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Traffic emission pollution sampling and analysis on urban streets with high-rising buildings

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Abstract

Air pollution at many types of intersections and other roadside "hot spots" is not accurately characterized by state-of-the-practice models. In this study, data were collected on traffic flows, second-by-second CO and NO_2 ambient concentrations in Shanghai, China. The sampled data were compared with CAL3QHC modeling results. We found that: (1) intersection hot spot emission concentrations were explained primarily by queuing activities of motor vehicles; (2) air quality concentrations are difficult to predict because of complex dispersion processes near high-rise buildings; and (3) screening models such as CAL3QHC are prone to large errors in dense cities with mixed traffic and high-rising buildings. Suggestions are made for improved models relevant to dense developing cities. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Traffic-induced air pollution in China first gained attention in the early 1980s (Sun, 1982). Some pollution effects from transportation are regional, usually ozone buildups resulting from high emissions of hydrocarbons and oxides of nitrogen, and others are more local. Many sources contribute to ozone and other regional air pollution problems, but the local effects near road facilities are almost totally related to vehicles. Here we focus on local effects. The local pollution problem in China is apparently becoming severe. Recent studies show that cyclists and traffic police stationed in intersections experience NO_x exposure levels twice that of the National Ambient Air Quality Standards (which requires daily average NO_x concentration of 0.10 mg/m^3) (Song, 1997).

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Modeling tools are needed to predict roadside air quality and to analyze travel behavior strategies to mitigate impacts. In the US, intersections and other road facilities with high levels of pollution are deemed "hot spots". When new facilities are planned to build and may cause traffic congestion deteriorate to "level of service" D or lower, air quality assessments are required (Environmental Protection Agency, 1992; Meng and Niemeier, 1998). There are a wide variety of modeling tools that can be used to assess local pollution impacts. The most widely accepted are the CAL3QHC models, certified by both the California Air Resources Board and US Environmental Protection Agency. These traffic-emission-dispersion modeling systems are developed for motor vehicle traffic in flat terrain. They are less reliable in places such as Shanghai, where land use densities are high and mixing of non-motorized and motorized traffic causes erratic and often slow speeds. They also do not have enough spatial or temporal resolution to estimate exposures to cyclists and pedestrians, and their use of Gaussian dispersion processes is not well suited to vehicle emission dispersion patterns near high-rise buildings, which dominate Chinese cities (Zhou et al., 1994).

A variety of efforts are underway to design better models for intersections, highway ramps and other hot spots. For instance, Barth et al. (1999) and others in the US are developing modal emission models that can estimate emissions from microscopic traffic conditions, while Yuan et al. (1998) measured instantaneous exhaust emission concentrations at tailpipes using a remote sensing system. These research efforts produce better modeling tools for emissions. But better air pollution dispersion models are also needed to predict traffic-induced pollution. However, most air dispersion modeling work is focused on large scale industrial pollution sources (see http://www.epa.gov/asmdnerl/). Recent efforts with respect to vehicle emissions include Moseholm et al. (1996), who conducted a sampling technique for "sheltered intersections," and Matzoros and Van Vliet (1992a,b) who analyzed emissions for traffic control strategies at intersections using queuing theory and traffic simulations.

In China, an increasing effort is being devoted to understanding traffic characteristics, emissions, and emission dispersion processes, and the relationships between these phenomena. In one case, an instrumented van collected data on traffic movements and recorded the operating mode in mixed traffic in Shanghai and six other cities (Tang et al., 1999). Vehicle emission factors (emission rates as a function of speed and other operating variables) were developed by the China National Mobile Source Emission Laboratory (Yuan et al., 1998). Zhou (1998) modeled micro-scale dispersion processes near high-rise buildings on urban streets using wind tunnels and numerical simulation.

This paper reports on a study in Shanghai of emissions along streets with mixed traffic and high-rise buildings. Our goal is to determine how to improve hot-spot traffic emission modeling tools for situations typical of China (and other dense cities). We begin by comparing collected data with predicted outputs of the CAL3QHC model.

2. Data collection

A roadside ambient CO and NO_x sampling system was developed with sensitive CO and NO_2 sensors. These sensors measure the ambient concentration and generate the analog signal and input to the data acquisition system, which consists of high speed and high discretion A/D and

PC. The sampling data are stored directly onto the hard disk. The entire sampling system was calibrated before field measuring.

Three typical sampling sites were selected. One is a traffic-light controlled intersection, and the other two are road segments, with and without an elevated overhead expressway.

The intersection is located at Dalian Road and Quyang Road in downtown Shanghai. Both roads are four lanes (two lanes in each direction) arterials, each about 40 m wide (see Fig. 1). The roads near the intersection are lined with 3–8 story buildings. In the northeast corner there is one 20-story building, but it is far enough away to have little effect on atmospheric dispersion near the intersection. CO and NO_2 concentrations were measured second-by-second on the sidewalk along the east approaching leg of the intersection. The receptor on the eastern side is 20 m from the stop line.

