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Achievements of a Dispersion Model for Predicting Micro-Environmental Pollution from Traffic Emissions

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ABSTRACT

Microscale pollutant dispersion models and field monitoring data from fixed stations at specific heights are often used to guide the development of emissions control strategies in the effort to attain National Ambient Air Quality Standards (NAAQS). Plus, these models are typically used to evaluate the environmental and sustainable development impacts of new construction projects. However, models currently in use often underestimate pollutant concentrations in micro-environments. Because air quality standards are set to protect public health, attention must be given to real-world exposure levels.

A theoretical formulation of a stochastic model for prediction of pollutant dispersion in micro-environments was previously introduced.[1] The formulation of the new model can better predict the pollutant levels for urban roads located near high-rise buildings. Model prediction results indicate that vehicle pollutant concentrations can become significantly elevated under worst case scenarios (at lower wind speeds). The model presented here can help road designers better estimate real-world emissions impacts. This paper discusses the new model framework and presents preliminary model evaluation results.

INTRODUCTION

Vehicles are continuously emitting exhaust and evaporative gases that impacts the urban environment. In a street canyon, the downwind concentrations result from the total contribution of pollutants emitted directly from automobiles, plus the contribution of background pollutant sources. For urban roads located close to high-rise buildings, maximum pollutant concentration can be found at about 20% of the canyon height[2], indicating entrapment of pollutants near the road surface. Normal horizontal and vertical dispersion and transport of pollutants occur as a results of inertial force, wind speed, and buoyant heat flux, provided there are no physical impediments like buildings near roads. In urban street canyons, pollutants become entrapped along the roadway.

The model presented here is based upon a familiar but complicated concept; street canyons restrict and distort normal pollutant dispersion. The new model has been developed to simulate the real-world complexities of pollutant dispersion in a street canyon. The model considers different vehicle types (engine and fuel types) and uninterrupted traffic flow characteristics for each section of urban road. The model can be applied to any highway orientation, canyon geometry, and wind direction. The new model includes predictive capabilities for both Carbon Monoxide (CO) and Oxides of Nitrogen (NO_X).

This paper first explains the current problems that the road environment plays in employing field data for wind and temperature collected along a road north of Nagoya, Japan. Next, the paper provides the atmospheric stability and dispersion parameters and then forecasts expanded emission estimates using the probability distribution functions. The modeled results are then compared to field data collected from mounted stations. Finally, the implications of the research findings are discussed.

EMISSION TRENDS

The Japanese ambient concentration standard for Nitrogen Dioxide (NO_2) requires daily average of hourly values to remain below 0.06 parts per million (ppm). In an area where the daily average of hourly values exceeds 0.06 ppm, efforts should be made to achieve the 0.06 ppm level. In an area where the daily average of hourly values falls within the range of 0.04 ~ 0.06 ppm, efforts should be made so that the ambient concentrations are maintained around the present level. The standard for carbon monoxide (CO) requires concentrations to remain below 10 ppm, expressed as a daily average hourly value.

Figures 1 and 2 present the hourly concentration trends for Nitrogen Dioxide (NO_2) and Carbon Monoxide (CO) at two fixed monitoring stations in Nagoya. Exhaust emissions from internal combustion engines result in severe air pollution that exceeds regulatory standards for NO_2 in Nagoya City, Japan. In Figure 1, it is clear that NO_2 concentrations fall within the concentration range of concern and sometimes exceed the 0.06 ppm NO_2 standard. The CO trends appear to fall within acceptable limits.

METHODOLOGY

The following basic factors are incorporated into the technical specification of the new model:

- Wind speed and temperature are two independent variables for the calculation of atmospheric stability. In a street canyon, both wind speed and temperature vary with height.
- Traffic flow and resulting emissions are the primary physical attributes for polluting urban roads. Traffic flow and emission rate are taken together to calculate source strength.
- Transport and dispersion are the most complicated processes in air quality modeling and are solved in stochastic manner. The exact solution to represent real-world-complexities is still unresolved. Gaussian solutions for dispersion have been assumed.
- Pollutant dispersion is a continuous process. For predicting pollution in micro-environments, multivariate normal probability density functions were employed.

Temperatures and Wind Speeds

An experiment to outline the effects of buildings on wind speed was first undertaken. Efforts were made to collect wind and temperature data every 10 minutes from 7 AM to 6 PM at various heights in the canyon (at 1 m height from the ground to the rooftop of the building). Analyzing the wind data permitted an empirical relationship obtained for that particular canyon geometry as:

$$U_g = 0.27452 * U_r^{1.7029}$$

where

U_g = wind speed near the road surface in m sec^{-1}
U_r = wind speed at rooftop level of buildings in m sec^{-1}.

