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Comparative Analysis of HIWAY, California, and CALINE2 Line Source Dispersion Models

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This paper provides a comparison of three different, idealized line source dispersion models—HIWAY, California Line Source, and CALINE2—that predict carbon monoxide concentrations near highways. All are based on the Gaussian dispersion equations and are compared by means of sensitivity analysis and model validation. The sensitivity analysis analyzes the dependence of normalized pollutant concentration on variations in several independent input parameters such as stability class, wind angle with respect to the highway, and receptor distance from the highway. The models are validated by comparing carbon monoxide concentrations measured near a highway with concentrations predicted by the models.

Determining the changes in air quality near proposed highway projects often involves the use of mathematical diffusion models (1, 2, 3). These models provide theoretical estimates of air pollution levels and their temporal and spatial variation for present and proposed conditions. The model estimates are a function of meteorology, highway geometry, and downwind receptor location. The sensitivity of model predictions to changes in these input parameter values can be used to evaluate the performance of the diffusion models for a variety of conditions.

The objective of this paper is to provide a comparison of three different line source dispersion models by means of sensitivity analysis and model validation. The sensitivity analysis was performed for specific sets of conditions for the three models. Field measurements of traffic, meteorological conditions, and carbon monoxide (CO) concentrations were used in the model validation.

DESCRIPTION OF MODELS

In the HIWAY model of the U.S. Environmental Protection Agency (EPA), concentrations are calculated by the approximation of a line source by a finite number of evenly spaced, continuous point sources of strength equal to the total line source strength divided by the number of sources used to simulate the line. The California Line Source model calculates concentrations of pollutants within a turbulent mixing cell above the highway as well as at receptor points downwind. Dispersion downwind is dependent on atmospheric stability class. In the case of parallel winds, the California Line Source model accumulates pollutants within the mixing cell to account for downwind buildup. Pollutants are then dispersed laterally at a rate dominated by stability class.

CALINE2, a revised version of the California Line Source model, maintains the mechanical mixing-cell concept of the original California model. In the case of a "pure" crosswind (a wind angle of 90° with respect to the roadway), the mathematical model is based on the Gaussian infinite line source diffusion equation. In the case of a pure parallel wind (a wind angle of 0° with respect to the highway), the highway length is divided into a number of area sources. Each area source is transformed into a virtual point source, and these sources are summed at the downwind receptor. For wind angles other than pure crosswind or pure parallel wind, CALINE2 assumes the wind angle has a crosswind and a parallel wind component. The concentration downwind is calculated from a weighted average of the pure crosswind and the pure parallel wind.

Major Differences

The major differences in the models are as follows:

1. The California Line Source model uses a Gaussian line source equation, and the EPA model uses an integrated point source equation. Under crosswind and parallel wind conditions, the California model requires separate equations for prediction; the EPA model needs only one equation. CALINE2 uses the Gaussian line source equation for the pure crosswind and an integrated point source equation for the pure parallel wind.
2. The EPA model requires separate traffic and emission data for each lane of highway. Both California models use the combined total traffic volume and emission rate for all lanes, assuming that all emissions are initially dispersed from a uniform mixing cell that extends from shoulder to shoulder of the road [medians of <9 m (<30 ft)].
3. The EPA model uses a virtual source correction that provides an initial vertical dispersion parameter of $\sigma_z = 1.5$ m (5 ft). The California models assume a mixing cell with an initial $\sigma_z = 4$ m (13 ft).
4. The EPA model uses dispersion coefficients that differ from the coefficients used by the California models (1, 2, 3).

Assumptions

The following basic assumptions are common to all three models:

1. The mass of pollutants is conserved throughout the downwind length of the plume. No material is lost by reaction or by sedimentation.
2. The ground surface, when it is encountered, is a perfect plume reflector.
3. There exists no wind shear in the vertical direction. The wind velocity used should be representative of the average wind velocity between $\pm\sigma_z$ from the plume centerline in the vertical sense.
4. Dispersion occurs only by turbulent diffusion, which varies according to the atmospheric stability categories developed by Pasquill.
5. Atmospheric stability is constant within the mixing layer that contains both sources and receptor.
6. There is no mixing of material in the x-axis (i.e., longitudinal mixing).
7. Emissions are from continuous sources.
8. The dispersion parameters (σ_y) and (σ_z) are useful for modeling atmospheric dispersion over flat, grassy terrain with no significant aerodynamic roughness or any artificial vertical instability induced by heat-island effects associated with urban areas.

