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

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Received 22 November 2003; received in revised form 16 July 2004; accepted 9 August 2004

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.

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

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.
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:

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

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

where $\rho$ is density (number of cars per unit road length), $v$ is traffic flow velocity, $\mu$ 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 $\mu$, $I$ 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
designated paths for all vehicles. However, it is possible to force the designated paths to comply with certain statistical conditions.

Another difficulty in modelling traffic in practice is the requirement for data, in order to quantify the road network, including road type, traffic lights and the sources and sinks of vehicles. In TEIS, coupled with a traffic GIS (geographic information system), the integration of dynamic models with vehicle and road network data is achieved.

The traffic emission simulation presented in this study is on the basis of the traffic flow simulation for Hong Kong Island. Since the emission factors specifically for Hong Kong are yet to be determined, those derived from COPERT II emission inventory programme (Ahlvik et al., 1997) are used in this study. COPERT II was recommended by the European Environment Agent and widely adopted in Europe for emission estimates from road transport (e.g. Mensink et al., 2000; Reynolds and Broderick, 2000).

The modelling results of traffic flow and major pollutant emission rates in Hong Kong Island network are compared with the traffic data obtained at several counting stations and air quality monitoring at roadside stations, as presented in Section 4.

2. Model description

Several databases are established for the modelling. These include (i) Hong Kong Island road network database, in essence an attribution table for the specification of network connectivities, speed limits and road classes [roads in Hong Kong are classified into catalogues of Tunnel (TUN), Main road (MRD), Secondary road (SRD) and Trail (TAL)]; (ii) vehicle database for the specification of vehicle characteristics and probability distribution of vehicle types; (iii) traffic emission factor database and (iv) air quality monitoring database.

2.1. Traffic flow model

According to traffic density, we introduce two traffic modes on a road network: a free traffic mode and a congestion mode. Let $\rho_c$ be a critical traffic density, separating the free traffic mode from the congestion mode. If $\rho < \rho_c$ on a road segment, then traffic is in the free traffic mode and vehicles would accelerate to a speed limit $v_{\text{lim}}$. If $\rho > \rho_c$, then traffic is in congestion mode and vehicles would decelerate to zero speed. Accordingly, the equation of motion for a vehicle can be written as:

$$\frac{dv_j}{dt} = \begin{cases} v_{\text{lim}} - v_j & \rho \leq \rho_c \\ -\frac{v_j}{\tau_a} & \rho > \rho_c \end{cases}$$

where $\tau_a$ and $\tau_b$ are vehicle acceleration and deceleration response times, respectively. These response times are mainly functions of traffic density, as they do not differ to a great degree among vehicles.

Suppose a road length is $L$ and the minimum allowed separation (on average) is $D$, then the maximum allowed number of vehicles on $L$ in free traffic mode is $N = L/D$. Therefore, the critical traffic density $\rho_c$ is:

$$\rho_c = \frac{N}{L} = \frac{1}{D}$$

Eq. (3) is a first-order ordinary differential equation, which can be easily solved (e.g. using the Runge–Kutta method), assuming initial traffic density $\rho_{0j}$ and speed $v_{0j}$ on road segment $j$ and $v_{\text{lim},j}$ are known.

By definition $\rho$ is the number of vehicles per unit road length. Suppose we start counting vehicle number at time $t$ on road segment $j$ of length $\Delta s_j$. If the counting interval is $\Delta t$, then over a time period $\Delta t$, $m (\Delta t/\Delta t)$ counts $N_1, N_2, ..., N_m$ are made. The average traffic density over $\Delta t$ at segment $j$ is:

$$\bar{\rho}_j(t + \Delta t) = \frac{1}{\Delta s_j} \sum_{i=1}^{m} N_i \frac{\Delta t}{\Delta t} = \frac{\Delta t}{\Delta s_j} \Delta t \sum_{i=1}^{m} N_i$$

Substituting $\bar{\rho}_j$ into Eq. (3), the speed of car $i$ on segment $j$, $v_{ij} = v_j(\bar{\rho}_j, t + \Delta t)$ can be determined. The overall traffic speed $V_j$ and traffic flow $Q_j$ on segment $j$ during $t$ to $t + \Delta t$ are:

$$V_j = \bar{v}_j$$

$$Q_j = \bar{\rho}_j V_j$$

This procedure is repeated for each vehicle on the road network from start time $t_0$ to end time $T$. Combining the determined trips with statistic constraints to traffic assignment (see Section 3.2), traffic density, velocity and flow at each road segment in time interval $\Delta t$ are simulated over the entire network.

