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Theoretical predictions and field measurements for potential natural ventilation in urban vehicular tunnels with roof openings

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ABSTRACT

Naturally ventilated urban vehicular tunnels with multiple roof openings have emerged in China; thus, the ventilation strategy needs to be studied and validated. The safety standards for CO concentration depend on people's exposure time: 125 mg/m^3 for 5 min, 100 mg/m^3 for 15 min, and 35–44 mg/m^3 for 1 h. Airflow and contaminant equations were established and solved based on one-dimensional and steady state assumptions. Three naturally ventilated and two mechanically ventilated urban vehicular tunnels were investigated from 11/2013 to 1/2014 using TSI7575-X and KIMO-VT200 for continuous and single-point measurements during congested periods. The survey reveals that piston winds existed in each tunnel but the effect in mechanically ventilated tunnels was more apparent compared to that in naturally ventilated tunnels. Furthermore, all temperature as well as CO and CO_2 concentrations increased from inlets to outlets. The theory model was validated by comparing the analytical air velocity and CO concentration of the XIANMEN Tunnel to that of the field measurement. Further theoretical analyses indicate that under a constant traffic flow of 1700 veh/h.lane, the air velocities depend largely on the vehicle speed v_t and the opening area ratio R_f; moreover, the maximum CO concentrations increase with a decrease in v_t and an increase in tunnel length L but are minimally affected by R_f. At 20 km/h, drivers are exposed for different times based on the tunnel length, and they are always safe against CO exposure in tunnels up to 3000 m.

1. Introduction

With economic development in China, an increasing number of vehicles have appeared, and traffic jams have become a significant problem, especially in large cities. To relieve ground traffic pressure, there has been an increase in shallow urban vehicular tunnels built in recent years. Multiple roof openings have been designed at intervals along the tunnel's longitude and built with their top openings being parallel to the ground outside, such as the XIANMEN Tunnel, which has a buried length of 1410 m and 24 roof openings, as illustrated in Fig. 1. Vehicle exhausts or smoke from fires are expected to be discharged out of roof openings forced either by the piston or buoyancy effect; consequently, mechanical ventilators are not required and pure natural ventilation is used, thus construction costs and energy consumption are significantly reduced.

This type of ventilation strategy often conflicts with the current code [1], which requires that a one-way vehicular tunnel should be mechanically ventilated when the product of its length and traffic volume is greater than 2000 (km.cars/h). With increasing public concern for air quality and fire safety, the local administrative department and fire protection institution give significant attention to this type of tunnel. As observed in most related articles, pure natural ventilation has only been utilized with inlets and outlets to reduce contaminant concentration [2–4], or mechanical fans operate at interval [5,6]. For example, J. Modic [2,3] found out that natural ventilation can be acceptable in tunnels up to 3000 m under a traffic volume ≦ 750 cars/h.lane and a vehicle speed ≧ 30 km/h.

In January 2007, three full-scale firing experiments were conducted in the XIANMEN Tunnel before its operation [7]. The results indicated that a significant amount of smoke was exhausted out of roof openings, especially near the fire source, the high temperature was lowered, and experimenters inside did not need to evacuate, even though visibility was slightly low. After that, air entrainment mode, effect of vertical shaft arrangement, characteristics of smoke extraction and diesel oil pool fire were further studied by other

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Fig. 1. Interior scene of tunnel XIANMEN at Nanjing in China.

researchers [8–11], but fire safety on different seasons is leaved to be investigated.

Under normal traffic conditions, pollutants primarily arise from vehicle exhausts, such as CO, NO_x and particulates. It is believed that [12] CO is an indicator of air quality in the environment as a result of petrol engine emissions while NO_x and particulates can be used to indicate diesel engine emissions. The acceptable limit of CO concentration depends on people's exposure time. Because pedestrians are not allowed to enter vehicular tunnels, the short-term exposure of drivers is the point of interest. The Hong Kong Environment Protection Department (EPD) recommends a safe CO level of 100 ppm (125 mg/m^3, CO density assumed to be 1.25 kg/m^3) for 5 min [13]. The World Health Organization (WHO) allows 100 mg/m^3 for 15 min and 35 mg/m^3 for 1 h [14]. The United States National Ambient Air Quality Standard (NAAQS) allows 35 ppm (44 mg/m^3) for 1 h [15]. A traffic/piston effect is highly complex, three-dimensional, unsteady and has a significant importance in forming airflows [16]. It exists in two-way traffic but its wind velocity is only a small percent of that in a one-way traffic tunnel caused by the opposing traffic [17]. The slope is another factor in airflows, especially during firing [18]. Other studies [19–23] revealed that roof openings can play a role effectively in strengthening natural ventilation.

Whether natural ventilation based on multiple roof openings can provide good air quality or not in urban vehicular tunnels is worth being investigated. Providing insight into the flow phenomena under normal traffic has great significance and is the primary goal of the current study.