Input Parameters

The input parameters required for the models are

1. Geometry of the highway, that is, road angle with respect to north and road elevation (at grade, elevated, or depressed);
2. Receptor location in both the horizontal and vertical directions with respect to the road;
3. Meteorology including wind speed, wind direction with respect to the road, and Pasquill atmospheric stability class; and
4. Pollutant emission rate from vehicles based on traffic volume and speed, vehicle mix by age, and mix of heavy-duty vehicles.

Model Operations

HIWAY

HIWAY simulates a highway with a finite number of point sources, and the total contribution of all points is calculated by a numerical integration of the Gaussian point source equation over a finite length. The concentration (χ) from the line source of length (L), incremental length ($d\ell$), and incremental emission rate ($q\ell$) is given by

$$\chi = (q\ell/n) \int_0^L F\, d\ell \qquad (1)$$

where the function (F), for stable conditions or conditions in which the mixing height is greater than or equal to 5000 m (16 500 ft), can be calculated as follows:

$$F = (1/2\pi\sigma_y\sigma_z) \exp[-\tfrac{1}{2}(y/\sigma_y)^2] (\exp\{-\tfrac{1}{2}[(z - H)/\sigma_z]^2\} + \exp\{-\tfrac{1}{2}[(z + H)/\sigma_z]^2\}) \qquad (2)$$

where

σ_y = horizontal dispersion parameter (m),
σ_z = vertical dispersion parameter (m),
z = height of receptor above ground level (m), and
H = height of road above ground level (m).

The value of the integral in Equation 1 is approximated by use of the trapezodial rule. Let $\Delta\ell = L/N$. Then the trapezodial approximation gives

$$\chi = q\Delta\ell/u \left[\tfrac{1}{2}(f_o + f_N) + \sum_{i=1}^{N-1} f_i \right] \qquad (3)$$

where f_i is evaluated from Equation 2 for $\ell + \Delta\ell$.

California Line Source Model

In the California Line Source model, the crosswind equation generally takes the form of the Gaussian line source equation:

$$C = (4.24Q/2K\sigma_z\overline{U}\sin\phi)\{\exp - \tfrac{1}{2}[(z + H)/\sigma_z]^2 + \exp - \tfrac{1}{2}[(z - H)/\sigma_z]^2\} \qquad (4)$$

where

C = concentration of pollutant (g/m^3),
Q = source emissions (g/s·m),
K = empirical coefficient = 4.24,
$\overline{U}$ = wind speed (m/s), and
ϕ = angle of wind with respect to highway alignment.

For parallel winds, the estimated concentrations within the mechanical mixing cell, where the ratio of 30.5/W is ≤1, can be determined from the following equation:

$$\{ppm\}_{mc} = A(Q/\bar{U})\,(1/K)\,(30.5/W) \qquad (5)$$

where

$\{ppm\}_{mc}$ = concentration of pollutant within the mechanical mixing cell (g/m^3),
A = downwind concentration ratio for parallel winds (accumulation term), defined as ($C\bar{U}K/Q$) (W/30.5) (2, Vol. 5, Figures 70 to 85),
30.5 = initial highway width used for the finite element of area in developing the model for parallel winds (m), and
W = width of roadway from edge of shoulder to edge of shoulder (m).

For parallel winds, the source emission strength (Q) is calculated by using the following equation:

$$Q = \text{emission factor} \times \text{vehicles per hour} \times 5.26 \times 10^{-6} \qquad (6)$$

where the numerical constant is a factor used to convert units of the product of vehicles per hour times the emission factor to grams per second for 30.5 m (100 ft) of highway.

To estimate ground-level pollution concentrations away from the highway (when the wind is parallel to the alignment), the following equation is used:

$$C = \{ppm\}_{mc}[\exp - \tfrac{1}{2}(Y/\sigma_y)^2] \times \tfrac{1}{2}\{\exp - \tfrac{1}{2}[(z+H)/\sigma_z]^2 + \exp - \tfrac{1}{2}[(z-H)/\sigma_z]^2\} \qquad (7)$$

where Y is the normal distance from the receptor to the near edge of the highway shoulder in meters.