This empirical relationship was used to estimate road level wind velocities from ambient wind measurements.

Table 1 contains average temperatures at the rooftop and ground levels from 7 AM to 6 PM for the study day . Rooftop measurements were taken at 12.25 meters from a building near the sampling sites. Table 1 also contains measured average hourly wind speed at the rooftop level, and computed average hourly wind speed at ground level.

Experimental evidence revealed substantial differences between ambient wind and temperatures at different levels of the street canyon. Wind speed near the roadway surface is much lower than that at the roof level in urban street canyons because wind loses inertia due to surface friction. On the other hand, temperatures are typically greater at ground level than at roof level, as a result of pavement surface heating and re-radiation from heat generated by automobiles.

Traffic Flow and Emission Rate

The model used traffic flow data for the emission rate calculation process. Traffic flow census data were available for weekdays from 7 AM to 6 PM. Weekday and weekend traffic flows vary substantially in urban areas. There are eight major categories of Japanese vehicles and the rate of emission from each category is estimated as a function of running speed and fuel categories. For calculation ease, eight polynomials represent the categories of vehicle emissions.[1] Some sub-fleet composition effects were included through the assumption of technology distributions. For example, total bus traffic was assumed to be represented by: 10% gasoline-powered micro-bus, 20% diesel-powered micro-bus, 10% gasoline-powered heavy-bus, and 60% diesel-powered heavy-bus.

Atmospheric Stability and Dispersion Parameters

In most dispersion models, six classes of stability are based upon Pasquil-Gifford (PG) curves. However, PG curves were originally established for downwind distances beginning at 100 m from a point source and do not necessarily provide a reliable description of near field dispersion. Instead, a mathematical representation of stability[3], based on the numerical values of Richardson's number, is employed in the new model. In this method, only three categories of stability are employed to represent microscale atmospheric conditions: stable, unstable, and neutral. In the real world, atmospheric conditions are changing at every moment, so the proposed established conditions are merely approximation of a natural process.

The measured and calculated wind and temperature data at various levels of the urban street canyon are employed to estimate Richardson's number for one hour average conditions. Table 2 provides the estimated hourly average Richardson's number and corresponding atmospheric stability for the study period.

The motion of pollutants in the atmosphere is caused by transport and dispersion. Transport is movement due to airflow. The movement (advection) of air across the surface of the earth can occur in one of two distinct modes: laminar and turbulent flow. In the atmosphere, transport of an air mass is almost always turbulent. Turbulent flow is characterized by violent swirling motions and the presence of eddies.

Dispersion is the separation of pollutants within an air flow, resulting from ambient turbulence, turbulence induced by automobiles, and heat generated from vehicles. For a system of pollutant sources and receptors, models are used to predict downwind pollutant concentrations, based upon dispersion parameters. Using previously collected field data, empirical dispersion relationships in established models[4, 5] were simplified and employed in the new model. The restructured dispersion parameters are described in detail in a previous paper.[1]

Dispersion parameters summarize the effects of vehicle induced turbulence, ambient turbulence, and heat flux. Hence, dispersion parameters are developed for each stability class, wind direction, road-canyon geometry, and traffic flow. Though gas particles have turbulent motion, prediction of the transport for pollutant is simplified by assuming dispersion in a trapezoidal volume[1] in the near vicinity of the source. For the computation of dispersion parameters:

- downwind distance, L = 0.0073 km,
- road width, B = 9.00 m,
- dispersion width in excess of road width, b = 1.5 m, and
- traffic flow per second (N_a) for each individual hour.

Vertical dispersion due to wake turbulence generated by traffic is a function of the cross-road wind component. For higher wind speed, vehicle turbulence impact on dispersion are considered to be constant. For a cross-road wind speed greater than 3.91 meters/second, vertical dispersion due to traffic induced turbulence is estimated to be 1.5 meters.[4] Under low cross-road wind conditions, dispersion can be caused by ambient turbulence and thermal turbulence. The dispersion due to heat flux takes into account the total effects of solar radiation and vehicle-generated heat. Heat generation from different categories of vehicles are definitely different, but an average value of 2.46 kilowatts/meter has been suggested in the literature[6] and was employed in the model estimation.

