-km), transport truck fire causing 39 deaths on March 4, 1999 and Tauern Tunnel in Austria (6.4-km), fire caused by collision of truck on May 29, 1999 leading to 13 deaths. Table 1 lists the analysis of the selected fire accidents in road tunnels around the world [13].

It is constructed with one pilot tunnel and two main tunnels for eastbound and westbound traffics. The total length is 12.94 km (8.04 mi) making the Hsueh-Shan Tunnel the second longest road tunnel in East Asia and the fifth longest road tunnel in the world, as shown in Fig. 1. For this study, an actual example of a fire that occurred in Hsueh-Shan Tunnel was used and elucidated to a deeper extent.

On May 7, 2012, the most severe car accident occurred in Hsueh-Shan Tunnel ever since its establishment on June 16, 2006. A car in 26.0 km south slammed on the brake when its tire blew out, vehicles at the back, including a Kamalan's bus, dodged aside. However, a van and a Capital's bus crashed into the Kamalan's bus, causing fire on the van, which spread to the Capital's bus soon. The tunnel immediately filled with smoke and high temperature. This accident caused two deaths, seven major and 15 minor injuries [14]. The victims described the tunnel as fallen chimney that there are hundreds of victims who evacuated were all covered with a layer of soot. According to Taiwan Area National Freeway Bureau, Ministry of Transportation and Communications, the temperature of the tunnel on fire was 54 °C as compared with 30 °C in average.

3. Introduction to Simulation Software

FDS version 5.0 is a CFD model developed by NIST to simulate the fire growth for low-speed Mach number. The program is approximated the Navier-Stokes equations [15] by discretization to the finite difference equations. The computation is treated as a DNS (direct numerical simulation) or LES (large eddy simulation). For DNS model, the dissipative terms are computed directly; For LES model, the large-scale eddies are computed whereas directly and the sub-grid scale

dissipative processes are modeled. The selection of DNS or LES depends on the objective of calculation and the required resolution of computational grid. Although it is possible to compute directly the heat and mass transfers when performing a DNS, heat and mass transfers to and from solid surfaces is usually handled with empirical correlations, and turbulence is treated by means of the Smagorinsky form [16] of LES. Therefore, this study adopted LES, the default mode of operation.

3.1 Conservation Equations

Followings are the conservation of mass, momentum, species and energy equations for the multi-component mixture of the idea gases [17]:

- conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0 \quad (1)$$

- conservation of momentum:

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right) + \nabla p = \rho \mathbf{g} + \mathbf{f} + \nabla \tau \quad (2)$$

- energy equation:

$$\frac{\partial}{\partial t} (\rho h) + \nabla \cdot \rho h \mathbf{u} - \frac{DP}{Dt} = Q - \nabla \cdot \mathbf{q}'' + \nabla k \nabla T + \nabla \cdot \sum_{\ell} h_{\ell} (\rho D)_{\ell} \nabla Y_{\ell} \quad (3)$$

- conservation of species:

$$\frac{\partial}{\partial t} (\rho Y_{\ell}) + \nabla \cdot \rho Y_{\ell} \mathbf{u} = \nabla \cdot (\rho D)_{\ell} \nabla Y_{\ell} + \dot{W}_{\ell}''' \quad (4)$$

3.2 Thermal Radiation Model

The FDS radiation model for the non-scattering gas is governed by Ref. [18]:

$$s \cdot \nabla I_n(x, s) = k_n(x) [I_{b,n}(x) - I(x, s)] \quad (5)$$

$$n = 1, 2, \dots, N$$

where:

$$I_{b,n} = F_n(\lambda_{\min}, \lambda_{\max}) \sigma T^4 / \pi \quad (6)$$

$$I(x, s) = \sum_{n=1}^N I_n(x, s) \quad (7)$$

where, $I_n(x, s)$ is the radiation intensity at wave length n , $I_{b,n}(x)$ is the source term given by the Planck

Table 1 Selected tunnel fire accidents happened in the world since 1947 [13].