CALINE2

In the CALINE2 model, the mathematical equation for pure crosswinds takes the form of the Gaussian line source equation:

$$C_{xwind} = (Q/\sqrt{2\pi}\sigma_z\bar{U})\{\exp - \tfrac{1}{2}[(z+H)/\sigma_z]^2 + \exp - \tfrac{1}{2}[(z-H)/\sigma_z]^2\} \qquad (8)$$

where C_{xwind} represents the concentration of the pure crosswind component in grams per cubic meter.

For pure parallel winds, the mathematical model uses the Gaussian point source equation:

$$C_p = (Q/2\sigma_y\sigma_z\bar{U})[\exp - \tfrac{1}{2}(y/\sigma_y)^2]\{\exp - \tfrac{1}{2}[(z-H)/\sigma_z^2]^2 + \exp - \tfrac{1}{2}[(z+H)/\sigma_z^2]\} \qquad (9)$$

where C_p represents the concentration of the pure parallel wind component in grams per cubic meter.

The highway length, which is assumed to be 0.8 km (0.5 mile), is divided into a series of square area sources (WXW, where W is the highway width). Each area source is transformed into a virtual point source by Equation 9, and these are summed at the receptor for a cumulative concentration. A scaling factor is then used to increase concentrations to those for a line source 8 km (5 miles) in length by stability classification (3), as given below.

Stability Class	Scaling Factor
A	1.00
B	1.06
C	1.16
D	1.37
E	1.64
F	2.08

The resulting concentration for pure parallel winds can be represented by the following formula:

$$C_{PARWIND} = sf\left(\sum_{n=1}^{NSEG} C_p\right) \qquad (10)$$

where

$C_{PARWIND}$ = resulting concentration of the pure parallel wind component (g/m^3),
sf = scaling factor, and
NSEG = number of area sources in a highway length of 0.8 km (0.5 mile).

For oblique winds, concentrations at receptor points are calculated from a weighted average of the terms for pure crosswind and parallel wind. The weighted average is represented by the following equation:

$$C = \sin^2\phi \times C_{xwind} + \cos^2\phi \times C_{PARWIND} \qquad (11)$$

where

C = concentration at the receptor point (mg/m^3) and
ϕ = wind angle with respect to the roadway (rad).

SENSITIVITY ANALYSIS

Method

The sensitivity of model predictions to changes in input parameter values was analyzed by comparing normalized pollutant concentration versus normal distance to the highway edge for crosswind, parallel wind, and oblique wind conditions. The model predictions are made for Pasquill stability classes B and E. Stability classes A and F were omitted because they represent extreme stability conditions.

Normalized pollutant concentration is defined for this analysis as Cu/Q (m^{-1}), where C is the resultant downwind concentration in micrograms per cubic meter, u is the mean wind speed in meters per second, and Q is the source strength in micrograms per second. Specific wind-angle values were chosen to represent the three wind-angle categories: $\phi = 90°$ for crosswinds, 0° for parallel winds, and 45° for oblique winds.

The highway configuration was an at-grade, two-lane highway with a total width of 7.3 m (24 ft) and with equal emissions from each lane. The highway length was assumed to be 2000 m (6600 ft). The receptor height above the ground was taken as 1.5 m (5 ft), and the effective vertical mixing height (EPA model input) was set at 1000 m (3300 ft).

Discussion of Results

Figure 1 shows variation in normalized pollutant concentration with downwind distance under crosswind conditions for all three models. The California Line Source model and CALINE2 perform similarly, the only difference being that CALINE2 predicts 20 percent less pollutant concentration for all downwind distances. [When CALINE2 was developed, a factor of $2/\sqrt{2\pi}$ ($\cong$0.8) was incorporated into the crosswind equation.] Generally, HIWAY predicts higher pollutant concentrations than the two California models for the crosswind case.