For wind parallel to traffic movements, lateral diffusion occurs due to traffic effects. The ratio between total dispersion for traffic induced turbulence and ambient turbulence is less than or equal to 10.[7] For wind directions perpendicular to the traffic direction, total diffusivity is dependent on wind speed and the ratio lies somewhere between 2 and 25.[7]

The dispersion parameters employed in the modeling exercise are listed in Tables 3 and 4. Table 3 provides the detailed hourly vertical dispersion parameters, and the total hourly vertical dispersion for NO_x. Table 4 presents hourly individual lateral dispersion parameters and total hourly lateral dispersion parameters employed for NOx. The values lie within the above recommended limits. For vertical dispersion, the ratio between total dispersion for traffic induced turbulence and ambient turbulence lies between 2 and 3, and for lateral dispersion the ratio lies between 3 and 5.

Prediction for Micro-Environmental Pollution

Pollutant concentrations and wind speed are continuous variables. Probability density functions of these continuous random variables follow a bivariate normal probability distribution. To estimate the maximum concentration at the exposure level, bivariate continuous probability density functions[8, 9] were employed:

$$\mathbf{F_X} = P\left[\chi \le A\chi_t ,\ U \le U_g\right]$$

$$= \frac{1}{2\pi\sigma_\chi\sigma_U\sqrt{\left(1-\rho_{\chi U}^2\right)}} *$$

$$\int_0^{U_g}\int_0^{A\chi_t} \exp\left\{-\frac{1}{2\left(1-\rho_{\chi U}^2\right)}\left[\left(\frac{\chi-\mu_\chi}{\sigma_\chi}\right)^2 - 2\rho_{\chi U}\left(\frac{\chi-\mu_\chi}{\sigma_\chi}\right)\left(\frac{U-\mu_U}{\sigma_U}\right)+\left(\frac{U-\mu_U}{\sigma_U}\right)^2\right]\right\} d\chi\, dU$$

where:

$\mathbf{F_X}$ = probability density function for $\mathbf{X}(\chi, U)$
P = probability
$A\chi_t$ = tailpipe emission concentration in time t
χ = ambient pollutant concentration
U = ambient wind speed
U_g = wind speed near ground
μ_χ = expectation of pollutant concentration
μ_U = expectation of wind speed
σ = standard deviations
ρ = correlation coefficient

Predicted ground level concentration:

$$\varepsilon\chi_t = \frac{\chi_t}{P_t\left[\chi \leq A\chi_t, U \leq U_g\right]}$$

where:

$\varepsilon\chi_t$ = Expanded (accumulated) concentration at time t
χ_t = Ambient pollutant concentration at time t.

and where background concentration consists of pollutants not transferred out of the system at time (t-1):

$$\delta\chi_{t-1} = \varepsilon\chi_t - A\chi_t$$

Numerical integration[10] of the density function predictions was performed to estimate wind speed and tailpipe pollutant concentrations. Exercising probability values, concentrations near the ground were calculated from corresponding field data at the appropriate height. Predicted concentrations are defined as the pollutants emitted directly from vehicle tailpipes at any event, plus pollutants from the previous event that were not transferred out of the canyon.

MODEL RESULTS

The experimental setup for pollutant concentration monitoring was similar to that of a previous micro-environment study in Taipei City, Taiwan.[11] While measuring exposure levels during Taipei experiments, the heights of sampling receptors were about 2.5 meters for roadside stations and about 12 meters for regional stations. The Taipei roadside stations were 1 to 3 meters away from traffic lanes. The heights of sampling receptors in Nagoya City were approximately 2.3 meters for CO stations and 8 meters for NOx stations. All Nagoya City stations were located approximately 7.5 meters from the roadway.

Hourly pollutant concentrations and wind speed values collected under similar traffic conditions were first assembled. Probability distribution functions were then developed from a data set of 1200 measurements (300 for NOx, 300 for CO and 600 for wind speed). Figures 3 and 4 are the graphical representations of the density function distributions.

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Traffic flows for these periods on our experimental road (3 lanes) were simultaneously 1187, 1181, 1050, and 1013 vehicles per hour. In the morning, maximum traffic flow occurs at 7 AM and peak point of concentration appears likely between 8 and 9 AM.

Figures 5 and 6 provide the model-predicted hourly concentrations near ground and at the mounted receptor site for NO_X and CO, respectively. The variation of traffic flows and wind speed with corresponding hours are also shown in Figures 5 and 6. Peak points of the pollutant concentrations in Figures 5 and 6 follow the peak traffic hours (from 7 to 9 AM and from 6 to 8 PM) on Japan's roads.

