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The impacts of roadside vegetation barriers on the dispersion of gaseous traffic pollution in urban street canyons

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ABSTRACT

Vegetation barriers have been widely applied along urban streets to improve roadside air quality. For a deep investigation of their influences, field measurements and numerical simulations are performed in this study. Carbon monoxide (CO) is selected as a representative of gaseous traffic emissions for both field observations and numerical models. Computational Fluid Dynamics (CFD) models of the standard k-ε turbulent model and Eulerian approach for species transport are solved by FLUENT solver. Results obtained from numerical simulations show a good agreement with field observations on the distribution of roadside CO. In perpendicular wind conditions, both field observations and numerical simulations present a prominent CO reduction over the slow lanes (footpath and bikeway) when vegetation barriers exist. To effectively mitigate roadside air pollution, numerical simulations also provide the optimal heights for roadside vegetation barriers in the given street canyons. For street canyons with an aspect ratio (the ratio of building height to street width) ranging from 0.3 to 1.67, 1.1 m can be used as an optimal height, and 2.0 m could serve as an alternative if tall vegetation barriers are considered. For street canyons with an aspect ratio of lower than 0.3, 0.9 m to 2.5 m can be considered as the optimal heights for roadside vegetation barriers. According to sensitivity analysis, the optimal heights for vegetation barriers are largely insensitive to wind velocities in the given street canyons. In the more complicated urban street canyons and complex meteorological conditions, the optimal heights can be determined by specific numerical simulations. These findings are expected to provide important insights into alleviation of gaseous mobile emissions in terms of vegetation barrier design in urban streets.

1. Introduction

Air pollution is a severe environmental problem, especially traffic emissions, which are predominant sources of air pollutants in urban environment globally (Kumar et al., 2013). Due to poor ventilation conditions, urban streets face more serious air pollution. To mitigate traffic-induced air pollution, scholars and practitioners have proposed several alleviation strategies. McNabola et al. (2013) summarized three approaches to improve urban air quality: (1) controlling the emitted quantity of pollutants (g), (2) controlling the emission intensity (g km^{-1}), and (3) controlling the source-receptor pathways. This classification of strategies for mitigating air pollution is also suitable for street-scale level. In spite of these efforts, it is becoming more difficult to control the quantity and intensity of traffic emissions due to a rapid increase in vehicles in developing countries such as China. A relatively effective yet still largely unexplored way for improving roadside air quality is to alter the space between vehicles and pedestrians. For this purpose, barriers, otherwise known as a passive control method, can be used to improve roadside air quality.

Gallagher et al. (2015) reviewed the specific effects of different types of barriers such as porous barriers (trees and vegetation barriers) and solid barriers (noise barriers, low boundary walls, and parked cars) on roadside personal exposure to traffic-emitted pollutants. Regardless of differences in physical characteristics, these two barrier types can, to some extent, improve roadside air quality in urban street canyons (Gallagher et al., 2011, 2012, 2013; Halim

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et al., 2015; Tong et al., 2016). Acting as physical barriers between emission sources and nearby population, vegetation barriers have been evaluated as an effective strategy (Bowker et al., 2007; Hagler et al., 2011). Compared with solid barriers, vegetation barriers are more eco-friendly, and widely used to afforest urban arteries. Vegetation barriers mitigate roadside air pollution by affecting localized turbulence and changing natural dispersion patterns of traffic-emitted pollutants (Gallagher et al., 2015; Janhäll, 2015). Steffens et al. (2012, 2013) summarized that two physical processes, dispersion and deposition, are mainly responsible for the mitigation function of vegetation barriers in roadside air pollution. The dispersion process is characterized by both deflection and recirculation of approaching air flows from the roadway. Accordingly, vegetation barriers affect the dispersion process of pollutants by altering in-canyon air flow structures. By contrast, the deposition process demonstrates Brownian diffusion, impaction, gravitation settling, and interception of particulate matters.

