CALINE2: AN IMPROVED MICROSCALE MODEL FOR THE DIFFUSION OF AIR POLLUTANTS FROM A LINE SOURCE

Charles E. Ward, Jr., and Andrew J. Ranzieri, Transportation Laboratory, California Department of Transportation

Compliance with the National Environmental Policy Act (NEPA) and the California Environmental Quality Act (CEQA) requires that an air quality assessment be included as part of the environmental impact report prepared for proposed transportation projects. In addition, the Federal-Aid Highway Act and the Clean Air Act of 1970 require air quality analyses for proposed transportation systems.

Transportation agencies must be able to estimate changes in air quality within the highway corridors to comply with these laws and their associated regulations. The highway corridor is defined as the region extending from the vehicular source of the pollutants to the point where ambient pollutant levels are again reached. The primary pollutants emitted from motor vehicles are hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), and particulates. Lead is the major form of particulates, but catalytic convertors have caused sulfate particulates to be of increasing concern. Reactive hydrocarbons (RHC), which are a major proportion of the total vehicular-emitted hydrocarbons, combine in the presence of sunlight with nitrogen oxides to form smog.

Photochemical formation of smog is a large-scale phenomenon and should be analyzed on a regional basis. For a corridor analysis, carbon monoxide is suitable as a tracer pollutant to define air pollutant dispersion because of its relative inertness in the photochemical smog process. Lead and sulfate particulates are not yet considered because of the lack of quantitative data on emission rates and dispersion characteristics. Line source computer models have been developed during the past few years to simulate the dispersion of carbon monoxide within the highway corridor. The California Department of Transportation model, CALINE2, has been so named because it is the second major version of the California line source dispersion model. The first version is described in the air quality manual (1).

Included in this paper are a discussion of the Gaussian dispersion theory, the mathematical assumptions of CALINE2, a sensitivity analysis, and a comparison of the CALINE2 predictive capabilities with observed data.

MATHEMATICAL ASSUMPTIONS

General Gaussian Assumptions

Gaussian Dispersion

The Gaussian dispersion equations, as described by Turner (2), were developed to describe the dispersion of an inert pollutant from a point source with a constant emission rate. The equations assume that the concentrations of pollutants follow a normal distribution in the horizontal and vertical directions. Figure 1 shows the dispersion in a typical case and the coordinate system used. The general form to describe the Gaussian diffusion equation is

$$C(x,y,z;H) = \frac{QF}{2\pi\sigma_y\sigma_z\bar{u}} \left\{ \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2 \right] \right\} \left\{ \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2 \right] + \exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2 \right] \right\} \quad (1)$$

where

C = concentration,
x,y,z = receptor location in 3-dimensional space,
H = effective stack height,
Q = source strength,
σ_y,σ_z = horizontal and vertical dispersion parameters,
$\bar{u}$ = mean wind speed, and
F = conversion factor to change input units to output units.

The edge of the Gaussian plume is defined as the point in the y-z plane where the pollutant concentration is a tenth that of the centerline. This point is at a distance of 2.15σ from the centerline. Perfect reflection of the plume is assumed when it contacts the ground surface. This assumption is incorporated into equation 1 by creating an imaginary point source that is an undersurface mirror of the actual source. The (z + H) term is related to the vertical dispersion downwind from the actual point source, and the (z - H) term is related to the vertical dispersion from the imaginary source. Equation 1 only calculates the concentration from the source itself. It does not include the upwind ambient level.

One of the shortcomings of Gaussian dispersion as stated in equation 1 is its inability to handle trapping of pollutants by the "lid" of an elevated inversion. However, in the microscale (highway corridor) region for which CALINE2 was developed, the vertical dispersion of pollutants from a line source usually does not reach the inversion base height. The basis of CALINE2 is that equation 1 is modified to accommodate a line, rather than a point, source. This modification is described in detail in a later section.

Atmospheric Stability Classes

The surface-layer stability of the atmosphere can be classified into separate Pasquill stability categories according to meteorological parameters as suggested by Turner (2). Pasquill developed a series of graphs for the dispersion parameters (σ_y and σ_z in equation 1) as a function of his stability classes and the downwind distance x from the source (Figures 2 and 3).

Unfortunately, the Pasquill dispersion parameters shown in the graphs are only valid for downwind distances from 0.1 to 100 km. Many line source impact analyses are concerned with receptors closer to the highway than 0.1 km, especially in the right-of-way range of 15 to 50 m. Modifications to the dispersion parameter curves to handle downwind distances less than 0.1 km are discussed in a later section.

In addition, Pasquill's original research was conducted in flat, open country or rural areas. It has been found that his stability classes do not adequately describe the atmospheric turbulence encountered in urban areas or rough or forested terrain (2, 3). Neither the aerodynamic roughness height nor the unnatural energy imbalance created by man-made surfaces is incorporated in his dispersion parameter graphs. Although no attempt has been made to incorporate the higher turbulence encountered in urban areas into the stability parameters in CALINE2, as was done in other Gaussian models (3), stability class D (neutral) can be used in urban project analysis to account for this increased instability.

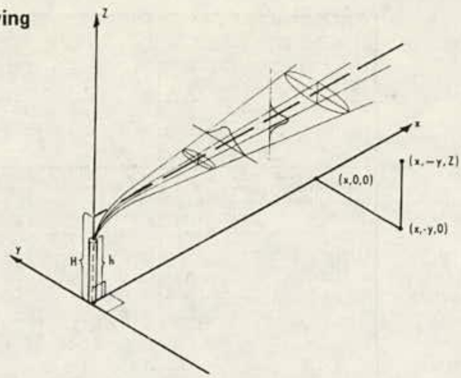


Figure 1. Coordinate system showing Gaussian distributions in the horizontal and vertical.

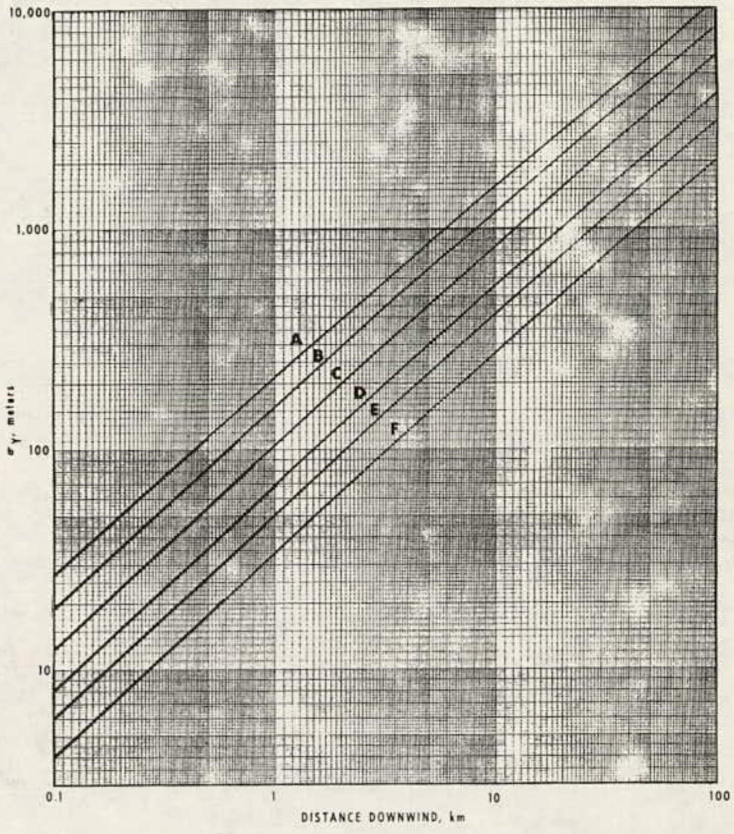


Figure 2. Horizontal dispersion coefficient σ_y as a function of downwind distance from the source.

Wind Shear

The wind speed within the atmospheric boundary layer varies from near zero at the ground surface to some finite free flow velocity at a height of around 500 m. This last figure is highly dependent on surface roughness characteristics and is closer to the ground for flat, even terrain and higher for central business districts with multistory buildings (Figure 4). The Gaussian dispersion equations do not incorporate the wind

Figure 3. Vertical dispersion coefficient σ_z as a function of downwind distance from the source.