The two road segments selected for sampling are parallel arterial streets, lined by four-story buildings (see Fig. 2). One segment is covered by elevated expressway with four lanes of two directions. The receptors are sited at ground level at the up-wind side of roadway.

The concentration sampling system consists of an electro-chemical sensor and data recording unit that can record the data automatically into a microcomputer as described above.

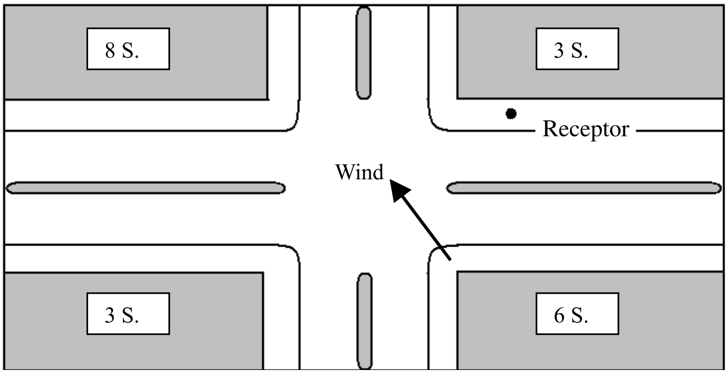

Fig. 1. Sampling site at intersection.

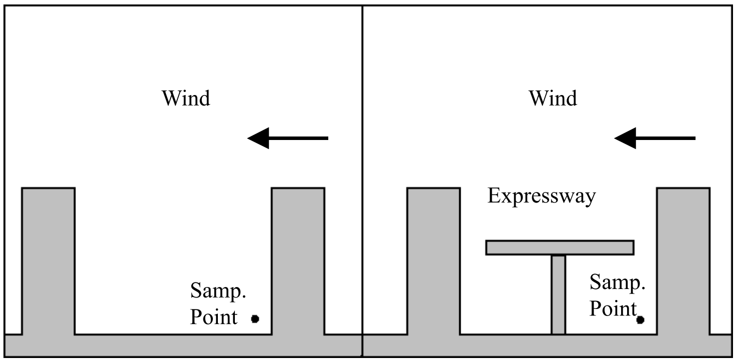

Fig. 2. Sampling sites at road segments w/ and w/o elevated expressway.

3. Data analysis

Data were sampled during morning peak hours of 6:30–9:30 on 16 April 1998. At the receptor, CO and NO_2 concentration data were recorded second-by-second continuously. Vehicles passing through stop lines of the eight approaching lanes in four directions were counted. For the approaching lanes in the east leg, queued vehicles were counted every 10 s in order to estimate the queuing delay and the queuing vehicles' modal activity. The intersection is controlled by a traffic light and coordinated with nearby intersections. The cycle length is 100 s in two phases. Green time is 50 s for the east–west bound movements. It was 18°C and cloudy that day, with wind speeds of around 3 m/s at the rooftop during the sampling time.

Figs. 3 and 4 are the sampled CO and NO_2 concentration profiles at the receptor, respectively. Fig. 5 is the delay per cycle of the movements in the sampled approaching lanes. The delay is calculated from queue length counting data using the method proposed for mixed traffic by Yang and Yang (1992). Fig. 6 is the flow rate in PCU/cycle of the approaching movements passing through the stop line.

We note that both CO and NO_2 concentrations vary roughly in proportion to traffic delay. CO concentrations fluctuated much more than NO_2 concentrations – as expected, since NO_2 is the result of continuing chemical reactions between tailpipe NO and O_2 in the air.

Each concentration peak corresponds to one delay peak (roughly queue length). High delay peaks occur around the periods of 7:00–7:10 and 7:40–8:00. There are concentration peaks corresponding to the first period of delay peaks, but that is not the case for the second period of delay peaks. That is because the atmosphere becomes unstable after the sun rises and warms the lower atmosphere, causing the dispersion rate of emissions to increase.

