Analysis of Particulate Matter Dispersion Near Urban Roadways

A Summary

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16. ABSTRACT

Particulate matter and its dispersion near urban roadways has become an issue of increasing concern because of the possible health risks to humans associated with the inhalation of small particulates. Despite the potential health risk, little is known about the concentration of particulates near urban roadways or the particulates emission rates of various vehicles. This research focused on particulate matter smaller than 2.5 micrometers (microns), typically denoted $PM_{2.5}$, because of the high potential health risks of such small particles. Data were collected along roadways on the University of Washington campus. The results of the data collection and subsequent statistical analysis revealed, as expected, that urban buses are far and away the major source of particulate emissions and that buses with low exhaust pipes are more of a threat to pedestrian traffic. More interestingly, our findings suggest that procedure AP-42 for calculating particulate matter near urban roadways is grossly inaccurate, producing values that are one to two orders of magnitude higher than actually observed $PM_{2.5}$ values.

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Research Project GC8719, Task 35
Particulate Matter Dispersion Near Urban Freeways

ANALYSIS OF PARTICULATE MATTER DISPERSION NEAR URBAN ROADWAYS

A SUMMARY

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DISCLAIMER

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SUMMARY

This report focuses on the collection and statistical analysis of particulate emissions near urban roadways. Specifically, we collected data on particulate matter smaller than 2.5 microns ($PM_{2.5}$) on roadways near the University of Washington, Seattle, campus. $PM_{2.5}$ was selected because of its high potential health risk. It is important to note that $PM_{2.5}$ can be attributed almost entirely to the combustion process; existing road dust should not contribute significantly to subsequent $PM_{2.5}$ measurements.

The statistical analysis of the data indicated that the determinants of $PM_{2.5}$ concentrations near urban roadways were a function of wind direction, number of cars, and number of buses. As expected, buses were the primary source of $PM_{2.5}$ emissions, and buses with exhausts below the bus contributed much more to the $PM_{2.5}$ levels likely to be encountered by pedestrians than buses with exhausts above the bus.

Another important finding resulted from the use of observed $PM_{2.5}$ concentrations in a dispersion model to arrive at vehicle emission rates. This procedure produced vehicle emission rates that were one to two orders of magnitude smaller than EPA estimated rates determined by procedure AP-42. This result suggests that procedure AP-42 is woefully inappropriate to forecast $PM_{2.5}$ levels near urban roadways. Although the EPA does not have compliance criteria that target $PM_{2.5}$ specifically, such criteria may be developed in the future. This possibility underscores the importance of the issue of $PM_{2.5}$ measurement — for Seattle and other metropolitan areas.

CONCLUSIONS AND RECOMMENDATIONS

The health risks associated with $PM_{2.5}$ make it the greatest concern of particulate matter. The Washington State Department of Ecology claims that motor vehicles emit 3,000 tons of combustion particles into the air and are responsible for another 177,000 tons of fine particulates from road dust per year. Particles resulting from combustion are clearly on the order of $PM_{2.5}$. However, when $PM_{2.5}$ is measured along paved urban roadways, there is little or no contribution from road dust. Therefore, when the health effects associated with particulate matter near roadways are discussed, combustion particles, not road dust, are of primary concern.

Our measurements of $PM_{2.5}$ on the University of Washington campus indicated that because of the high, short-term rises in $PM_{2.5}$ concentrations that result from passing diesels, more real-time studies are necessary. Since major particulate matter polluters usually pass at varying intervals, modelling them as continuous sources can be erroneous. The health effects of high, short-term exposures should be studied and standards should be determined.

Bus exhausts are sometimes put under the vehicle to reduce the noise associated with the bus. However, they tend to increase the particulate matter concentrations close to the roadway. In fact, buses with exhausts below the vehicle can have roughly twice the effect on $PM_{2.5}$ that buses with exhausts above the vehicle do.

The procedure in AP-42 for calculating particulate matter concentrations along paved urban roadways is inappropriate for calculating $PM_{2.5}$. It produces values that are from one to two orders of magnitude higher than those actually observed.

