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Prediction of PM_{10} concentrations at urban traffic intersections using semi-empirical box modelling with instantaneous velocity and acceleration

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ABSTRACT

At urban traffic intersections, vehicles frequently stop with idling engines during the red-light period and speed up rapidly during the green-light period. The changes of driving patterns (i.e., idle, acceleration, deceleration and cruising patterns) generally produce uncertain emission. Additionally, the movement of pedestrians and the influence of wind further result in the random dispersion of pollutants. It is, therefore, too complex to simulate the effects of such dynamics on the resulting emission using conventional deterministic causal models.

For this reason, a modified semi-empirical box model for predicting the PM_{10} concentrations on roadsides is proposed in this paper. The model constitutes three parts, i.e., traffic, emission and dispersion components. The traffic component is developed using a generalized force traffic model to obtain the instantaneous velocity and acceleration when vehicles move through intersections. Hence the distribution of vehicle emission in street canyon during the green-light period is calculated. Then the dispersion component is investigated using a semi-empirical box model combining average wind speed, box height and background concentrations. With these considerations, the proposed model is applied and evaluated using measured data at a busy traffic intersection in Mong Kok, Hong Kong. In order to test the performance of the model, two situations, i.e., the data sets within a sunny day and between two sunny days, were selected to examine the model performance. The predicted values are generally well coincident with the observed data during different time slots except several values are overestimated or underestimated. Moreover, two types of vehicles, i.e., buses and petrol cars, are separately taken into account in the study. Buses are verified to contribute most to the emission in street canyons, which may be useful in evaluating the impact of vehicle emissions on the ambient air quality when there is a significant change in a specific vehicular population.

1. Introduction

Recently, vehicle emission has been regarded as the major sources of air pollution in urban area and has attracted much attention, especially at urban traffic intersection. At intersections, vehicles frequently stop with idling engines during the red-light period and speed up rapidly in the green-light period, which generate higher velocity fluctuation and produce more pollutants than any other situations such as cruise. Additionally, the interaction of pedestrian movement and the influence of wind may further cause the random dispersion of pollutants. It is very difficult to simulate the effects of such dynamical factors on the resultant emission rates using conventional deterministic causal models (Xie et al., 2003; Gokhale and Khare, 2004). Therefore, the semi-empirical models have been recently developed and verified as a practical alternative approach for evaluating the pollutant dispersion at intersections with a reasonable accuracy (Dirks et al., 2002, 2003; Kassomenos et al., 2004; Gokhale and Pandian, 2007).

The semi-empirical model generally comprises three components, i.e., traffic, emission, and dispersion components. The purpose of traffic component is to obtain the information on traffic volume, velocity; while the emission component is to determine the relation between the traffic flow and the road emission rate, also involving different emission factors of various types of vehicles in the total flow. The third dispersion component is to estimate the pollutant concentration using a semi-empirical box model as well as meteorological data. Finally, the performance of the model is evaluated through certain parameters such

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as correlation coefficient, index of agreement, root mean square error (RMSE), and relative RMSE, etc.

In previous studies, Dirks et al. (2002, 2003) developed semi-empirical box model to predict the effect of changes in traffic flow patterns on carbon monoxide concentration at intersections and Kassomenos et al. (2004) applied it to model the benzene concentration in street canyons. Gokhale and Pandian (2007) classified the vehicles into different categories (cars, buses, three-wheelers, two-wheelers, etc.) and utilized this approach to estimate the hourly average carbon monoxide concentrations at one of the busiest traffic intersections in Delhi. Unfortunately, the vehicle emissions in these studies were all calculated based on the average velocity and density. These parameters are originated from continuous traffic flow theory and regarded as more appropriate in motorways rather than urban traffic especially at traffic intersections where driving pattern (i.e., deceleration, idle, acceleration and cruising) frequently changes (Daganzo, 1997). Moreover, the vehicle emission at an intersection has been proved to highly depend on instantaneous velocity and acceleration (Panis et al., 2006). Therefore, it is necessary to attempt the microscopic traffic flow model to obtain the instantaneous velocity and acceleration for estimating the vehicle emission. For this reason, a simple semi-empirical model is developed and evaluated in this study for the prediction of PM_{10} concentration at traffic intersection based on the existing data of wind speed, traffic volume and PM_{10} concentration collected at the sampling site of interest.

