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Prediction of pollutant concentration and ventilation control in urban bifurcate tunnel, China

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A R T I C L E I N F O

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A B S T R A C T

The changes in the complex structural features and traffic characteristics of urban bifurcate tunnel have led to variation in the emission of pollutants and distribution of their concentration, and this presents new challenges to the operation of ventilation systems. A one-dimensional steady-state pollutant mass transfer model was developed to quantify the influence of the confluence and distributary ramps and determine the ventilation control. This model was based on the mass conservation theory, a scale model experiment and measurements, and was effectively verified by four-years field-measured data from three urban tunnels in Shanghai and Changsha, China. According to the calculation results of the model, the distribution of the CO pollutant concentration and the ventilation system control of the main tunnel in an urban bifurcate tunnel can be quantitatively evaluated under the corresponding traffic flow conditions. The results show that the combined effect of the confluence ramp on the increase pollutant concentration in the downstream segment of the main tunnel is limited, However, the distributary ramp has a significant effect on the decrease of pollutant concentration downstream in the main tunnel.

1. Introduction

Compared with the single-point access of a straight tunnel, the structural feature and traffic characteristics are more complex in an urban bifurcated tunnel with multiple entrances and exits. This leads to the fact that pollutant emissions and concentration distribution characteristics do not increase linearly along the vehicle driving direction; thus, the corresponding ventilation control system is significantly different from that in a straight tunnel.

Many researchers are now applying advanced technologies for analysis of pollutant distribution and evaluation of ventilation efficiency in tunnels. Computer simulations are carried out to study airflow patterns and pollution levels generated by vehicle emissions in the westbound Melbourne City Link tunnel under severely congested traffic jam conditions (Bari and Naser, 2010). By studying the air flow in curved tunnels, it has become clear that the movement of vehicles and the traffic flow play an important role for the diffusion of pollutants (Wang et al.,2011). The turbulent behavior of the airflow around different-shaped vehicles and its impact on the pollutant dispersion have been studied through three-dimensional computational fluid dynamics (CFD) (Bhautmage and Gokhale, 2016). In recent years, the research on pollutant concentration distribution in bifurcated tunnel has been initiated. The flow, aerodynamics and pollutant diffusion models established in steady-state flow tunnel sections, according to the ramp metering, optimal time of the main entrance traffic, and use of non-linear programming technology, have been proposed to guide the traffic control (Tan and Gao, 2015). Perkins et al. (2013) measured the concentrations of fine particulate matter in the tunnels of the Central Avenue with multiple ramps and calculated the fine particle emission factors of the hybrid vehicle. The influencing factors of pollutant concentration between the entrances and exits of the Baziling ridge HuRong tunnel expressways are analyzed by a model experiment (Tan et al., 2015). Deng et al. (2015) measured CO and NO_X concentrations in the Shanghai East Yan'an Road tunnel and Changsha Yingpan Road tunnel and the average emission factors were calculated. There are relatively few studies on experimental models of pollutant mass transfer in tunnels. The concentration decay method by CO_2 transmitters has been experimentally validated in the case of cross-ventilation (Cui et al., 2015). A tail quasi-three-dimensional mathematical model was developed for tailrace tunnels to simulate heat and moisture transfer based on airflow analysis (Yu et al., 2015).

The main objective of this study is to develop a special mass transfer

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Nomenclature

A_r	the cross-sectional area, m^2
A_{ri}	the tunnel cross-sectional area of section i, $i = 1–3$, m^2
C_i	the pollutant concentration of section i, $i = 1–3$, mg/m^3
C_{in}	the tunnel inlet pollutant concentration, mg/m^3
$C(x)$	the pollutant concentration at x location, mg/m^3
$C_{1\text{-}3}$	CO_2 concentration decay rate of section 1–3, that is distributary ramp ratio, %
$Cs\ (x)$	the average mass concentration at x in the road surface, mg/m^3
C_2/C_1	CO_2 concentration decay rate of section 1–2 in main tunnel, %
c_p	the constant pressure heat capacity, J/(kg·K)
$EF(x)$	the average pollutant emission factors, g/(km·veh)
h	the convective mass transfer coefficient, m/s
h_m	the convective mass transfer coefficient, m/s
$K(x)$	that is K, the emission coefficient of the vehicle pollutants, m/s
L	the tunnel length, m
N	the traffic flow, veh/h
Nu_f	the Nusselt number of the air flow
P_i	the air pressure at section i, Pa
P_r	the Prandtl number of the air flow
Q_{co}	the required ventilation dilution of CO, m^3/s
Re	the Reynolds number of the air flow,
x	the vehicle traveling direction from inlet, m
x_i	at section i of the vehicle traveling direction from inlet, m
x_j	at section j of the vehicle traveling direction from inlet, m
y	the tunnel horizontal direction, m
z	the tunnel height direction, m
W	the width of the tunnel, m
S	the total pollutants source, $mg/m^3{\cdot}s$
S_v	the vehicle emission pollutants, $mg/m^2{\cdot}s$
S_b	the ramp source term including the confluence ramp, $mg/m^2{\cdot}s$
V_t	the vehicle speed, m/s
V_r	the average air velocity of the tunnel, m/s
V_{ri}	the air velocity of section i, $i = 1–3$, m/s
V_{rj}	the air velocity of the distributary ramp section j, m/s
V_{rx}	that is V_r, the air velocity of direction x, m/s
V_{ry}	the air velocity of direction y, m/s
V_{rz}	the air velocity of direction z, m/s
W	the width of the tunnel, m
T	the time of vehicles in the tunnel, s
P	the density of the air
λ	the thermal conductivity of the air