Year	Tunnel length	Location country	Vehicle where fire occurred	Most possible cause of fire	Duration of fire	Consequences		
						Consequences people	Damaged vehicles	Structures and installations
1949	Holland, 2,550 m	New York, USA	Lorry with 11 t of carbon disulfid	Load falling off lorry; Explosion	4 h	66 injured smoke in halation	10 lorries, 13 cars	Serious damage over 200 m
1974	Mont Blanc, 11,600 m	France-Italy	Lorry	Motor	15 min	One injured		
1978	Velsen, 770 m	Velsen, the Netherland	Four lorries, two cars	Front-rear-collision	1 h 20 min	Five dead, five injured	4 lorries 2 cars	Serious damage over 30 m
1979	Nihonzaka, 2,045 m	Shitsuoka, Japan	Four lorries, two cars	Front-rear-collision	159 h	Seven dead, one injured	127 lorries 46 cars	Serious damage over 1100 m
1980	Kajiwara, 740 m	Japan	One truck with 3,600 L of paint in 200 cans	Collision with side wall and overturning	-	One dead	1 truck, 4tons 1 truck, 10tons	Serious damage over 280 m
1982	Caldecott, 1,028 m	Oakland, USA	One car, one coach, one lorry with 33,000 L of petrol	Front-rear-collision	2 h 40 min	Seven dead, two injured	3 lorries 1 coach 4 cars	Serious damage over 580 m
November 3, 1982	Salang, 2,700 m	Mazar-e-Sharif-Kabul, Afghanistan	Soviet military column, at least one petrol truck	Front collision; Destroyed tank	-	> 400 dead	-	-
1983	Pecorila Galleria, 662 m	Gênes, Savone, Italy	Lorry with fish	Front-rear-collision	-	Nine dead, 22 injured	10 cars	Little damage
1986	L'Arne, 1,105 m	Nice, France	Lorry with trailer	Braking after high speed	-	Three dead, five injured	1 lorry 4 cars	Some equipment destroyed
1987	Gumefens, 343 m	Berne, Switzerland	One lorry	Front-rear-collision	2 h	Two dead	2 lorries 1 van	Slight damage
1993	Serra Ripoli, 442 m	Bologne-Florence, Italy	One car and one lorry with rolls of paper	Collision	2 h 30 min	Four dead, four injured	5 lorries 11 cars	Little damage
1994	Huguenot, 3,914 m	South Africa	Bus with 45 passengers	Electrical fault	1 h	One dead, 28 injured	1 coach	Serious damage
April 10, 1995	Pfander, 6,719 m	Austria	Lorry with trailer	Collision	1 h	Three dead in the collision, four injured	1 lorry 1 van 1 car	Serious damage
March 18, 1996	Isoladelle, Femmine, 148 m	Palermo, Italy	One tanker with liquid gas and one little bus	Front-rear-collision	-	Five dead, 20 injured	1 tanker 1 bus 18 cars	Serious damage tunnel closed for 2.5 days

(Table 1 continued)

Year	Tunnel length	Location country	Vehicle where fire occurred	Most possible cause of fire	Duration of fire	Consequences		
March 24, 1999	Mont Blanc, 11,600 m	France-Italy	Lorry with flour and margarine	Oil leakage; Motor	-	39 dead	23 lorries 10 cars, one motor cycle, two fire engines	Serious damage Tunnel reopens; December 22, 2001
May 29, 1999	Tauern, 6,401 m	Salzburg-Spittal, Austria	Lorry with paint	Front-rear-collision; Four cars and two lorries	-	12 dead, 49 injured	14 lorries, 26 cars	Serious damage
August 6, 2001	Gleinalm, 8,320 m	Austria	Car	Front collision lorry; Car	-	Five dead, four injured	One lorry, one car	
October 24, 2001	St. Gotthard, 16,918 m	Switzerland	Lorry	Front collision; Two lorries	2 days	11 dead	13 lorries, four vans, six cars	Serious damage; Closed two months
July 13, 2003	Northern National Highway No. 2, Zhonghe, 850 m	New Taipei City, Taiwan	Trailer nine cars	A trailer drove into the last car in a pile-up	2 h	Three dead	One trailer, nine cars	Serious damage over 10 km
June 4, 2005	Fréjus, 12,895 m	France-Italy	(1) Load: tyres; (2) Load cheese; (3) Load: scrap (two dead); (4) load: glue	Diesel leakage in lorry loaded with tires; Spread to three other lorries	6 h	Two dead, 21 injured	Four lorries, three fire fighting vehicles	Serious damage; Tunnel closed
September 16, 2006	Viamala, 742 m	Switzerland	Car and bus	Front collision	-	Six dead, 6 injured	One bus, two cars	-
March 23, 2007	Burnley, 3,400 m	Australia	Three lorries, four cars	Rear-end collision	-	Three dead	-	-
September 10, 2007	San Martino, 4,800 m	Italy	Lorry	A lorry crashed into the wall and caught fire	-	Two dead, 10 injured	-	-
July 7, 2010	Huishan Tunnel, 1,556 m	Wuxi, Jiangsu Province, China	One bus	A breakdown of machinery	-	24 dead, 19 injured	One bus	-
May 7, 2012	Hsueh-Shan, 12,900m	New Taipei City, Taiwan	Small truck, bus	Small truck tire blew out and collided the bus in front	78 min	2 dead, 22 injured	Two buses, two cars	Serious damage; Tunnel closed
December 3, 2012	Sasago Tunnel, 4,400 m	Japan	Three cars	A concrete part of the ceiling fallen off	-	Nine dead	One van, one car and one lorry	The ceiling collapsed
January 1, 2013	Brattli Tunnel, 3,600 m	Tysfjord, Norway	One lorry	A truck carrying 29.8 t of goat cheese caught fire	-	-	One lorry	Closed for several weeks