2.2. The traffic emission model

Traffic emission rate is related to a number of vehicle characteristics: model, engine size, age, annual mileage by vehicle age and exhaust control equipment (Bachman et al., 2000). To estimate the emission of a vehicle fleet, the vehicle population is divided into several categories. Seven categories are used in this study:

- Motor Cycle (MC): motor-propelled 2- or 3-wheeled vehicle;
- Private car & Taxi (PC, TX): gasoline passenger car and taxi. $1.41 < CC < 2.01$;
• Public Light Bus (PLB): passenger carrying vehicle with capacity of 17 seats. CC > 2.01;
• Passenger Van (PV): dual purpose gasoline van with capacity not exceeding 17 seats with weight less than 3.5 t;
• Bus (BUS): diesel urban buses and coaches;
• Light Goods Vehicle (LGV): four wheeled lorry or dual purpose van which is not provided with side windows covering the full length of the vehicle body, with weight less than 3.5 t;
• Heavy Goods Vehicle (HGV): lorry with more than four wheels, including fire engines, refuse vans, military trucks, petrol tanks and other similar vehicles, with weight exceeding 3.5 t.

For vehicle category \( i \), the emission rate of pollutant \( j \) on road \( k \) is calculated by:

\[
E_{ijk} = C_{ij} V_k
\]  

(8)

where \( V_k \) is the traffic flow of vehicles type \( i \) on road \( k \) and \( C_{ij} \) is the emission factor of pollutant \( j \) emitted by vehicles type \( i \). Further, \( V_{ik} \) can be expressed as:

\[
V_{ik} = P_{ik} V_k
\]

where \( P_{ik} \) and \( V_k \) are the fraction of vehicle type \( i \) and the traffic flow of all vehicle types on road \( k \), respectively. The emission rate of pollutant \( j \) of the vehicle fleet on road \( k \) can then be calculated by:

\[
E_k = \sum_{i=1}^{n} E_{ijk} = \sum_{i=1}^{n} P_{ik} V_k C_{ij} = V_k \sum_{i=1}^{n} P_{ik} C_{ij}
\]  

(9)

where \( V_k \) is calculated using the traffic flow model, and \( P_{ik} \) is estimated based on in-situ investigation conducted by local government departments. Table 1 shows the proportion of various vehicles by counting at the exit of three cross-harbour tunnels of Hong Kong in year 2000 (HKTD, 2001). The values listed are averages over 16 h (0700–2300). In the traffic census of Hong Kong, there are 203 counting stations in total on the island, although we only listed data from three stations.

The emission factors \( C_{ij} \) are estimated by COPERT II methodology (Ahlvik et al., 1997). The reason we chose COPERT II for Hong Kong is that Europe emission standards have been implemented in Hong Kong since 1995 under Air Pollution Control Regulations. The Hong Kong government introduced the EURO I and EURO II emission standards in 1995 and 1997, respectively. Furthermore, the government tightened the emission standards for newly registered motor vehicles (design weight less than 3.5 t) to EURO III level in 2001.

Three emission modes are taken into account for calculation of emission factors: (i) hot emissions, these are the emissions from vehicles after they have warmed up to their normal operating temperature; (ii) cold-start emissions, these are the emissions from vehicles while they are warming up and the water temperature is below 70 °C; and (iii) evaporative emissions, these are associated with the relevant quantities for gasoline vehicles in the form of no-methane VOC (subtracting CH₄ from VOC) emissions.

The resultant hot emission factors of CO, NOₓ and PM₁₀ adopted in this study are listed in Tables 2–4. ‘Conventional’ vehicle category is applied for all except 93/59/EEC for LGV in the form of NOₓ emission in Table 3 and 91/441/EEC for PLB in the form of CO and NOₓ emissions in Tables 2 and 3. The cold emissions are taken into account as additional emissions per kilometer by introducing cold to hot ratio of emissions, \( e_{cold}^{e_{hot}} \), and the fraction of mileage, \( \beta \), driven with cold engines or catalyst operated below the light-off temperature. They are the function of ambient temperature and the average trip length. The calculation formula for these parameters can be found in Ahlvik et al. (1997).

### 3. Model application to Hong Kong

We have applied the models to the simulation of traffic flow and traffic-related emission on Hong Kong Island. The road network on the island is shown in Fig. 1, which is represented by over 6000 line features in ArcGIS. The traffic on the island is an isolated system with only three harbour tunnels linking to the outside—i.e., Kowloon and the New Territory. This significantly simplifies the simulation. The traffic data obtained in the three tunnels—from left to right in Fig. 1, Western Tunnel, Cross Harbour Tunnel and Eastern Tunnel—are used as boundary conditions for the modelling.