As shown in Figs. 7 and 8, emission concentrations were found to be proportional to traffic delay, rather than to traffic flow rates of the approaching lanes. Eqs. (1) and (2) are the regression

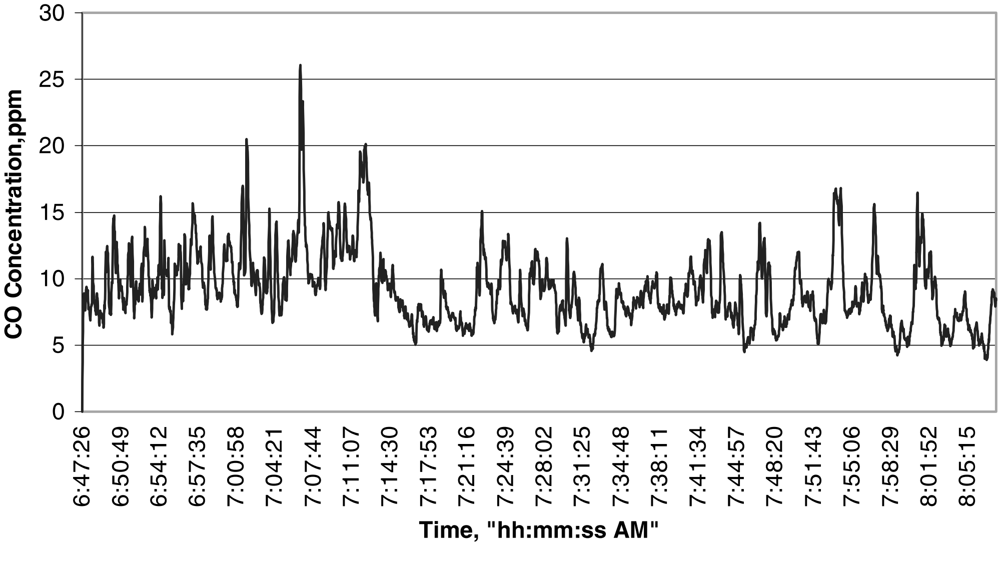

Fig. 3. Second-by-second CO concentration at the intersection.

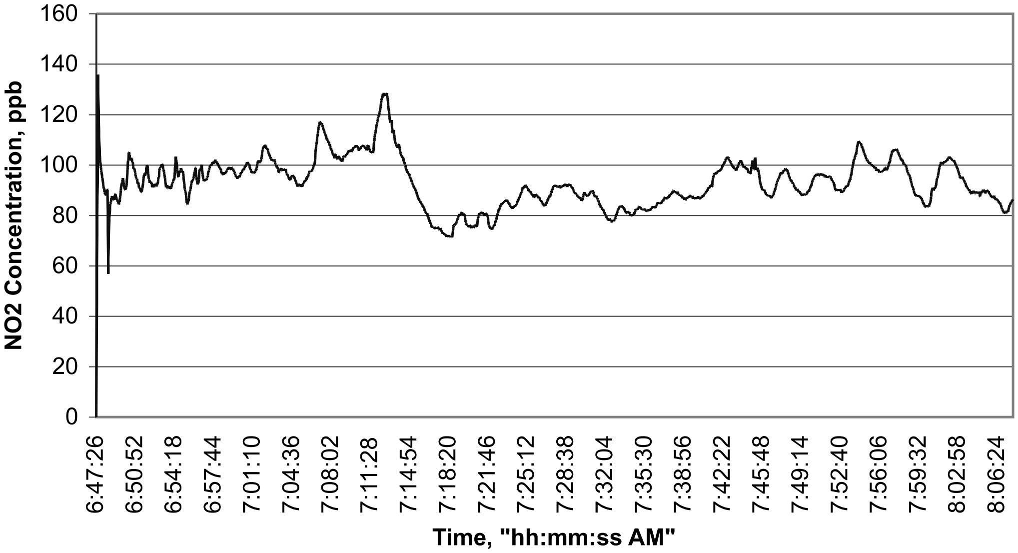

Fig. 4. Second-by-second NO_2 concentration at the intersection.

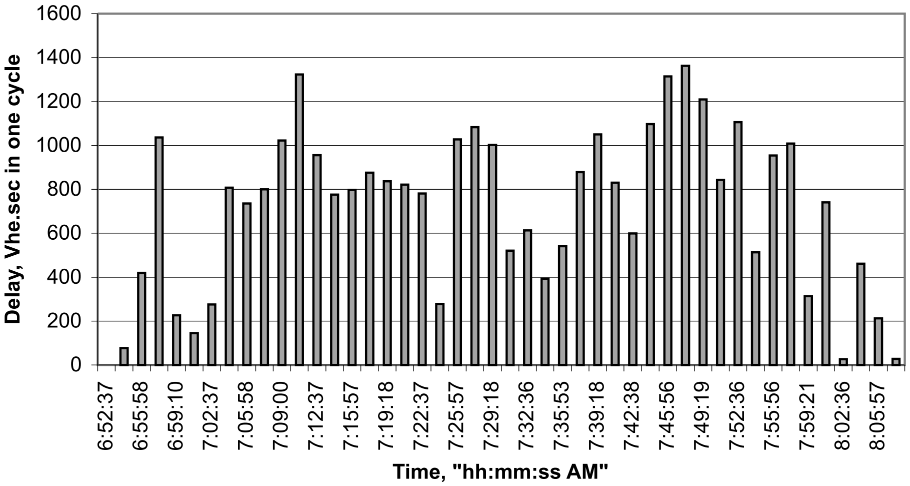

Fig. 5. Delay of the approaching movements, vehicle-s per cycle.