Fig. 1 Perspective of Hsueh-Shan Tunnel.

function, s is the unit normal direction vector and $k_n(x)$ is the absorption coefficient. The bounding condition for the radiation intensity leaving a gray diffuse wall is given as:

$$I_w(s) = \varepsilon I_{bw} + \frac{1-\varepsilon}{\pi} \int_{s' \cdot n_w < 0} I_w(s') |s' \cdot n_w| d\Omega \quad (8)$$

where, I_w is the intensity at the wall, I_{bw} is the black body intensity at the wall, and ε is the emissivity rate.

3.3 Thermal Boundary Conditions

The type of thermal boundary conditions applied at any given surface depends on whether that surface is to heat up and burn, whether the burning rate will simply be prescribed, or whether there is to be any burning at all.

3.3.1 Convective Heat Transfer to Walls

This condition is used in a solid surface consisting of gains and losses from convection and radiation. In DNS calculation, the convective heat flux to a solid surface q_c'' is obtained directly from the gas temperature gradient at the boundary.

$$q_c'' = -k \frac{\partial T}{\partial x} \quad (7)$$

In LES calculation, the convective heat flux to the surface is obtained from a combination of natural and forced convection correlations:

$$\dot{q}_c'' = h \Delta T \quad (8)$$

$$h = \max \left[C |\Delta T|^{1/3}, 0.037 \frac{K}{L} \left(\frac{|U|L}{V} \right)^{0.8} P_r^{1/3} \right] \quad (9)$$

3.3.2 Pyrolysis Model with Thermally-Thick Solid

If the material is assumed to be thermally-thick, a one-dimensional heat conduction equation is applied. The equation is [19]:

$$\rho_s C_s \frac{\partial T_s}{\partial t} = k_s \frac{\partial^2 T}{\partial x^2} \quad (10)$$

$$-k_s \frac{\partial T_s}{\partial x}(o, t) = \dot{q}_c'' + \dot{q}_r'' \quad (11)$$

where, ρ_s , C_s and k_s are the (constant) density, specific heat and conductivity of the material, $\dot{q}_c''$ and $\dot{q}_r''$ are the convective and radiative heat fluxes at the surface. If the material is assumed to ignite and burn at some prescribed temperature T_p , then Eq. (12) can be described as follows:

$$T_s(0, t) = T_p; \quad \dot{q}_p'' = \dot{q}_c'' + \dot{q}_r'' + k_s \frac{\partial T_s}{\partial x}(0, t) \quad (12)$$

where, $\dot{q}_p''$ is the energy available for paralyzing fuel, which can be specified and expressed as Eq. (13):

$$\dot{m}'' = \frac{\dot{q}_p''}{\Delta H_v} \quad (13)$$

3.3.3 Pyrolysis Model with Thermally-Thin Solid

If the material is assumed to be thermally-thin and the temperature is uniform across width, the governing Eq. (14) is annotated as below:

$$\frac{dT_s}{dt} = \frac{\dot{q}_c'' + \dot{q}_r''}{\rho_s C_s \delta} \quad (14)$$

where, δ is thickness. In this case, the individual values of the parameters, and are not as important as their products. The pyrolysis temperature is expressed as Eq. (15):

$$T_s = T_p; \quad q_p'' = q_c'' + q_r'' \quad (15)$$

4. Common Ventilation System and Smoke Control Mode in Long Tunnel

When the fire in Hsueh-Shan Tunnel occurred, the timing of ventilation control and the constant pressure exhaust system are not proper for escape and rescue operation, causing serious casualties, as shown in Fig. 2 [19]. Cross-flow ventilation system involves a relatively larger excavation area and requires higher power and higher construction cost. However, it is suitable in long tunnel as exhaust gas accumulates less. In view of the above-mentioned, the post-disaster recovery of Gotthard Road tunnel and many of the reconstruction or construction of long tunnel ventilation system around the world adopt the central

exhaust system [20]. The ventilation and exhaust system can be classified into longitudinal ventilation, transverse ventilation (Fig. 2a), semi-transverse ventilation (Fig. 2b), and longitudinal with point extraction ventilation (Fig. 2c) which are the latest trend [21, 22]. Hsueh-Shan Tunnel is the longitudinal ventilation and exhaust system.

