Research on Pollution Dispersion of CO and NOx Based on Inverse Problem Method with Source Item in Urban Multi-ramps Tunnel

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Abstract
Compared with the straight tunnel, pollutants emission, migration and accumulation in the main tunnel is affected by the complex tunnel structures, and ultimately the pollutants concentration distribution in the entire tunnel is complicated. Results in a research gap on multi-ramps urban tunnel ventilation engineering design. The aim of this study was to show the dynamic diffusion characteristics influenced by ramps. The pollutant source item accumulated values from vehicle emissions and multi-ramps pollutants were obtained with mass transfer equation through the inverse problem method, which based on the measurement results. Results show that the average back calculated CO and NOx source accumulated value was 0.37mg/m’s and 0.044mg/m’s, respectively. In congestion conditions of workday morning peak hours, pollutants into main tunnel from confluence ramp made a slight increase of 4.8% total pollutants source, and flowed into distributary ramp from main tunnel was 5.2%. The result can provide a quantitative assessment method to support pollutant concentration control and contribution of the required air volume by traffic flow in multi-ramps urban tunnel.

Key words: Multi-ramps urban tunnel; CO and NOx pollutant; inverse problem; mass transfer; source item accumulated values

1. INTRODUCTION
The previous studies were mostly focused on vehicle emissions and pollutant diffusion mechanism in a straight tunnel for the tunnel ventilation engineering. The applicable design standards and methods are also for straight tunnel. However, vehicle emissions and diffusion characteristics in the main urban multi-ramps tunnel are no longer single-valued linear increasing like straight tunnel, due to the impacts of the vehicles driving out of the diversion ramp and coming from the confluence ramp constantly. The traffic characteristics, traffic force distribution and air flow are more complicated in complex tunnel structures. Thus these factors affect pollutants emission, migration and accumulation in the main tunnel, and ultimately affect the pollutants concentration distribution of the entire tunnel. Measurement results show that when the vehicle flow speed is 30 km/h, the air flow that came from the confluence ramp is 5.6 times the required air volume to control the pollutant concentrations. Similarly, the distributary ramp can split out pollutants from the main tunnel and ventilation contribution at the distributary ramp for the main tunnel is 16.7%. The bifurcation tunnel namely has a constructive role to reduce pollutant concentration levels in the main tunnel. The pollutant diffusion and ventilation system in the multi-ramps urban tunnel are more complex. Many problems will be raised to the multi-ramps urban tunnel if we simply copy with standards and parameters for the normal road tunnel or foreign standards.

The research results of pollutant diffusion have mainly focused on the effect of diffusion due to traffic force in straight tunnel. The vertical distribution of pollutants concentration in Japanese KAN-ETSU highway tunnel (length 10.885km) is studied which used one-dimensional pollutant diffusion equation and numerical solution method (Ohashi et al.,1982). Bari S and Naser J have studied the concentration levels of pollutants under the effect of jet fans through simulation methods (Bari S, Naser J, 2010). Lee, c. et al. (2006), based on GM and Crank-Nicholson model, established FCM model, which can be analyzed to calculate the pollutants turbulent diffusion under ventilation and traffic force. Wang et al. used dynamic mesh method to investigate the piston effect by a moving vehicle and the effective drag coefficient in a series of tunnels with various radii for a large size vehicle (Wang, 2011, 2014). Domestic research on the pollutants diffusion is still in the stage of exploration. Deng Shun-xi et al. (2004) created the one dimensional equation of tunnel air quality which focused on pollutant diffusion concentration distribution with different ventilation modes. But the solution model was not considered the turbulent diffusion effect along vehicle travel distribution. Hu Yufeng et al. (2003) studied the problem of air flow and pollutant diffusion in the tunnel and established an air total motion equations in the tunnel with the finite difference numerical method based on the simplified tunnel ventilation shaft. Fine particulate matter concentrations in American Central Avenue tunnel with a plurality of ramp has been
measured and fine particulate matter emission factor under the mixed vehicle fleet has been calculated (Jessica et al., 2013). But this research didn’t analyze the influence on fine particle concentration distribution because of confluent, shunt ramp. Fu Qiongge et al. (2014) built a multi-ramp tunnel model test-bed which is 1:10, analysed the air flow law in the main tunnel and ramp under the normal operation and fire conditions and the different ventilation schemes have the impact on airflow organization form by experiment.