Tables 5 and 6 list predicted concentrations at the receptor site from 7 AM to 6 PM for NO_X and CO, respectively. The data in Tables 5 and 6 indicate that pollutant concentrations after dispersion has occurred are much higher than exhaust gas pollutant concentrations emitted from tailpipes. The data in the tables indicate that wind speed substantially dominates the dispersion process. At 7 and 8 AM, wind velocities are very low resulting in inadequate dispersion and hence higher concentration levels. If we examine the wind profile, the periods of higher concentrations correspond to very mild wind velocities, around 1 to 2 meters/second. When wind speeds are higher, in the periods from 2 to 4 PM, concentration are lower. Strong winds reduce the buildup of pollutants along the road. As expected, worst case situations occur under conditions of low wind speeds. The time lag between the concentration peaks are due to inadequate instantaneous dispersion (i.e., pollutant during the previous moments can not be transferred sufficiently to the surroundings and upper air levels). Deficient transport, caused by the street canyon's hindrance of pollutant movement, contributes to a buildup of pollutants in the street canyon.

Figures 5 and 6 indicate that there are marked differences between predicted roadside concentration and monitored concentrations at elevated monitoring stations. When wind velocity is less than 1.5 meters per second, the ratios between Computed Roadside Concentration (CRC) and monitored Concentration at Mounted Receptor (CMR) are around 22 for NOx and 6 for CO. For wind speeds from 1.5 to 2 meters per second, the CRC/CMR values are around 9 for NOx and 3 for CO. For wind velocities between 2 and 2.5 meters per second, the ratios are 7 and 2.5 for NOx & CO, respectively. For wind velocities between 2.5 and 3.0 meters per second, the CRC/CMR values are 5 and 2 for NOx & CO, respectively. The findings indicate a critical level of wind speed (3 meters per second) beyond which the ratios of concentration at different levels approaches unity.

The differences between monitored and predicted concentrations should be in part due to the fact that the monitoring stations are elevated above the roadway. The ratio of NOx concentrations for elevated and ground-level receptors is higher than that for CO under all wind conditions. The difference is believed to be due in part to the fact that the NOx receptor is located higher above road level than the CO receptor.

The biggest differences between predicted and monitored CO concentrations are indicated in the morning, and the biggest differences for NOx are in the afternoon. It may be that temperature effects on emission rates are inadequately accounted for in the model. There are also a number of other theoretical or experimental factors that may contribute to these differences. Hence, the study indicates that additional research is necessary. In designing the next experiment, emissions concentrations will be monitored at multiple locations and at various heights in the street canyon to validate the model and to help develop model improvements.

CONCLUSIONS

As previous studies have indicated[12], excessive buildup of pollutants generated from traffic in urban areas are controlled by wind flow along roads. The model developed for this effort can be used to predict downwind pollutant concentrations for urban roads where street canyons restrict normal pollutant dispersion. The model results indicate:

- The new model results appear to conform with common theoretical criteria.
- Predicted concentrations at the road level are significantly higher than the concentrations that would be expected only from concentrations emitted directly from the tailpipes of vehicles.
- Model outputs coincide with the characteristics of peak traffic flows on the roads of Japan. Peak concentration hours are the same as peak traffic hours.
- Model results indicate that a severe buildup of pollutants occurs under very low wind speed conditions in street canyons.
- Wind speed plays a vital role for the dispersion process that might be enhanced by applying mechanically-generated artificial winds during low ambient wind conditions.
- The noted CO concentration ratios for the Nagoya City site (1.5 to 6) correlate well with previous experimental field data from Taipei that indicated the ratio between concentrations at various micro-environmental locations (on motorcycle, in bus and private cars etc.) and regional stations ranged from 4 to 7.
- After additional validation studies are conducted, the model techniques can be used to effectively plan new roads and abate pollutant concentrations to protect receptors - people walking through the footpaths or vehicle occupants.

Air pollution problems from highway transport systems would be abated if automobile emissions were eliminated, but this is neither simple nor likely over the short term. Although there is a great deal of ongoing alternative fuels research, the marketplace has yet to adopt electric or fuel-cell vehicles. Until these technologies penetrate the vehicle fleet, continued research into pollutant dispersion in street canyons will be needed.

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Table 1: Wind speed and temperature at different levels of canyon.

Time (h)	Ambient Wind at roof top (m sec^{-1})	Computed Wind near ground (m sec^{-1})	Ambient Temperature at roof top (^0C)	Ambient Temperature near ground (^0C)
7	1.2	0.37	2.7	3.5
8	1.3	0.43	3.0	3.9
9	1.9	0.82	3.7	4.0
10	2.2	1.05	4.0	4.3
11	2.4	1.22	3.7	4.0
12	2.6	1.4	5.0	6.3
13	3.1	1.89	5.7	6.0
14	3.4	2.21	7.0	6.8
15	3.3	2.1	6.0	4.8
16	3.3	2.1	5.2	5.7
17	3.0	1.78	3.0	4.2
18	2.3	1.13	2.9	3.7

Table 2: Atmospheric condition for different times of a day.

