Development and Verification of the California Line Source Dispersion Model

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A description of the California Line Source Dispersion Model, CALINE4, is given, along with a brief history of the model's development. CALINE4 is based on the Gaussian plume methodology and is used to predict air pollutant concentrations near roadways. Predictions can be made for carbon monoxide, nitrogen dioxide, and suspended particulates. An option for modeling air quality near intersections is described. CALINE4 represents an updated and expanded version of CALINE3. The newer model can handle a greater variety of problems and has improved input/output flexibility. Estimates of vertical and horizontal dispersion are enhanced by accounting for vehicle-induced thermal turbulence and wind direction variability. CALINE4 is verified by using results from five separate field studies. Comparisons to CALINE3 indicate modest improvements in the accuracy of the newer version.

The California Department of Transportation (Caltrans) published its first line source dispersion model for predicting carbon monoxide (CO) concentrations in 1972 (1). Model verification using preliminary field observations was inconclusive. In 1975, the original model was replaced by a revised version, CALINE2 (2). The new model was able to compute concentrations for depressed sections and for winds parallel to the roadway. Subsequent studies indicated that CALINE2 seriously overpredicted concentrations for stable, parallel wind conditions (3, 4).

In 1979, a third version of the model was developed (5, 6). This version, CALINE3, retained the basic Gaussian dispersion methodology but used new vertical and horizontal dispersion curves modified for the effects of surface roughness, averaging time and vehicle-induced turbulence. It also replaced the virtual point source model used in CALINE2 with an equivalent finite line source and added multiple link capabilities to the model format. The changes helped reduce the magnitude and frequency of overpredictions for stable, parallel wind conditions. The performance of CALINE3 was evaluated by several independent investigators and found to be comparable to other published line source models (7, 8). In 1980, the Environmental Protection Agency (EPA) authorized CALINE3 for use in estimating concentrations of nonreactive pollutants near highways (9).

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CALINE4 is the most recent version of the CALINE series (10). It represents a refinement and extension of the capabilities contained in CALINE3. Concentrations of CO, nitrogen dioxide (NO_2), and aerosols can be predicted by the model. An option for modeling intersections has been added. The model employs a modified Gaussian plume approach similar to the one used in CALINE3 but with new provisions for lateral plume spread and vehicle-induced thermal turbulence. Submodels for CO modal emissions and reactive plume chemistry are included.

MODEL DESCRIPTION

CALINE4 divides individual highway links into a series of elements from which incremental concentrations are computed and summed. As shown in Figure 1, each element is modeled as an "equivalent" finite line source (FLS) positioned normal to the wind direction and centered at the element midpoint. Element size increases with distance from the receptor to improve computational efficiency. The emissions from an element are released uniformly along the FLS and dispersed in a Gaussian manner by the model. Incremental downwind concentrations are computed by using the crosswind Gaussian formulation for a line source of finite length:

$$C(x, y) = \frac{q}{\pi \sigma_z u} \int_{y_1 - y}^{y_2 - y} \exp\left(\frac{-y^2}{2\sigma_y^2}\right) dy \qquad (1)$$

where q is the lineal source strength, u is the wind speed, σ_y and σ_z are the horizontal and vertical Gaussian dispersion parameters, and y_1 and y_2 are the FLS endpoint y coordinates.

The model permits the specification of up to 20 links and 20 receptors. Each link defines a relatively straight segment of roadway with a constant width, height, traffic volume, and vehicle emission factor. The location of the link is specified by the endpoint coordinates of its centerline. The locations of receptors are similarly defined in terms of a uniform coordinate system.

CALINE4 treats the region directly above the highway as a zone of uniform emissions and turbulence. This "mixing zone" is defined as the region over the traveled way plus 3 m (about two vehicle widths) on either side. The additional width
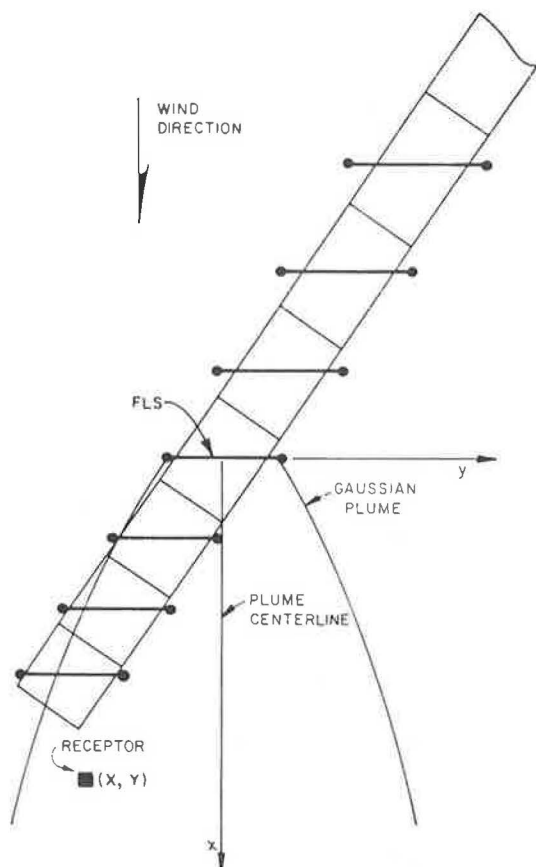
FIGURE 1   CALINE4 link representation as a
series of elements with equivalent finite line sources
superimposed.