The design standards of tunnel ventilation system used around the world are virtually the same; The majority of them use natural, longitudinal, semi-transverse or transverse ventilation. In short tunnels, piston effect could participate in longitudinal and transverse ventilation. Furthermore, semi-transverse ventilations are needed in the case of long tunnels. For the ventilation system to perform smoke exhaust, the ventilation channel and devices must be thermal-resistant.

Long tunnels in Taiwan, especially those on freeway, are separated twin-bore tunnels. In the case of Hsueh-Shan Tunnel, three sets of ventilation and relay stations are established, with separated shafts for fresh air and exhaust gas to enter and escape. By using exhaust fans for longitudinal ventilation, air quality can

Fig. 2 Evolution of international road tunnel exhausted system [11]: (a) transverse ventilation; (b) semi-transverse ventilation; (c) longitudinal & point extraction ventilation.

be guaranteed with less energy waste. With fire brigades reside at both ends of the tunnel, once fire is detected, the firefighters will be in operation with fire motorbike, guiding the victims to evacuate within the optimum rescue period.

5. Simulation and Analysis

This research aimed on investigating better smoke control system for reducing the number of casualties in fire than current configuration. According to “*Plan of Road Accidents and Overall Precaution & Rescue of Hsueh-Shan Tunnel*” approved by Executive Yuan, Taiwan, R.O.C., 2012, when fire breaks out in a tunnel, in order to provide victims a proper environment to escape, the fans ought to be in operation as preset. Furthermore, this operation can be divided into two steps.

5.1 Evacuation Mode

To help victims adequately escape from fire site, the first step is shutting down the fans and closing affiliated air doors to prevent smoke from spreading to neighboring tunnels. Furthermore, the operation of blowers, exhaust fans, and jet fans follows the ventilation program. In one-way traffic, the wind speed at fire scene should be kept at 2.0~4.0 m/s to force the smoke to spread downwind so as to protect the victims upwind. However, the fans from 250.0 m upwind to 500.0 m downwind of the fire scene should not be turned on to decrease the disturbance of smoke layer. Meanwhile, all the fire and smoke doors in tunnel cross-passages should be closed.

5.2 Smoke Exhaust Mode

When the victims have already escaped through cross-passages, to avoid the equipment damage caused by high temperature, the smoke exhaust mode must be launched by staff in control center. In addition, to assist the firefighters to operate promptly, all the blowers exhaust fans, and jet fans must be activated to make higher wind speed.

However, on May 5, 2012, the fire accident at 26.0 km, southbound in Hsueh-Shan Tunnel caused numerous victims suffered from smoke inhalation injury. Moreover, the cross-passages and shafts were all filled with smoke. Therefore, to find a better way which can alleviate the damage caused to victims, this research is to compare the current 2-step smoke exhaust mode with the others.

This simulation is based on a real case in a tunnel 200.0 s before the fire accident happened; The blowers were activated to keep the wind at a stable speed of 2.0~4.0 m/s. After that, one vehicle was simulated to be on fire at the 201th second. Moreover, the maximum fire load of simulated tunnel was 30.0 MW (Table 2) [13, 23] as referred to the structural design of Hsueh-Shan Tunnel. The control center would confirm the fire case within 60.0 s and launch the smoke exhaust mode at the 260th second. The followings are three different smoke exhaust modes to probe the scenario, as listed in Table 3:

(1) Mode 1: Follow the first step of current ventilation operating mode so that the fans within the fire scene 250.0 m upwind and 500.0 m downwind are shut down at the 260th second;

Table 2 Details of relevant simulation parameters.

Parameters	Detail	
Tunnel space	Size (length × width × height)	5,000.0 m × 10.0 m × 7.0 m
Fire source	Fire load	30.0 MW
	Fuel	Diesel fuel
	Area of fire	2.0 m × 2.5 m
Relevant simulation parameters	Environmental starting temperature	25.0 °C
	Simulation time	800.0 s

Table 3 Threesmoke exhaust operation modes to probe the scenario.

Mode	Operation mode	
	Before 260th second	After 260th second
Mode 1	Turn on one vehicle for each set	Shut down the fans within the fire scene 250.0 m upwind and 500.0 m downwind
Mode 2	Turn on one vehicle for each set	Remains unchanged
Mode 3	Turn on one vehicle for each set	Launch all the two jet fans in each set

Fig. 3 Countercurrent at different timings of Mode 1.