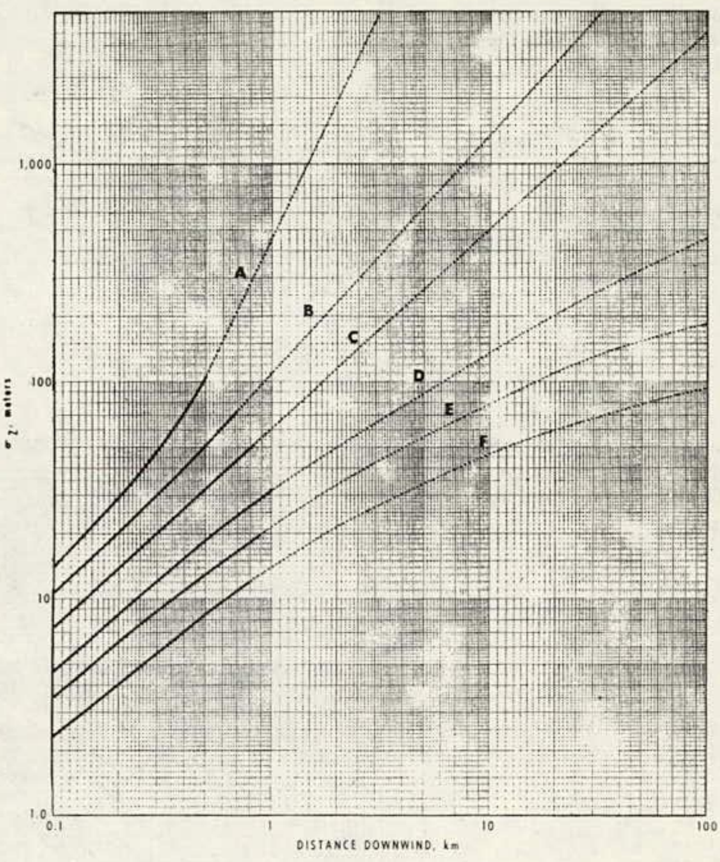
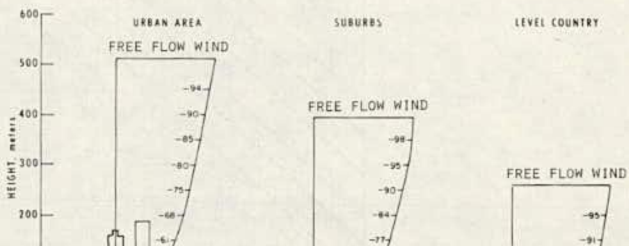


Figure 4. Examples of wind shear with different size roughness elements (numbers are percentages of free flow wind).



shear. Rather, they assume a uniform vertical wind flow field with some mean wind velocity, $\bar{u}$, as shown in Figure 5, that is not influenced by surface roughness.

Aerodynamic Eddies

Physical objects in the path of a uniform wind flow field, such as buildings, highway viaducts, or street canyons, cause the flow to separate and form turbulence eddies. Cavities, areas of divergence, and areas of convergence form, which may disperse or concentrate pollutants, depending on the configuration and interaction of the different eddies.

For example, cavities formed in street canyons have been found to allow inadequate dispersion of pollutants under otherwise turbulent atmospheric conditions (4). Aerodynamic eddies are not included in the Gaussian dispersion theory. Therefore, other means have to be sought to account for these important effects. One such approach is discussed later.

Gaussian Line Source Assumptions

Mixing Cell Concept

It was surmised that the physical movement of the vehicles on a typical line source, a highway, would create a well-mixed region surrounding the highway that would not be affected by surface atmospheric stability. To test this theory, the California Department of Transportation conducted a series of smoke plume dispersion tests on an abandoned airport runway north of Sacramento in 1972 (5). By observing and photographing the initial dispersion of smoke from sources placed in the tailpipes of test vehicles, it was determined that the theory was sufficiently valid. The plume studies indicated that the limits of the mixing cell are approximately equal to the width of the paved surface and twice the height of the vehicle. As a representative average of the vehicle mix, the vertical limit of the mixing cell was set equal to 4 m. The width of the mixing cell, which is also called the highway width, is determined by adding the width of all the lanes, up to the edge of traveled pavement, plus the median, and an extra distance equal to approximately 3 m on each side of the highway. This last is to account for the horizontal turbulence created by the mix of heavy-duty and light-duty vehicles. The same horizontal turbulence is assumed to create a well-mixed region across the median, as long as the median is less than 9.1 m wide. If the median is greater than 9.1 m in width, each direction will have to be simulated separately, as discussed later.

The mixing cell is used as a uniform, well-mixed pollutant source from which the pollutants are then dispersed downwind in a Gaussian manner. Figure 6 shows this concept and also shows how the ambient or base-line pollutant level has been excluded. It is assumed that the concentrations of pollutants within the mixing cell are unaffected by regional meteorological conditions because of the turbulence generated by the moving traffic. The mixing cell can be represented by a tunnel in which the air is thoroughly mixed.

Dispersion Parameter Modifications

To determine dispersion parameters for downwind x distances less than 0.1 km, we set the initial dispersion of a line source equal to that found at the edge of the mixing cell. Interpolative curves were then drawn between these points and the original Pasquill curves. From the empirical evidence of the smoke study, the initial vertical dispersion parameter was set at 4 m (Figure 7).

So that the individual project's width can be accommodated, the initial horizontal dispersion is found by dividing the highway width by the plume width constant, which equals 4.3. (Since the edge of the plume is at a distance of 2.15σ from the plume centerline, the plume width is twice this amount, or 4.3σ. Therefore, the plume width constant is 4.3.) The reason for this, which is more completely explained in a later section, is based on the fact that the horizontal dispersion parameter is only incorporated in the parallel wind equations. A point along an extrapolation of the stability class A curve as defined by Beaton et al. (6) (Figure 8) is found that corresponds to this initial horizontal dispersion, and the first portions of the other stability class curves are modified to begin at this point. For example, the horizontal dispersion parameter for stability class F is assumed to be linear (on a log-log plot) with downwind distance from the initial dispersion parameter of approximately 1 km, at which point it intersects the previously established curve. Figure 9 shows this situation for different highway widths.

Figure 5. Uniform vertical wind flow field.

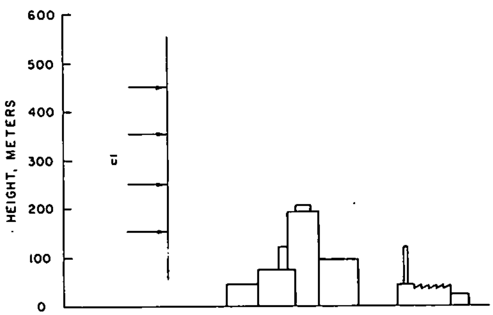


Figure 6. Mixing cell.

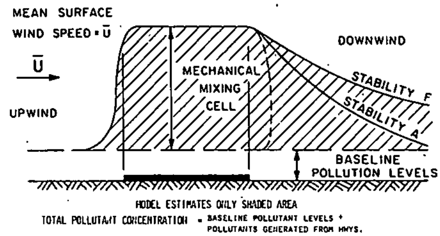


Figure 7. Vertical dispersion parameters.

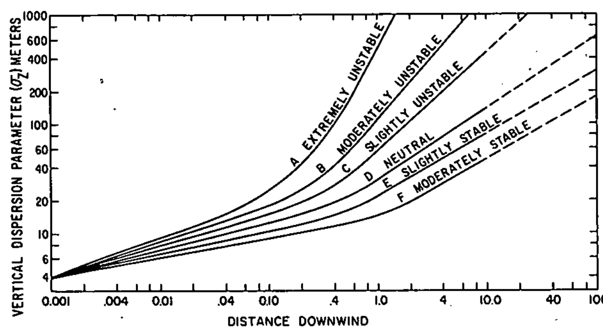


Figure 8. Horizontal dispersion parameters.

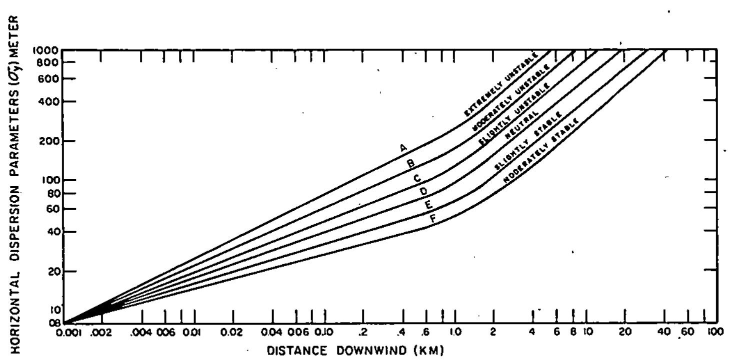
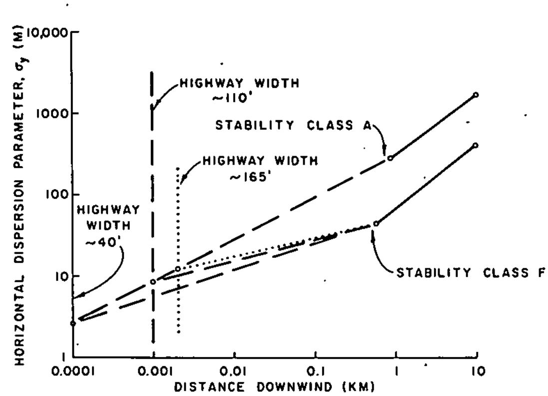


Figure 9. Modification of σ_y for variations in highway width.