Initial concentrations (at x = 0 m) predicted by the California models are not sensitive to stability classification, whereas HIWAY predicts initial concentrations as a function of stability class. The rate of dispersion for the California models is greater than that of HIWAY within 20 m (66 ft) of the highway. Beyond 20 m, HIWAY has a greater rate of dispersion. Figure 2 shows normalized pollutant concentration as it varies with downwind distance for parallel winds. HIWAY and CALINE2 perform similarly for this case except that, although both models predict initial pollutant concentrations as a function of stability class, HIWAY predicts an initial concentration that is approximately two times that predicted by CALINE2. The California Line Source model generally predicts higher pollutant concentrations for the parallel wind case than those predicted by HIWAY and CALINE2.

Figure 3 shows normalized pollutant concentration versus normal distance from the highway for oblique wind conditions. The EPA model generally predicts higher pollutant concentrations than the California models for this case, with two exceptions: (a) For stability class E and x < 30 m (98 ft), CALINE2 predicts higher concentrations; and (b) for stability class B and x > 70 m (230 ft), the California Line Source model predicts higher pollutant concentrations. HIWAY and CALINE2 predict initial pollutant concentration as a function of stability class; the original California model does not.

Figure 1. Normalized pollutant concentration versus normal receptor distance from road edge for perpendicular wind conditions.

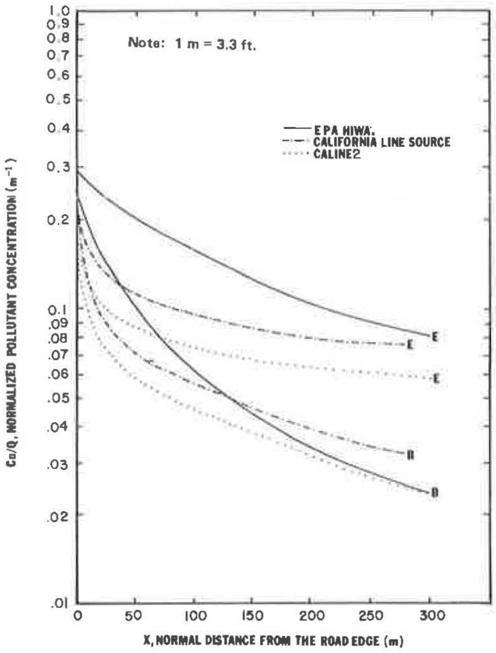
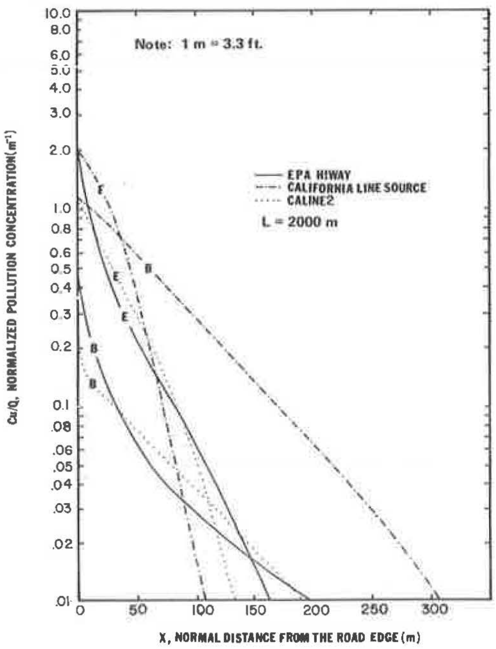


Figure 2. Normalized pollutant concentration versus normal receptor distance from road edge for parallel wind conditions.



MODEL VALIDATION

Experimental Procedure

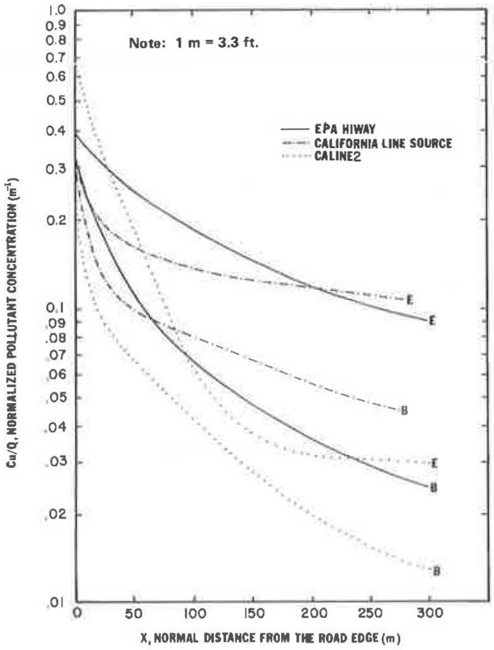
Air pollution, meteorological, and traffic measurements were made near a major arterial in Nashville, Tennessee, over a 5-d period in July and an 8-d period in August of 1973. The site was at grade; a 76-m (250-ft), flat, grass-covered area extended north from the road. A small hill 21 m (70 ft) high with a gradual slope was located 670 m (2200 ft) to the southwest.