The use of emission standards as emission factors in line source models seems to be a valid approach for determining particulate matter concentrations near roadways. However, adjustments must be made to account for poorly maintained vehicles.

Highways with complex terrain can have both line source and street canyon characteristics. While buildings are predominantly responsible for canyon characteristics, gaps between buildings and perpendicular roads can produce line source characteristics. These effects were seen at the Stevens Way location on the University of Washington campus. The buildings on the upwind side of the road and the trees, shrubs, and sloped ground on the downwind side produced both canyon and line source effects.

INTRODUCTION AND BACKGROUND

PROJECT MOTIVATION

Highway traffic has long been identified as one of the most significant sources of air pollution in urban areas. Of the numerous pollutants associated with highway vehicles, particulate emissions are becoming a focus of attention, particularly because the characteristics of urban areas make them susceptible to high airborne concentrations. Low vehicle speeds, high traffic volumes, and complex topographical features (i.e., tall buildings and closely spaced streets) all contribute to high concentrations of particulate matter. In Washington state, fine particulate pollution contributes to an estimated 100 deaths each year. The many health and environmental impacts associated with particulate matter underscore the importance of understanding particulate emissions and concentrations.

To determine particulate matter concentrations near roadways, engineers must currently rely on generic emission factors that are highly uncertain. This research will enable a more realistic assessment of the environmental impacts of traffic on particulate air pollution.

Historically, the concentration and behavior of particulate matter has not been well characterized near roadways because sampling is difficult and has traditionally required a filtration method that operates for long periods (6 to 24 hours). This project studied the characteristics of particulate matter near paved roadways by using integrating nephelometers, which measure the portion of the integrated light scattering coefficient (defined by the variable b_{sp}) that is produced by the particulate matter. At a University of Washington campus site, the researchers established a relationship between the measurement of b_{sp} and the portion of particulate matter smaller than 2.5 micrometers (μm, or microns), typically referred to as $PM_{2.5}$. This relationship allowed $PM_{2.5}$ to be calculated near roadways. Weather and traffic data were gathered concurrently with

$PM_{2.5}$ data, and these data were used to establish statistical relationships between $PM_{2.5}$, emissions, traffic, and weather conditions. Fourier transforms were run, and the characteristics of $PM_{2.5}$ were analyzed in the frequency domain.

RESEARCH OBJECTIVES

The objectives of this project included the following:

1. Collect particulate matter data near urban roadways.
2. Statistically analyze the particulate matter data to determine the sources and factors that influence concentrations.
3. Develop conclusions regarding the accuracy of particulate matter measurements near urban roadways.

RESEARCH APPROACH

For this research, particulate matter concentrations, wind speed and direction, temperature, and pressure were measured. To determine particulate matter concentrations, two M 901 integrating nephelometers, a MINIRAM Model PDM-3 aerosol monitor, and Harvard samplers were used. A portable weather station measured wind speed and direction. A thermometer at the sampling site measure temperature. A barometer on the University of Washington campus in More Hall measured barometric pressure.

To determine $PM_{2.5}$ concentrations along the roadways, only the M 901 integrating nephelometers were used. The MINIRAM was not used because its accuracy was only to the nearest 10 ug/m^3, which was not satisfactory for measuring roadway levels near 20 ug/m^3. The Harvard sampler could not be used near roadways because it required a sampling interval of approximately 8 hours to accurately determine the particulate matter concentration.

Site Selection/Data Collection

Two locations were chosen for this study. The first location, Lake Washington Boulevard in the University of Washington Arboretum, was chosen because restrictions on the roadway resulted in predominantly automobile traffic. The second location, Stevens Way on the Seattle campus of the University of Washington, was chosen because of its high ratio of buses to automobile traffic.

Data Preparation and Modelling

The typical approach for analyzing air pollution along the roadway is to estimate emission factors and put these factors in dispersion models to calculate air pollution concentrations near roadways. However, one approach used for this project was to take 5-minute average $PM_{2.5}$ concentrations measured near roadways and regress them with traffic data to determine the relative $PM_{2.5}$ contributed by specific types of vehicles. These $PM_{2.5}$ contributions were put into dispersion models to determine an emission factor. These emission factors were then compared to those typically used in the analysis of $PM_{2.5}$ near paved roadways. Figure 1 compares the typical procedure with that used in this analysis.

