A Modelling Framework for estimating Road Segment Based On-Board Vehicle Emissions

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Abstract. Traditional traffic emission inventory models aim to provide overall emissions at regional level which cannot meet planners’ demand for detailed and accurate traffic emissions information at the road segment level. Therefore, a road segment-based emission model for estimating light duty vehicle emissions is proposed, where floating car technology is used to collect information of traffic condition of roads. The employed analysis framework consists of three major modules: the Average Speed and the Average Acceleration Module (ASAAM), the Traffic Flow Estimation Module (TFEM) and the Traffic Emission Module (TEM). The ASAAM is used to obtain the average speed and the average acceleration of the fleet on each road segment using FCD. The TFEM is designed to estimate the traffic flow of each road segment in a given period, based on the speed-flow relationship and traffic flow spatial distribution. Finally, the TEM estimates emissions from each road segment, based on the results of previous two modules. Hourly on-road light-duty vehicle emissions for each road segment in Shenzhen’s traffic network are obtained using this analysis framework. The temporal-spatial distribution patterns of the pollutant emissions of road segments are also summarized. The results show high emission road segments cluster in several important regions in Shenzhen. Also, road segments emit more emissions during rush hours than other periods. The presented case study demonstrates that the proposed approach is feasible and easy-to-use to help planners make informed decisions by providing detailed road segment-based emission information.

Keywords: Floating Car Data, On-road Vehicle Pollutant Emissions Model, Speed-Flow Model, Temporal and Spatial Distribution of Road Segment Emission, CMEM Model

1. Introduction

Vehicle emissions are a dominant source of urban air pollution in China. Transportation systems contribute significantly to carbon monoxide (CO), nitrogen oxides (NOₓ), and hydrocarbon (HC) emissions in urban areas [1]. The control and reduction of the traffic pollution is a main component of research on sustainable transportation development [2]. Emission models are becoming increasingly

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important for the evaluation of road investment projects, transport network and national emission levels regulations, and for the design and evaluation of local emission control policies. Traffic emission models can be divided into three classes: macroscopic, microscopic, and mesoscopic. Macroscopic models deal with overall traffic emissions inventory for air quality simulation and air pollution control at regional level. This could be at the city or state level. Microscopic models simulate emissions from individual vehicles in second by second measurements. Lastly, mesoscopic models estimate emissions based on the behaviors of fleet on each road link or segment using macroscopic variables such as link flows and link travel times. Normally, the mesoscopic model is more suitable for transportation planning, due to its ability to allow planners to analyze the impact of traffic system on traffic emissions by providing detailed traffic emission information at road link level. In this study, a mesoscopic analysis framework is designed for better supporting planning by analyzing traffic emissions at the road segment level.

Acquisition of road traffic data is essential in a traffic emission model. Various methods are generally used to collect traffic data, such as traffic surveys, traffic model simulations, stationary sensor/camera based methods and air/space-borne methods. However, those methods have many limitations. For example, traffic survey data are limited by survey time and locations, and will therefore lead to uncertainty when they are extended to larger areas. There is also an accuracy issue in survey data as many survey respondents cannot (willingly or unwillingly) accurately record their travel details. Floating car technology is an advanced means of collecting information of traffic condition of roads, which can overcome the limitations of previous mentioned methods. The term floating car data (FCD) refers to data that is continuously collected by a fleet of vehicles, which can be considered as a distributed network of sensors [3]. FCD have been widely used to acquire traffic flow information for properties of high coverage rate and data accuracy. Many feasible solutions and methods are achieved based on FCD in recent years to solve the problems of above traffic data collection methods [3, 4]. However, FCD is seldom used in traffic emission study even though it provides great opportunity for emission analysis, including continuous data on vehicle speed and occupancy at the individual vehicle or road segment level.

The objective of this research is to analyze traffic emission at the road segment level based on FCD. Thus, one mesoscopic on-road vehicle emission analysis framework is used. Here, a road link is divided into segments by unit length in order to fully use the information contained in FCD.