Wind speed and direction were measured continuously during the field investigation. During the first monitoring period, a single MRI wind instrument was mounted 3.7 m (12 ft) above the ground and 9.1 m (30 ft) from the road edge. During the second monitoring period, an additional wind instrument was mounted at a height of 9.1 m.

CO concentrations were measured at various distances north of the highway by using a sampling array of five probes along a horizontal profile perpendicular to the highway. Each of the probes was at a height of 1.5 m (5 ft) above the ground. Air samples were pumped continuously through tubing to a sampling manifold located at a mobile air-monitoring trailer and were analyzed by using a nondispersive infrared (NDIR) CO analyzer.

During the second field monitoring period, large variations in wind direction occurred. Because of this, CO concentrations were measured on both sides of the highway. A bag sampling network was used on the south side of the road (9).

Figure 3. Normalized pollutant concentration versus normal receptor distance from road edge for oblique wind conditions.



Accuracy in pollutant concentration measurements was ensured by calibrating the analyzers before and after each peak-traffic sampling period. A two-point calibration procedure was employed that used a zero and a span gas. Before field use, linearity of the instruments was checked in the laboratory by using span gases of different concentrations (10). Two different procedures of calibration—for sampling lines and instruments—were performed in the field.

Fifteen-minute traffic counts were made by pneumatic counter-recorders. A separate counter was used for inbound and outbound traffic volumes. Average vehicle speed was measured by timing vehicles over a known distance. The time-averaging method uses an observer who times a randomly chosen vehicle between two easily recognizable end points. Adequate course length [>152 m (>500 ft)] and a stopwatch provide the necessary accuracy of measurement. The heavy-duty vehicle mix was obtained by manual count.

Table 1. Results of regression analysis comparing measured CO concentrations and concentrations predicted by California Line Source model.

Data Set	N	Mean	CV (%)	r	M	b	k
0-0-0	568	1.6	70	0.51	0.38	1.10	0.84
11-0-0	44	1.8	55	0.83	0.35	0.11	2.70
12-0-0	226	1.5	64	0.65	0.69	0.62	0.84
13-0-0	298	1.7	52	0.74	1.46	0.35	0.55
11-0-1	14	3.4	24	0.92	0.35	0.96	2.06
11-0-2	30	1.1	68	0.70	0.22	0.20	3.65
12-0-1	75	2.4	48	0.64	0.60	1.15	0.84
12-0-2	151	1.0	73	0.38	0.46	0.64	0.84
13-0-1	109	2.6	43	0.68	1.33	0.65	0.57
13-0-2	189	1.2	61	0.48	1.28	0.39	0.53
0-1-0	6	1.6	29	0.96	1.25	-0.33	0.97
0-2-0	223	1.5	61	0.59	1.26	0.45	0.56
0-3-0	281	1.6	72	0.51	0.43	1.05	0.85
0-4-0	26	1.9	45	0.74	0.38	1.04	1.20
0-5-0	26	2.2	66	0.70	0.31	0.74	2.10
0-6-0	6	0.3	20	0.96	0.89	-0.34	2.54

Note: Measured background subtracted.

Table 2. Results of regression analysis comparing measured CO concentrations and concentrations predicted by HIWAY model.