Fourier transforms are typically performed to identify the frequency components that make up a continuous wave form. Fourier analysis was used to describe the rapid fluctuations in $PM_{2.5}$ concentrations that occurred on time scales of less than 5 minutes. The consideration of more rapid fluctuations allowed the researchers to determine averaging times that would better describe the data than the 5 minutes used in the regression analysis.

The "fast" Fourier transform was used for this analysis. This is a finite, discrete version of the Fourier transform. The half-second b_{sp} coefficients taken at Stevens Way on July 29, 1991, were smoothed and differenced. Next, the fast Fourier transform was performed. The transform's output consisted of real and imaginary components of the discrete Fourier transform. The sum of the squares of these complex Fourier components

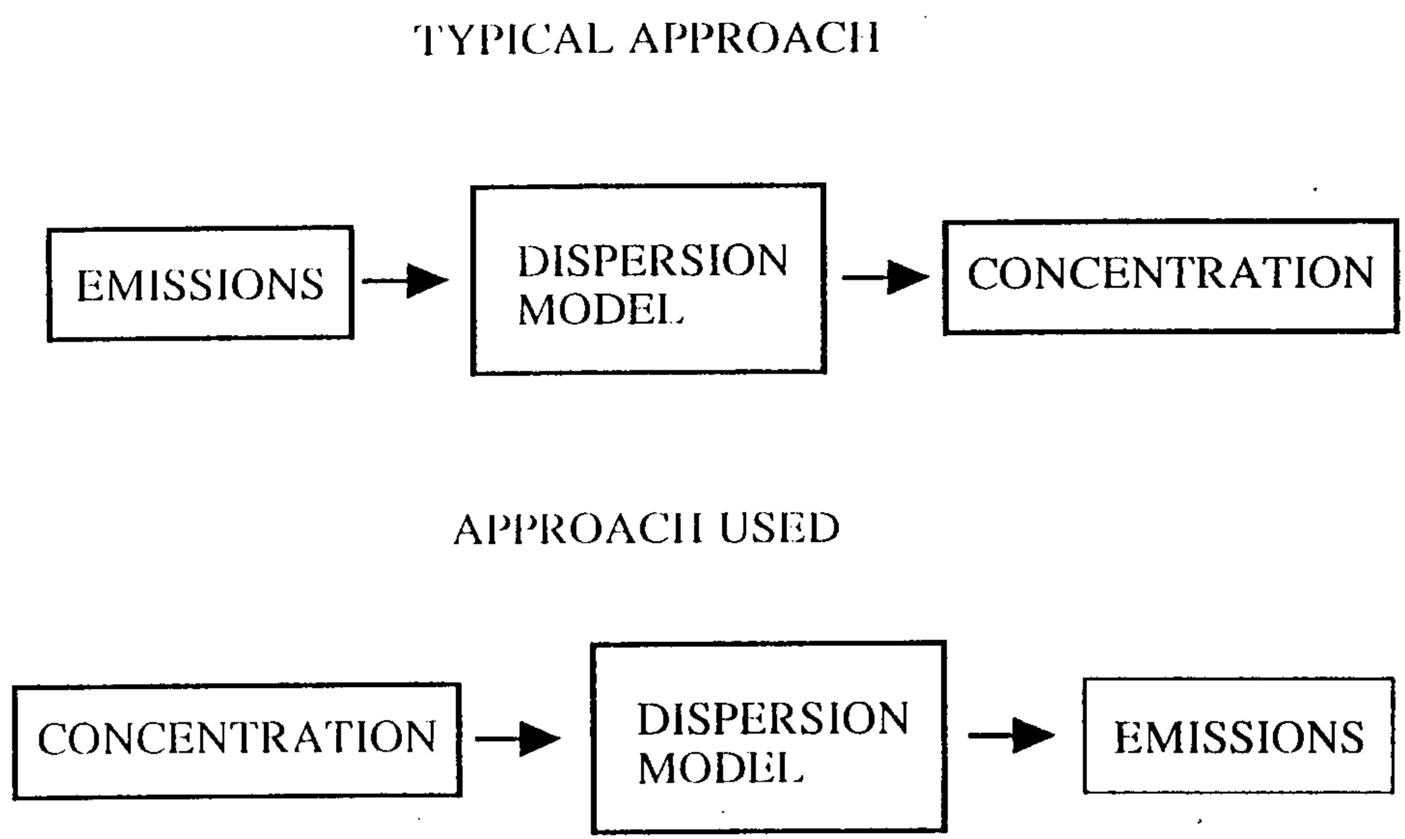

Figure 1. Modelling Approaches

were used to develop a periodogram. The periodogram was then used to study the power spectrum of the data.

PROCEDURES, APPLICATION, AND IMPLEMENTATION

The procedures undertaken in this study, along with concerns about their application and implementation, are summarized below. Please see the technical report of this project for further details.

LAKE WASHINGTON BOULEVARD