results between the measured concentrations and traffic flow rate and delay at the stop line. The regression work is carried out with the data analysis tools in EXCEL. Delay is measured as overall delay per cycle, in s, and the traffic flow rate in PCU/cycle.

$$[CO] = 0.0115 \times \text{Delay} + 0.0026 \times \text{Flow}, R = 0.986, \qquad (1)$$

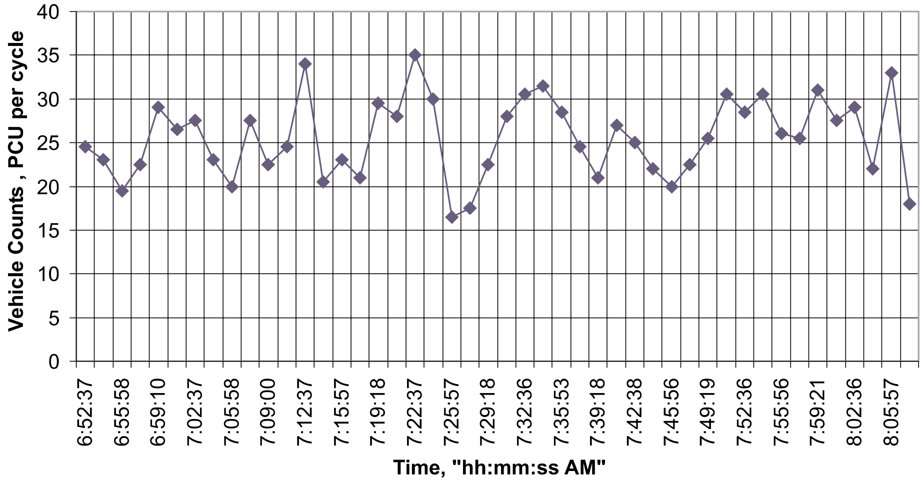

Fig. 6. Flow count of the approaching movements, PCU per cycle.

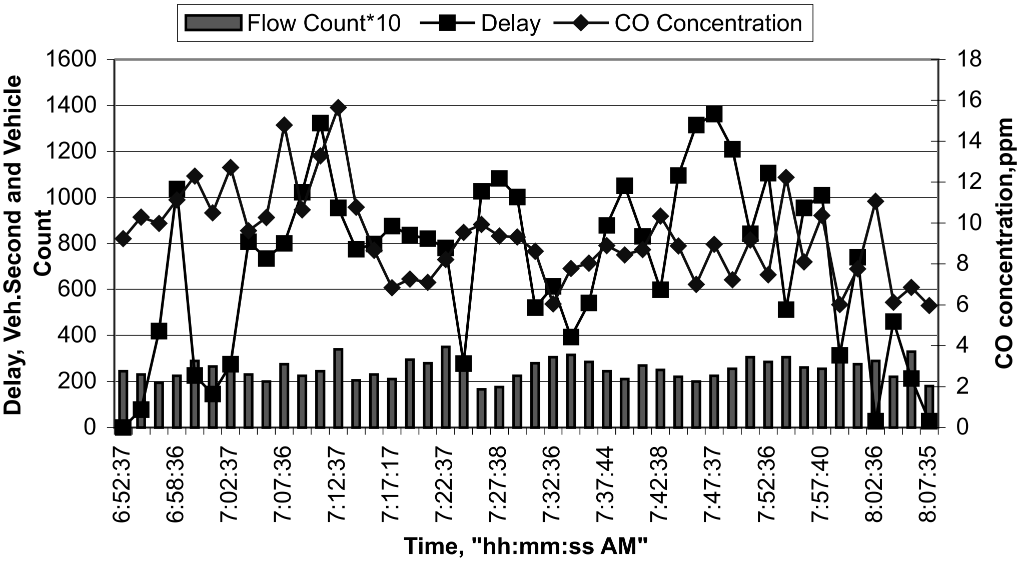

Fig. 7. CO concentration, delay and traffic flow rate regression.

$$[\mathrm{NO}_x] = 0.1054 \times \mathrm{Delay} + 0.0443 \times \mathrm{Flow}, R = 0.921. \tag{2}$$

During the sampling period, the traffic flow at the intersection was over-saturated most of the time. The flow rate is controlled by the saturated flow rate. The traffic emission rate is roughly controlled by the delay.

It was also found that high NO_2 concentrations can occur in the vicinity of intersections, where formerly only CO pollution had been prominent. The high NO_2 concentration comes from the "creeping" of over-saturated queuing traffic.

