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Modelling of traffic flow and air pollution emission with application to Hong Kong Island

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Abstract

In this study, we propose a Lagrangian model for the simulation of traffic flow on a complex road network. This simple approach is quite efficient if adequate road network data are available and statistical constraints are applied to confine the model behavior. We have established a traffic information database for Hong Kong Island and applied the model for traffic flow simulation. It is shown that by specifying three types of traffic routes (random turn, preferred turn and shortest path) and providing traffic flow data at selected stations, the model is capable of simulating traffic flow on the road network. This is confirmed by comparing model simulated and observed traffic flow patterns at several monitoring stations. The simulated traffic flow is then used as the basis for the estimation of traffic induced emission of air pollutants on the island. Using empirical emission factors for a number of vehicle categories, the emission rates of major air pollutants, CO, NO_x and PM_{10}, are estimated. The predicted emission rates are compared with measurements for several air quality monitoring stations.

Keywords: Traffic; Traffic flow model; Road network; Traffic emission; Urban air pollution

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1. Introduction

Traffic generated air pollution is of great concern to the general public. Motor vehicles emit nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC) and particulate matter (PM), which constitute a major source of air pollution in large cities, such as Hong Kong. Traffic generated air pollutants, such as NO_2 and PM, are of health concern; and traffic generated greenhouse gases, such as carbon dioxide (CO_2), may contribute to global warming. As motor vehicles are the major contributor to urban air pollution, controlling strategies need to be developed that minimize the environmental impacts but maximize the efficiency of motorized transport.

In order to provide a viable method for quantifying the contribution of traffic emission to regional air quality, we develop an integrated Traffic Emission Information System (TEIS) which allows the prediction of traffic induced air pollution in real-time. More details on TEIS are given in Section 3.4. As the key components of TEIS, the traffic flow model and traffic emission model are developed and presented in this study.

The emission factor based approach is widely used in modelling traffic-related pollution emission (e.g. Salles et al., 1996; Mensink et al., 2000; Lin and Lin, 2002; Jensen et al., 2001). The accuracy of this approach depends very much on the reliability of traffic data (traffic volume and velocity, their temporal and spatial variations, on road vehicle composition etc.) and the choice of emission factors. The methodology to derive these two types of data is consequently critic to emission factor based modelling of traffic pollution emissions.

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Traffic data are generally obtained by either in-situ observation or numerical modelling. The former most accurately reflects traffic conditions in real-time, but is usually carried out on selected road links only, e.g. highways and artery roads. The amount of observed data is often insufficient for adequately quantifying the traffic on a road network. Further, in-situ measurements are usually done on a daily or even a monthly basis. This temporal resolution is insufficient for refined (usually hourly) emission modelling. A complement is to make temporal and spatial extrapolation with many assumptions to allocate traffic volume, e.g. Salles et al. (1996) and Jensen et al. (2001). Another approximate methodology previously adopted, as pointed out by Cohen et al. (2004), is to distribute traffic emission over model grid cells, resulting in improper grid-based averaging emission rate instead of that along actual mobile source. Lin and Niemeier (1998) used observed traffic data to estimate hourly allocation factors and disaggregated traffic volume into hourly values. These indirect methods inevitably lead to inaccuracies in emission modelling. In theory, numerical modelling of traffic flow on road can provide every detail required for the calculation of traffic emissions. Unfortunately, previous efforts failed to do this because of road network complexity and, as we will see below, difficulties in solving the traffic flow equations.

Continuum hydrodynamics was firstly introduced to traffic flow theory in the 1950s (Lighthill and Whiteman, 1955). Prigogine and Herman (1971) applied statistical methods, as in classic fluid dynamics, to traffic flow studies. The work of Prigogine and Herman, known as the kinetic theory of traffic, considered vehicles on road as interacting particles in traffic flow which can be described by one-dimensional compressible fluid equations. Suppose there is neither creation nor destruction of vehicles on road, the continuity equation and the equation of motion for traffic flow can be written as:

$$\frac{\partial \rho}{\partial t}+v\frac{\partial \rho}{\partial s}=0 \tag{1}$$

$$\frac{\partial v}{\partial t}+v\left(\frac{\partial v}{\partial s}\right)=\frac{1}{\rho}\left(\frac{\partial}{\partial s}\left(\mu\frac{\partial v}{\partial s}\right)-\frac{\partial p}{\partial s}\right)+I \tag{2}$$

where ρ is density (number of cars per unit road length), v is traffic flow velocity, μ is viscosity, and p is local pressure. The first term on the right hand of Eq. (2) models viscosity, a presumed tendency to adjust vehicle speed to that of the surrounding traffic (Nagatani, 1998). The last term I is all inner forces due to interaction between individual cars (Kerner and Konhauser, 1993). In practice, the continuum hydrodynamic approach is difficult to implement for two reasons. One is that the quantities such as μ, I and p are not well defined and cannot be readily determined, and the other is that the numerical solution of Eqs. (1) and (2) requires their discretization for complex road networks. The numerical treatments for the diffusion and advection terms are rather cumbersome.

As an alternative, some researchers established equilibrium relations between traffic density and traffic flow velocity for the closure of Eq. (1) instead of using Eq. (2). By definition, traffic flow is the product of traffic density and velocity. If traffic density is zero, then traffic flow is also zero; and when traffic density reaches the maximum, i.e., traffic is congested, traffic velocity decreases to zero, so traffic flow is also zero. Newell (1993), Daganzo (1994) and Wong and Wong (2002) suggested piecewise-linear flow–density relationships. De Angelis (1999) studied nonlinear hydrodynamic modelling of traffic flow in theory. The linear diffusion term was taken into account in the governing equations. De Angelis found that a second order flow–density relation gives a satisfactory fitting to the experimental results of Leutzbach (1988). Critical analysis on a similar model but with additional phenomenological relation between density and velocity was presented by Bonzani (2000) and Marasco (2002). Velan and Florian (2002) explored the implications of nonsmooth equilibrium flow–density relationships. However, all these studies were concerned with traffic flows on individual highways. We are not aware of traffic model applications to complex road networks.

Our approach is different. In contrast to the continuum hydrodynamic approach, we consider the motion of individual vehicles and determine the macroscopic traffic flow quantities on the basis of vehicle movement. Although the problem of traffic on network is highly complicated, the movement of individual vehicles is quite simple. Vehicle movement is analogous to that of gaseous molecules. However, while molecules move randomly, vehicles are confined to the road network and follow certain designated paths. Hence, the movement of individual vehicles is predictable.

We are therefore motivated to track vehicles on road network using the Lagrangian methodology. This approach requires no predefined velocity–density relationship. Instead, we introduce a critical traffic density and two time scales. The motion of an individual vehicle is governed by a first-order ordinary differential equation which can be solved by using, for example, the Runge–Kutta method. Macroscopic traffic flow quantities, such as traffic flow velocity and traffic density, can be estimated once the velocity and position of individual vehicles are known. The Lagrangian approach is very simple in theory and involves little mathematical difficulties. However, we recognize that the implementation of such a model on a road network requires the knowledge of designated paths for individual vehicles. For a given road network, we may be dealing with millions of vehicles and it is impossible to determine the