In this paper, the pollutant source item accumulated values from vehicle emissions and multi-ramps pollutants were obtained with mass transfer equation through the inverse problem method, which based on the measurement results. We conducted tunnel measurements from May 22 to June 2, 2013 in Chongsha Yingpan Road Tunnel, which can represent Chinese conditions. The aim of these measurements was to collect information on traffic characteristics, air velocity and pollutant concentrations. The research results provide a theoretical basis for the required air volumes and tunnel pollutants control theory in the urban tunnel construction with multi-ramps in China.

2. METHODOLOGY

2.1 The analysis principle

For multi-ramps tunnel, the pollutant convective mass transfer process is included the vehicle emission source, pollutant origins from the confluence ramp and pollutant converges to the diversion ramp. The forward problem method for mass transfer equation couldn’t solve the impact of pollutant dispersion in multi-ramps tunnel. But if traffic flow, vehicle type ratio, vehicle speed and pollutant concentrations are known through the tunnel measurement, the total pollutant source item can be calculated by the inverse problem method (Atmadja, 2001; Michalak, 2004; Shi, 2014). Then the ramp pollutant origins are got from the total source item subtracting vehicle emissions. The inverse problem method is suitable for the parameters dynamically changing with vehicle traffic conditions and the tunnel structure. This method has a higher accuracy and its main idea is follows as: according to the initial values of the source term in the mass transfer process given by the measured results, the initial concentration distribution is solved combined with the boundary conditions. Then the measured pollutant concentrations in each point are brought into the equations using adjoint assimilation method to calculate the objective function and correct the source term to get the relative real pollutant emission accumulated values.

2.2 Inverse problem model

The pollutant source term S includes emissions from vehicles in the tunnel and the amount of pollutants into and out the main tunnel through ramps. For convective diffusion equation, the inverse problem method was used to calculate S under corresponding conditions. The pollutant diffusion problem in tunnel can be seen as a one-dimensional, steady-state process. This is shown in Equ.1.

\[
\frac{\partial C}{\partial t} = K \frac{\partial^2 C}{\partial x^2} + Q_{EF} \pm q_{trans}
\]

Where:

\[
S = Q_{EF} \pm q_{trans}
\]
\[ Q_{\text{EF}} = \frac{1}{3600A_r} \sum_{i=1}^{n} \lambda_{ij}(v) \cdot EF \cdot N \] (3)

\[ EF = \frac{A_r \cdot u}{N} \cdot \frac{\partial c_i}{\partial x} \approx \frac{A_r \cdot u}{N} \cdot \frac{c_i - c_j}{x_i - x_j} \] (4)

\[ q_{\text{trans}} = (u_m C_{\text{in}} - u_{\text{out}} C_{\text{out}})/A_r \] (5)

\[ u_{\text{in}} = \frac{V_{\text{rm}} A_m}{L_m} \] (6)

\[ u_{\text{out}} = \frac{V_{\text{out}} A_{\text{out}}}{L_{\text{out}}} \] (7)

According to the methodology of pollutants mass-conservation in the tunnel proposed by Tal Y. Chang (Tal Y. and Sara, 1990), we can determine the average vehicle pollutants emission factor and build the following equation. In Eq.4, The pollutant emissions from vehicles was not only influenced by its own emission characteristics, but also depended on the local implementation of motor vehicle emission standards. Therefore, it is essential for us to amend the pollution emissions Q in Eq.3. This is shown in Eq.8.

\[ Q_{\text{EF}} = q(v,i) \cdot f_h \cdot f_i \cdot f_c \] (8)

CO emission \( Q_{CO} \) is shown in Eq.9 and mainly depended on the characteristics and influencing factors of the road tunnel.

\[ Q_{CO} = \frac{1}{3.6 \times 10^6} \cdot q_{CO} \cdot f_a \cdot f_d \cdot f_h \cdot f_{\text{in}} \cdot L \cdot \sum_{m=1}^{n} (N_m \cdot f_m) \] (9)

In summary, when traffic flow, vehicle type ratio, vehicle speed and pollutant concentrations are known through the tunnel measurement, the total pollutant source item can be calculated by the inverse problem method according Eq.1 to Eq.9. Then the ramp pollutant origins are got from the total source item subtracting vehicle emissions.

