Influence of Ventilation And Decentralized Purification on Pollutant Control in Urban Highway Tunnels without Exhaust Shaft

Dapeng He¹, Zhen Yue¹, Yindong Zhang², Fei Xie³, Moning Chang³, Qiwei Dong³*, Yemin Liu¹, Xiaoliang Shao², and Xianting Li⁵

¹Beijing Gonglian Highway Connecting Line Co., Ltd., Beijing 100161, China
²Beijing Capital Highway Development Group Co., Ltd., Beijing 100073, China
³Beijing General Municipal Engineering Design & Research Institute Co., Ltd., Beijing 100082, China
⁴School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China
⁵Department of Building Science, School of Architecture, Tsinghua University, Beijing 100084, China

Abstract. Limited by multiple factors, such as land use planning, landscape coordination and environmental standards, the ventilation conditions of the urban highway tunnels are insufficient, and therefore the joint control of ventilation and purification becomes a necessary solution. In this study, the effect of number, location of decentralized purification equipment, and the tunnel ventilation rate on pollution in the tunnel are studied using one-dimensional calculation. The results show that the arrangement of purification equipment can reduce the design ventilation rate to a certain extent. When purification equipment is arranged, the maximum NO₂ concentration can be reduced by up to 30.9%, and the average NO₂ concentration can be reduced by up to 18.2% compared with that without purification. The purification equipment arranged in the rear section of the tunnel is conducive to reducing the concentration of pollutants at the exit, while the arrangement in the middle section of the tunnel is conducive to reducing the average concentration of pollutants in the tunnel.

1 Introduction

With the development of economy, the density of road network is increasing, and the problem of urban traffic congestion is becoming more and more serious. In order to alleviate the traffic pressure, the number of urban tunnels is increasing. The particulate matter, CO, NO₂ and other pollutants emitted by vehicles in urban tunnels have an impact on driving safety and the residential environment around the tunnel [1]. Therefore, tunnel air pollutants need to be treated [2]. The use of ventilation to dilute pollutants is the most common means of treatment. However, in most cases, it is difficult to control tunnel pollution only by ventilation, and the tunnel air purification is a favorable alternative measure.

At present, the research for tunnel ventilation focus on three methods: transverse, semi-transverse and longitudinal ventilation [3]. Regarding tunnel air purification, the main methods include bypass type, ceiling type and shaft type [4]. Unfortunately, there are few studies on the combined control of pollutant concentration by ventilation and purification. Due to the realistic flexibility of small size purification devices, the performance of multiple decentralized purification devices when applied in the tunnels is worth studying. In this study, the influence of ventilation and decentralized purification on the pollutant control of urban highway tunnel without exhaust shaft is analyzed. The number, location of purification equipment, and the tunnel ventilation rate are studied by one-dimensional calculation method.

2 Case design

Fig. 1. Layout of purification equipment in tunnel

Ventilation restriction in the tunnel is particularly prominent in the super long tunnel. Therefore, in this study a 10 km long super long tunnel is selected as a representative. The NO₂ is selected as the target pollutant.
A total of 18 cases are set up according to the combination of number, layout of purification devices and tunnel ventilation rate, as listed in Table 1. The tunnel is evenly divided into three sections, the starting (Zone 1), middle (Zone 2) and rear section (Zone 3), as shown in Fig. 1. The purification air rate of a single unit is 30 m$^3$/s, and the purification efficiency is 80%. Case 1 is set as the reference without purification equipment. Cases 2-5 analyze the NO$_2$ concentration at different purification positions. Cases 6-9 analyze the NO$_2$ concentration under different number of purification equipment. Cases 10-18 analyze the NO$_2$ concentration under reduced ventilation air rate.

### Table 1. Setup of case parameters

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<th>Case number</th>
<th>Number of purification equipment</th>
<th>Layout of purification equipment</th>
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<th>Ventilation rate (m$^3$/s)</th>
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</table>

### 3 Calculation method of ventilation and purification

In the ventilation and purification calculation, it is very important to determine the pollutant source intensity in the tunnel. According to the method in Reference [5], the NO$_2$ emission in the tunnel can be determined.

The calculation method in this study mainly considers the concentration change along the length direction and carries out one-dimensional calculation. Starting from the inlet, the pollutant concentration at each position is calculated by using the pollutant mass conservation relationship at an interval of 1 m. When the purification device exists in the calculated interval, the calculation is based on the mass conservation relationship between the two flow paths of purification air rate and tunnel residual air rate, ignoring the actual length of the purification device, which is considered to work only in the 1 m range. The expression for the concentration at position $x$ from the tunnel inlet can be expressed as

$$ C_x = \left[ C_{x-1} + \frac{q_x}{Q} \right] \left( Q - Q_m \eta \right) / Q $$

(1)

where $C_x$ is the NO$_2$ concentration at position $x$ m along the length of the tunnel, mg/m$^3$, $x = 1, 2, \ldots, L$; $C_{x-1}$ is the NO$_2$ concentration at position $x-1$ m along the length of the tunnel, mg/m$^3$, $C_0 = 0$; $q_x$ is the emission per unit length of the tunnel at position $x$, mg/(m $\cdot$ s); $Q$ is tunnel ventilation rate, m$^3$/s; $Q_m$ is the purified air rate of a single purification equipment, m$^3$/s, when $Q_m = 0$, it means that no purification equipment is arranged at position $x$; $\eta$ is the purification efficiency of a single purification equipment, %.