The Lake Washington Boulevard data were put into a statistics program called StatView II created by Abacus Concepts Inc., 1988. This is a Macintosh based statistics program. With this program, multinomial regressions were attempted. Theoretically, regression models could be developed with these data to predict $PM_{2.5}$, but because of the limits in the range of $PM_{2.5}$, the models were inconsequential. $PM_{2.5}$ ranged from approximately 2 ug/m^3 to 18 ug/m^3, which was not a large enough range of concentration to yield satisfactory models.

Even though models were not developed, some interesting relationships between upwind and downwind concentrations, and parallel and crosswind wind directions were revealed (see the Lake Washington Boulevard box plots presented in Figure 2). For these box plots, the $PM_{2.5}$ concentration was estimated from b_{sp}. The average $PM_{2.5}$ concentration was approximately 6 ug/m^3. "Parallel" was defined as wind blowing at 0° to 45°, 135° to 225°, or 315° to 0° to the roadway, and "crosswind" was defined as wind blowing at 45° to 135° and 225° to 315° to the roadway. Most interesting was that the fourth spread, the difference between the upper fourth and the lower fourth of the data, was much smaller when the wind was parallel to the road than when it was crosswind. The fourth spread for the parallel situation was approximately half of what it was for the crosswind case. This difference can probably be explained by the fact that when the wind blows parallel to the road, car wakes have a greater effect on dispersion than when it blows perpendicularly. During this study the flow of traffic was steady while the wind