Crosswind Line Source Equation

The dispersion of pollutants from an infinite line source with a perpendicular wind (90 deg) can be described by the following equation (6):

$$C_1 = \frac{Q_1 F_1}{\sqrt{2\pi}\,\sigma_z \bar{u}} \left\{ \exp\left[-\frac{1}{2}\left(\frac{z + H}{\sigma_z}\right)^2 \right] + \exp\left[-\frac{1}{2}\left(\frac{z - H}{\sigma_z}\right)^2 \right] \right\} \qquad (2)$$

where

Q_1 = VPH × EF,
VPH = vehicles per hour,
EF = emission factor, and
H = height of pavement above ground surface.

The subscript 1 on C_1, Q_1, and F_1 refers to the crosswind component of the pollutant concentration, line source strength, and conversion factor. Equation 2 is valid as long as the end of the line source is far enough away from the point being analyzed that end effects are unimportant. Figure 10 shows a display of the crosswind situation.

Parallel Wind Line Source Equation

When the wind is parallel to the highway alignment (0 deg), a buildup of pollutants occurs in the downwind mixing cell because an air parcel continues to amass pollutants as it travels along the highway. When the wind is parallel, the assumption can no longer be made that the highway has no width. The following equation is used to account for these factors:

$$C_2 = \sum_{i=1}^{\infty} \frac{Q_2 F_2}{2\pi \sigma_{y_i} \sigma_{z_i} \bar{u}} \left\{ \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_{y_i}}\right)^2 \right] \right\} \left\{ \exp\left[-\frac{1}{2}\left(\frac{z + H}{\sigma_{z_i}}\right)^2 \right] + \exp\left[-\frac{1}{2}\left(\frac{z - H}{\sigma_{z_i}}\right)^2 \right] \right\} \qquad (3)$$

where

$Q_2 = Q_1 \times W$, and
W = highway width.

The subscript 2 on C_2, Q_2, and F_2 refers to the parallel wind component of the pollutant concentration, line source strength, and conversion factor.

The assumption is made that a highway with a parallel wind can be approximated by the summation of a series of square area sources, each having the same source strength but a different distance to the receptor. The area sources themselves are approximated by virtual point sources. This last is why equation 3 is the same form as equation 1 for the summation. To agree with the infinite line theory of the crosswind case, the summation is made over an infinite distance downwind. However, the summation need be carried out only to a finite distance, which is dependent on stability class. At this distance, the contribution of pollutant from area sources located farther upwind from the receptor becomes negligible. Since this distance is only dependent on stability class, a scaling factor (Figure 11) for each class can be used to increase the calculated concentration from a short finite parallel wind segment to that for the infinite line source. The short finite segment has been determined as 0.8 km to allow the incorporation of different highway widths (and, thus, different σ_y curves) with minimal error while shortening the computer time necessary to make the reiterative summation. Figure 11 shows the mixing cell CO concentrations as a function of summation length and stability class.

A virtual point source is defined as a point source that has the same emission strength as the actual area source, is located at a distance upwind of the area source, and yields the same horizontal dispersion parameter as that at the upwind edge of the area source. To find the initial horizontal dispersion parameter of the area source, one divides the width of the area source (which is the highway width) by the plume width constant 4.3, which yields the σ_y for the upwind edge (2). The virtual distance corresponding to this σ_y is found on the horizontal dispersion curve for the appropriate stability class (Figure 9). The vertical dispersion parameter σ_z is assumed to follow the same virtual distance as σ_y. In other words, the virtual distance determined for σ_y is used to find the appropriate σ_z with the curves in Figure 7. Figure 12 shows the basic conceptualization of the parallel wind-virtual point source situation.

The virtual point source should theoretically be aligned with the centerline of the area source. However, this would presume that the concentration across the area source would follow a normal distribution, thereby disagreeing with the definition of the mixing cell. The mixing cell definition mandates a constant concentration throughout the area source. Essentially what has to take place to again agree with the mixing cell definition is that the axis of the virtual point source (the x-axis) has to be shifted toward the edge of the mixing cell. Shifting the axis toward the edge causes the normal distribution to be intersected by the mixing cell edge at a point closer to the mean of the distribution, yielding a higher concentration. The higher concentration is then said to be the concentration of the mixing cell, or area source. This shifting of the x-axis artificially imposes the mixing cell definition on a normal distribution. The shifting of the x-axis is incorporated in the y term of equation 3; i.e.,

$$y = y' + s \qquad (4)$$

where

y' = horizontal distance from the edge of the mixing cell to the receptor, and
s = distance of the x-axis shift.

The distance s is found by solving equations 2 and 3 (the latter for only the first area source segment) for z, H, and unmodified y set equal to 0 (which is the location of the mixing cell), resulting in equations 5 and 6.

$$C_1(x,0,0;0) = \frac{2Q_1F_1}{\sqrt{2\pi}\sigma_z\bar{u}} \qquad (5)$$

$$C_2(x,0,0;0) = \frac{2Q_2F_2}{2\pi\sigma_y\sigma_z\bar{u}} \qquad (6)$$

Neglecting F_1 and F_2, since they are only conversion factors, and remembering that $Q_2 = Q_1 \times W$, we see that equations 5 and 6 differ only by a factor of $W/(\sqrt{2\pi}\sigma_y)$. Since the mixing cell concentrations for a crosswind line source and the first area source segment of a parallel wind line source should be the same, for given atmospheric conditions and roadway configuration, a factor of $(\sqrt{2\pi}\sigma_y)/W$ is required in the parallel wind equation (equation 6). Because the axis has to be shifted, this factor is assumed to be obtained through exp $[-\frac{1}{2}(s/\sigma_y)^2]$. Therefore,

$$\exp\left[-\frac{1}{2}\left(\frac{s}{\sigma_y}\right)^2\right] = \frac{\sqrt{2\pi}\sigma_y}{W} \tag{7}$$

and

$$s = \sigma_y\left[-2\,\ln\left(\frac{\sqrt{2\pi}\sigma_y}{W}\right)\right]^{1/2} \tag{8}$$

For any given values of W and σ_y, s approximately equals the σ_y associated with the virtual point source. Therefore, the physical interpretation of the above mathematics is that the shifted x-axis lies between the actual centerline and the mixing cell edge, at a distance approximately equal to W/4.3 (the σ_y of the virtual point source) from the edge of the mixing cell.

Oblique Wind Line Source Equation

The consideration of a wind blowing at an oblique angle to the highway (0 deg < angle < 90 deg) is made easier by the fact that both the crosswind and the parallel wind equations are for infinite line sources. This similarity allows components of the 2 "pure" wind angle equations to be added via weighted vectorial coefficients.

Figure 13 shows that a wind $\bar{u}$ can be broken down into a crosswind component $\bar{u}$ sin ϕ and a parallel wind component $\bar{u}$ cos ϕ. However, the concern with CALINE2 is to find the pollutant concentration resulting from an oblique wind, and not the vector components of the wind. By the use of the trigonometric identity, $\cos^2\phi + \sin^2\phi = 1$, the concentration from an oblique wind was assumed to be equal to

$$C_3 = \sin^2\phi\, C_1 + \cos^2\phi\, C_2 \tag{9}$$

where the subscript 3 on C_3 refers to the oblique wind pollutant concentrations, C_1 and C_2 are as defined in equations 2 and 3, and ϕ is the acute wind angle. In this case, the trigonometric relation was used to functionally smooth the sum of the components from each of the pure wind angle equations. The preliminary verification study supports this assumption.

Source Height Adjustments

The H term in equations 2 and 3 is used to indicate a highway section that is depressed in relation to the surrounding terrain or at grade or raised above the terrain, as in a fill or viaduct section. Highway sections that are other than at grade are difficult to handle in a line source model because the Gaussian theory does not account for aerodynamic eddies, as discussed earlier.

The carbon monoxide data gathered in Los Angeles in 1972 (7), which included measured concentrations for 2 depressed sites up to 7 m deep, were used to develop a set of empirical ratios to approximate the nonuniform wind flow through a depressed highway section. By the use of multiple stepwise linear regression, the variables were determined that had the most correlation with the measured pollutant concentrations directly above the highway at the level of the surrounding terrain (8). The variables considered were traffic volumes, emission factors, wind speed, wind direction, pavement height, and Pasquill stability class. From the analysis, regression coefficients were determined that related the most significant variables to the carbon monoxide concentrations. The empirical equations for depressed sections are categorized by stability class.

For stability class A,

$$R = 10^{(-0.18164+0.01448H+1.439\times10^{-5}VPH+7.9\times10^{-4}\phi)} \tag{10}$$

For stability class B,

$$R = 10^{(0.21754+0.01431H-7.2\times10^{-4}\phi-0.02252\bar{u})} \tag{11}$$

For stability classes C through F,

$$R = 10^{(0.02019+0.0138H+4.98\times10^{-6}VPH-5.73\times10^{-3}\bar{u})} \tag{12}$$

where R = the empirical ratio, and the other variables are as previously defined. The empirical ratio R was derived from the CO concentrations measured at 1.2, 3.6, 6.1, 10.9, or 13.4 m, divided by the CO concentration at 1.6 m. All heights are heights measured above the pavement height, and not the height of the surrounding terrain. Any height above 1.6 m had an R value of less than 1, although the ratio at 3.6 m always had a value quite close to 1, reinforcing the concept that a uniform mixing cell exists. In a few cases, the aerodynamic eddies caused some increase of CO concentrations with height. These cases were excluded from the analysis and will be subjected to future research.

