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Dispersion of traffic derived air pollutants into urban parks

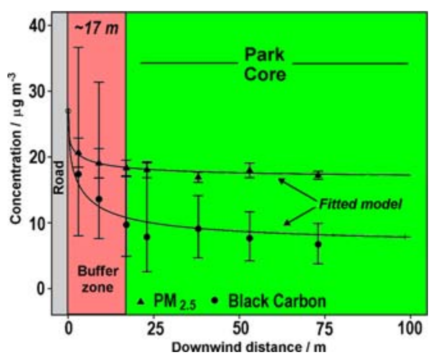
Yang Xing [a], Peter Brimblecombe [a,b,*]

[a] School of Energy and Environment, City University of Hong Kong, Hong Kong
[b] Guy Carpenter Climate Change Centre, City University of Hong Kong, Hong Kong

HIGHLIGHTS

- Traffic derived air pollutants are readily detected in urban parks.
- Measurements suggest a rapid decay of pollutants from roadside into parks.
- Pollutant gradients in parks are explored using an analytical dispersion equation.
- Traffic derived pollutants halve after ~17 m from the road edge.
- Future park design should emphasise a separation between park interiors and roads.

GRAPHICAL ABSTRACT



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ABSTRACT

Scarce land resources in dense cities means that small urban parks are important as a leisure and amenity resource for the urban population. However, streets with heavily traffic often surround these fragmented parks and increase the potential user exposure to air pollutants from vehicles. The dispersion profiles of $PM_{2.5}$ and black carbon from roadside into urban parks at pedestrian level, in Hong Kong, were measured using mobile high time resolution instruments. In the downwind direction, pollutant concentrations decreased rapidly from roadside and by some tens of metres reached relatively constant values. An even sharper gradient is found in the upwind direction, with a rapid increase detected within 2 m of the road edge. The distinct decay profiles were explained with an analytical dispersion model formulated based on the *gradient transport theory* using an Eulerian approach. The simulations using the dispersion model suggest 17 m as a typical halving distance under normal urban conditions, which is introduced to simplify the description of dispersion profiles. Using Hong Kong as an example, ~90% of urban parks, to different extent, overlap with the 17 m halving distance from roads, which means few urban parks in Hong Kong avoid the impact from nearby traffic emissions. Thus, from the perspective of human exposure to air pollutants in urban parks, this study provides observations of relevance for future park design in dense cities.

1. Introduction

Small roadside urban parks, an important leisure and amenity resource in cities, expose vulnerable people to traffic derived air pollutants. In dense cities, urban parks are often allotted limited remnant urban area. These small and fragmented parks, frequently just a few hectares or less in area, are commonly found adjacent to main streets

* Corresponding author at: School of Energy and Environment, City University of Hong Kong, Hong Kong.
E-mail address: p.brimblecombe@uea.ac.uk (P. Brimblecombe).

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to ensure easy access and serve more urban dwellers (Gong et al., 2016). The busy roads surrounding these small parks increase the potential park user exposure to air pollutants from vehicles, such as particulate material which has been widely linked with increased risk of adverse health effects (Brugge et al., 2007; Tam et al., 1987; Zhang and Batterman, 2013). The sharp gradient in air pollutant concentrations away from the roadside has frequently been detected in research on near-road air quality (Ducret-Stich et al., 2013; Karner et al., 2010). These rapid declines in concentration are likely to cause heterogeneous occupant exposure within parks (Klingberg et al., 2017; Yin et al., 2011). Thus we need to understand dispersion of pollutants into parks and the rate at which concentration decays.

Previous studies on near-road air quality mainly considered dispersion over hundreds of metres and often took place under more rural conditions. Thus these studies examined spatial scales and wind conditions, quite different from those found in urban parks in crowded cities. The current field measurements and model simulation provide an improved understanding at reduced spatial scales and in urban spaces where wind speeds are often low.

Roadside measurements from some forty studies were synthesized in a review by Karner et al. (2010). They observed that often decay profiles be classified into three distinct categories: (i) at least a 50% decrease in peak concentration by 150 m, followed by gradual decay (e.g., carbon monoxide); (ii) gradual decay (e.g., benzene, nitrogen dioxide); or (iii) no trend. In addition to the qualitative description of the decay profiles, an exponential model was successfully used to describe the observation of concentration gradients away from the road. An entrainment rate constant was introduced to represent decay rate, which has been found to relate to atmospheric conditions (Choi et al., 2012; Hu et al., 2009; Zhu et al., 2004; Zhu et al., 2006; Zhu et al., 2009).