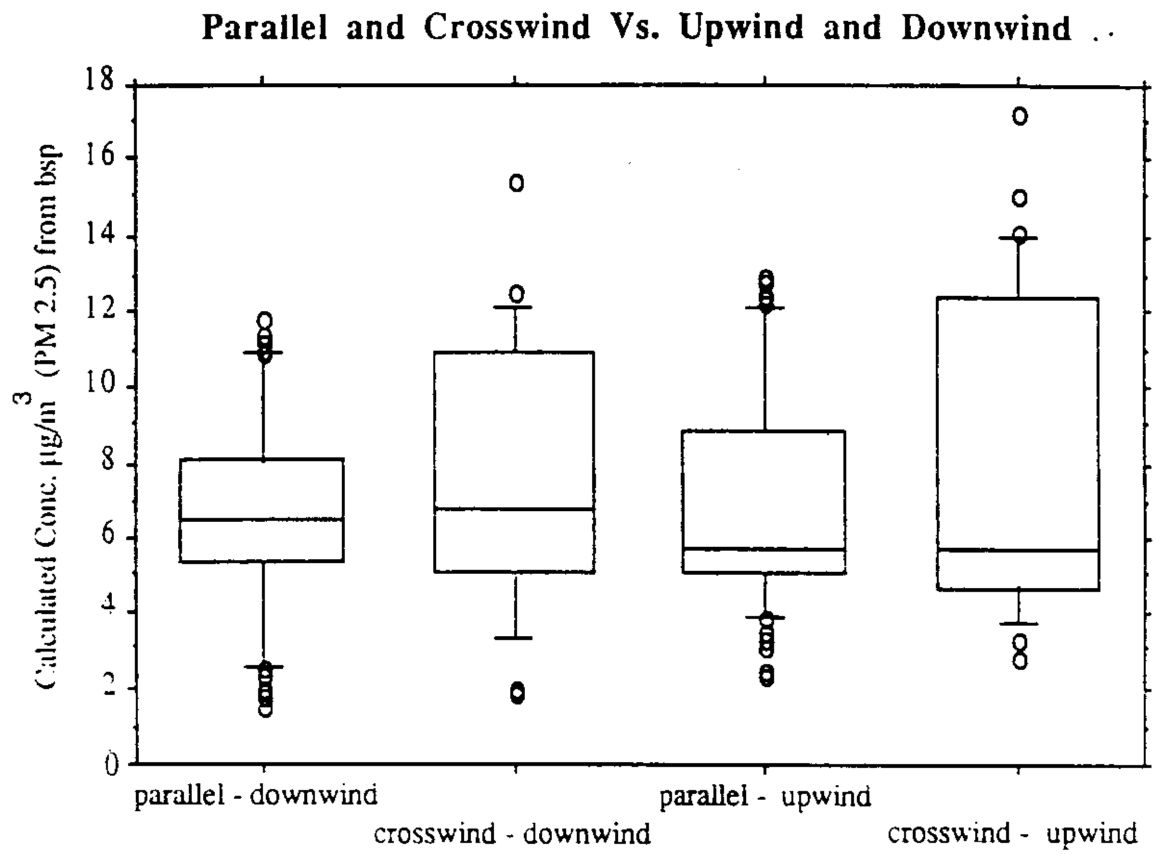

Figure 2. Box Plots for Lake Washington Boulevard

would often gust. Thus, perpendicular wind gusts affected the concentrations, but the effects of parallel wind gusts were negated by the vehicles.

STEVENS WAY

At the Stevens Way location, nephelometers were placed 2 meters from the roadway, and upwind and downwind concentrations were estimated in approximately half-second intervals. On July 11, 1991, half-second concentrations were calculated only for the downwind location, while on July 29, 1991, half-second concentrations were calculated for both the downwind and upwind locations. Concentration versus time graphs were developed for these data. These graphs (see Figure 3) show that each time a bus passed the sampling location, the downwind $PM_{2.5}$ concentration rose from approximately 5 ug/m^3 to 15 ug/m^3 and then returned to its initial level over a period of 1 to 1.5 minutes. The result was short-term, high concentrations in $PM_{2.5}$ each time a bus passed.

On the upwind side of the roadway on July 29th, three short-term spikes in concentrations were observed. These concentrations ranged between 35 ug/m^3 and 65 ug/m^3. Two spikes could be traced to Gray Line Tour buses with exhaust below the bus. However, the third spike was questionable because of an interruption in the bus data collection process.

These data show that the effects of one bus were not always additive to that of a previous bus. Depending upon the frequency of the buses, their emissions could be additive or their wakes could be deleterious. Automobiles tended to have very little impact on $PM_{2.5}$ concentrations. As the number of automobiles rose, the $PM_{2.5}$ concentrations also rose, but at a very low, consistent rate. When congestion occurred or the traffic speed became very low, the concentration rose and tended to stay at a high level for a longer period. Typically, congestion occurred only in one direction; therefore, while the vehicle turbulence effects were lost in the congested direction, the uncongested