Data Set	N	Mean	CV (%)	r	M	b	k
0-0-0	538	1.6	73	0.49	0.33	1.13	0.89
11-0-0	19	2.2	55	0.85	0.24	0.59	3.11
12-0-0	224	1.4	65	0.67	0.76	0.44	0.91
13-0-0	295	1.7	58	0.67	1.33	0.15	0.69
11-0-1	5	5.2	28	0.61	0.10	3.61	2.98
11-0-2	14	1.1	60	0.81	0.19	0.40	3.35
12-0-1	69	2.4	35	0.83	0.96	0.71	0.73
12-0-2	155	1.0	73	0.44	0.39	0.58	1.10
13-0-1	103	2.7	42	0.67	1.34	0.67	0.56
13-0-2	192	1.2	61	0.52	0.80	0.38	0.84
0-1-0	6	1.6	29	0.95	2.03	-0.45	0.64
0-2-0	207	1.6	51	0.73	1.90	-0.12	0.57
0-3-0	273	1.6	65	0.67	0.80	0.49	0.87
0-4-0	20	1.6	31	0.87	1.76	-1.40	1.16
0-5-0	26	2.2	64	0.72	0.21	0.96	2.66
0-6-0	6	0.3	29	0.91	2.63	-2.56	4.00

Note: Measured background subtracted.

Table 3. Results of regression analysis comparing measured CO concentrations and concentrations predicted by CALINE2 model.

Data Set	N	Mean	CV (%)	r	M	b	k
0-0-0	568	1.6	70	0.53	0.49	1.05	0.72
11-0-0	44	1.8	62	0.78	0.41	0.57	1.66
12-0-0	226	1.5	69	0.58	0.54	0.86	0.77
13-0-0	298	1.7	60	0.63	1.46	0.38	0.53
11-0-1	14	3.4	34	0.83	0.39	1.49	1.46
11-0-2	30	1.1	77	0.58	0.26	0.54	1.96
12-0-1	75	2.4	49	0.63	0.56	1.42	0.71
12-0-2	151	1.0	73	0.37	0.30	0.78	0.84
13-0-1	109	2.6	46	0.62	1.43	0.83	0.48
13-0-2	189	1.2	65	0.37	0.74	0.66	0.60
0-1-0	6	1.6	34	0.94	2.42	0.14	0.38
0-2-0	223	1.5	55	0.69	2.11	0.08	0.45
0-3-0	281	1.6	61	0.70	1.15	0.44	0.64
0-4-0	26	1.9	38	0.82	0.66	0.46	1.16
0-5-0	26	2.2	41	0.90	0.50	-0.49	2.45
0-6-0	6	0.3	46	0.75	0.39	-0.41	6.53

Note: Measured background subtracted.

Atmospheric stability measurements were based on surface wind speed, insolation (strong, moderate, or slight), percentage of cloud cover, and time of day (angle of the sun). A hygrothermograph was used in the field to determine temperature changes. Field estimates were made of insolation and percentage of cloud cover. Stabilities were classified in one of the six Pasquill stability classes—A, B, C, D, E, or F—which range from extremely unstable to extremely stable (11).

Data Presentation

Tables 1, 2, and 3 present the results of the correlation and regression analysis that compared measured ambient CO concentrations to concentrations predicted by the HIWAY, California Line Source, and CALINE2 models. The raw data used for statistical analysis consisted of 568 data sets of CO concentrations measured downwind of the highway, background concentrations measured upwind of the highway, and the concentration predicted by the models. Measured versus predicted concentrations have been evaluated according to wind angle, receptor distance, and stability by using the following criteria (12).

1. Wind angles with respect to the road alignment were separated into three categories: parallel (0° to 13°), oblique (13° to 60°), and perpendicular (60° to 90°).
2. The distance from the sampling probe to the center of the road is the receptor distance. The data were separated only according to those receptors at the edge of the road shoulder or mixing cell (roadside receptor) and those located at distances farther downwind.
3. Pasquill's six stability categories were used to separate data subsets.

Tables 1, 2, and 3 use the following code: (a) a three-digit coded description of the data set in which the digits indicate wind angle [11 = parallel winds, 12 = oblique winds, and 13 = perpendicular winds (with reference to the road)], stability category (1 = A, 2 = B, 3 = C, 4 = D, 5 = E, 6 = F), and receptor distance [1 = roadside, 2 = downwind, to 91.4 m (300 ft) from center of road] and 0 means all data in the category; (b) N, the number of data points in the data set; (c) mean, the mean measured CO concentration; (d) CV(%), the coefficient of variation, equal to the ratio of the standard error of y from the regression line divided by the mean measured concentration; (e) r, the correlation coefficient; (f) M, the slope of the calculated least squares regression line; (g) b, the intercept of the regression line; and (h) k, the ratio of the mean predicted concentration divided by the mean measured concentration.