<table>
<thead>
<tr>
<th>Speed [km h⁻¹]</th>
<th>Emission factor [g km⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10–60</td>
<td>–0.0011V² + 0.172V + 18.1</td>
</tr>
<tr>
<td>60–110</td>
<td>0.00011V² + 0.059V + 21.5</td>
</tr>
<tr>
<td>10–130</td>
<td>0.000957V² – 0.151V + 8.273</td>
</tr>
<tr>
<td>10–130</td>
<td>0.01104V² – 1.5132V + 57.789</td>
</tr>
<tr>
<td>10–130</td>
<td>0.00691V² – 0.0793V + 3.45358</td>
</tr>
<tr>
<td>0–50</td>
<td>0.0055V – 0.7447</td>
</tr>
<tr>
<td>10–130</td>
<td>0.00021V² – 0.0256V + 1.8281</td>
</tr>
<tr>
<td>0–100</td>
<td>37.28V⁰.⁶⁹⁴⁵</td>
</tr>
</tbody>
</table>

Table 1: Counted fraction (%) of vehicles in cross-harbour tunnels of Hong Kong

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>MC, PC, TX</th>
<th>PV</th>
<th>PLB</th>
<th>BUS</th>
<th>LGV</th>
<th>HGV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross Harbor Tunnel</td>
<td>3.6</td>
<td>59.6</td>
<td>1.7</td>
<td>0.6</td>
<td>7.8</td>
<td>22.4</td>
</tr>
<tr>
<td>Eastern Tunnel</td>
<td>2.9</td>
<td>65.9</td>
<td>1.6</td>
<td>1.3</td>
<td>4.1</td>
<td>20.4</td>
</tr>
<tr>
<td>Western Tunnel</td>
<td>1.5</td>
<td>70.1</td>
<td>1.7</td>
<td>4.1</td>
<td>8.0</td>
<td>11.9</td>
</tr>
</tbody>
</table>
3.1. Traffic data for Hong Kong

The year 2000 traffic data for Hong Kong Island, published in the Annual Traffic Census 2000 by the Transport Department of Hong Kong (HKTD), are used for specifying the initial and boundary conditions of the model. The data are also used for model validation.

3.1.1. Traffic counting stations

In the Annual Traffic Census 2000, traffic flow is surveyed at 806 counting stations over Hong Kong, of which 203 are on Hong Kong Island. In this census, the road network on the island is divided into four categories:

(a) Urban 1: areas corresponding more or less to the business district;
(b) Urban 2 (major roads): areas including major road links in other urban areas;
(c) Recreational: areas including much of the Peak and the central part of the beach areas;
(d) Remote: South-eastern part of Hong Kong Island.

We chose three counting stations on the island (Fig. 1) for model comparison (Section 4.1), each of which represents a traffic category:

(a) Station 1001: Harcourt Road, representing the Urban 1 category;
(b) Station 1002: Victoria Park Road, representing the Urban 2 category; and
(c) Station 1011: Repulse Bay Road & Stanley Gap Road, representing the Recreation category.

The observed traffic flow data is divided into two main groups: one represents the average traffic flow on working days (Mon–Fri) and the other average traffic flow on weekends (Sat–Sun).

3.1.2. Traffic flow entering Hong Kong Island

Fig. 2 shows the averaged hourly inward (south bound) traffic flow on weekdays in three tunnels. There exists a morning (0800 and 0900) and an afternoon peak hour (1800 and 1900) in both Western and Eastern Tunnel, while a relative steady daytime flow appears in Cross Harbour Tunnel from 0800 to 1900. All three tunnels present minimum inward flow at dawn. In total, the Cross Harbour Tunnel has the highest traffic flow (61,816 veh day$^{-1}$), while the Western Tunnel has the lowest traffic flow (22,165 veh day$^{-1}$) during weekdays.

Fig. 3 presents the average incoming traffic flow during weekend in the three tunnels. The variation pattern for Cross Harbour Tunnel is similar to weekdays with the lowest traffic flow occurring around 0500. The morning peak time is delayed until 1000. In fact, traffic flow remains high from 1000 to 1900 before becoming less at 2100. After that, a night peak hour appears from 2200 to 2300. The traffic in both Western Tunnel and Eastern Tunnel show similar patterns to Cross Harbour Tunnel, but with much lower traffic flow during daytime. Again, among the three tunnels, the Cross Harbour Tunnel has the highest traffic flow (61,480 veh day$^{-1}$) and the Western Tunnel has the lowest traffic flow (18,013 veh day$^{-1}$) at weekends.