Concentration Vs Time

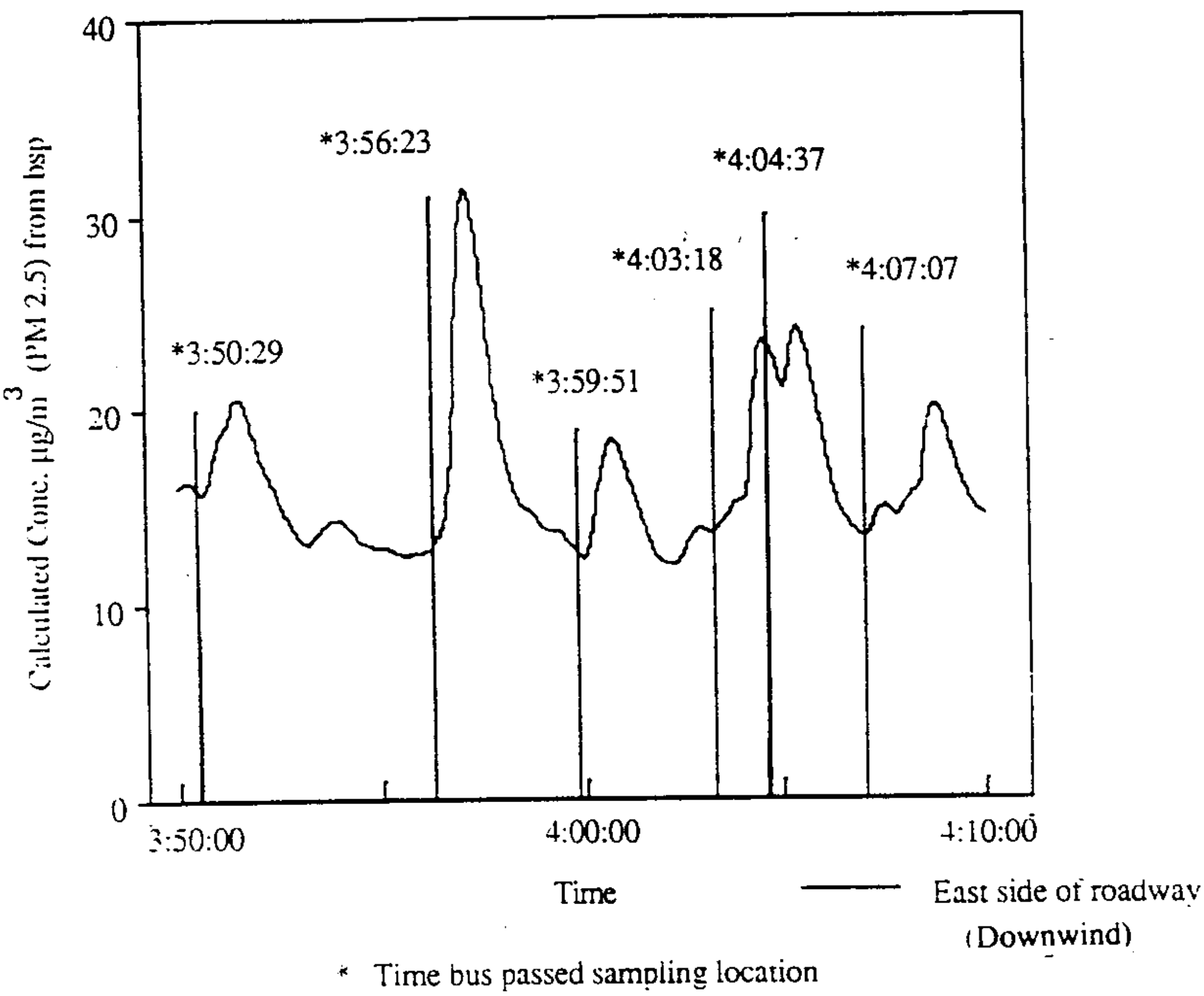

Figure 3. $PM_{2.5}$ Graph, 7/11/91, 3:50 PM to 4:10 PM

direction continued to cause turbulence. Also, if a larger vehicle passed by slowly in the congested lane, it could still cause enough turbulence to lower the $PM_{2.5}$ concentration.

Stevens Way Regression Modelling

The Stevens Way data were put into a statistics program called Statistical Software Tools (SST), 1986. This is a DOS based statistic program and was used to perform multiple regressions. All data used in the following regressions were taken in 5-minute intervals. Details on each regression can be seen in the technical report of this project.