2. Methodology

As illustrated in Figure 1, the methodology employed for estimating road segment-based emissions in this paper consists mainly of three parts: (a) ASAAM (Average Speed and Average Acceleration Module), which calculates road segment average speed and average acceleration at a given time using FCD, (b) TFEM (Traffic Flow Estimation Module), which operates on the outputs of ASAAM to estimate the traffic flow of each road segment in different time of a day based on the relationship between speed and flow and also the temporal-spatial distribution of traffic flow, and (c) TEM (Transportation Emission Module), which estimates the emissions of CO, HC and NO\textsubscript{x} produced along...
each road segment by using traffic flows of road segments calculated using TFEM and the average road segment speed and acceleration is calculated by ASAAM.

2.1. Average Speed and Average Acceleration Module

This module computes the average speed and average acceleration of a road segment by taking an average of all FCD that are on this road segment, which is finally supported by GIS technology. However, there are typically two problems that needed to be solved when FCD are used.

First, road sections have different speeds and acceleration characteristics. For example, the start and end of the road link are associated with higher acceleration and lower speeds, whereas low acceleration and higher speed in the middle section. It is problematic to apply average speed for traffic emissions, as emissions are sensitive to both speed and acceleration. In order to solve this problem, the road link is split into smaller unit segments to reflect the variation of speed and acceleration of road sections in this paper.

Second, there is no acceleration data in the original FCD. As taxicab sends data to server in about 30 second intervals, it is reasonable to calculate the taxicab’s average acceleration by its speed changing between adjacent positions. Thus, the acceleration of floating car at position \( i \) is:

\[
acc_i = \frac{v_{j} - v_{i}}{T_{j} - T_{i}}
\]

where, \( v_{i} \), \( v_{j} \), \( T_{i} \), \( T_{j} \) are the speeds and time when taxicab is at position \( i \) and next adjacent position \( j \), respectively.

2.2. Traffic Flow Estimation Module

Due to the nature of FCD, estimations of traffic flow based on a speed-flow model are possible. There are different types of speed-flow model such as linear model [5], logarithmic model [6], exponential model [7], the BPR model [8] and Akcelik equation [9]. Dowling et al (2008) compare the BPR model, exponential model and the Akcelik equations and found that the Akcelik equation performed better than any other models because it adds signal delay to the segment free-flow travel time, rather than treating delay as a multiplicative [10]. Li et al (2002) believe that the exponential model can be directly used for estimating traffic flow [11].

Yang et al (2006) put forward a speed-flow model based on the relationships among traffic flow, vehicle speed and traffic flow density. Similar three-phase traffic theory is also discussed in several papers [12-15]. After testing this model on different road links in Hangzhou City in China, the results indicated that this model is validated and feasible for traffic flow estimation [16]. Thus, this model is chosen in our study. In this study, traffic flow for each road segment is calculated using Yang’s model [12].

2.3. Traffic Emission Module

Traditional on-road emission inventory model uses composite emission factors expressed in grams per mile and the miles travelled by total vehicles to calculate traffic emission. The fundamental processes such as speed and acceleration, affecting emissions are characterized by the nature of traffic occurring on them [16]. Recent studies have shown that CMEM (Comprehensive Modal Emission Model) emission factors are suitable to conditions in China [17, 18]. The methodology described here relies on emission rate estimated from CMEM and EMFAC2000, which is also recommended in NCHRP report 535 [19]:

\[
E_{R} = \sum_{i,j} q_{R}(i,j) \times v(i,j)
\]

where \( E_{R} \) is the emissions for pollutant \( R \) in terms of grams, \( q_{R}(i,j) \) is the emission rate for pollutant \( R \) in terms of grams per hour for movement at speed \( i \) and acceleration \( j \), which could be obtained from the emission rate tables of average rates for each acceleration and speed category,
developed with the Comprehensive Modal Emission Model (CMEM) under NCHRP Project 535[19] and \( v(i, j) \) is the VHT at speed \( i \) and at acceleration \( j \).

\[
VHT = N \cdot \bar{T} = L \cdot F \cdot T \cdot m \cdot L/v
\]

where \( N \) = number of light duty vehicles that pass through the road segment within time \( t \); \( \bar{T} \) = the average time by which vehicle pass this road segment. \( L \) = number of lane. \( F \) = road segment traffic flow, taken come from the traffic flow estimation module described above; \( L \) = road segment length. \( V \) = the average speed; \( m \) = the rate of light duty vehicle of total.