There is only one equation for stability classes C through F (equation 12) because insufficient data were obtained for stability classes E and F because of meteorological conditions. Until further data are gathered, the relation derived for stabilities C and D are assumed to apply to stabilities E and F.

A physical interpretation of the above equations is that an imaginary mixing cell is created at the level of the surrounding terrain and has a smaller source strength than the actual mixing cell on the highway below (Figure 14). Other than the decreased source strength, the imaginary mixing cell has all the characteristics of the original: the same dimensions, the same uniform distribution of pollutants, and so on. The pollutants in this imaginary mixing cell are then dispersed in the normal Gaussian manner downwind.

At this time, no attempt has been made to develop empirical equations to handle the raised highway section where aerodynamic eddies occur. At present, a raised section is simply considered as an elevated source whose pollutant emissions are dispersed downwind in the same manner as an at-grade line source using the Gaussian equation.

Summary of Assumptions

1. Gaussian (normal) dispersion of pollutants is in horizontal and vertical directions of plane perpendicular to wind direction.
2. A uniform wind flow field exists, with no vertical wind shear or aerodynamic eddies from uneven surface roughness.
3. No buildup of inert pollutants occurs due to elevated inversion conditions for microscale prediction of air quality.
4. No chemical reactions or gravitational settling occurs that affects the pollutant

Figure 10. Schematic of general Gaussian dispersion of pollutants from an infinite line source under crosswind conditions.

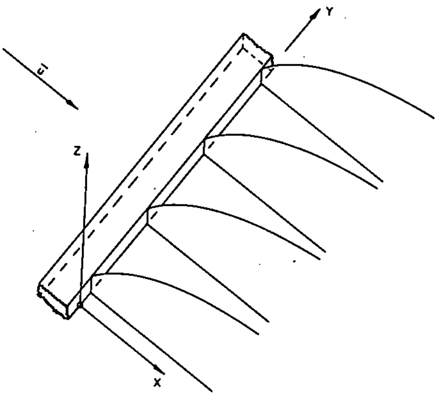


Figure 11. Mixing cell concentrations as a function of highway length parallel to wind.

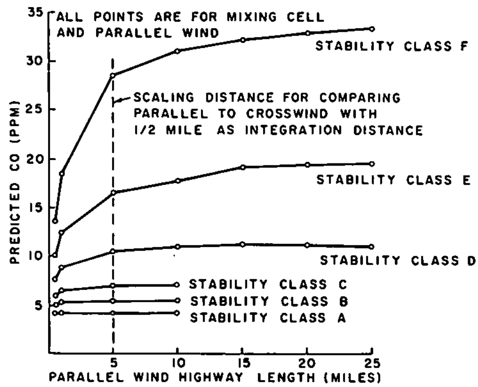


Figure 12. Schematic of general Gaussian dispersion of pollutants from first virtual point source under parallel wind conditions.

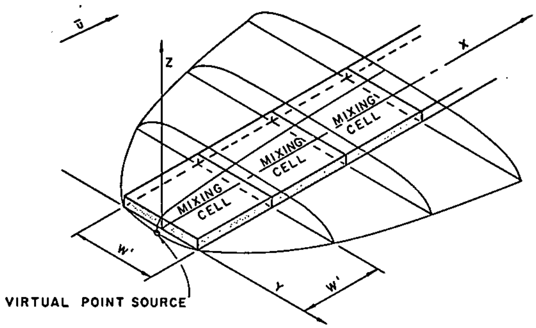


Figure 13. Vector components of an average wind speed with an angle to the highway of ϕ.

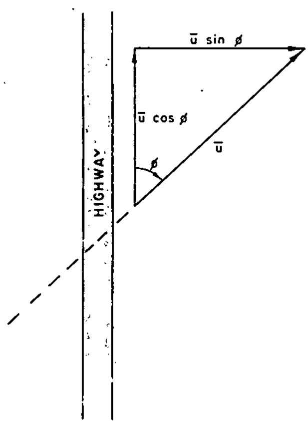


Figure 14. Imaginary mixing cell for depressed highway sections.

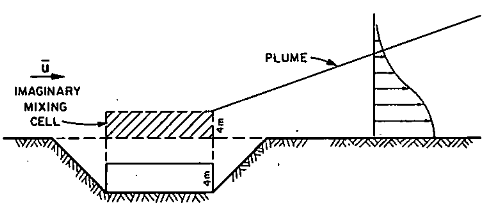
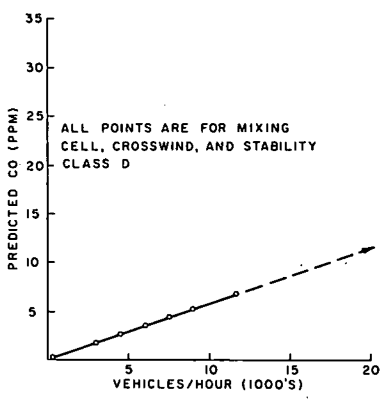


Figure 15. CALINE2 sensitivity to vehicles per hour.



during the period of analysis.

5. Vehicles using the line source represent a continuous and constant source of emissions.

6. The initial vertical and horizontal dispersion of pollutants within the mixing cell is twice the height of the average vehicle (or 4 m) and a function of the highway width respectively.

7. Pollutants are uniformly distributed throughout the mixing cell region regardless of surface atmospheric stability conditions.

8. Perfect plume reflection occurs when the plume intersects the ground surface.

9. Parallel winds cause a buildup of pollutants.

10. A line source having a width W can be approximated by a series of square area sources with W-length sides, which can in turn be approximated by virtual point sources.

11. A finite highway segment can be approximated by "infinite" line source equations.

12. Pasquill stability classes and modified dispersion parameters adequately describe the turbulence of the atmosphere.

13. Predictions are only made above ambient levels.

DATA FORMAT ASSUMPTIONS

Time Interval

The CALINE2 line source model makes calculations of pollutant dispersion based on hourly averages only. This implies that the output is the concentration of carbon monoxide averaged during 1 hour. The constraints are that all data on which the calculations are based, such as the meteorology and traffic volumes, must be hourly values. Obviously, consistency must be maintained in the definition of the hourly average; i.e., if an hour is defined as the period of time between 30 min before 1 hour until 30 min before the next, this definition must apply to all variables.

Input Data Requirements

As input, CALINE2 requires the following:

1. Traffic volume, in vehicles per hour;
2. Average emission factor, in grams per kilometer or mile;
3. Hour's average wind speed, in kilometers or miles per hour;
4. Hour's average wind angle to highway, in degrees;
5. Hour's surface atmospheric stability class;
6. Average pavement height of the section under consideration, in meters or feet, in relation to the surrounding terrain;
7. Average highway width in meters, including median (if less than 9.1 m), all lanes, and 3 m on each outer side of the highway;
8. Receptor distance, in meters or feet, as measured in the perpendicular distance from the nearest outside edge of the traveled roadway lane plus 3 m; and
9. Receptor height, in meters or feet, in relation to the surrounding terrain.

The meteorological data should be as representative of the individual site as possible, which implies that the guidelines set forth in the meteorology manual (9) should be closely followed. One of the most important of these guidelines is that the meteorological measurements of wind speed and direction be made at 10 m above the surrounding canopy.

There are 2 constraints that must be observed when input data are acquired for the model. Since pollutant concentration is inversely proportional to wind speed, a decrease in wind speed causes a hyperbolic increase in the calculated concentration. As the wind speed approaches zero, the concentration approaches infinity. The lowest wind speed recommended in Gaussian models is 1 m/s, approximately 2 mph (6). A disproportionate increase in concentration occurs if the wind speed is allowed to go below 1 m/s.

The second constraint is that the empirical ratios for depressed sections were developed for sections 7.3 m below grade, as discussed in an earlier section. Since the model is only valid down to 7.3 m, it is not recommended that this model be applied to depressed sections greater than 9.1 m. (Based on our experience in monitoring CO along roadways, we feel that the empirical ratios for depressed sections can be extrapolated up to 9.1 m and still provide reasonable estimates of CO.)

SENSITIVITY ANALYSIS

Definition of Sensitivity Analysis

Mathematical computer models are used in the decision-making process because they are capable of describing the complex physical transport and diffusion of air pollutants. They require little time to make the calculations. However, it is sometimes difficult to conceptualize the interactions of a complex numerical model of a real-world process. Since each small part of the model has to be developed separately and later interfaced with the other parts, synergistic and nonrealistic situations develop internally when the model is used. Therefore, sensitivity analysis must be used on a complex model to determine those inconsistencies and minimize their effects on the output of the model.