### 2.3 Solution of inverse problem

The finite difference method was used to discretize Eq.1, the paper gives out the following differential equations.

\[ \frac{u}{\Delta x} C_i - C_{i+1} - K \left( \frac{C_{i+1} - 2C_i + C_{i-1}}{\Delta x^2} \right) - S_i = 0 \] (10)

An objective function \( J \) should be defined to calculate \( S \) if we use the method for solving the inverse problem. \( J \) can be expressed as Eq.11.

\[ J = \frac{1}{2} \sum_{i=1}^{N-1} (C_i - F_i)^2 \] (11)

Furthermore, Lagrange equation 12 was established, with Eq.11 as target function and Eq.10 as constraint condition.

\[ L = J + \lambda^a \left( \frac{u}{\Delta x} C_i - C_{i+1} - K \left( \frac{C_{i+1} - 2C_i + C_{i-1}}{\Delta x^2} \right) - S_i \right) \] (12)

\[ \frac{\partial L}{\partial C_i} = 0 \]

With the condition of \( \lambda_{i} \), the adjoint equation of Eq.10 can be built. This is shown in Eq.13.

\[ (C_i - C_{i+1}) + \frac{u}{\Delta x} (\lambda_i - \lambda_{i+1}) - \frac{K}{\Delta x^2} (\lambda_{i+1} - 2\lambda_i + \lambda_{i-1}) = 0 \] (13)

After establishing Eq.10 and 13, \( S \) in Eq.1 can be calculated in inverse method. Figure 2 is the flow chart of solution for inverse problem. Taken together, the procedure of correct \( S \) in Convection-diffusion Equation 1 with adjoint assimilation method can be summarized as such 6 steps:
Step 1: Given the initial assumption value $S_0$ of $S$.
Step 2: Solve Eq.10 with boundary conditions and initial assumption value $S_0$ to obtain the distribution value of pollutant concentration $C_i$.
Step 3: On the condition of $C_i$, solve the adjoint equation 13, obtain the value of $\lambda_i$.
Step 4: Calculate the gradient of objective function $J$ to source term $S_i \left( \nabla_S J \right)_i$ with the value of $\lambda_i$, the formula is shown in Eq.14.

\[
\left( \nabla_S J \right)_i = -\lambda_i
\]  

(14)
Step 5: Based on Eq.15, correct the initial assumption value $S_0$, where $\alpha$ is the correction step (usually use $1e^{-8}$).

\[
S_{0(i)} = S_{0(i)} - \alpha \left( \nabla_S J \right)_i
\]  

(15)
Step 6: Plug $C_i$ in step 2 into Eq.11, after several times of iterative computation, the calculated distribution value of pollutant concentration would get close to the measured value until $J \leq \varepsilon$; Otherwise plug the corrected value $S_0$ into Eq.2 and iterates again. Where $\varepsilon$ in the cycle program is the terminate parameter given in advance.

**Figure 2.** The flow chart for inverse problem

3. CALCULATE CASE ANALYSIS

3.1 Tunnel measurements
Changsha Yingpan Road tunnel, shown schematically in Fig. 3, is a typical urban cross-river tunnel located in a residential area of Changsha which has a quite complex structure of underground interchange and ramps. It consists of two separate parallel tunnels, the westbound bore towards the residential area and the eastbound bore towards the commercial area in city centre, with two driving lanes in each. Both of the westbound bore and the eastbound bore contain two entrances and two exits. Entrance A and C are at west bank, exit B and D are at east bank. The tunnel is 2.7 km in length, the first 620 m of eastbound bore has a down-slope of 5.92%, followed by 1025 m of flat surface 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 in that order. The vehicle speed limit of main tunnel and ramps is 50 km/h and 40 km/h, respectively. The sectional area of main tunnel and ramps are 54.14 m² and 45.82 m², respectively.