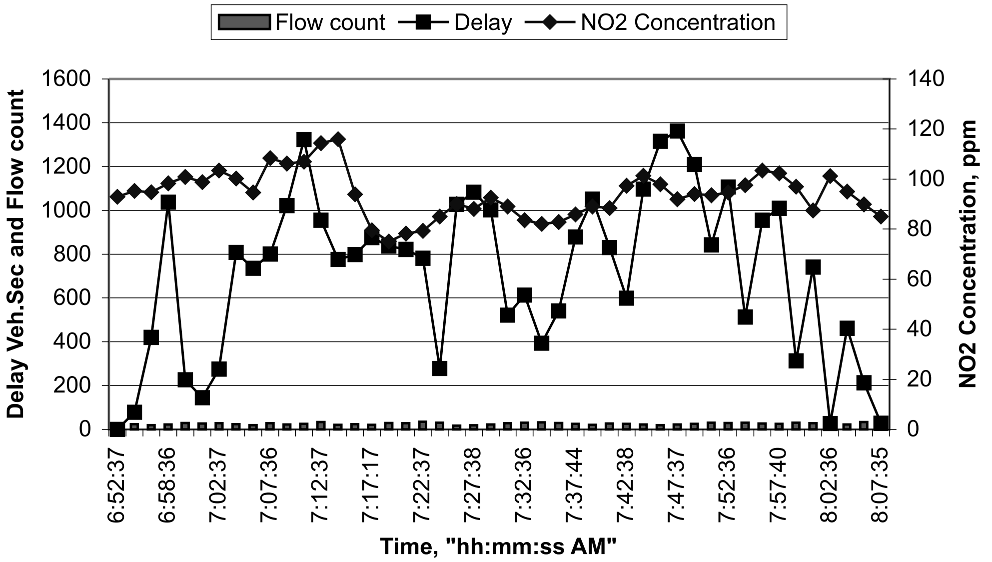

Fig. 8. NO_2 concentration, delay and traffic flow rate regression.

The road segment part of this study was designed to test the effect of tall buildings and overhead roads on roadside concentrations. The sampling configuration is shown in Fig. 2 above. The sampling points were located at ground level.

Only CO concentrations, traffic flow rates, and speeds were measured. Based on a preliminary investigation of the roads, it was found that the two sites had similar traffic characteristics in terms of vehicle type, flow rate, traffic controls for the upstream and downstream intersections, traffic flow rate variation over time, and bike flow rate. Sampling results for the two road segments are presented in Fig. 9.

In general, concentrations under the expressway were found to be 2.5 times higher than those on the uncovered road at the same flow rate. CO concentrations for both locations varied with the traffic flow rate of the lanes next to the sampling point.

The correlation between CO concentration and traffic flow rate is stronger for the uncovered arterial than the covered. That is because the overhead expressway forms a closed space, altering in unpredicted ways the dispersion of emissions. Some of that unpredicted dispersion may be related, in the case of the covered arterial, to greater than expected influences of emissions from traffic on the opposite side of the street. Indeed, we did find some correlation for the covered arterial between concentrations and traffic flow on the opposite side.

4. Accuracy of the US dispersion model

CAL3QHC is a widely used state-of-the-practice dispersion model used in the US to predict local concentrations at intersections and along roadways (Environmental Protection Agency, 1992). To explore its applicability for China (and other non-US situations), the sampled CO concentrations at the three locations noted above were compared with CAL3QHC predicted data.