Time (h)	Richardson's Number (R_i)	Stability
7	- 0.474	Unstable
8	- 0.479	Unstable
9	- 0.114	Unstable
10	- 0.100	Unstable
11	- 0.095	Neutral
12	-0.371	Unstable
13	-0.090	Neutral
14	0.071	Stable
15	0.326	Stable
16	- 0.139	Unstable
17	- 0.319	Unstable
18	- 0.232	Unstable

Table 3: Vertical dispersion parameter for different physical attributes.

Time (h)	Dispersion for vehicle wake (m sec^{-1})	Dispersion for ambient turbulence (m sec^{-1})	Dispersion for heat flux (m sec^{-1})	Total dispersion (m sec^{-1})
7	2.934	1.128479	0.349	3.49278
8	2.881	1.128479	0.347	3.44161
9	2.563	1.128479	0.309	3.10937
10	2.404	1.128479	0.190	2.84546
11	2.298	0.920723	0.250	2.72568
12	2.192	1.128479	0.192	2.65785
13	1.927	0.920723	0.259	2.39488
14	1.768	0.679225	0.297	2.19115
15	1.821	0.679225	0.288	2.23160
16	1.821	1.128479	0.270	2.41212
17	1.980	1.128479	0.298	2.57705
18	2.351	1.128479	0.255	2.86319

Table 4: Lateral dispersion parameter for different physical attributes.

Time (h)	Dispersion for vehicle wake (m sec^{-1})	Dispersion for ambient turbulence (m sec^{-1})	Dispersion for heat flux (m sec^{-1})	Total dispersion (m sec^{-1})
7	6.504	1.751724	0.286	7.02128
8	6.451	1.751724	0.284	6.96867
9	6.133	1.751724	0.253	6.63082
10	5.974	1.751724	0.155	6.38067
11	5.868	1.444269	0.204	6.24758
12	5.762	1.751724	0.157	6.1797
13	5.497	1.444269	0.212	5.89548
14	5.338	1.092797	0.243	5.69165
15	5.391	1.092797	0.235	5.73613
16	5.391	1.751724	0.221	5.88903
17	5.550	1.751724	0.244	6.06354
18	5.921	1.751724	0.209	6.38347

Table 5: Calculated different sample concentration of Oxides of Nitrogen.

Time (h)	Tailpipe Emission Concentration($A\chi_t$) ($^1/_{10}$th ppm)	Expanded concentration ($\varepsilon\chi_t$) ($^1/_{10}$th ppm)	Background Concentration ($\delta\chi_{t-1}$) ($^1/_{10}$th ppm)
7	0.6506	20.2881	19.6376
8	0.6879	23.0504	22.3625
9	0.7217	13.2031	12.4814
10	0.7448	8.39597	7.65117
11	0.6954	6.10707	5.41162
12	0.7909	3.64936	2.85845
13	0.8293	2.43258	1.60323
14	1.135	1.33245	0.19766
15	1.012	1.5920	0.58035
16	0.9135	1.91412	1.00064
17	0.8905	2.20659	1.31606
18	0.7163	4.82104	4.10474

Table 6: Calculated different sample concentration of Carbon Monoxide.

Time (hour.)	Tailpipe Emission Concentration ($A\chi_t$) (ppm)	Expanded Concentration ($\varepsilon\chi_t$) (ppm)	Background Concentration ($\delta\chi_{t-1}$) (ppm)
7	0.18082	6.67282	6.492
8	0.18377	11.2113	11.0276
9	0.18809	6.67831	6.49023
10	0.19795	4.05302	3.85506
11	0.18153	2.50981	2.32829
12	0.20978	1.61702	1.40725
13	0.22464	1.16345	0.938811
14	0.28977	1.14897	0.859201
15	0.27409	1.0338	0.759716
16	0.23347	1.2482	1.01472
17	0.23588	1.49443	1.25855
18	0.18755	2.7969	2.60936