Measurements in Changsha Yingpan Road tunnel were performed in the eastbound bore in the morning rush hour (7:00-8:30) and in the westbound bore in the evening rush hour (17:30-19:00) between 25th of May and 3rd of June, 2013. Twenty measuring points were set along the eastbound bore and westbound bore to monitor CO and NOX concentration and air velocity on the right-hand side of the tunnel at a height of approximate 2 m. CO concentrations were measured simultaneously with NO concentrations by high-resolution CO (GXHCO-3051, 0-100 ppm, ±2%) and NO (GXHNO-3051, 0-25 ppm, ±2%) analyzers, respectively. They apply the non-dispersive infrared and chemiluminescence methodologies and can record continuously with 30 sec time resolution. Vehicle speeds were measured with traffic radar (VELOCITY 10-1921). Air velocity was monitored by a hand-held anemometer (Testo 435-2). All of the analyzers were calibrated before the measurement. Traffic volume and vehicle type were measured by manual counts every 10 minutes during the measurement periods at the entrance and exit of the tunnel from which hourly averages were calculated. During the measurement, the ventilation of the tunnel was switched off and the wind in tunnels was produced by the moving traffic only for the entire period.

Figure 3. Measurement points distribution in the tunnel

3.2 Calculation conditions
Traffic flow, vehicle type ratio, vehicle speed and pollutant concentrations are known through the tunnel measurement. Vehicle emissions are calculated by the measurement data and it is condition for the ramp pollutant origins from the total source item. To simplify the analysis, diffusion coefficient K value is 0 according to the gas pollutants in the tunnel cross-section rapid spread evenly.
3.2.1 Traffic characteristic

The proportion of gasoline-fuelled vehicle reach 97.3% because of large diesel vehicles is refused into the tunnel. The tunnel is densely trafficked when morning peak hours of workdays. The average vehicle speed was less than 30 km/h and average traffic volume of each lane was 1394pcu/h. Table 1 shows the basic measurement conditions of Changsha Yingpan Road tunnel. The average air velocity of main tunnel (before confluence, before diversion and after diversion) ranged from 2.46~3 m/s. The average air velocity in the confluence ramp and distributary ramp were 1.37 m/s and 1.08 m/s, respectively. It can be seen that average air velocity in main tunnel generally greater than that in ramps because of the difference between traffic volume.

Table 1. Measurement traffic characteristic

<table>
<thead>
<tr>
<th>Date</th>
<th>05-30</th>
<th>05-31</th>
<th>06-01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air velocity (m/s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decline</td>
<td>2.27</td>
<td>2.525</td>
<td>2.29</td>
</tr>
<tr>
<td>Flat</td>
<td>1.916</td>
<td>2.342</td>
<td>3.3</td>
</tr>
<tr>
<td>Incline</td>
<td>1.615</td>
<td>2.05</td>
<td>2.5</td>
</tr>
<tr>
<td>Confluence ramp</td>
<td>1.673</td>
<td>1.384</td>
<td>1.650</td>
</tr>
<tr>
<td>Diversion ramp</td>
<td>1.751</td>
<td>1.081</td>
<td>1.167</td>
</tr>
</tbody>
</table>

| Traffic flow (veh/h) |       |       |       |
|                      | 05-30 | 05-31 | 06-01 |
| Decline              | 1680  | 2176  | 1174  |
| Flat                 | 2592  | 2636  | 2073  |
| Incline              | 1764  | 1905  | 1140  |
| Confluence ramp      | 1008  | 1276  | 900   |
| Diversion ramp       | 917   | 786   | 933   |

3.2.2 Vehicle Emission

There is a big difference between different vehicle emission factors under different fuel type and emission standards. Vehicle type in different cities impact vehicle emission greatly. Eq.9 cannot be used to calculate vehicle emission of urban tunnel. It is unscientific to reference design parameters of highway tunnel indiscriminately when the design object is urban tunnel. It will lead to excessive cost of ventilation system and huge waste. Annual decline rate of $q_{co}$ should be dynamically. In Fig.4, a huge gap can be seen between measurement CO vehicle emission and CO vehicle emission formulated by standard of Specifications for Design of ventilation and Lighting of Highway Tunnel and PIARC 2012.