accounts for the initial horizontal dispersion imparted to
pollutants by the vehicle wake. Within the mixing zone, the
mechanical turbulence created by moving vehicles and the
thermal turbulence created by hot vehicle exhaust are treated
as significant dispersive mechanisms (11, 12).

A number of studies have noted a correlation between
crossroad wind speed and initial vertical dispersion (3, 12–14).
Each of these studies has concluded that lower wind speeds
result in greater initial vertical dispersion. In CALINE4, it is
assumed that initial vertical dispersion at the edge of the
mixing zone, $\sigma_{z(i)}$, is determined by the length of time air
resides in the mixing zone, t_r. An empirically derived
equation,

$$\sigma_{z(i)} = 1.5 + (t_r/10) \tag{2}$$

relates $\sigma_{z(i)}$ in meters to t_r in seconds (10).

The Pasquill-Smith vertical dispersion curves (15) are mod-
ified by CALINE4 to incorporate the effects of vehicle-
induced thermal turbulence. A composite heat release rate of
24.6 J/cm per vehicle (based on an assumed average fuel
economy of 8.5 km/l, 0.6 heat loss factor, and specific energy
of 3.48×10^7 J/l) is used in conjunction with Smith's stability
nomograph (16) to predict a modified stability class over the
mixing zone. The rate of vertical plume spread is assumed to
follow the modified stability curve until either the plume
centerline or more than 50 percent of the plume mass falls

outside of the mixing zone. The model does not incorporate a
modification to the heat release rate for vehicle speed or
percent cold starts. Additional research and improved ac-
curacy of model inputs are needed to justify such refinements.

Horizontal dispersion is estimated directly from the wind
direction standard deviation, σ_θ, using a method developed by
Draxler (17). This approach is preferred to the stability
classification scheme used in CALINE3 because it can address
site-specific conditions and unique meteorological regimes
(e.g., directional meander caused by low wind speed). An
adjustment is included to account for the effect of wind shear
on lateral plume spread. Values for σ_θ may be obtained by
direct measurement or estimated by various methods (18, 19).

An algorithm suggested by Turner (20) has been incorpo-
rated into the model to handle bluff and canyon situations. The
algorithm computes the effect of single or multiple horizontal
reflections for each FLS plume in much the same way that
mixing height reflections are handled. The model also includes
a method to account for surface deposition of gases and
gravitational settling of aerosols (21).

Intersection Link Option

CALINE4 normally requires that the user assign a composite
emission factor for each link. At controlled intersections,
however, the operational modes of deceleration, idle, accelera-
tion, and cruise have a significant effect on the rate of vehicle
emissions. Traffic parameters such as queue length and aver-
age vehicle delay define the location and duration of these
emissions. The net result is a concentration of emissions near
the intersection that cannot be modeled adequately by using a
single, composite emission factor. For this reason, a spe-
cialized intersection link option has been added to CALINE4.

A CALINE4 intersection link encompasses the acceleration
and deceleration zones created by the presence of the intersec-
tion for one direction of traffic flow. A stop line distance is
referenced to the link endpoints, and approach (vph$_i$) and
depart (vph$_o$) traffic volumes are assigned. A full intersection
can be modeled by using four of these links.

Cumulative modal emissions profiles representing the aver-
age deceleration, idle, acceleration, and cruise emissions per
signal cycle per lane are constructed for each intersection link.
These profiles are determined by using the following input
variables:

v = Cruise speed,
t_a = Acceleration time,
t_d = Deceleration time,
t_1 = Maximum idle time,
t_2 = Minimum idle time,
n_c = Number of vehicles per signal cycle per
lane, and
n_d = Number of vehicles delayed per signal
cycle per lane.