3. Results analysis and discussion

Shenzhen, China was used as a case study. Road segments in Shenzhen highway network are classified into five basic categories. On-road light duty vehicle emission data for each road segment of Shenzhen is obtained through the analysis framework discussed above. Table 1 shows the summary of the Shenzhen’s on-road light duty vehicle emissions, where we can see that daily emission on weekday is a little higher than weekend day.

|                      | CO  | HC  | NOX |
|----------------------|-----|-----|-----|
| Daily emission on weekend day (Ton) | 2315 | 141 | 141 |
| Daily emission on weekday (Ton)     | 2376 | 145 | 145 |
| Annual emission (Ton)              | 860967 | 52582 | 52681 |

3.1. Spatial distribution of daily emissions

As shown in Figure 2, road segments with high daily emission rate are mainly expressways. That is because of the high average speed and high traffic of expressways. Most high emission road segments are located in the Shenzhen Special Economic Zone (SSEZ), which indicates that traffic flows are spatially clustered due to more traffic trips generated by the high level economic activities in SSEZ. The SSEZ is suffering higher traffic emission pollution, because of the high quantity and density of high emission road segments. Therefore, more attention should be paid to road segments with high emissions, especially those in SEZ, for future transportation planning.
3.2. Temporal Distribution of Daily Emissions

Total hourly emissions of CO, HC and NO\textsubscript{x} from Shenzhen traffic network are illustrated by Figure 3. The characters of temporal distribution of daily emissions could be summarized as:

- The curves of CO, HC and NO\textsubscript{x} have similar shape, which indicates that all types of emissions have similar temporal distribution. That could be explained in the above methodology (equation 4 and 5). Emissions from a road segment are determined by emission rates and vehicle hour travelled (VHT). Since all types’ emission rates has the same speed and acceleration distribution, the same temporal distributions displays when all types of emissions from the same traffic network.

- The maximum emissions happen on weekdays from 8 am to 11 am and from 1 pm to 7 pm. This is seen by the increased traffic, which leads to frequent acceleration and deceleration and lower traffic speeds, caused by the rush hour commute and high business activities during those two periods. Emissions on weekend day evenly lasted from 8 am until 21 pm due to the non-business trips for recreation, which are not so strictly restricted by time schedule as business trips. Therefore, there is a more obvious bimodal distribution (8am-11am and 13pm-19pm) on weekday rather than weekend day.

- Emissions on weekday are slightly higher than weekend day, which indicates that the traffic conditions during weekday are more serious than those on the weekend. The reason is that many people choose stay at home or travel by foot instead of car in weekend day. Therefore, higher traffic flow, lower speed and more frequent accelerations in weekday are observed.

![Figure 3](image)

**Figure 3.** Hourly emissions of Shenzhen city’s traffic network. a: CO; b: HC; c: NO\textsubscript{x}.

4. Conclusions

Traffic emission is a major contributor to urban air pollution. A traffic emission analysis, based on FCD, provides useful traffic emission information at the road segment level, which can then be used for urban air quality control and transportation planning. The results of this study show that high emission road segments cluster in several regions. For example, the SSEZ has higher density of high emission road segments. Road segments emit more pollutants on workday than weekend day and at peak hour than other time. Thus, special consideration should be paid to those segments with high emission rate and regions with high density of high emission road segments.

Compared to traditional traffic emission inventory models, this framework is easy-to-use. It can provide detailed real-time traffic emissions information of each road segment based on FCD. Thus, it is very helpful in guiding city and environmental planning activities. Planners can put limited financial resources to road segments or regions which emit more emissions than others, for example, to develop Intelligent Transportation System to smooth traffic flow or build green belt to absorb traffic emissions.
Also, planners can figure out reasons that lead to high emissions by linking the emissions to the nature of the road segment, which helps their solutions making.

In the future work, an information system should be developed based on this analysis framework to provide real time emissions for public decision makers and planners using real time FCD. New technologies should be developed in order to get traffic flow data more accurately.

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