3.3 Result and discussion

3.3.1 Source Accumulated Values

CO and NO, source accumulated values are shown in Fig.5 and Fig.6. Inverse problem model can back calculate vehicle emission source which reflect tunnel structural feature and vehicle emission characteristic dynamically. But forward problem only can calculate average emission source which is changeless. Pollutants diffusion characteristic in multi-ramps tunnel not shows linearly increasing regularity any more. The structure of the measured tunnel is underground concave, so vehicles through declining slope, flat surface and inclining...
slope in order. At the same time, the confluence ramp and distributary ramp influence traffic volume, it significantly increase at confluence and decrease at diversion point. With the combined effect of traffic force, air flow at the confluence ramp and distributary ramp, the average CO and NO\textsubscript{x} concentration of main tunnel exit in workday was 20.3ppm and 1.83ppm, respectively. The average back calculated CO and NO\textsubscript{x} source accumulated value was 0.37mg/m\textsuperscript{3}s and 0.044mg/m\textsuperscript{3}s, respectively.

Figure 5. CO source item accumulated values

![Figure 5](image)

Figure 6. NO\textsubscript{x} source item accumulated values

![Figure 6](image)

3.3.2 The CO source item affected by the Ramp

The back calculated CO source accumulated values of 30\textsuperscript{th} May are shown in Fig.7. In congestion conditions of workday morning peak hours, pollutants with air flow flowed into main tunnel from confluence ramp. It made a slight increase of 4.8% total pollutants source. Most of CO source in main tunnel from accumulated vehicle emission directly, only 16.3% of total pollutants source from decline section. In a similar way, pollutants flowed into distributary ramp from main tunnel was 5.9% of total pollutants source while accumulated vehicle emission of flat section and incline section were 46.5% and 38.0%, respectively. Vehicle emission factors are important input parameters for emission source. Taking into account that vehicle emissions are not only affected by a vehicles own emission characteristics, but also closely related to driving condition, fuel quality, vehicle speed and implementation of vehicle emission standards, they are dynamic parameters. Thus, presenting vehicle emission factors accurately and dynamically plays an important role to control pollutants concentration in tunnels. As pollutants flow into distributary ramp and then exhaust out of ramp, CO concentrations of main tunnel exit decrease significantly together with CO source accumulated values. So the quantity of air flow necessary in the tunnel also decreases reasonable.
3.3.3 The NOx source item affected by the Ramp

The back calculated NOx source accumulated values of 30th May are shown in Fig. 8. Because of limited measurement conditions, the NOx measurements of confluence ramp are not available. So NOx source accumulated values of flat section not include the quantity of pollutants which flow into main tunnel from confluence ramp. In congestion conditions of workday morning peak hours, pollutants flowed into distributary ramp from main tunnel was 5.2% of total pollutants source while accumulated vehicle emission of flat section and incline section were 47.7% and 30.6%, respectively. Presenting vehicle NOx emission factors accurately and dynamically also plays an important role to control NOx concentration in tunnels. As pollutants flow into distributary ramp and traffic force effect, NOx concentrations of main tunnel exit decrease significantly too. Though the NO concentration of main tunnel exit was lower than the 5ppm threshold value (according to NO2 threshold value is 1ppm in 20min), it is beyond the safe value threshold of Ambient air quality standards of 1ppm. NOx will be the focus of environmental quality in urban tunnels.