Essentially, sensitivity analysis involves the perturbation of individual input variables over a wide range of realistic values, yielding variations in output. The resulting variation in output, as a function of the input variables, is compared with the real world to ensure that the output is what is expected, taking into consideration the assumptions inherent to the model. Initially, only one input variable at a time should be varied, and the others should be held constant. Then, if time, resources, and complexity of the model warrant, combinations of variables can be varied simultaneously.

Another function of sensitivity analysis is to determine the input variables to which the model is most sensitive. The implication from such an analysis would be that the more sensitive the model is to a given input, the more effort should be expended to obtain the most correct or representative value for that input.

CALINE2 is a fairly straightforward model in terms of the interactions of the input variables. The sensitivity analysis performed on CALINE2 is, therefore, more of an exercise to demonstrate that the output behaves as one would intuitively expect from the form of the equations. As a model becomes more complex and less intuitively obvious, a properly conducted sensitivity analysis becomes more necessary.

Sensitivity to Source Strength

The source strength terms in CALINE2 consist of the traffic volume VPH, the average emission factor EF, and, for parallel winds only, the highway width W. Since these terms are in the numerators of the line source equations (equations 2, 3, and 5), the calculated pollutant concentrations are directly proportional to them, and the resulting sensitivities are linear. Figures 15 and 16 show that, for a given change in either VPH or EF, the predicted CO changes correspondingly. In other words, if either VPH or EF is doubled, the predicted CO is doubled.

Figure 17 shows that the highway width has an inverse effect on the predicted CO, i.e., as W increases, CO decreases. This effect occurs because W is not only incorporated into the source strength term for parallel winds, but is also used to modify the initial segment of the σ_y curve as discussed in an earlier section. It appears reasonable that, as the volume of air in the mixing cell increases, while the VPH and EF remain the same, the predicted CO concentration should decrease.

Only the predicted CO concentrations in the mixing cell are shown for only 1 wind angle, an at-grade highway, and 1 stability class. For most of the CALINE2 sensitivities, the sensitivity in the mixing cell (for a given wind angle and so on) will be similar to the sensitivity at a receptor away from the highway (and for different wind angles and so on). In the cases where it is not, sensitivities at separate removed receptors (or different wind angles and so on or both) are shown.

Sensitivity to Wind Speed

CALINE2 sensitivity to wind speed is shown in Figure 18. The hyperbolic increase in predicted CO levels as wind speed decreases is clearly shown. The limit of the model of 3.2 km/h or 2 mph is indicated by the dashed line. Both cross and parallel wind mixing cells are displayed, and one can see the similarity between the two.

Sensitivity to Wind Angle

Figure 19 is the sensitivity of the concentration of the mixing cell to changes in the angle of the wind for all stability classes. All stability classes have the same mixing cell concentration for an exactly perpendicular (ϕ = 90 deg) wind, and they have the greatest difference for an exactly parallel (ϕ = 0 deg) wind. Obviously, since stability class F is the most stable, the most parallel wind buildup in the mixing cell will occur with this class, and this is what Figure 19 shows. On the other hand, stability class F will confine the pollutants near the highway under parallel winds because of very little turbulence to spread the plume. For stability class A the large degree of turbulence will spread the plume away from the highway. Figure 20 shows this situation for a receptor 120 m away from the highway at ground level. In this case, a 90-deg wind yields the greatest spread in concentrations, as a function of stability class, since the wind is blowing directly toward the receptor, with the most stable air causing the highest pollutant level at the receptor. The scale of predicted CO shown in Figure 19 is greatly reduced from that shown in Figure 20. The uncertainty of the quality of the input and the Gaussian assumptions result in estimates that are at best accurate to the nearest part per million (or microgram per cubic meter) and not to a tenth of that unit. Therefore, the concentrations shown are in reality all the same and are close to ambient. However, for the sensitivity analysis, the calculated values are used to demonstrate the relative importance of input variables.

Sensitivity to Pavement Height

CALINE2 sensitivity to pavement height is a more difficult analysis to make. The definition of the mixing cell determines that the concentration within the mixing cell will be the same regardless of where the highway is in relation to the surrounding terrain. Thus, the sensitivity for the input parameter of pavement height is shown in Figure 21 for a receptor that is parallel to the edge of the mixing cell but at ground level. This implies that the receptor will be above the highway for a depressed section (negative pavement height) and below the highway for a raised section (positive pavement height). As expected, the predicted CO concentration for this receptor decreases as the highway is either lowered or raised from grade. Parallel winds cause the decrease to be larger.

Sensitivity to Stability Class

The definition of the mixing cell used in CALINE2 implies its concentration is independent of surface atmospheric stability. This is shown in Figure 22 for crosswinds. For parallel winds, an exponential increase in concentrations is evidenced as stability increases because of the buildup.

Figure 16. CALINE2 sensitivity to emission factor.

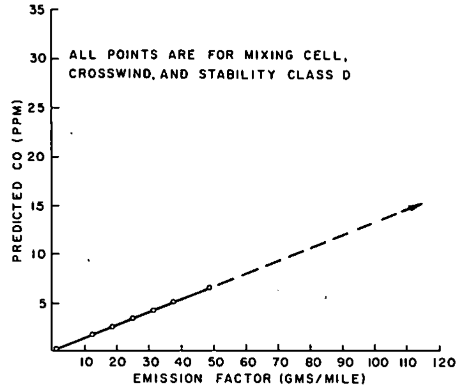


Figure 17. CALINE2 sensitivity to highway width.

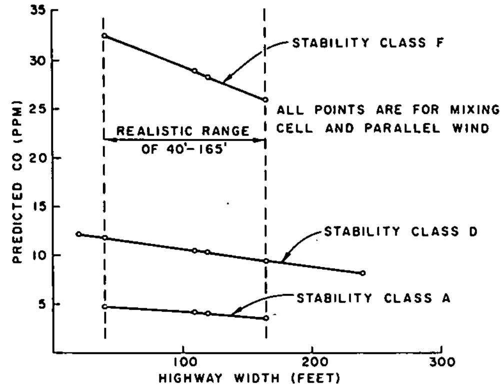


Figure 18. CALINE2 sensitivity to wind speed.

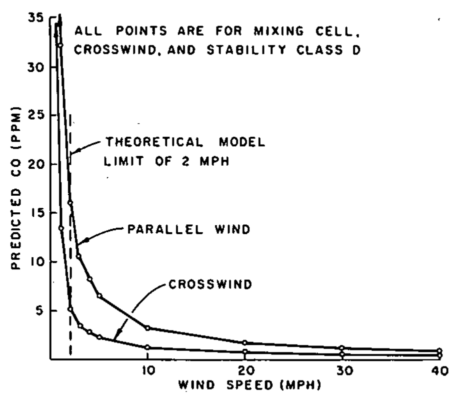


Figure 19. CALINE2 sensitivity to wind angle and mixing cell concentration.

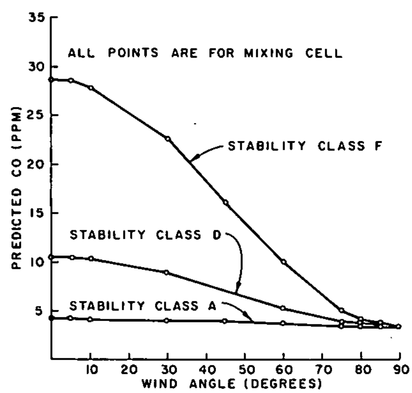


Figure 20. CALINE2 sensitivity to wind angle and off-highway concentration.

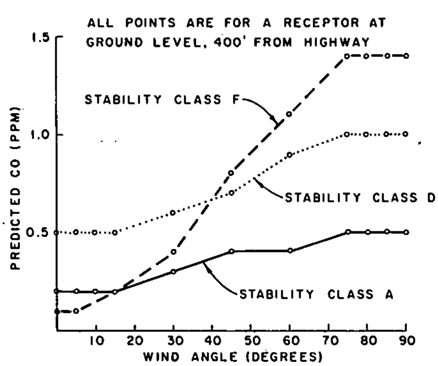
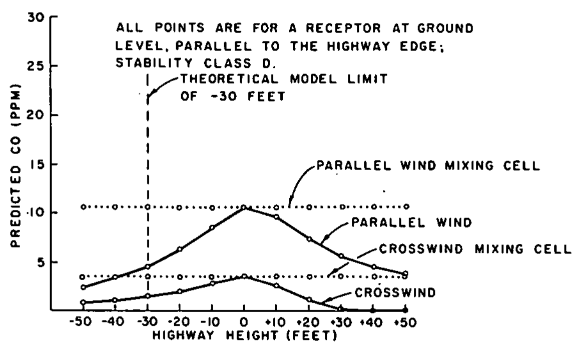


Figure 21. CALINE2 sensitivity to pavement height.