Discussion of Results

The output of the regression analysis can be used to indicate the precision and the accuracy of mathematical model predictions when they are compared with measured pollutant concentrations. The method of analysis uses the correlation coefficient (r) as an index of the precision of the association between predicted and measured concentrations. Whenever the correlation coefficient is high, the model performs well under the conditions included in the data set.

A second parameter (k), equal to the ratio of the average predicted pollutant concentration divided by the average measured concentration, is used as an indication of the relative accuracy of the model. Values of k greater than one indicate that, on the average, the model tends to overpredict the measured concentration; k-values less than one indicate underprediction. The size of the data set (n) is also important and must be considered when the significance of the values of r and k is evaluated. It is also important to note that model accuracy is dependent on precision to the extent that k-values tend to be meaningless when correlation coefficients are quite low.

Experimental Error

Variability in the comparison of measured and predicted concentrations results from two sources: (a) inadequacies of the model to predict accurately under the range of conditions contained in a data set and (b) experimental error. An estimate of experimental error can be made by comparing the expected accuracy of CO measurements to the concentrations typically observed in the field. The sensitivity of CO analyzers, as reported by the manufacturers, is 0.6 mg/m^3 (0.5 ppm). More than half of the field measurements of CO were less than 2.3 mg/m^3 (2.0 ppm). Therefore, errors of a magnitude equal to (0.5/2.0) × 100 percent = 25 percent or greater probably occur frequently in the data. Background concentrations averaged less than 1.1 mg/m^3 (1 ppm); therefore, errors of 50 percent and greater probably occur in these data because of analyzer sensitivity. Additional errors can be attributed to the use of different analyzers.

Model Performance

The overall precision of the EPA model is reflected in the correlation coefficient, r = 0.49, which is significantly improved when the data are separated by wind angle (where r = 0.85 for parallel winds and r = 0.67 for perpendicular and oblique winds). HIWAY tends to overestimate for parallel winds and underestimate for crosswind conditions. The parallel case overpredicts by $\cong 3$. The average accuracy of perpendicular and oblique wind predictions ranges from 44 percent underprediction to 10 percent overprediction. Model precision tends to be better for roadside receptors, but accuracy is better for downwind receptors. The relative accuracy of downwind receptor predictions compared to roadside-edge receptor predictions is approximately 40 percent for perpendicular and oblique wind conditions.

HIWAY also tends to overestimate for stable atmospheric conditions and to underestimate for unstable conditions. The error ranges from 43 percent underprediction for class B to 166 percent overprediction for class E.

The California Line Source model performs similarly. The overall correlation coefficient, r = 0.51, is improved when the data are separated by wind angle (where r = 0.83 for parallel, 0.65 for oblique, and 0.74 for crosswind conditions). The model tends to overpredict for parallel winds by a factor of from 2 to 3.6 and to underpredict for oblique wind and crosswind conditions by 16 and 45 percent respectively. Although the California model is generally less precise than the EPA model, the accuracy of its roadside receptor prediction is comparable to downwind receptor predictions for both crosswind and oblique wind, which indicates that the California Line Source model tends to predict the rate of downwind dispersion rather well.

The overall precision of CALINE2 is slightly greater than that of HIWAY and the California Line Source model, as reflected in the correlation coefficient, r = 0.53. This precision is improved when the data are separated by wind angle (where r = 0.780 for parallel, 0.579 for oblique, and 0.632 for perpendicular winds), but it is generally less than that exhibited by the other models for the same categories. CALINE2 tends to overpredict for parallel winds and underpredict for oblique and perpendicular winds. The model overestimates by 66 percent for parallel winds, which is significantly less than the overestimates observed for the EPA model (211 percent) and the California Line Source model (170 percent) for the same case. The model underpredicts by 23 percent for oblique winds and 47 percent for perpendicular winds. In the category of atmospheric stability, CALINE2 tends to overestimate for stable conditions and underestimate for unstable conditions. The CALINE2 estimates range from a 56 percent underprediction for the B stability class to a 145 percent overprediction for the E stability class.

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