Downwind Study

The downwind $PM_{2.5}$ concentration was regressed with the total number of diesels (i.e., buses) and the total number of cars. In this model, when measurement occurs 2 meters from the roadway and wind speeds are approximately .5 m/s, the 5-minute average $PM_{2.5}$ concentration can be determined by the following equation:

$$C_{down} = 10.77 + 0.04505(\#cars) + 1.849(\#buses) \quad \text{(Eq. 1)}$$

where 10.77 is the background concentration, which is close to the actual measured concentration of 10 ug/m^3. Using this equation in a dispersion model (see Figure 1), the emission factors were calculated at 0.012 g/veh/km for automobiles and 0.51 g/bus/km for buses.

These emission factors were within the range of those used in previous studies. As discussed previously, it is appropriate to assume a particulate emission factor for light duty, gasoline powered vehicles for 1976 to 1981 of 0.02 g/veh/km, and for 1981 to 2000 of 0.01 g/veh/km. Also, heavy-duty diesels have possible emission factors of 1.0 g/veh/km for the years 1980 to 1985, 0.9 for 1986, 0.38 g/veh/km for 1987, and 0.16 g/veh/km for 1987 to 1991. These findings reinforce the possible emission factor of 0.51 g/bus/km calculated by this study.

The AP-42 computation for paved urban roads produces emission factors that range from 0.73 g/veh/km to 2.42 g/veh/km. Putting these factors into the finite line source model resulted in $PM_{2.5}$ concentrations of 108 ug/m^3 for 40 vehicles at 0.73 g/veh/km and 530 ug/m^3 for 60 vehicles at 2.42 g/veh/km. The range of observed 5-minute average $PM_{2.5}$ concentrations was 12 ug/m^3 to 26 ug/m^3. Therefore, the paved urban roadway computations resulted in $PM_{2.5}$ concentrations from 9 to 20 times higher than those actually measured. Even if every vehicle on the roadway was a heavy-duty diesel bus (i.e., 0.51 g/bus/km) the maximum concentration would not have exceeded concentrations calculated with the AP-42 recommended factor of 0.73 g/veh/km.

In summary, the regression models and the line source model produced emission factors much lower than those that resulted from the AP-42 study. Table 1 compares the emission factors calculated in this study with those of Black and AP-42.

Upwind

Multiple regression was also performed on the upwind $PM_{2.5}$ concentrations. To get any reasonable model, the variable "number of buses with exhausts below the bus" had to be used. All model variables were 5-minute averages. The first model resulted from a regression of upwind $PM_{2.5}$ concentrations with the total number of buses with exhaust above the vehicle (#top), the total number of buses with exhaust below the vehicle (#bottom), and the total number of cars (#cars). In this model, when measurements were taken 2 meters from the roadway and wind speeds were

Table 1. Emission Factor Comparison by Study

Type of Vehicle	Black's Study	AP - 42 Study	This Report
Cars	0.01 - 0.02	None	0.013
Heavy Duty Diesels/Buses	0.9 (before 87) 0.38 (1987) 0.16 (88-91)	None	0.51
Entire Roadway	0.06	0.73 - 2.42	0.05

approximately .5 m/s, the $PM_{2.5}$ concentration in 5- minute averages could be determined by the following equation:

$$C_{up} = 16.08 - 0.615(\#top) + 3.98(\#bottom) + (-71.84/\#cars) \quad \text{(Eq. 2)}$$

In this model, the location of the exhaust was very important to upwind concentration. Buses with exhausts above the vehicle actually lowered the upwind concentration. This is because the wake of the bus dispersed the pollution, lowering the $PM_{2.5}$ concentration, while its emissions were released high enough that they did not increase the $PM_{2.5}$ concentration. On the other hand, if the exhaust was below the bus, the emissions were carried by its wake, travelling along the ground and registering on the nephelometer, thus increasing the upwind $PM_{2.5}$ concentration.

In summary, this model related very interesting characteristics of particulate matter near roadways. However, they were severely restricted. Both low wind speed and a constant sampling distance caused the limitations.