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A study of wind effects on smoke extraction strategies in vehicle tunnels

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ABSTRACT

The effects of winds on smoke spread in a vehicle tunnel have been studied. A 2.6 km vehicle tunnel in Taiwan was taken to be the case study with 50 MW ultra-fast fire scenarios. It has been found that wind can have adverse effects on smoke control. The results show that winds from the tunnel ends would cause high temperature smoke spreading through the tunnel. This study explored the strategies of using tunnel ventilation jet fans and point smoke extraction in combination to counter the wind effects. It has been found that proper control strategies could restrain smoke spread in the tunnel for a period of time. Different control strategies are presented separately for fire occurs at the tunnel center and at the tunnel entrance. The results were evaluated in terms of temperature, visibility and CO concentration, specifically at 2 m height from the floor level. The results show that smoke can be contained to a span of about 100 m for more than 300 s, and for as long as 900 s in more favorable cases. The results show that tenable conditions can be maintained a period of time to prolong the evacuation time.

1. Introduction

Traverse point smoke extraction has been found to be effective for vehicle tunnel fires by Lin and Chuah (2007). They found that for multi-port exhaust design, single-port dampers open near the fire site would be a better strategy to reduce smoke spread and prolong the evacuation time. However Lin and Chuah (2007) considered only the air movement due to the smoke extraction but not the wind effects. Therefore this study is a further investigation into the problems of smoke control in vehicle tunnel with the inclusion of wind effects.

Taiwan has mountainous terrains and therefore many vehicle tunnels; many more are in planning some are under construction. Other than typhoons that occur in the summer, Taiwan has monsoon winds especially during the cooler months. Wind effects have been a great concern for smoke control in vehicle tunnels. Table 1 shows the monthly average highest wind speed in the Keelung area in the year 2015. A vehicle tunnel in this area is studied to improve the smoke control. It can be seen that wind speed is greater than 3 m s^{-1} in many months of a year.

In 2012 a car fire occurred in the 13 km long Snow Mountain Tunnel (SMT) in Taiwan after a bus accident, some injuries was caused by fire and smoke (MOTC, 2012). That incidence attracted much attention on the fire safety of vehicle tunnels in Taiwan. Fan et al. (2014) modeled vehicle tunnels equipped with natural ventilation shafts for smoke exhaust. Their results indicated that the more the ventilation shafts higher wind speed would cause more smoke emissions in a fire. Lee and Tsai (2012) carried out a small scale experiment aided with computer simulation. Their results showed that tunnel clogged with larger vehicles might result in higher heat release rate. Tsai et al. (2011) further investigated the problem of fire site near to the tunnel entrance. They found that critical wind speed would reduce due to the environmental conditions at the tunnel entrance. However Tsai et al. (2011) did not consider the impact on smoke spread in the tunnel due to the winds.

Hu et al. (2010) studied temperature and CO concentration decay in a tunnel fire with different heat release rates. They found that the decay increased with higher critical wind speed. Hu et al. (2006) further carried out full-scale fire experiments with fire sizes 1.6 MW and 3.0 MW in two tunnels, separately 3.27 km and 1.032 km in length. They found that the temperature simulated by FDS (Fire Dynamic Simulation) agreed well the measured ones. At 6 m from the fire site the simulated temperature differed from the measured values by less than 11 °C (9.8%). The average difference was less than 3.6 °C (3.5%). Lee and Ryou (2006) used model experiments and computation to study the effects of aspect ratio; they found that smoke and temperature spread could be affected by tunnel aspect ratio.

Hwang and Edwards (2005) used the reported incidence of Memorial Tunnel (Massachusetts Highway Dep., 1999) and the experimental results of Wu and Baker (2000) in their analysis of critical wind speed by FDS simulation. Their results showed that the increase in critical wind speed would level off at higher fire heat release. Bwalya et al. (2003) reviewed the scale of road tunnel fire using the pre-flashover

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Nomenclature

$\dot{Q}$	heat release rate (50,000 kW)	V_c	critical velocity ($m \cdot s^{-1}$)
H	tunnel height (4.75 m)	ρ_∞	outside air density (1.124 $kg \cdot m^{-3}$)
A	vehicle tunnel sectional area (45.125 m^2)	C_p	specific heat (1.008 $kJ \cdot kg^{-1} \cdot K^{-1}$)
grade	tunnel grade (0%)	g	acceleration of gravity (9.81 $m \cdot s^{-2}$)
T_∞	ambient temperature (300 K)	F_r	Froude number 6.7–4.5 (4.5)
T_f	fire temperature (K)	K_g	grade factor r (–)
		K_l	inertia force factor (–)

Table 1
Keelung climatological data annual report.

2015												
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean speed (m/s)	3.7	2.8	3.1	2.7	2.0	2.2	2.7	3.1	3.1	3.1	3.0	3.9

Note: From Central Weather Bureau Republic of China (Taiwan).

and post-flashover model. Kashef et al. (2003) in their review of a tunnel fire incidence citing PIARC fire test and hot smoke tunnel experiments.