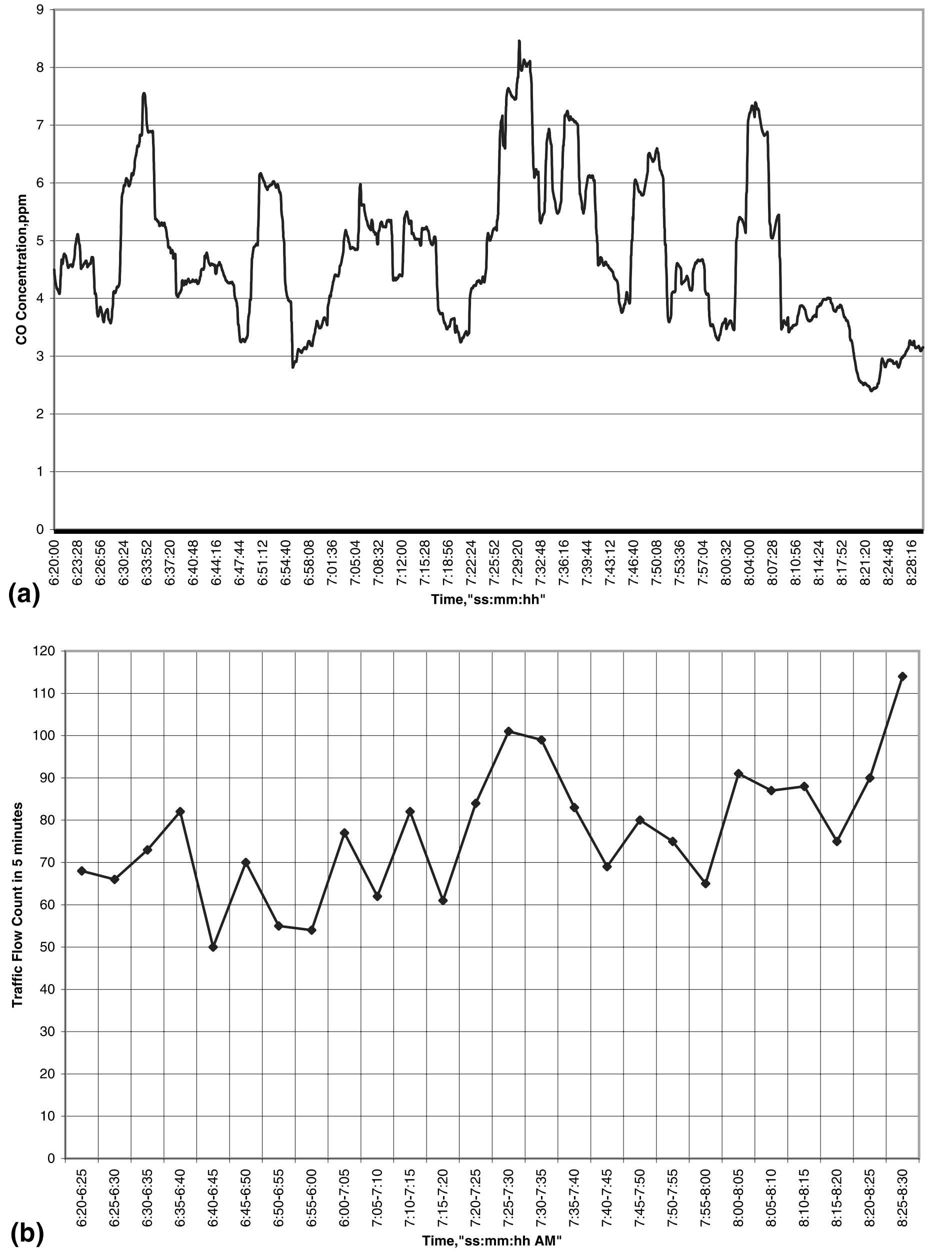

Fig. 9. (a) CO concentration at pedestrian level of road segment 1 (open space); (b) flow rate at the sampling side of road segment 1 (open space); (c) CO concentration at pedestrian level of road segment 2 (under elevated expressway); (d) flow rate at the sampling side of road segment 2 (under elevated expressway).

The input data for CAL3QHC for the intersection case include lane geometry, traffic flow count, weather conditions and CO emission factors for motor vehicles. (We used 487 g/veh-h for idling and 47.6 g/veh-mile for vehicles moving at 11.2 mph. Though these emission factors were