Ranking of Sensitive Parameters

From the preceeding sensitivity analysis, the following general ranking can be placed on the input variables. CALINE2 is most sensitive to the wind vector because it affects a number of inputs to the model. The direction of the wind vector in relation to the highway is important since angles approaching 0 deg cause parallel wind buildup. Stability class is a function of wind speed and is a fairly sensitive input, since F stability confines pollutants and A allows substantial dispersion. Wind speed itself is important because the calculated concentrations are inversely proportional to it, which means that a halving of the wind speed would cause a doubling of the predicted concentration. The source strength terms of VPH and EF are as sensitive as the wind vector, although they do not have a multiple influence on the model. The predicted concentrations are a direct function of VPH and EF, and a change in either term causes a corresponding change in the output. Pavement height and highway width are important parameters, but are relatively less important to CALINE2 than any other input.

PRELIMINARY VERIFICATION

Interpretation of Results

The California Department of Transportation is under contract with the Federal Highway Administration to provide an aerometric data base for the purpose of verifying and calibrating line source models (10). As part of this work, a preliminary data base for hourly averages of carbon monoxide concentrations was obtained by using bag sampling procedures in the Los Angeles area in 1972 (7). Three types of highway geometrics were monitored, including 2 depressed sections, 1 at-grade section, and 1 fill section. Figure 23 shows the locations of the sites.

Measurements for this study at any 1 site consisted of as many as 24 carbon monoxide sampling points for the integrated 1-hour CO concentrations, 1-hour values of surface wind speeds and directions, and 1-hour traffic counts. This last information and the highway configuration were used as input to CALINE2 to produce simulations that were then compared with the measured CO concentrations. The comparisons were used to determine the predictive capabilities of the model.

Linear regression analysis was used to compare the scatter plot of observed CO concentrations versus predicted CO concentrations. The figures referred to in this section that show the preliminary verification results contain the regression information for each comparison. This information includes the regression line, the regression equation, the sample size n, the standard error of the estimate, the correlation coefficient r, and the F-test value for a 5 percent level of significance.

The regression line shows how well the model predicts in comparison with measured concentrations. If the line slope is less than 1, the model overpredicts. If the line slope is greater than 1, the model underpredicts. If the line is coincident with the 45-deg line, the model is making nearly perfect predictions, depending on the values of the other regression parameters. Since the model calculates downwind concentrations from the line source only (i.e., above ambient), the upwind (ambient) level was subtracted from the measured mixing cell and downwind concentrations before a comparison was made to the simulated values.

The verifications are separated into highway configurations (at-grade, depressed, and fill), wind angles (cross and parallel), and on- and off-highway sites to better determine how each of these situations can be handled by CALINE2. Obviously, some of the verifications are questionable because of the small sample size; however, they were included to give a relative indication of CALINE2 capabilities. Larger sample sizes could have been obtained by combining all sites and situations, but this would have resulted in data gaps and thereby obscured the predictive characteristics of the model for each individual situation.

For instance, the mixing cell generally has higher concentrations than off-highway points have. When plotted together, the mixing cell points may form a cluster away from the origin, while the off-highway points may cluster close to the origin, leaving a gap between the 2 clusters. A regression analysis would indicate that there is a good regression between these 2 clusters, but would not indicate the correlation within each cluster. Therefore, the clusters are broken into separate categories, as in this analysis.

For all of the regressions, all stability classes have been combined, because there were insufficient data pairs to separate the analyses by stability. The predominant stability classes encountered were those for unstable through neutral surface atmospheric conditions, i.e., classes A through D. Only a few cases had stabilities of E or F. Therefore, it is difficult to draw any conclusions about the ability of CALINE2 to handle stable and very stable atmospheric conditions. A more extensive verification of CALINE2 is planned in which data recently gathered in the Los Angeles area will be used with the transportation department's mobile air quality vans (10). At that time, the analysis will be separated into as many verification categories as possible, including stability classes.

At-Grade Site

The at-grade site was located at the weigh station on the San Diego Freeway, just southeast of the junction with the Harbor Freeway. Figure 24, a schematic of the site, shows how the probes were placed for the prevailing west wind. Probe 3 was designed to be used as the upwind sampling intake. Probes 6 and 9 were averaged by using weighted factors derived from the traffic flow in each direction to obtain the "measured" mixing cell concentration.

Figures 25, 26, and 27 show the crosswind situation for the at-grade site and show that CALINE2 overpredicts by a factor of 2 for the mixing cell points, does fairly well for off-highway sites, and yields a reasonable correlation for the combined plots. The parallel wind (Figures 28, 29, and 30) sampling sizes are much smaller, but generally show that CALINE2 is able to handle parallel wind situations reasonably well.

The regression for the crosswind and mixing cell may indicate a falsely high overprediction because of the manner in which the measured mixing cell concentrations were obtained. The concentration at probe 6 tended to be much lower than that at probe 9 under moderate wind speeds, thereby disagreeing with the assumption that a uniform mixing cell exists across the width of the highway. Simulations for each traffic direction might yield better correlations, but this task has yet to be undertaken.

Depressed Sites

The depressed sites were at the Fourth Avenue pedestrian overcrossing of the Santa Monica Freeway and the Harbor Freeway at 146th Street. These were true depressed sites, being depressed from the surrounding terrain for noise control or other purposes, and not simple cuts into the sides of hills. Figure 31 is a schematic of the Santa Monica site. The probes are equally distributed on either side of the site because parallel winds were anticipated and it was necessary to maintain maximum flexibility for downwind probe sites. Probes 10 and 11 were averaged to obtain the mixing cell concentration for this site. Figure 32 is the schematic of the Harbor Freeway site; probes 3 and 4 were designed to be used as the upwind intakes. Probes 6 to 10 were averaged via weighted factors in the same manner as the at-grade site to obtain the measured mixing cell concentrations.

Figures 33 through 38 show that CALINE2 appears to be able to handle the depressed section situation quite well, with a slight overprediction. However, one must remember that data from these same sites were used to develop the depressed section ratios discussed earlier. Full verification of the model for this situation must wait until the CO data are available from the department's research project (10).

Figure 22. CALINE2 sensitivity to stability class.

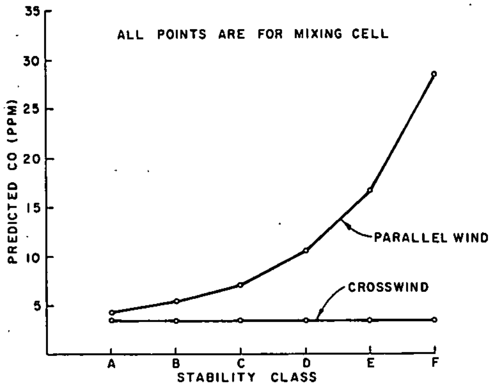


Figure 23. Los Angeles sampling project.

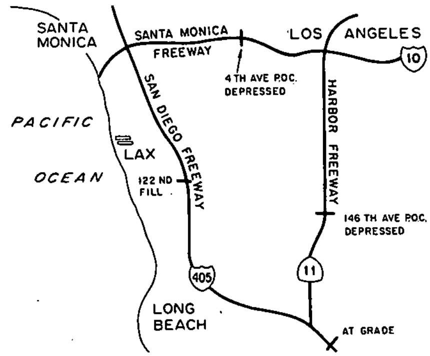


Figure 24. Probe locations at weigh station on San Diego Freeway.

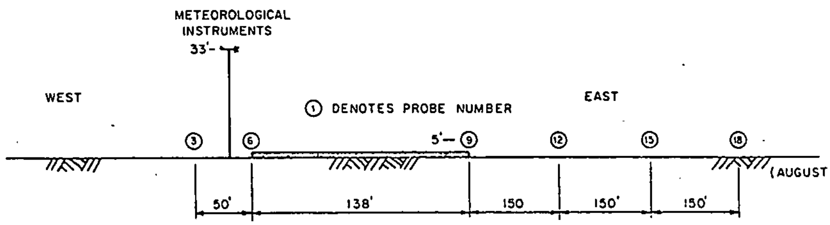


Figure 25. At-grade site, crosswind, and mixing cell points.

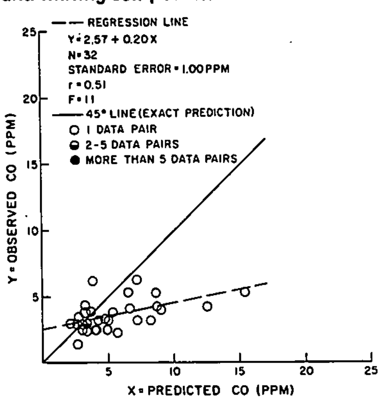


Figure 26. At-grade site, crosswind, and off-highway ground-level points.

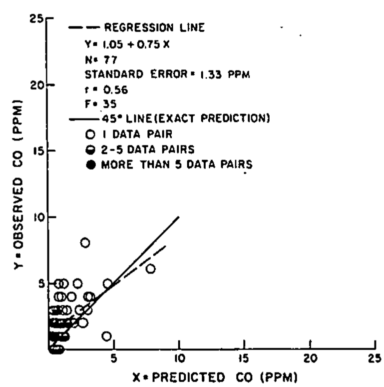


Figure 27. At-grade site, crosswind, and off-highway ground-level and mixing cell points.