(2) Mode 2: Maintain the ventilation operating mode running, but the fans from 250.0 m upwind to 500 m downwind of the fire scene stay on at the 260th second;

(3) Mode 3: Maintain the ventilation operating mode running and launch all the jet fans at the 260th second (there are two jet fans at the same location).

The length of Hsueh-Shan Tunnel is 12.9 km. However, in this case the simulated tunnel is 5.0 km, and the fire load is the same of the construction design of the Hsueh-Shan Tunnel which is 30.0 MW. The followings are the analytical results of the three different modes:

(1) In the 430th second of Mode 1, the length of countercurrent is 82.0 m, which is the longest one among the 800.0-s simulation, as shown in Fig. 3. In Mode 2, the longest of the countercurrent is 5.0 m, and the happened time is still around 430th second, as shown in Fig. 4. However, there is no countercurrent happened in Mode 3, mainly because the wind speed

is faster than that of countercurrent when all the jet fans are in operation, as shown in Fig. 5. The distances of the countercurrent of Modes 1-3 are given in Table 4, and the visibility 30.0 m away from the fire source and the temperature 6m above the fire source are presented in Table 5;

(2) In Fig. 6, the visibilities 30.0 m away from fire source of each mode are below 10.0 min at the 400th second, which may affect the victims' escape;

(3) In Figs. 7-9, whether the jet fans were switched on affected the upwind temperature profoundly.

The graph of temperature 6 m above the fire source are disclosed in Fig. 10. In Mode 1, shutting down the fans leads to heat accumulation upon the fire source and causes structural damage. Summarizing the results of Figs. 3-10, in the case of a coach, it would take 2.0 min for all passengers to get off. Furthermore, conservatively estimating, the walk speed is 0.8~1.2 m/s. Therefore, only Modes 2 and 3 can ensure the victims' safety when they escape.

Fig. 4 Countercurrent at different timings of Mode 2.

Fig. 5 Countercurrent at different timing of Mode 3.

Table 4 Distances of countercurrent at different timing of each mode.

Mode	Timing		
	430.0 s	620.0 s	800.0 s
Mode 1	82.0 m	26.0 m	15.0 m
Mode 2	5.0 m	2.0 m	0.0 m
Mode 3	0.0 m	0.0 m	0.0 m

Table 5 Visibility and temperature of three modes.

Mode	Visibility at 30.0 m from fire scene (400.0 s)	Temperature 6.0 m above the fire source (420.0 s)
Mode 1	11.1 m	775.0 °C
Mode 2	30.0 m	568.0 °C
Mode 3	30.0 m	334.0 °C

Fig. 6 Visibilities 30.0 m away from fire source.

Fig. 7 Sectional view of temperature at different timings of Mode 1.

Fig. 8 Sectional view of temperature at different timings of Mode 2.

Fig. 9 Sectional view of temperature at different timings of Mode 3.

Fig. 10 The change map of temperature 6 m above the fire source.

6. Conclusions

Because the fact that Hsue-Shan Tunnel is the longest tunnel among all of the Taiwan's, it took a long time to construct. Meanwhile, it is also the most important road to communicate the east and west of Taiwan. Therefore, the maintenance and care of the tunnel are vital. However, the traffic accidents are still unavoidable, leading to an important fact that how to keep the safety to the people inside the tunnel when the fire breaks out and how to reduce the damages they might take also the damages to the tunnel. This analysis

used FDS to implement the scenario evaluations. The FDS is the fire simulation software to make sure the applicability toward this case. Furthermore, the followings are the results drawn from this study:

- (1) In the comparison of Modes 1 and 2, it can be seen that, without shutting down upwind and downwind fans as in Mode 2, the distance of the countercurrent smoke layer is shorter than that in Mode 1. It favors the escape of victims upwind;
- (2) In the case of 2.0~4.0 m/s wind speed, the distance of the countercurrent smoke layer is shorter than 50.0 m. To avoid disturbance of smoke layer and

pursue the safety of upwind victims, it is suggested to shorten the condition of shutting down the fans from within 250.0 m upwind to within 50.0 m upwind;

(3) The activation of axial fan can affect the heat accumulation upon the fire source, avoiding partial high temperature which leads to damaging in the interior structure of tunnel;

(4) The escape of victims should be given the highest priority. Thus, the authority is suggested to adopt Mode 3 to ensure safety of upwind victims by avoiding the existence of countercurrent smoke layer.

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