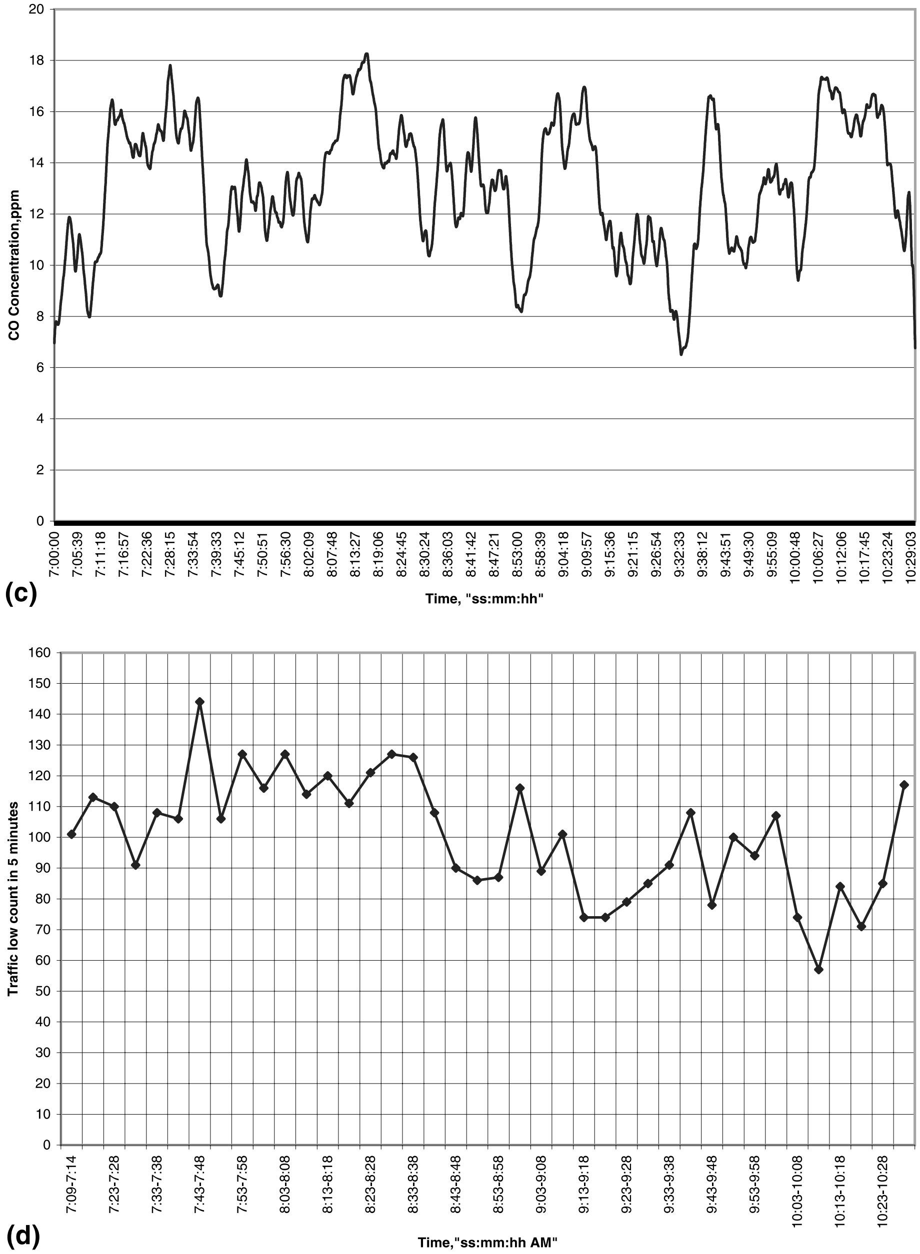

Fig. 9 (*continued*)

obtained from typical light duty vehicles in China operating at typical speed conditions, their accuracy is uncertain. The emission factors are likely equivalent to those in the US in the early 1980s.) Traffic flow data for the same period are shown in Table 1. Table 2 summarizes the sampled and predicted CO 1 h average concentration for receptors for 6:55–7:55 a.m.

Table 1
Traffic volume data in PCU/h

	East	West	South	North
Left	55	188	244	333
Right + through	1051	806	417	903

Table 2
CO concentration in ppm, 1-h average

	Sampled	CAL3QHC
Receptor	11.1	6.9

Table 3
Traffic volumes and measured and calculated CO concentrations

	South B. flow rate	North B. flow rate	Measured CO ppm	CAL3QHC CO ppm
Uncovered arterial	1793	1441	5.22	3.9
Covered arterial	1821	1640	13.4	4.3

Data for the non-intersection road segment cases were also prepared and inputted in the CAL3QHC model. Table 3 shows the inputted traffic data, and measured and modeled CO concentrations. The time period tested was 7:10–8:10. The emission factors for the open and covered arterials are 49.6 and 52.4 g/veh-mile, corresponding to speeds of 8.8 mph and 3.4 mph.

The calculated values of the CAL3QHC model significantly underpredict CO concentrations for the uncovered (open) road segment – about 25% below measured values. For the covered arterial, the error is huge – off by a factor of 4 – with predicted model values only 25% of the actual measured concentrations.

As explained below, the prediction errors for the intersection seem to be related to the mixed traffic characteristics seen in non-OECD countries and the presence of high-rise buildings nearby; the errors for the covered arterial seem to be due to the unique dispersion patterns caused by overhead obstructions.

The mixed traffic, with many bicycles and other slow vehicles, causes more interruptions to motor vehicles passing through than is characteristic of the US, resulting in larger speed fluctuations. The flow rate of queue dissipation is relatively lower than the value calculated according to the Highway Capacity Manual (Transportation Research Board, 1994), meaning more delay for the queuing motor vehicles.

Vehicle queuing activity affects not only emission rates, but also the spatial distribution of emissions. These variations in spatial distribution cannot be addressed with average traffic data. We illustrate the importance of this variable in conditions of heavy traffic, with the following calculations.