3.2. Vehicle behavior on network

Every vehicle on road has its own origin and destination (O–D). The traveling route of the vehicle depends on the driver’s need and traffic conditions. Numerous traffic assignment models have been developed aiming at determining the network flow patterns in order to provide route guides during times of concern (e.g. morning peak hours). A review of dynamic traffic assignment (DTA) models can be found in Peeta and Ziliaskopoulos (2001). A discussion of DTA problems was recently presented by Peeta and Yang (2003). Existing DTA models generally involve high complexity. In some studies, the problem is much simplified with specifications (Papageorgiou, 1990) such as: steady-state conditions (Sheffi, 1985); single destination (Sarachik and Ozguner, 1982; Wie, 1988; Ziliaskopoulos, 2000); fixed routes (D’Ans and Gazis, 1976) etc. The disadvantage of the simplifications is that they do not adequately reflect vehicle behavior on road network.

To overcome the problem, we propose a combination of deterministic and statistic constraints of three typical travel options for all vehicles—random turning trip, preferred turning trip and shortest path. In this study, we assume the origin of all vehicles be one of the three

<table>
<thead>
<tr>
<th>Speed dependency of PM$_{10}$ emission factors</th>
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<tbody>
<tr>
<td>Vehicle class</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>7</td>
</tr>
</tbody>
</table>
cross-harbour tunnels, ignoring the sources on Hong Kong Island.

3.2.1. Random turning trip

In this travel option, a vehicle travels randomly on road, i.e., it turns randomly to any linked road when encountering a traffic light or being at the intersection of multiple roads, only subject to traffic rules. Among all vehicles on a road network, only a small proportion of vehicles adopts this option of travel. We assume such proportion to be 10%. Fig. 4 shows an example of this option. A vehicle origins from the Western Tunnel and ends the trip on South Lane, Sham Wan, a no-through road.

3.2.2. Preferred turning trip

In this study, all roads are classified into four categories: tunnels, main roads, secondary roads and trails. For the preferred turning option, a vehicle at an intersection turns preferably to a higher class road. We assume 20% of the vehicles on road behave this way. Fig. 5 shows the driving route of a vehicle making
a preferred turning trip. It also originates from the Western Tunnel and, after exit from the tunnel, it travels along Connaught Road West toward Central.

3.2.3. Shortest path trip

Most drivers make a trip as short as possible to reach their destination. Our model is capable of finding the shortest path between the origin and destination of a trip using the Dijkstra algorithm, which is based on the Bellman optimality principle (e.g. Kreyszig, 1988).

Fig. 6 shows two shortest paths originating from the Cross Harbour Tunnel. One destination is located at intersection of High Street and Western Street, Sai Ying Pun and another destination is at King’s Road, Taikoo Shing. The shortest ways determined by the model are quite reasonable for given O–D.

3.3. Air quality monitoring

3.3.1. Site information

Air quality monitoring (AQM) in Hong Kong is carried out regularly at monitoring stations by Hong Kong Environmental Protection Department (HKEPD). This network covers Hong Kong Island, Kowloon and New Territory. The monitored pollutants include sulphur dioxide (SO\textsubscript{2}), nitric oxide (NO), nitrogen dioxide (NO\textsubscript{2}), carbon monoxide (CO), respirable suspended particulates (RSP) and ozone (O\textsubscript{3}). We use the hourly monitoring data of CO, NO\textsubscript{x} and RSP at three

Fig. 3. Incoming traffic flow in tunnels during weekends.

Fig. 4. An example for random turning trip.
roadside monitoring stations on Hong Kong Island for validating the model estimates.

The site information of three monitoring stations is as follows (HKEPD, 2000):

(a) Central/Western: located in a residential area and the sampling height is 18 m (4 floors) above ground;
(b) Causeway Bay: located in a busy commercial area and the sampling height is 2 m above ground;
(c) Central: located in a busy commercial/financial area and the sampling height is 4.5 m above ground.

The locations of the stations are shown in Fig. 1.