4. CONCLUSION

In this paper, the pollutant source item accumulated values from vehicle emissions and multi-ramps pollutants were obtained with mass transfer equation through the inverse problem method, which based on the measurement results. The research results are shown as follows:

1) Pollutants diffusion characteristic in multi-ramps tunnel is not shown linearly increasing regularity any more. With the combined effect of traffic force, air flow at the confluence ramp and distributary ramp, the average back calculated CO and NOx source accumulated value was 0.37mg/m3s and 0.044mg/m3s, respectively.
2) In congestion conditions of workday morning peak hours, pollutants with air flow flowed into main tunnel from confluence ramp. It made a slight increase of 4.8% total pollutants source. Pollutants flowed into distributary ramp from main tunnel was 5.9% of total pollutants source while accumulated vehicle emission of flat section and incline section were 46.5% and 38.0% respectively.

3) In congestion conditions of workday morning peak hours, pollutants flowed into distributary ramp from main tunnel was 5.2% of total pollutants source while accumulated vehicle emission of flat section and incline section were 47.7% and 30.6%, respectively.

4) As pollutants flow into distributary ramp and then exhaust out of ramp, pollutant concentrations of main tunnel exit decrease significantly together with pollutant source accumulated values. So the quantity of air flow necessary in the tunnel also decreases reasonable. Vehicle emission factors accurately and dynamically plays an important role to control pollutants concentration in tunnels.

Urban underground road construction is one of the major steps to reduce traffic congestion in China. However, due to heavy traffic, large quantities of vehicle emission pollutants (CO, NOx, and PM) and frequent fog and haze in parts of China are inextricably linked. The impact of vehicle emissions on the environment and the pollutant diffusion level is increasingly becoming the focus on the complex structure urban tunnel. Based on the results of previous studies, the project team now is studying on vehicle emission factors, traffic force and source item in multi-ramps urban tunnel. We will further research on the pollutant dispersion model and predict pollutant concentrations in the complex structure urban tunnel. The results can provide theoretical and technical methods and reference for Chinese urban tunnel to design ventilation system, develop energy security operations strategy, and project environmental assessment.

**NOMENCLATURE**

- $C$ the pollutant concentration, mg/m$^3$
- $\bar{u}$ the mean air velocity, m/s
- $x$ the distance from the tunnel entrance, m
- $K$ diffusion coefficient in the tunnel cross-section, m$^2$/s
- $Q_{EF}$ vehicle emission, mg/m$^3$s
- $q_{trans}$ source due to transverse ventilation, mg/m$^3$s
- $\lambda_i(v)$ vehicle speed factor for i tape vehicle emission j pollutant
- $v$ vehicle speed, m/s
- $\bar{EF}$ the average vehicle emission factors of pollutant j, g/(km.veh)
- $A_r$ the tunnel cross-sectional area, m$^2$
- $N$ the traffic flow, veh/s
- $u_{in}$ supplied air volume flow per length tunnel, m$^3$/s
- $u_{out}$ exhausted air volume flow per length tunnel, m$^3$/s
- $C_{in}$ pollutant concentration in confluence ramp, mg/m$^3$
- $C_{out}$ pollutant concentration in diversion ramp, mg/m$^3$
- $\bar{V}_{in}$ the mean air velocity in confluence ramp, m/s
- $\bar{V}_{out}$ the mean air velocity in diversion ramp, m/s
- $A_{in}$ the confluence ramp tunnel cross-sectional area, m$^2$
- $A_{out}$ the diversion ramp tunnel cross-sectional area, m$^2$
- $L_{in}$ length of confluence ramp, m
- $L_{out}$ length of diversion ramp, m
- $q(v,i)$ base emission factor, g/(h.veh)
- $f_a$ altitude factor
- $f_t$ influence factors for years differing from the base year
- $f_e$ influence factor for technology standards
- $Q_{co}$ CO emission, m$^3$/s
- $q_{co}$ CO base emission, m$^3$/veh.km
- $N_{m}$ Design traffic flow, veh/h
- $L$ the tunnel length, m
- $f_v$ vehicle condition factor
- $f_d$ vehicle density factor
- $f_b$ Altitude factor
- $f_l$ Longitudinal tunnel and vehicle speed factor
- $f_n$ vehicle type factor
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REFERENCES