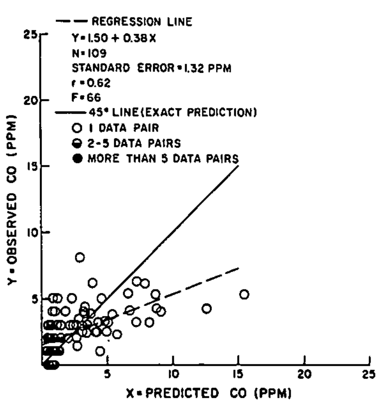


Figure 28. At-grade site, parallel wind, and mixing cell points.

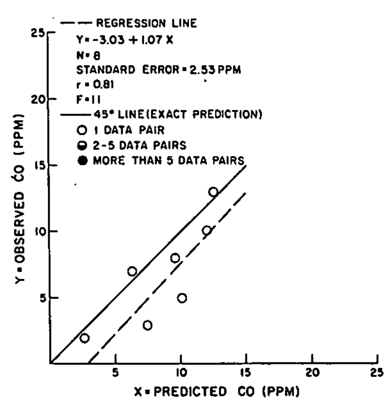


Figure 29. At-grade site, parallel wind, and off-highway ground-level points.

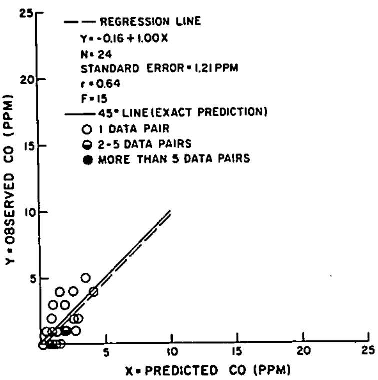


Figure 30. At-grade site, parallel wind, and off-highway ground-level and mixing cell points.

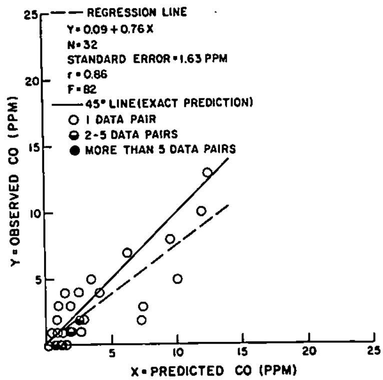


Figure 31. Probe locations at Santa Monica Freeway at Fourth Avenue.

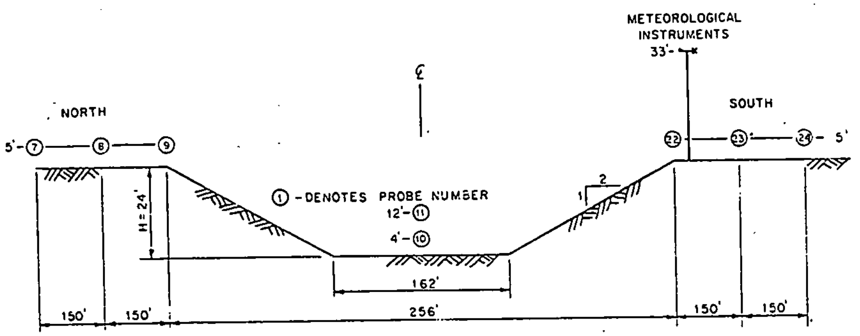


Figure 32. Probe locations at Harbor Freeway at 146th Street.

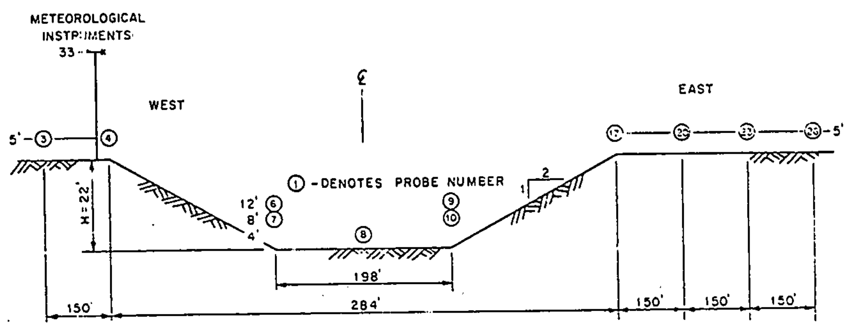


Figure 33. Depressed sites, crosswind, and mixing cell points.

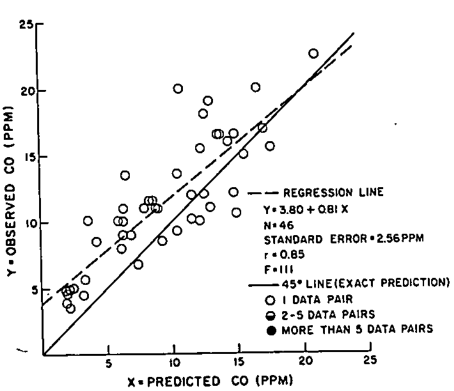


Figure 34. Depressed sites, crosswind, and off-highway ground-level points.

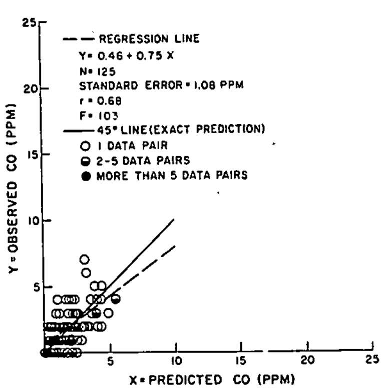


Figure 35. Depressed sites, crosswind, and off-highway ground-level and mixing cell points.

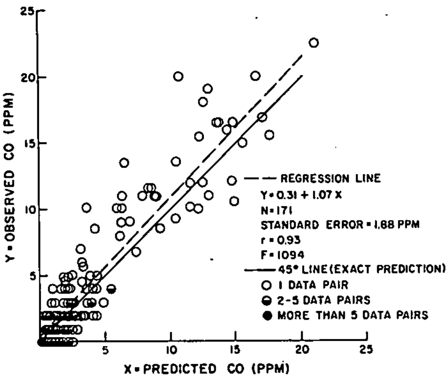


Figure 36. Depressed sites, parallel wind, and mixing cell points.

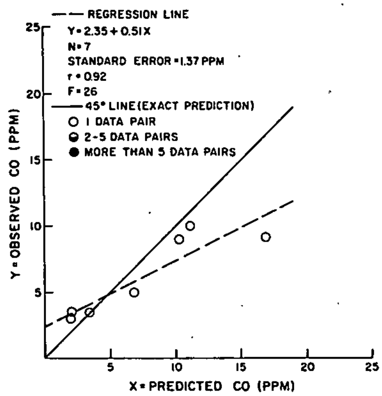


Figure 37. Depressed sites, parallel wind, and off-highway ground-level points.

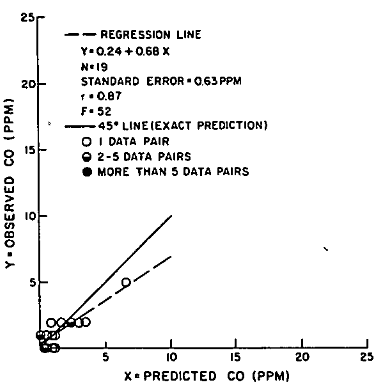


Figure 38. Depressed sites, parallel wind, and off-highway ground-level and mixing cell points.

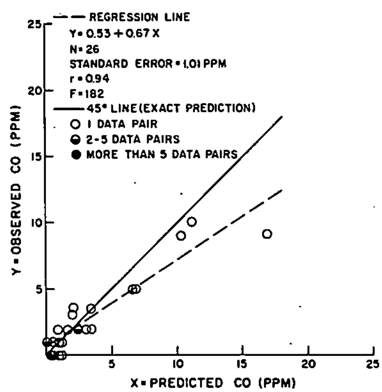
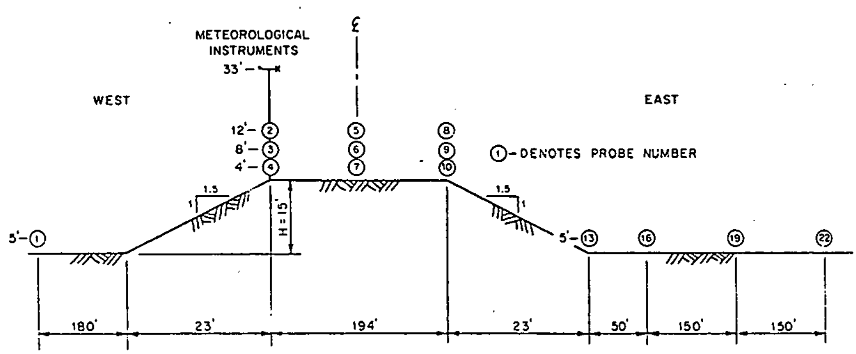


Figure 39. Probe locations at San Diego Freeway at 122nd Street.



Fill Site

The fill site was on the San Diego Freeway at 122nd Street and is shown schematically in Figure 39. Probe 1 was obviously the upwind probe, and probes 2 to 10 were averaged in the same manner as the other sites to obtain the measured mixing cell concentrations.