3.3.2. Observed pollution concentration

The monitored hourly concentrations of CO, NO$_x$ and RSP (PM$_{10}$) at the three stations in year 2000 are plotted in Fig. 7. The diurnal variation of the concentrations shows a degree of similarity with that of the workday's traffic flow observed in the same function district (Fig. 7d). The concentrations in Fig. 7a–c present the maximum values at 0800–0900 and 1700–1800, corresponding to the morning and afternoon peak hours of traffic in the area. This temporal feature is clearly observed at Central and Central/Western. At Causeway Bay, although the morning maximum of CO (Fig. 7a) and the afternoon maximum of NO$_x$ (Fig. 7b)
are not observed, another maximum is still notable in the plots. The minimum concentrations of pollutants appear at 0300–0500, when the traffic flow is at the lowest as well.

3.4. GIS and models

The models discussed in this study are the key components of the Traffic Emission Information System...

Fig. 7. Monitoring concentrations of (a) CO, (b) NOx, and (c) PM10. (d) Diurnal variation of traffic flow.

Fig. 8. Framework of TEIS.
(TEIS). TEIS consists of three modules: a traffic flow model, a traffic emission model and a pollution dispersion model. Together with the databases and post-processors, TEIS is integrated into a GIS framework. ArcGIS is used for the maintenance of model database and the visualization and analysis of model results. Fig. 8 illustrates the framework of the modelling system, in which the system database, including road network, territorial data, traffic features and vehicle characteristics as well as the meteorological and geographic data, and model output are stored, maintained and eventually visualized and analyzed in ArcGIS. The external models, traffic flow model, traffic emission model and air dispersion model coded in Fortran, are integrated into GIS by ArcInfo AML.

4. Results and discussions

4.1. Simulation of traffic flow

4.1.1. Traffic boundary and initial conditions

As Hong Kong Island is connected to the outside only with three cross-harbour tunnels, all vehicles entering our simulated domain are through the three tunnels. Therefore, the incoming traffic flow in the tunnels discussed in Section 3.1 is assigned as boundary conditions for the simulation. Our aim is to simulate traffic flow on network over 24-h time span. The simulation starts at 0:00 am, and the initial traffic flow on the entire network is assumed to be zero.

4.1.2. Traffic flow in tunnels

We first examine the simulation of traffic flows in the tunnels, at locations about 200–900 m away from the tunnel entries. Fig. 9a shows the simulated and observed traffic flow on weekdays at the examination point in the Cross Harbour Tunnel. The simulated traffic flow well reproduces the observations. Also, the simulations for the Eastern Tunnel and the Western Tunnel also show good agreement with the observed traffic flow (Fig. 9b and c).

4.1.3. Traffic flow at counting stations

We also simulated 24-h traffic flows for weekdays outside the tunnels. The simulated results are compared with traffic flow data obtained at three counting stations described in Section 3.1.

Fig. 10 shows the simulated traffic flow (normalized by its maximum value) at counting stations for weekdays. The observed traffic flow is also plotted for comparison. Station 1001 belongs to the Urban 1 category. The daytime traffic flow during weekdays (Fig. 10a) is characterized by the morning and afternoon rush hours around 0800–0900 and 1700–1800. Fig. 10a shows that the simulation reproduces the observed 24-h traffic pattern satisfactorily although the traffic flow from 1000 to 2400 is slightly underestimated.

A similar comparison for Station 1002 is shown in Fig. 10b. Station 1002 falls into the Urban 2 category. The road links within this category are mainly used for traveling to and from work on weekdays. They are also heavily used during weekends for recreational and social activities (HKTD, 2001). There are more obvious traffic peaks observed between 0800 and 1700. The model successfully simulated the bi-peak structure of the observed traffic flow although the first traffic peak at 0800 is somewhat over predicted. Also, the simulated traffic flow at night (after 1800) is somewhat lower than the observed values. This discrepancy may be caused by ignoring the sinks and sources on the network in this work, remaining as an important consideration to improve the modelling performance in future.

The simulated and observed traffic flow at Station 1011 is compared in Fig. 10c. Station 1011 falls into the
Recreational category. While most vehicles passing through this station on weekdays are also used for work trips, the observed traffic flow presents a different pattern in comparison to those at Stations 1001 and 1002 (Fig. 10a and b). In contrast to Stations 1001 and 1002, only one traffic peak is observed in the afternoon (1600) at Station 1011, while the simulated traffic flow presents the peak values during both morning (0800) and afternoon (1600). It is shown in Fig. 10c that the observation at this station is well produced by the model.