The traffic parameters, n_c and n_d, are chosen to represent the
dominant movement for the link. The model assumes a
uniform vehicle arrival rate, constant acceleration and de-
celeration rates, full stops for all delayed vehicles, and an "at
rest" vehicle spacing (d_0) of 7 m. The time rate modal
emission factor, $\dot{e}$, is computed for each mode from composite

emission rates for average route speeds of 0 (idle) and 26 km/hr. This method employs the acceleration-speed product as a measure of power per unit mass expended during acceleration modes (22) and the proportionality of drag force to v^2 for cruise modes. Deceleration emissions are assumed to be 1.5 times the idle emission rate.

A cumulative emissions profile for a given mode is developed by determining the time that vehicles are in the mode as a function of their location on the link, multiplying by the appropriate $\dot{e}$, and summing the results over the number of vehicles per cycle per lane. The elementary equations of motion are used to relate time in mode to location. The assumed value of d_0 is used to specify the positional distribution of the vehicles. Individual profiles are based on the assumption that $\dot{e}$ is constant throughout the modal event. This means that the cumulative modal emissions from a vehicle are directly proportional to the time that the vehicle has spent in the mode.

In the case of an acceleration starting from an "at rest" position, the cumulative emissions for the ith vehicle are given as

$$ECUM_i = \dot{e}_a \, (2t_a d/v)^{1/2} \tag{3}$$

where d equals the distance from the start of the acceleration. The total cumulative acceleration emissions per cycle per lane is obtained by summing Equation 3 over the number of vehicles delayed, as follows:

$$ECUM(d) = \dot{e}_a \, (2t_a/v)^{1/2} \sum_{i=1}^{n_d} [d - d_0 \, (i - 1)]^{1/2} \tag{4}$$

where d is now defined as the distance from the end of the vehicle queue to the point where the cumulative emissions are being calculated. Similar reasoning is used for developing the other modal profiles.

To obtain the average lineal emission rate over an element, CALINE4 computes the total cumulative emissions for the four modes at each end of an element. The difference between these amounts represents the emissions released over the element per cycle per lane. This quantity is multiplied by either vph_i/n_c or vph_o/n_c, depending on whether the element is before or after the stop line, respectively, and divided by the element length to yield a lineal emission rate.

Turn movements are not handled explicitly by CALINE4. Instead, the cumulative emissions profile per cycle per lane for the dominant approach movement is prorated by the approach or departure volume, depending on the relative location of the stop line. This method implicitly assigns a turning vehicle's deceleration, idle, and part of its acceleration emissions to its approach link. The remainder of its modal emissions are assigned to its departure link. The method assumes that the acceleration patterns for turning and through vehicles are roughly similar.

NO₂ Option

A number of methods have been developed to expand the use of the Gaussian plume formulation to reactive species such as NO₂ (23). These include the exponential decay, ozone limiting, and photostationary state methods. An unfortunate weakness of these methods is their assumption that reactants mix instantaneously as they disperse and that the resulting time-averaged concentrations determine the reaction rates (24, 25). Because the component reactants, nitrogen oxide (NO) and ambient ozone (O₃), are not mixed instantaneously by the relatively large-scale dispersive processes of the atmosphere, the assumption leads to overestimates of NO₂ production (26, 27).

In CALINE4 a computational scheme that models the dispersion of reactants separately from the plume chemistry is used to predict NO₂ concentrations. As with the preceding methods, a simplified set of controlling reactions is assumed:

$$NO_2 + h_v \rightarrow NO + O \tag{5}$$

$$O + O_2 + M \rightarrow O_3 + M \tag{6}$$

$$NO + O_3 \rightarrow NO_2 + O_2 \tag{7}$$

where h_v represents an interacting photon of sunlight and M is an unspecified catalytic agent.

Because of the relatively high concentration of O_2, the reaction given in Equation 6 is assumed to occur instantaneously. It is further assumed that emissions and ambient reactants are fully mixed over the roadway, that initial tailpipe NO$_x$ emissions are 92.5 percent NO and 7.5 percent NO₂ by mass, and that parcels of the mixed reactants retain their identity relative to molecular scales of motion for distances of ~300 m downwind.