Figures 40, 41, and 42 show how CALINE2 overpredicts the concentrations resulting from a fill section for a crosswind. There was no parallel wind data for this site. As for the at-grade site, the overprediction factor of 2 for the mixing cell could be a false comparison, for the concentrations for the upwind probes on the edge of the highway (probes 2 to 4) tended to be much lower than those for the probes on the downwind edge (probes 8 to 10).

APPLICATIONS

Overall Use of CALINE2

CALINE2 should be used to determine the air quality impact of a proposed highway or other relatively constant linear source of air pollutants. Although CALINE2 only calculates the estimated dispersion of carbon monoxide from a line source, this dispersion will give an indication of the atmospheric movement of other pollutants, such as lead and sulfate particulates, nitric oxides, and hydrocarbons. (This assumes that the particulates can be characterized in their transport and diffusion as gases and that there are no chemical reactions of the other pollutants.) The model cannot, in its present form, be used to calculate the resultant concentrations of these other pollutants because of the gravitational settling of particulates and chemical reactions. It can, however, yield hourly average CO estimates that are slightly on the conservative side of actual CO concentrations for most cases as long as the constraints and assumptions of the model are observed.

CALINE2 can be used in the design process of a proposed line source (highway) to determine which configurations would result in the smallest CO concentrations for the given meteorology of a site. An analysis can be made of alternative sites (along with alternative configurations) to determine which meteorology will disperse the pollutant load most adequately.

Most proposed line source projects will be more than a simple straight line maintaining a constant angle to the prevailing winds and at the same height above or below grade. CALINE2 has no internal capability of superposition that would allow the calculation of pollutant contributions from different configurations of sections, but the contribution of each section can be simulated on a separate run of the model and then summed later either by hand or by another computer program. When the proposed project involves a number of short varying segments (shorter than 1.6 km in length), or complex situations, such as cloverleaf interchanges, other assumptions and simplifications will have to be made about the configurations of the project before CALINE2 is used. These simplifications will result in a greater departure from the real-world situation, but the estimated dispersions should still give an approximate idea of the actual dispersion.

Of course, other environmental design considerations will have to be taken into account in the decision reached on the line source configuration. Environmental siting of a line source should not be based on air quality impact alone.

CALINE2 Simulations

Figure 43 shows the flow of information into the model, the calculations made in model, and the resulting output. The output can be in micrograms per cubic meter or parts per million. Figure 44 shows a printout of the carbon monoxide concentrations in parts per million as calculated by CALINE2 for a crosswind, oblique wind, and parallel wind.

Figure 40. Fill site, crosswind, and mixing cell points.

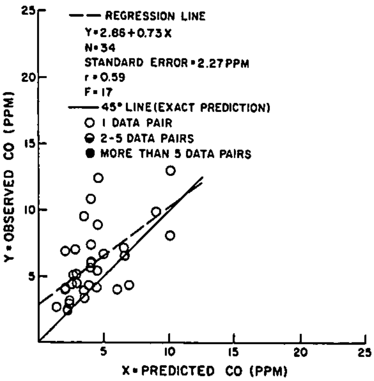


Figure 41. Fill site, crosswind, and off-highway ground-level points.

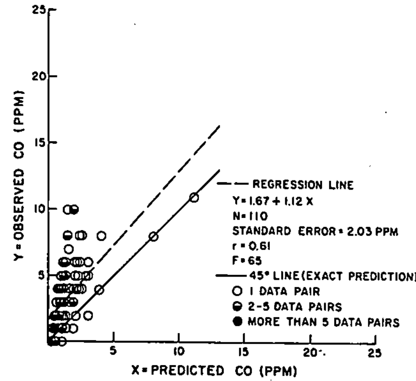


Figure 42. Fill site, crosswind, and off-highway ground-level and mixing cell points.

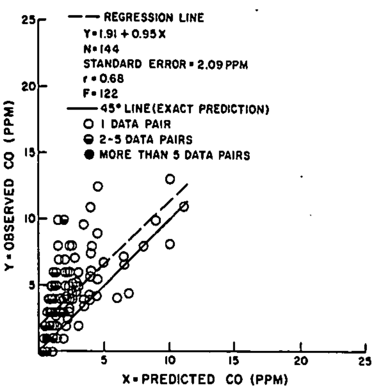


Figure 43. Flow chart for CALINE2 model.

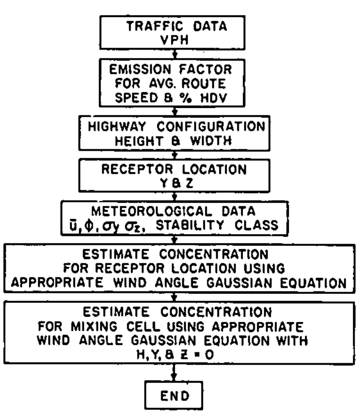


Figure 44. Printout of CALINE2 simulations.

CALINE2 SIMULATION WITH CROSS WIND

PREDICTED CO CONCENTRATION (PPM)

VARIABLES		RECEPTOR HEIGHT (Z FEET)	DISTANCE PERPENDICULAR TO HIGHWAY (D FEET) 0	100	200	400	800	1000
VPH=	6000							
EF=	25 GMS/MI							
U=	3 MPH	60	0.0	0.2	0.3	0.4	0.4	0.4
PHI=	90 DEGREES	40	0.0	0.6	0.7	0.7	0.6	0.6
H=	0 FEET	20	1.1	1.2	1.0	0.9	0.8	0.7
CLAS=	4 (D)	10	3.4	1.4	1.2	1.0	0.8	0.8
W=	120 FEET	5	3.4	1.4	1.2	1.0	0.8	0.8

MIXING CELL CONCENTRATION = 3.4 PPM

CALINE2 SIMULATION WITH OBLIQUE WIND

PREDICTED CO CONCENTRATION (PPM)

VARIABLES		RECEPTOR HEIGHT (Z FEET)	DISTANCE PERPENDICULAR TO HIGHWAY (D FEET) 0	100	200	400	800	1000
VPH=	6000							
EF=	25 GMS/MI							
U=	3 MPH	60	1.5	1.2	0.8	0.4	0.2	0.2
PHI=	45 DEGREES	40	2.1	1.9	1.2	0.5	0.3	0.3
H=	0 FEET	20	4.0	2.5	1.6	0.7	0.4	0.4
CLAS=	4 (D)	10	7.0	2.8	1.7	0.7	0.4	0.4
W=	120 FEET	5	7.0	2.8	1.8	0.7	0.4	0.4

MIXING CELL CONCENTRATION = 7.0 PPM

CALINE2 SIMULATION WITH PARALLEL WIND

PREDICTED CO CONCENTRATION (PPM)

VARIABLES		RECEPTOR HEIGHT (Z FEET)	DISTANCE PERPENDICULAR TO HIGHWAY (D FEET) 0	100	200	400	800	1000
VPH=	6000							
EF=	25 GMS/MI							
U=	3 MPH	60	2.9	2.3	1.4	0.3	0.0	0.0
PHI=	0 DEGREES	40	4.3	3.1	1.8	0.4	0.0	0.0
H=	0 FEET	20	6.9	3.9	2.2	0.4	0.0	0.0
CLAS=	4 (D)	10	10.5	4.2	2.3	0.5	0.0	0.0
W=	120 FEET	5	10.5	4.2	2.3	0.5	0.0	0.0

MIXING CELL CONCENTRATION = 10.5 PPM

Cost and Availability

CALINE2 requires minimal computer time for simulation runs, especially when used on the large digital computers. On the IBM 370/168, a typical computer run of 42 separate line source simulations (with 36 receptor sites per simulation) requires 11.5 CPU seconds at an approximate cost of $3. Generally, therefore, CALINE2 represents a relatively cheap, fast method to obtain reasonable estimates of CO concentrations for a future highway or other line source.

CALINE2 is currently programmed in FORTRAN on the California IBM system 370/168 and in BASIC on the Department of Transportation's TENET time-sharing facility. A computer listing and source deck of the program as written in FORTRAN IV-G for the IBM 370/168 can be obtained at a nominal cost by public agencies on request to the California Department of Transportation. With the approval of the Federal Highway Administration, the same information can be released to private enterprises.

Future Work

CALINE2 does not yet represent a polished end product, merely an interim tool that can be used by transportation planners to obtain estimates of impacts of highways on local air quality. Work remaining to be done includes the following:

1. Fine-tuning calibration and verification with extensive field sampling data that are becoming available (10);
2. Development of a grid or superposition version of the model that will allow the analysis of multiple line sources and modal systems;
3. Evaluation of a possible modification of the model to estimate dispersion of lead and sulfate particulates; and
4. Comparison of predictive capabilities of CALINE2 with those of other line source models, such as HIWAY of the U.S. Environmental Protection Agency.

The state of the art for air pollution modeling is rapidly changing, and attempts will be made to keep CALINE at the forefront of those changes.

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