The average concentration $C_{ave}$ in the tunnel is

$$ C_{ave} = \frac{\sum_{i=1}^{L} C_x}{L} $$

(2)

where $L$ is the tunnel length, m.

### 4 Results and discussion

The NO$_2$ concentration at different purification equipment locations are shown in Fig. 2 (6 sets). Without purification (Case 1), the maximum concentration of NO$_2$ in the tunnel (tunnel exit) is 0.323 cm$^3$/m$^3$, and the average concentration of NO$_2$ in the tunnel is 0.144 cm$^3$/m$^3$. When the purification equipment is arranged in the starting section of the tunnel (Case 2), the removal effect of pollutant concentration in the whole tunnel is poor. Compared with that without purification, the NO$_2$ concentration at the exit is only reduced by 2.7% and the average concentration is reduced by 4.8%. When the
puriﬁcation equipment is arranged in the middle and rear sections (Cases 3 and 4), the reduction rate of NO₂ concentration in the tunnel is signiﬁcantly higher than that in the starting section. The NO₂ concentration at the portal is reduced by 9.1 % and 17.1 % respectively, and the average concentration is reduced by 10.0 % and 6.1 % respectively. This indicates that the arrangement of puriﬁcation equipment in the downstream section is more conducive to reducing the concentration of pollutants at the exit, while the arrangement of puriﬁcation equipment in the middle section is more conducive to reducing the average concentration of pollutants in the tunnel.

Fig. 2. NO₂ concentration at different puriﬁcation equipment positions (6 sets)

The NO₂ concentration at different puriﬁcation equipment locations when the number of puriﬁcation equipment increases from 6 to 12 are shown in Fig. 3. Compared with Case 3, the concentration reduction rate of NO₂ at the exit increases from 9.1 % to 16.6 % and the average concentration reduction rate increases from 10.0 % to 18.2 % (Case 7). Under the arrangement of puriﬁcation equipment in the rear section, the NO₂ concentration reduction rate at the exit increases from 17.1 % to 30.9 %, and the average concentration reduction rate increases from 6.1 % to 11.3 % (Case 8). Further increasing the number of puriﬁcation equipment will further reduce the maximum concentration and average concentration of NO₂ in the tunnel, but it will also increase the investment cost.

Fig. 3. NO₂ concentration at different puriﬁcation equipment positions (12 sets)

The NO₂ concentrations for each puriﬁcation layout when ventilation rate is reduced are shown in Fig. 4 and Fig. 5. When the ventilation rate is reduced by 20 %, compared with Case 1 without puriﬁcation, the NO₂ concentration at the exit increases by 20.8 % and the average concentration increases by 17.5 % (Case 11). When the puriﬁcation equipment is arranged in the middle section (Case 12), the concentration increase at the exit is 11.0 % and the average concentration increase is 9.7 %. In addition, when the air rate is reduced, increasing the number of puriﬁcation equipment can also reduce the pollutant concentration to a certain extent (Fig. 5). When the number of puriﬁcation equipment increases from 6 to 12, the middle section layout and the uniform layout of the whole tunnel (Cases 16 and 18) can achieve the same tunnel outlet guarantee effect as that in Case 1 without puriﬁcation. When the rear section is arranged (Case 17), the concentration at the tunnel exit is lower than that in Case 1 without puriﬁcation. This indicates that the ventilation rate can be reduced and the puriﬁcation equipment can be increased to achieve the same puriﬁcation effect.

Fig. 4. NO₂ concentration at different puriﬁcation equipment positions when ventilation rate is reduced (6 sets)

Fig. 5. NO₂ concentration at different puriﬁcation equipment positions when ventilation rate is reduced (12 sets)
5 Conclusion

The effects of number, location of purification equipment, and the tunnel ventilation rate on the NO₂ concentration are studied by one-dimensional calculation method. The main conclusions are as follows:

(1) The arrangement of purification equipment can reduce the design ventilation to a certain extent.

(2) Under the same ventilation rate, when the purification equipment is arranged, the maximum NO₂ concentration can be reduced by up to 30.9%, and the average NO₂ concentration can be reduced by up to 18.2% compared with that without purification.

(3) The arrangement of purification equipment in the rear section of the tunnel is more conducive to reducing the concentration of pollutants at the tunnel exit, while the arrangement of purification equipment in the middle section of the tunnel is more conducive to reducing the average concentration of pollutants in the tunnel.

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References