2. Data collection

The measurements of particulate matter were performed at a selected traffic intersection in Mong Kok, Hong Kong. The measurement equipment is located on the roadside at the selected location, which is 30 cm high and very close to the roadway. Hence, such settings can provide the best chance for the equipment to capture the exhausts when vehicles in queue move through intersection. The number concentration of particulate matter was measured by a Fluke 983 Particle Counter and the mass concentration was obtained through a formula relating them to each other in previous studies (De Nevers, 2000; Tuch et al., 2000; Wittmaack, 2002; Weijers et al., 2004; Tittarelli et al., 2008). Additionally, the wind speed was secondly detected using the Q-track Model 7565 with air velocity probe 962 while the traffic volume was recorded by a digital camera. Since the traffic volume was counted within green-light period, the measured data during the green-light period were then selected and averaged for a better comparison with predicted value. The measurements were performed for one and half an hour in two situations, i.e., in morning and afternoon sessions respectively on a sunny day in November of 2008 and in two afternoon sessions on sunny days in March 2009.

According to the Monthly Traffic and Transport Digest from the Hong Kong Transport Department, 75% of vehicles in Hong Kong consume petrol and 21% of them consume diesel (HKTD, 2008). All double-decker buses in Hong Kong run on diesel and they were observed to frequently appear in this street. Hence, two types of vehicles, i.e., buses and petrol cars, are separately taken into account in this work.

3. Methodology

The whole model in this study constitutes three parts (Fig. 1), i.e., traffic, emission and dispersion components. The traffic component is developed using a generalized force traffic model which describes the starting movement of vehicles in queue from microscopic viewpoint. The velocity and acceleration for vehicles in queue when moving through an intersection can be obtained in this part. Based on it, the distribution of vehicle emission in street canyon during green-light period is calculated. According to traffic volume (bus and petrol car) observed during green-light period, the total emission in a street canyon during this period can be obtained. Then the dispersion component of the model is developed to estimate the PM_{10} level using a modified empirically optimized box model as well as average wind speed. Finally, the predicted values in all green-light periods were collected to evaluate the model through comparing them with corresponding observed data using correlation coefficient, index of agreement, root mean square error (RMSE) and relative RMSE (RRMSE).

3.1. Traffic component

The purpose of the traffic component in the model is to determine the characteristics of traffic flow at intersections for calculating the vehicle emission. In previous studies (Dirks et al., 2002, 2003; Gokhale and Pandian, 2007), the traffic parameters were all originated from continuous traffic flow and could not provide detail descriptions of traffic flow at intersection from microscopic viewpoint. Therefore, the generalized force model (Helbing and Tilch, 1998) in traffic dynamics is adopted to lead to a more realistic representation of the urban traffic situation.

The generalized force model assumes that the dynamics of a vehicle n at time t with velocity $v_n(t)$ at place $x_n(t)$ is given by the equation of motion (Helbing and Tilch, 1998).

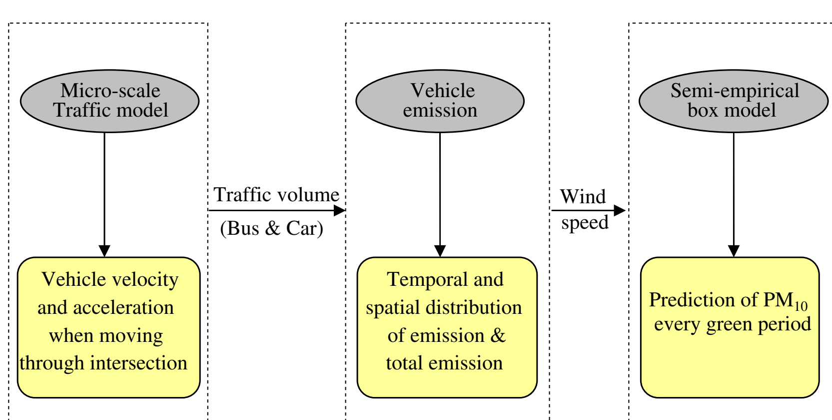

Fig. 1. Procedure of constructing modified semi-empirical box model.