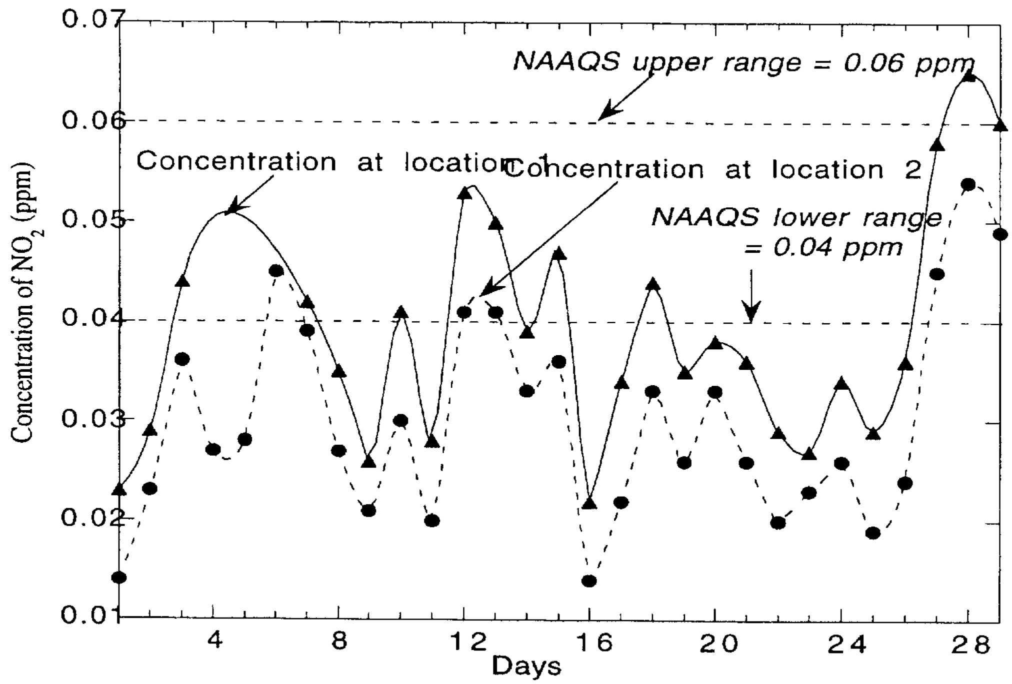

Figure 1: Daily Average NO_2 Concentrations Near Two Roads in Nagoya City, Japan.

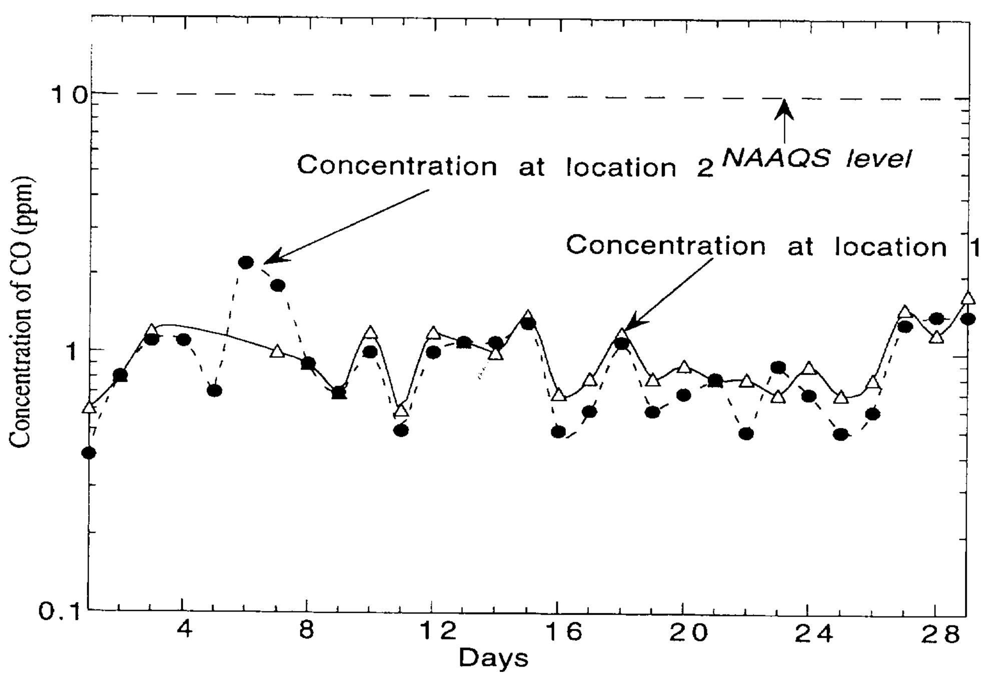

Figure 2: Daily Average CO Concentrations Near Two Roads in Nagoya City, Japan.