The initial mixing zone concentrations of the reactants are determined on the basis of upwind concentrations of NO, NO₂, and O₃ and vehicular contributions of NO$_x$. The dispersion of this initial mix is characterized as a scattering of discrete parcels, with reactions proceeding as isolated processes within each parcel. The initial concentrations and time of travel from element to receptor govern the final concentration of NO₂ within the discrete parcels. The reactions proceed independently of the dispersion process because the reaction rates are controlled by the reactant concentrations within a small neighborhood (of the scale of the mean free path of the molecules), whereas the dispersion process acts on a much larger scale. The reactions can therefore be modeled in accordance with the first-order rates for the reactions presented as Equations 5 and 7 on the basis of the photolysis rate constant and temperature input by the user, until concentration gradients are reduced to the extent that molecular diffusion becomes significant. For microscale modeling applications, travel times are usually not long enough for this to occur.

Discrete parcel NO₂ concentrations are computed by CALINE4 for each element-receptor combination because of the variable travel times involved. These concentrations are not, of course, the same as time-averaged NO₂ concentrations. To arrive at time-averaged values, the link source strength is adjusted by element to yield an initial NO₂ mixing zone concentration equal to the discrete parcel concentration at the receptor. The model then proceeds to compute the time-averaged concentration exactly as the concentration for a nonreactive species such as CO would be computed.

The discrete parcel approach is appropriate only when the assumptions of fully mixed initial reactants and short travel times are reasonably met. Use of the NO₂ option under parallel

wind conditions or strongly convective regimes is not recommended. However, the approach appears to be well suited for stable, crosswind conditions.

FIELD STUDIES

The CALINE4 model was verified by using data from several independent field studies. These studies represent a variety of possible model applications, including the intersection link and NO_2 options.

General Motors Sulfate Dispersion Experiment

The General Motors (GM) Sulfate Experiment was conducted at GM's Michigan test track in October 1975 (28). The track is 5 km long and is surrounded by lightly wooded, rolling hills. A total of 352 cars, including 8 vehicles emitting SF_6 tracer gas, were driven at a constant speed of 80 km/hr around the track. Monitoring probes were stationed at 6 upwind and 11 downwind locations located out to a distance of 113 m from the track centerline. Wind speed and direction measurements were made at various locations by using Gill UVW anemometers. Data for 66 half-hour sampling periods were compiled. Most of these tests were conducted during the early morning hours.

Illinois EPA Freeway/Intersection Study

This 1978 study involved the measurement of CO concentrations near two urban sites located just outside of Chicago, Illinois (29). SF_6 tracer releases were made as part of the study, but these results were not used for CALINE4 verification because only a single release vehicle was used.

A section of the Eisenhower Expressway (I-90) between Des Plaines and First Avenue was chosen by the Illinois Environmental Protection Agency (EPA) as a representative freeway site. This is a heavily traveled six-lane freeway with average daily traffic in excess of 100,000 vehicles. The test section traverses terrain covered with grass and scattered trees. Air samples were collected for 1-hr averaging periods during June–August at eight locations near the test section. Distances ranged from 3 to 192 m from the roadway edge.

A second site was monitored during October and November at the intersection of two six-lane arterials, North and First Avenues. The site is typical of a high-volume urban intersection. It is surrounded by a mix of single-story buildings, parking lots, and forest preserve. Eight bag sampling locations were established near the intersection. A ninth background sampler monitored concentrations 100–150 m upwind of the intersection. Meteorological data were collected at a tower located in the southeast quadrant.

EPA NO_2/O_3 Sampler Siting Study

In August 1978 a study was conducted by EPA along a section of the San Diego Freeway (I-405) in Los Angeles, California, to quantify the effect of mobile source NO_x emissions on ambient O_3 concentrations immediately downwind of a heavily traveled freeway (30). The test took place 0.8 km north of Wilshire Boulevard in relatively flat terrain. I-405 carries approximately 200,000 vehicles per day at this location. Six

monitoring sites were spaced from 8 to 400 m downwind of the roadway. Continuous sampling was conducted at a height of 3 m, with results averaged over 1 hr. A 10-m-tall meteorological tower measured wind speed and direction immediately upwind of the freeway.

Caltrans Intersection Study

From January through March of 1980, the California Department of Transportation (Caltrans) performed a detailed study of air quality at the intersection of Florin Road and Freeport Boulevard in Sacramento, Calif. (6). At the time of the study, the intersection was surrounded by bare ground for a distance of at least 50 m in all directions. The nearby terrain was level and occupied by scattered single-story residential developments.

Fifteen sampling locations were established in the northwest and southwest quadrants of the intersection. A 10-m-tall meteorological tower was located in each of these quadrants, at least 15 m back from the traveled ways. CO concentrations averaged over 1 hr were recorded concurrently with pertinent traffic and meteorological parameters.