4.1.4. Sensitivity tests

Model simulations are also made for weekend cases. As discussed in Section 3.1, traffic patterns in the three tunnels during weekends differ from those observed during weekdays. In particular, no obvious traffic peaks are observed in the Western Tunnel and the Eastern Tunnel during the daytime. As most traffic travel for different purposes on weekends, different traffic patterns are also observed at the counting stations.

Fig. 11 shows the traffic flow patterns at three stations on weekends. Both observed and simulated traffic flow are plotted for comparison. Again, the simulation reproduces the observed traffic pattern quite well. Unlike the weekday cases, there is no obvious traffic peak during daytime at Stations 1001 and 1002 (Fig. 11a and b). This is understandable as there are less business trips to these areas on weekends. The peak hour at Station 1011 is at 1600 (Fig. 11c). This reasonably reflects the preferred time when the most business trips take place.

Fig. 10. Simulated against real-time traffic flow at counting stations (weekdays): (a) 1001; (b) 1002; (c) 1011.

Fig. 11. Simulated and observed weekend traffic flows at three counting stations: (a) 1001; (b) 1002; (c) 1011.
traffic for recreational purposes are on roads to the recreational area.

4.2. Simulation of traffic emission

Traffic emission rates (kg h\(^{-1}\) km\(^{-1}\)) are calculated using Eq. (9). The predicted diurnal variations of CO, NO\(_x\) and PM\(_{10}\) at Central, Causeway Bay and Central/Western are plotted in Fig. 12. It is observed that the variation of traffic flow in Fig. 7d is completely reflected in the curves in Fig. 12. This means the linear relation between traffic flow and traffic induced emission rates.

Figs. 7a–c and 12a–c are not directly comparable because pollution concentrations are measured at the monitoring stations while the model predictions are pollution emission rates. Instead, we analyze the correlation between the predicted emission rates and measured concentrations as a validation of the emission model.

The predicted hourly emission rates (kg h\(^{-1}\) km\(^{-1}\)) against the observed concentrations (µg m\(^{-3}\)) of CO, NO\(_x\) and PM\(_{10}\) at Central, Causeway Bay and Central/Western are shown in Figs. 13–15. The linear regression equations and the correlation coefficients \(R^2\) are also shown in the charts.

Figs. 13–15 indicate that the observed hourly pollution concentrations have a close linear correlation with the predicted traffic emissions at the three stations. For CO, the correlation coefficients, \(R^2\), at both Causeway Bay and Central are larger than 0.8. The \(R^2\) of NO\(_x\) at Central is as high as 0.86. While it is somewhat lower at Causeway Bay and Central/Western, it still has the value of 0.78 and 0.74. The \(R^2\) of PM\(_{10}\) at the three stations are between 0.82 and 0.85. The correlation coefficients are summarized in Table 5. These results confirm the good performance of both the traffic flow model and the traffic emission model.

5. Conclusions

A Lagrangian traffic flow model and an emission factor based traffic-related air pollution emission model have been developed in this study. The traffic flow model
is simple, but has been found to be quite efficient. With the specification of travel behavior, the model is capable of simulating traffic flow on a road network. The model has been applied successfully to Hong Kong Island. The simulated traffic flows in three cross-harbour tunnels and at three counting stations on the island for weekdays and weekends have been compared with observations. Good agreement has been found. The temporal variations of traffic flow in the cross-harbour tunnels and at the counting stations are reproduced by the model at satisfactory level.

Using the simulated traffic flow and empirical vehicle emission factors, the hourly emission rates of CO, NOx, and PM10 are predicted and compared with the corresponding pollution concentrations at three air quality monitoring stations. It is found through a correlation analysis that the two data sets are well correlated. This shows that the emission factor based approach for the prediction of traffic induced pollution emission in urban area is adequate.

In addition to providing traffic flow data for traffic-related pollution simulation, the traffic flow model presented in this work can also be used to predict the congestion cases at select traffic black points due to such impacts as vast traffic amount, design faults of signal system and management.

| Table 5 | Summary of correlation between hourly concentrations and traffic emissions |
|---------|-------------------------------|-------------------|-------------------|
|          | Station CO NOx PM10          |                   |
| Causeway Bay         | 0.80   | 0.78   | 0.83   |
| Central            | 0.84   | 0.86   | 0.85   |
| Central/Western    | --     | 0.74   | 0.82   |
Acknowledgements

This study is supported by the Strategic Research Grant of City University of Hong Kong (SRG7001254). Traffic flow data were provided by the Transport Department of Hong Kong and the air pollution data were provided by the Environment Protection Department of Hong Kong.

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