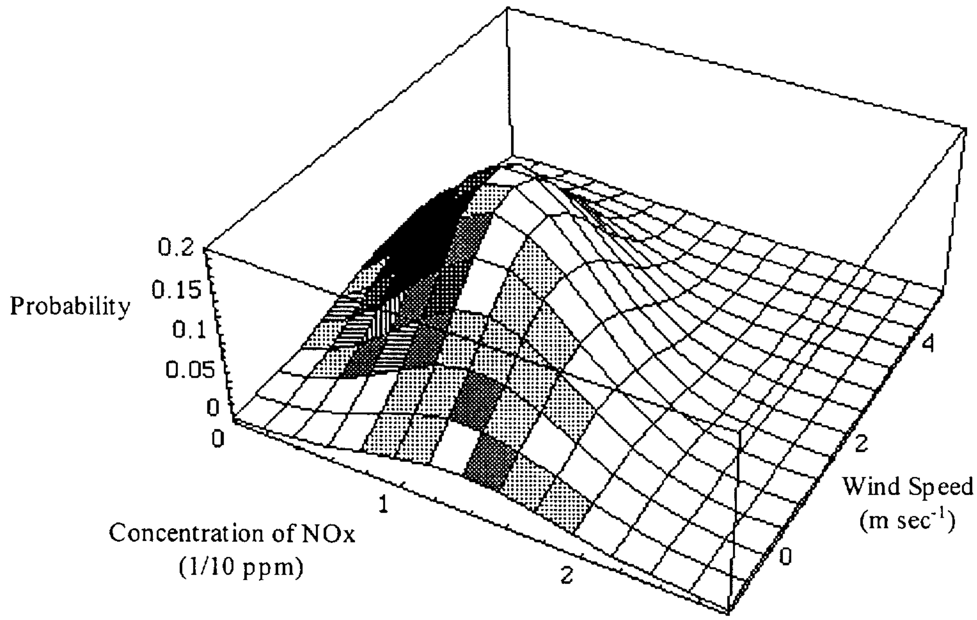

Figure 3: Computed Bivariate Continuous Probability Distribution for NOx.

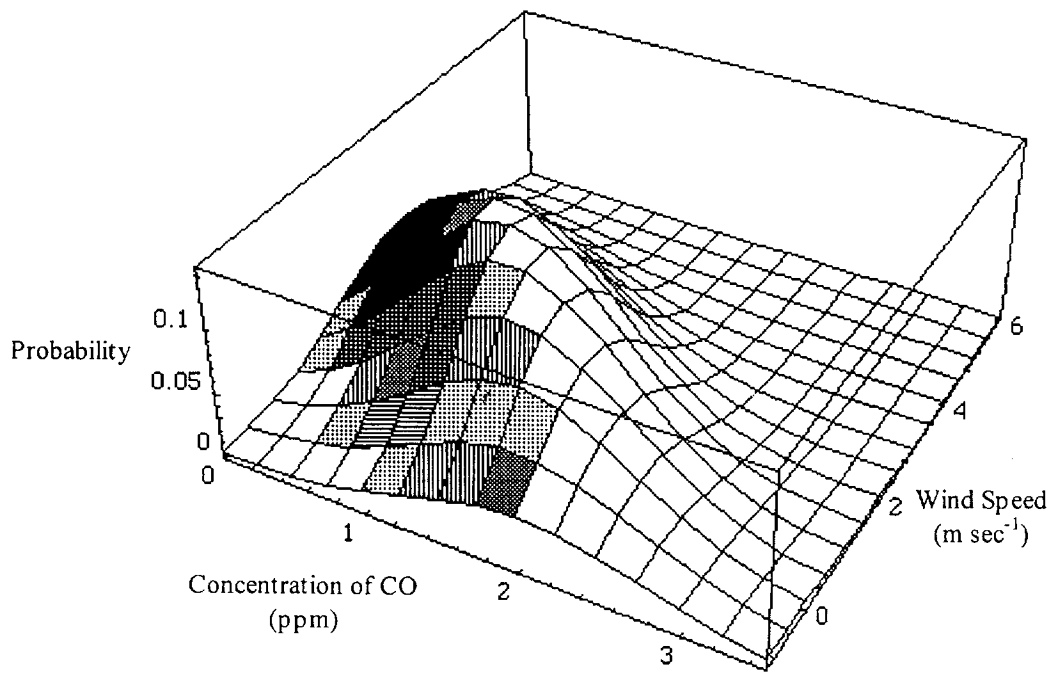

Figure 4: Computed Bivariate Continuous Probability Distribution for CO Concentrations.