Petterson (2002) pointed out that FDS model could be generally applied to simulate fires but some temperature prediction errors were expected at the fire site. Wu and Baker (2000) studied the control of smoke flow with longitudinal ventilation. They carried out 1/20 down scale experiments and then proposed a regression model for dimensionless fire size and critical air speed.

It can be noted that most related studies did not address specifically the effects of ambient winds on the spread of fire smoke in vehicle tunnel fires. Especially for a single tube bi-directional tunnel it is critically important to contain the smoke near the fire site for a period of time. Therefore overcoming the wind effects by proper smoke control strategies is an important research issue.

2. The tunnel model and smoke exhaust

The vehicle tunnel studied was of single tube bi-direction. It was designed with a traverse point extraction system as shown in Fig. 1. The exhaust duct was located above the traffic space. Tunnel exhaust fans EF-1 and EF-2 were installed respectively at the north and south ends of the tunnel. When fire occurs EF-1 and EF-2 serve to extract smoke from the tunnel through the smoke dampers in the smoke control zones (S01–S15). Hot smoke ultimately would be exhausted out of the tunnel through the smoke shafts. Jet fans JF-1 and JF-2 were installed above the traffic for tunnel ventilation. Jet fans JF-1 and JF-2 each consisted of four fans but denoted as JF-1 and JF-2 for simplicity, as shown in Fig. 2.

It can be seen in Fig. 2 that each of the fifteen dampers corresponds to a smoke exhaust zone. Two fire locations were studied; one at the center and the other near the tunnel entrance. This study took advantage of the symmetry of the system in the computer model. Therefore computation cells were constructed for 300 m in length that containing the fire sites, as the problem is longitudinal in nature. For fire occurs at the center the computation cells span a length of 300 m in the central zones S07–S09. Similar for fire near the entrance computation cells span 300 m centered in in the zones S01–S03. In this study the longitudinal gradient of the tunnel zero therefore the use of a shorter model can be justified. The cross section dimensions of the tunnel space are 9.5 m × 4.75 m. The cross section dimensions of the exhaust duct are 8.0 m × 1.35 m as shown in Fig. 3.

3. Numerical simulations

3.1. FDS analysis

Fire Dynamics Simulator (FDS version 5.5.3, NIST, 2010) was based on large-eddy simulation. FDS solves for the distribution of temperature, velocity, pressure and other scalar items emitted from combustion processes. Post processing unit Smoke View (NIST, 2010) can be used to generate 2D distribution or 3D animation.

3.2. Grid resolution analysis

Numerical grid convergence was tested for grid size selection near the fire where maximum temperature gradient would occur. The symmetry of the computation domain settled for numerical grids spanning 160 m (L) × 9.5 m (W) × 4.75 m (H). The characteristic fire diameter D^* can be calculated using Eq. (1) (Baum and MaCaffery, 1989).

$$D^* = [\dot{Q}/(\rho_\infty \cdot C_p \cdot T_\infty \cdot \sqrt{g})]^{2/5} \quad (1)$$

The fire scenario assumed a heavy goods car fire releasing heat at the rate of 50 MW, adopted from the PIARC recommendation (PIARC, 1998). D^* was calculated to be 4.6 m from Eq. (1). Grid resolution near fire site was estimated to be 0.1 D^* or equal to 0.46 m. Four grid sizes of 0.6 m, 0.5 m, 0.45 m, and 0.25 m were tested. The results of grid size test are shown in Table 2.

In the grid analysis temperature detector points were located at 2 m

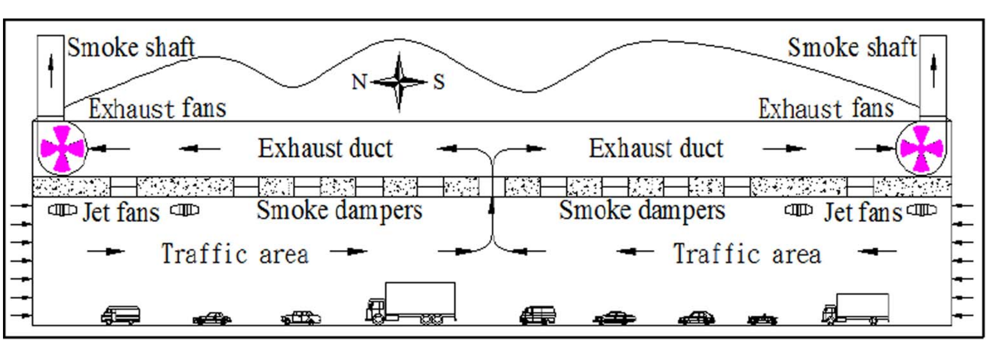

Fig. 1. Tunnel ventilation system.