model for bifurcate tunnels with multiple entrances and exits and to evaluate the ventilation efficiency with the confluence and distributary ramps. This model was based on the mass conservation theory with a scale model experiment and was effectively verified by four-years of field-measured data from three urban tunnels in Shanghai and Changsha, China. The result can provide a quantitative assessment method to support the concentration ventilation control and obtain an energy saving operation in urban bifurcate tunnels.

The structure of the paper is as follows: measurement and research on the actual operating tunnel are provided in Section 2.1. The 1:8 scale model experiment with the Changsha tunnel is discussed in Section 2.2. The model of pollutant mass conservation is developed and quantitative evaluation of pollutant concentration reduction in the distributary ramp is discussed in Section 2.3. Section 3 provides an application of the method and discussion on the results before drawing a set of clear and concise conclusions in Section 4.

2. Materials and methods

2.1. Measurement and research on actual operating tunnel

The confluence and distributary ramps and traffic characteristic are important factors influencing the pollutant mass transfer in urban bifurcate tunnels. Our project team conducted a study in Shanghai, Changsha and other cities from October 2011 to July 2015 (Li et al., 2015, Deng et al., 2015). The traffic force and pollutants concentration were measured in the peak hours. The traffic force in the tunnel, mainly composed of moving vehicles, directly affects the pollutant diffusion characteristics, and it can partially replace the role of the tunnel fan. At the same time, we investigated the vehicle emission standards and related pollutant control standards in China. This section focuses on three aspects: (1) the difference in traffic characteristics between the straight and bifurcation tunnels; (2) the effect of ramps on pollutant concentration distribution, and (3) the effect of vehicle emissions characteristics on pollutant mass transfer. The results were combined with the field measurements from three tunnels, including the Shanghai Xiangyin Road tunnel (straight tunnel), Shanghai Yan'an East Road tunnel (straight tunnel), and Changsha Yingpan Road tunnel (bifurcate tunnel).

The Changsha tunnel consists of two unidirectional bores. The eastbound and westbound bores are 2510 m and 2506 m long respectively and both contain two entrances and two exits. The first 620 m of this eastbound bore has a decline of −5.92%, followed by 1025 m of a flat segment, with a slight declining slope of −0.35%, and the rest of the tunnel has inclining slopes of +3.85%, +0.35% and +5.85% for 645 m, 120 m, and 290 m, respectively.

The Shanghai Xiang Yin Road tunnel is also located in the city center area, and its tunnel structure is relatively simple. The speed limit in the tunnel is 80 km/h, total length is 2.6 km, and tunnel cross-sectional area is 43.4 m^2.

In the measurement process, parameters such as traffic flow, vehicle speed, air velocity, and CO concentration level are discussed. The traffic is mainly composed of light-duty vehicles (LDV), and NO has the same mass transfer characteristic as CO. Relevant measurement conditions and measurement methods are detailed in the reference literature (Li et al., 2015).

2.1.1. Traffic characteristics

The Shanghai tunnel measured data shows that the average vehicle speed in the tunnel is relatively low owing to the traffic flow, maximum vehicle speed limit, and other factors during the morning and evening peak periods. The proportion of LDV in the tunnel is as high as 91.7%, owing to limitation by vehicle type. The average traffic flow per lane is about 1400 veh/h, and the corresponding vehicle speed is about 41 km/h. The Changsha tunnel survey results show that the proportion of LDV is 97.3%, owing to restrictions on heavy goods vehicles (HGV), and the average hourly traffic flow per lane is about 1394 veh/h. The maximum traffic flow in each lane after the confluence ramp is about 1560 veh/h, and the corresponding vehicle speed is about 33.6 km/h.

Fig. 1 shows the relationship between air velocity and vehicle speed in the Changsha main tunnel after the confluence ramp, along with a comparison between the Changsha bifurcate tunnel and the Shanghai straight tunnel. The traffic flow and the average vehicle speed in each segment of the bifurcate tunnel are dynamic; therefore, the air velocity changes with these factors. Fig. 1a shows that the air velocity in the Changsha main tunnel increases with the increase in vehicle speed, but it is lower than that of the Shanghai tunnel, which is due to the increase in flow resistance of the complex structure of the Changsha tunnel. In