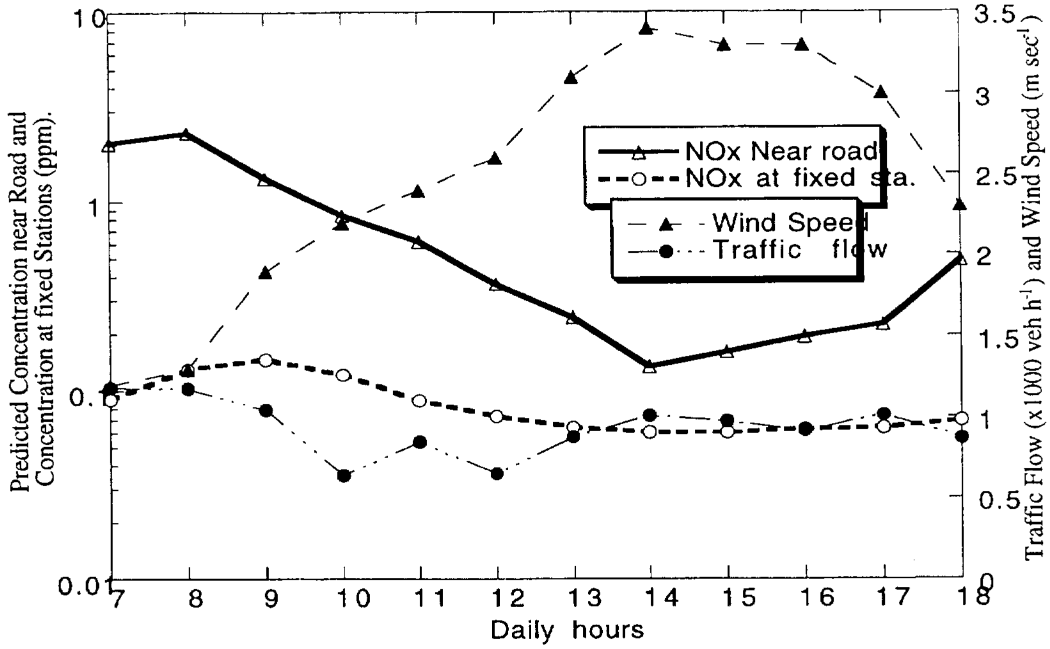

Figure 5: Comparison of Predicted Road Level NOx Concentrations and Concentrations Measured at a Local Monitoring Station

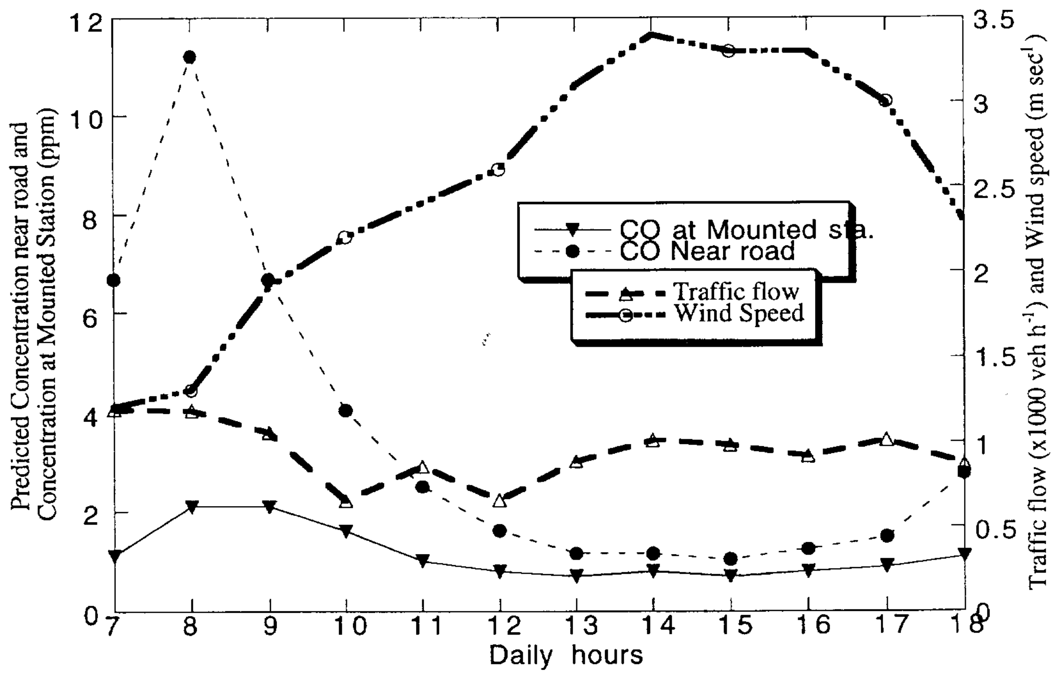

Figure 6: Comparison of Predicted Road-Level CO Concentrations and Concentration Measured at a Local Monitoring Station.