In this work, we explore the dispersion pattern of traffic derived $PM_{2.5}$ and black carbon in urban parks under weak winds conditions (<2 m s^{-1} for example Arya, 1995) using both field measurements and analytical modeling. The observed and modelled profiles are used to assess the influence of adjacent traffic sources on the distribution of pollutants in urban parks in Hong Kong. The higher air pollution concentrations near park boundaries seem an important consideration in park design.

2. Methodology

The urban parks considered in this work include public parks, gardens, playgrounds and sitting out areas, while the other urban green spaces such as green walls, street greening and reserves are not included.

2.1. Field measurements

Samples were collected during spring 2017 at three locations, representing different scenarios: (i) a park with a single road along one of its borders; (ii) two parks separated by a road; (iii) a park with roads along paralleled borders, as shown in Table 1 and on the map in Fig. 1. Geographic maps, which include urban parks and roads in Hong Kong as layers, were downloaded from the Open Street Map (OSM) website (https://www.openstreetmap.org/) on 22nd Aug. 2016 and handled using Geographic Information Systems software (QGIS).

High time resolution air monitors (listed in Table 2) were used to measure $PM_{2.5}$ and black carbon concentrations in parks along a transect at a metre elevation, normal to the roadside. Concentration variance caused by temporal changes in background concentration and source strength was reduced by using three sets of instruments. Two were placed at fixed positions measuring concentration at the roadside and in the middle of park and revealed variations on a short-time scale. These were used to remove any apparent drift in background concentrations in measurements from a third set, which was moved along the transect. The wind speed and direction and traffic volume were recorded during the measurements (as shown in Table 2).

The measurement campaign took place between 13:00 and 17:00 local time to ensure the relatively constant traffic flow. The mobile instruments moved, in duplicate transects, from the roadside into the parks at intervals of 10 or 20 m. It took about 15 min to complete the measurements at each point along the transect at short sampling times. The sampling data collected when the wind was nearly parallel to the roads were not used for further analysis.

2.2. Model formulation

Various mathematical models have been applied to study the dispersion profiles from traffic derived pollutants (Choi et al., 2014; Heist et al., 2013; Venkatram et al., 2007; Zhu and Hinds, 2005). However, individual models can have particular limitations, so tend to be appropriate for specific applications. For example, the extensively used Gaussian plume model, a standard approach for studying the transport of airborne pollutants, was built with the slender-plume approximation. This simplifying assumption assumes that the plume is thin or slender, which can be theoretically valid only when winds are moderate or strong (>2 m s^{-1}), or by ignoring near-source diffusion (Arya, 1995). In the urban parks considered here winds are weak and concentration profiles represent the dispersion of pollutants over short distances (<200 m), which has not been well described in theory. Thus a solution for this specific situation is developed in this work.

The dispersion of pollutants in the atmosphere can be described with the advection-diffusion equation based on the *gradient-transport theory*. Considering a source released in atmospheric boundary layer, the standard advection-diffusion equation can be written in the Cartesian coordinate system as (Arya, 1999):

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+w\frac{\partial C}{\partial z}=\frac{\partial}{\partial x}\left(K_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial C}{\partial z}\right)+R+S \quad (1)$$

where C (μg m^{-3}) is the mean concentration of pollutant; u, v, w (m s^{-1}) are the mean wind velocities and K_x, K_y, K_z (m^2s^{-1}) are eddy diffusivities in x, y and z direction, respectively; R and S represent sources and sink terms arising from chemical or physical transformation and removal. The physical meaning left-hand side of this equation can be interpreted in two parts an initial term representing time dependent variation and remaining terms the advection caused by wind in three directions. This is equated to the diffusion of pollutants represented by

Table 1
Characteristics of the sampling locations.

Location no.	Urban parks		Adjacent roads		
	Name	Size/ha	Name	Road type	Traffic flow/d^{-1}
1	Choi Hung Road Playground	3.96	Choi Hung Road	District road	35,820
2	Fa Hui Park	3.19	Boundary Street	Primary road	48,150
	Yuen Po St. Bird Garden	0.65			
3	Sham Shui Po Park	3.13	Lai Chi Kok Road	Primary road	21,120
			West Kowloon Corridor	Urban trunk road	66,630