In most situations, vegetation strategies used as passive controls are often characterized by trees and vegetation barriers. A number of studies have been conducted to investigate the impacts of trees and vegetation barriers on urban air quality at the macro-scale level, that is, within hundreds of meters of a roadway (Brücher et al., 2000; Nowak et al., 2006; Tallis et al., 2011; Vos et al., 2013). However, the impacts of vegetation barriers at the micro-scale level (street-scale level, such as, at pedestrian level in the slow lanes) are seldom revealed. At the micro-scale level, the mitigation functions of vegetation barriers are limited by meteorological conditions, street configurations, vegetation barrier shapes, and so on. The literature revealed that, in most cases, perpendicular wind conditions are not favorable for ventilation in urban street canyons (Nazridoust and Ahmadi, 2006; Tominaga and Stathopoulos 2011, 2013). Especially in perpendicular wind conditions (such as 0 m s^{-1} to 20 m s^{-1}, and normal to vegetation barriers) with the presence of roadside trees, an obvious increase of pollutant concentrations on the leeward side (illustrated in Figs. 1 and 2) can be observed, and a moderate decrease of pollutant concentration on the windward side (illustrated in Fig. 2) is found at pedestrian level (Buccolieri et al., 2009; Gromke, 2011; Amorim et al., 2013; Abhijith and Gokhale, 2015). Vegetation barriers flanking roadways are able to act like low boundary walls to decrease roadside pollutant concentrations (Bowker et al., 2007; King et al., 2009; Gallagher et al., 2015). Tong et al. (2016) presented that an increase of vegetation barrier width is more favorable for mitigating roadside air pollution than vegetation barrier height. But this cannot determine if the influence of vegetation barrier height is negligible due to a limited spatial scale of this research, which is approximately 100 m to the roadway. Additionally, the impacts of vegetation barrier height on the dispersion of gaseous traffic-emitted pollutants over the slow lanes (footpath and bikeway) are seldom mentioned in previous studies.

One objective in this study is to investigate the impacts of vegetation barriers on the dispersion of roadside air pollution. The other one is to attempt to find the optimal vegetation barrier heights to effectively reduce traffic-emitted pollutants over the slow lanes of urban streets to the greatest extent. Only dispersion processes of gaseous pollutants are investigated in this study. Any other processes that could lead to chemical transformations are not considered. Carbon monoxide (CO) is selected as a representative of gaseous traffic-emitted pollutants. Numerical models are configured based on the physical features and dimensions of the experimental site, and calibrated by field measurements. Computational Fluid Dynamic (CFD) code solver FLUENT 6.3.2 is used to perform numerical simulations. The findings presented in this study may not be generalizable in all types of street canyons and meteorological conditions, whereas provide urban planners with options when designing vegetation barriers in urban street canyons.

2. Methodology

2.1. Experiment site and street description

Shanghai is one of the most densely populated metropolises in China with a population of approximately 24.25 million. Situated in the Yangtze River delta and adjacent to the East China Sea, Shanghai has a mild monsoon climate with warm humid summers and mild damp winters. With a large vehicle ownership, Shanghai is heavily polluted by traffic-induced pollutants. Therefore, traffic emissions have been a major contributor to urban air pollution, and account for approximately 21% of total carbon-related pollutants (Cao et al., 2012; Liu et al., 2015). Thus, effective measures are urgently needed to alleviate traffic-induced air pollution in urban environment.

To investigate the potential effects of vegetation barriers in a real world urban street canyon, Dongchuan Road is selected as a case study. Dongchuan Road is a busy traffic corridor linking the Zizhu National High and New-Tech Development Zone to the Minhang Development Zone. As shown in Fig. 1(a), a section of street (121°25′47.28″E, 31°1′15.96″N) on Dongchuan Road located in the Minhang district is selected as the field monitoring site, and a prototype for numerical models. This road section is oriented northeast-southwest with four lanes in each direction, two of which are slow lanes (footpath and bikeway, shown in Fig. 1(b)), and the other two are motor lanes. As illustrated in Fig. 1(b) and Fig. 2, this road section is lined with camphor trees which have an average standing space of 5.5 m, on footpath. Two rows of vegetation barriers, which are densely foliated evergreen shrubs, flank the roadway. The vegetation barrier is 0.9 m in height and 1.5 m in width (see Fig. 1(b)). The total width of this road section, including footpaths and bikeways (slow lanes), is approximately 38 m. This street is flanked by buildings between 2 and 6 stories, and has an aspect ratio (AR, the ratio of building height to street width, H/W) of approximately 0.4. According to a classification of urban streets based on AR, the flow regime in this street canyon belongs to wake interference flow (WIF) (Li et al., 2009). Field observations were performed on the leeward, northwest-facing side of this road section.

This road section is selected as the experimental site and numerical model prototype for several reasons. (1) This road section connects Shanghai Jiao Tong University and Auchan shopping mall. Additionally, several residential communities are also located nearby, generating a large pedestrian flow and making roadside air pollution a serious problem. (2) Except for Humin Road which intercepts Dongchuan Road approximately 100 m southwesterly and may be a potential CO contributor, no other major emission sources of CO are found in proximity to this monitoring site. Thus, CO emissions in this street canyon are predominantly emitted by vehicles. (3) Monitoring instruments can be located in Minhang campus of Shanghai Jiao Tong University to make continuous background records. (4) This road section includes two distinct parts, one is flanked by both trees and vegetation barriers, and the other is only flanked by trees.

2.2. Numerical model

Two dimensional (2D) numerical models are developed to investigate the impacts of vegetation barriers on improvement of roadside air quality in urban street canyons.

2.2.1. Description of general flow and dispersion

A cross section of street canyon model is outlined in Fig. 2. As indicated by previous studies, the standard k-ε model is suitable for reproducing turbulence patterns in a simple street canyon