Consider the profiles of calculated CO and NO_x emission rates for one queueing cycle (in the studied approaching lane) as depicted in Fig. 10. The queue formation (slowing and stopping) and dissipation (leaving) rate come from the traffic count data. The modal emission data come from

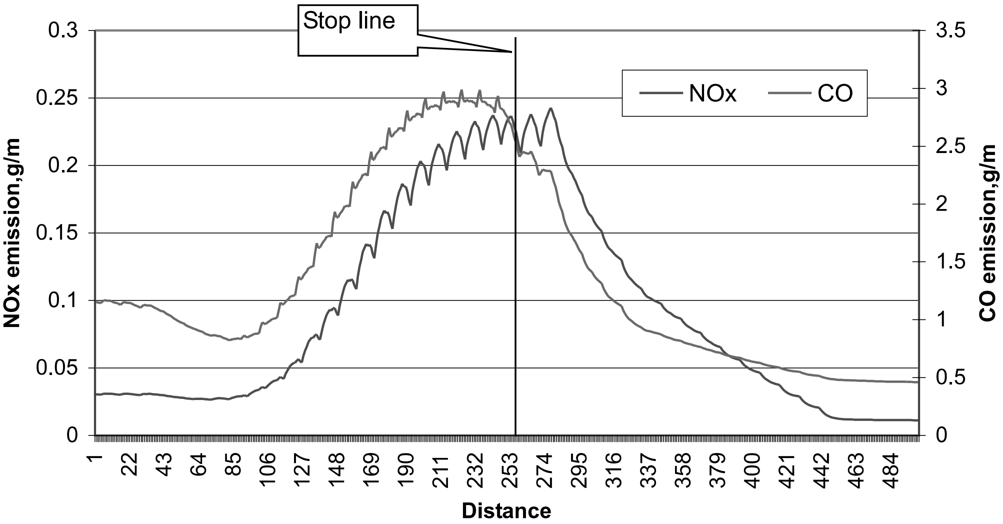

Fig. 10. Simulated CO and NO_x emitting intensity from the queue along the approaching lane.

several vehicle tests (Yuan et al., 1998). From Fig. 10, we note that: (1) CO and NO_x emission densities increase in the approaching lane towards the stop line. The highest emission rate occurs around the stop line. CO emissions decline right after the stop line, whereas NO_x emissions increase a little after the stop line. This is because CO emissions come mostly from idling and acceleration whereas NO_x emissions come mainly from acceleration. (2) At the queue tail, CO emissions tend to be higher, considerably more than NO_x emissions, in this case because CO emission rates from vehicles are significantly higher than NO_x emission rates during deceleration.

In summary, queuing effects at intersections with over-saturated traffic can have large effects on pollution concentrations and pollution spatial distribution. To be accurate, models need to address not only stop-line delay, but also vehicle queuing activity. The current CAL3QHC queue model focuses mainly on average queuing delay, rather than the spatial variation of emission rates. This shortcoming of CAL3QHC is especially critical in China, since it greatly underestimates the exposure of cyclists (and pedestrians).

Even more data and enhanced modeling are needed to understand and predict accurately the apparently high pollution exposure of cyclists. The CAL3QHC model uses a “fixed” receptor and 1-h average concentrations; this hides the frequent high exposures experienced by cyclists (and others near intersections). An improved model would include more temporal and spatial disaggregation, more traffic data, and would use a “moving point” receptor to estimate cumulative exposure.

5. Discussions and conclusion

In this study, air quality and traffic flow were sampled and modeled for a variety of street infrastructure and traffic conditions in Shanghai, China. It was found that measured emissions tend to be considerably higher than predicted by the state-of-the-practice CAL3QHC model. Pollutant concentrations were considerably higher at intersections and even much higher where streets were covered with elevated expressways.

A major source of the under-prediction at intersections seems to be related to delays and erratic flows, resulting from the extensive use of bicycles and other slow vehicles. The large amount of queuing of vehicles, with additional deceleration, idling and acceleration, causes not only more CO emissions, but also more NO_x. Indeed, high NO_x concentrations were measured at intersections. These elevated emissions are especially problematic because of the high exposure by cyclists, pedestrians and other unprotected individuals.

Another source of the modeling errors is the use of Gaussian plume dispersion processes. A Gaussian model is well suited to "flat terrains" of highways and urban arterials, but not if surrounded by tall buildings and overhead obstructions, as is common in Shanghai. One solution is to develop numerical dispersion algorithms to model these more complex dispersion processes (Zhou, 1998).

Another enhancement would be more elaborate treatment of traffic flows and queuing. The goal would be better descriptions of traffic behavior, especially related to mixing of non-motorized vehicles, and better descriptions of temporal and spatial distributions of emissions around the hot spot.

These suggested enhancements require better understandings of traffic behavior and dispersion processes. The bigger challenge, though, may be collection of more data. In any case, the growing scale of urban pollution problems in China and other rapidly developing countries is obliging governments to re-think infrastructure investment plans and to adopt increasingly severe rules for vehicle movement and traffic management. To inform these actions, it is urgent that data and models be developed that are relevant to cities outside OECD.

Acknowledgements

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