2. Theoretical method

2.1. Traffic wind pressure

To simplify its theory model, air velocity is considered to be uniform at any roof opening or tunnel cross-section; thus, a one-dimensional assumption can be used. Furthermore, the temperature difference between the inside and the outside of the tunnel is neglected and airflows are caused only by traffic and ambient wind. Slope effect is neglected because the tunnels studied in this report are shallow with a typical depth of 6 m. Roof openings are numbered as 1, 2, … ., m in turn from inlet to outlet, and the tunnel is divided into m+1 control volumes by m roof openings, as indicated in Fig. 2. The air velocity of each control volume (CV) is unique but differs due to the inflows or outflows of the roof openings.

For a one-way traffic tunnel, the CV$_i$'s traffic wind pressure ΔP_{ti} (Pa) can be identified as follows:

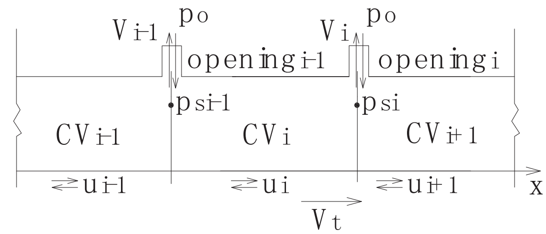

Fig. 2. Schematic plan of roof openings and control volumes for a naturally ventilated tunnel.

$$\Delta p_{ti} = n_i \cdot C_D \cdot \left(\frac{A_p}{A_r}\right) \cdot \frac{\rho}{2} \cdot \left(\frac{v_t}{3.6} - u_i\right) \cdot \left|\frac{v_t}{3.6} - u_i\right| \tag{1}$$

where v_t is the vehicle speed (km/h); u_i is the CV$_i$'s mean air velocity (m/s); C_D is the averaged drag coefficient of vehicles [24]; A_p is the vehicle's windward area (m^2); A_r is the tunnel's net cross-sectional area (m^2); ρ is the air density at 1.2 kg/m^3; and n_i is the vehicle number of the CV$_i$. It should be noted that u_i is considered to be positive when the airflow is in the same direction as the vehicle movement; otherwise, it is considered negative. Furthermore, the absolute value of (v_t/3.6 $-u_i$) is assumed to maintain the same sign between ΔP_{ti} and (v_t/3.6$-u_i$).

2.2. Air velocity

The following equation can be obtained based on energy conservation for the entire tunnel:

$$\sum_{i=1}^{m} (\Delta p_{ti} - \Delta p_{zi} - \Delta p_{mi}) = 0 \tag{2}$$

where Δp_{zi} (Pa) and Δp_{mi} (Pa) are the frictional and local energy losses of the CV$_i$'s airflow, respectively, as follows:

$$\begin{aligned} \Delta p_{zi} &= \lambda_i \frac{l_i}{d_e} \cdot \frac{\rho}{2} \cdot \left(u_i \cdot |u_i| + v_a^2\right) \\ \Delta p_{mi} &= \zeta_i \cdot \frac{\rho}{2} \cdot \left(u_i \cdot |u_i| + v_a^2\right) \end{aligned} \tag{3}$$

where d_e (m) is the equivalent diameter of the tunnel cross-sectional area, which is $(4A_r/\pi)^{1/2}$; λ_i and ζ_i are the frictional and local loss coefficients, respectively; l_i (m) is the length of the CV$_i$; and v_a (m/s) is the ambient wind formed in the tunnel, which varies frequently and is typically 2–3 m/s contributing to the energy losses [1]. The absolute value of u_i is used to consider the possibility of the signs of u_i and v_a being identical.

p_{si} (Pa) is defined as a point pressure on the bottom of the roof opening i, which is also the pressure on the front side of the CV$_i$, as indicated as in Fig. 2 p_o (Pa) is the ambient air pressure and assumed to be 0. The pressure difference Δp_{si} (Pa) between p_{si} and p_o should be equal to the superposition of Δp_t, Δp_z and Δp_m from the tunnel entrance to the front side of the CV$_i$, and the airflow energy losses in the roof opening i as follows:

$$\begin{aligned} \Delta p_{si} &= \sum_{k=1}^{i} (\Delta p_{tk} - \Delta p_{zk} - \Delta p_{mk}) \\ &= -\frac{\rho}{2} \cdot \left(\lambda_{si} \frac{h_{si}}{d_{si}} + \zeta_{si}\right) \cdot v_i \cdot |v_i| \end{aligned} \tag{4}$$

where λ_{si}, ζ_{si}, h_{si}, and d_{si} are the friction and local loss coefficients, height (m), and equivalent diameter (m) of opening i, respectively; and v_i (m/s) is the mean air velocity of the opening i and is