Caltrans Highway 99 Tracer Experiment

A series of SF_6 tracer experiments was conducted by Caltrans during winter 1981–1982 along a 4-km section of US-99 in Sacramento (10). The four-lane divided highway carries more than 35,000 vehicles daily, with a peak hourly volume of 3,450 vehicles. The nearby terrain consists of open fields, parks, and scattered residential developments. The sampling site was located 1 km from the south end of the test section. Three locations were sampled on each side of the highway at 50, 100, and 200 m from the highway centerline and a height of 1 m. A 12-m-tall meteorological tower was located near the south end of the test section, in an open, plowed field.

The SF_6 was released from eight specially equipped sedans. The distribution of the tracer vehicles was controlled at a staging area by spacing departures at 90-sec intervals. In all, 14 tracer release tests were made. Most of these were morning tests with half-hour samples taken from 6:30 to 8:30 a.m.

MODEL VERIFICATION

A statistical method involving the computation of an overall figure of merit (FOM) on the basis of six component statistics (31) was used to evaluate CALINE4's performance in comparison to that of CALINE3. These statistics are defined as follows:

- S_1: The ratio of the largest 5 percent of the measured concentrations to the largest 5 percent of the predicted concentrations,
- S_2: The difference between the predicted and measured proportion of exceedances of a concentration threshold or air quality standard,
- S_3: Pearson's correlation coefficient for the paired measured and predicted concentrations,
- S_4: The temporal component of Pearson's correlation coefficient,

- S_5: The spatial component of Pearson's correlation coefficient, and
- S_6: The root mean square (rms) of the difference between the paired measured and predicted concentrations.

The six component statistics are transformed into individual figures of merit (F_1, F_2, etc.) on a common scale from 0 to 10. They are then weighted and summed as follows:

$$FOM = \frac{F_1 + F_2}{6} + \frac{F_3 + F_4 + F_5}{9} + \frac{F_6}{3} \qquad (8)$$

Scatter plots and relative error plots were also used to evaluate model performance.

Highway Sites

A direct comparison between CALINE3 and CALINE4 on the basis of FOM values was made for the three highway sites for which measured concentrations of SF_6 or CO were available. A summary of the individual and overall FOMs is presented in Table 1. The results were based on measured (M) and predicted (P) concentrations at downwind locations only. For the Illinois EPA study, the sample locations north of I-90 did not match the locations to the south, making it necessary to compute separate statistics for each. The threshold values used for computing F_2 were 1.0 parts per billion (ppb) SF_6 for the two tracer studies and 10 parts per million (ppm) CO for the

Illinois EPA study. These values were selected to yield statistically significant measures of F_2.

For both the GM and Caltrans studies, the individual and overall FOMs clearly indicate improved performance by CALINE4. However, the results for the Illinois EPA study are inconclusive. Although CALINE4 displays slight improvements in temporal correlation and residual error, it does not perform as well in predicting high concentrations.

The higher values of F_1 obtained for CALINE3 by using the Illinois EPA data could have been the result of bias in the emission factor calculations. Emission factors were computed by using the MOBILEI emission factor model (*32*). An examination of the actual values of the statistic S_1 demonstrated that CALINE4 was overpredicting the high concentrations to a slightly greater degree than CALINE3. The uncertainty of the modeled emission factors make it difficult to attach any significance to this, especially when results from the two independent tracer studies indicate, overall, an improved performance by CALINE4.

A comparison between F_4 and F_5 in Table 1 indicates that both models predicted spatial patterns of observed concentrations better than they do temporal sequences. The result is not surprising, given the consistent spatial pattern of downwind concentrations apparent in the data. Virtually all ground-level concentrations decreased with distance from the roadway in both tracer studies. Similarly, elevated sampling sites in the GM study followed repeatable patterns. The models had little

TABLE 1   COMPARISON OF CALINE3 AND CALINE4 FIGURES OF MERIT

Study	Number of Locations	Number of Periods	Model	F_1	F_2	F_3	F_4	F_5	F_6	FOM
Highway Sites										
GM	11	62	C3	6.5	10.0	7.8	7.1	9.7	2.0	6.2
			C4	8.5	10.0	8.3	7.2	9.7	2.8	6.8
Caltrans	3	56	C3	5.7	9.9	5.6	3.5	10.0	2.5	5.6
			C4	8.6	10.0	5.9	4.2	10.0	3.2	6.4
Illinois EPA (North)	4	249	C3	9.7	10.0	7.3	4.3	9.9	3.6	6.9
			C4	8.8	10.0	7.5	4.6	9.9	3.7	6.8
Illinois EPA (South)	4	49	C3	9.9	10.0	7.2	2.4	9.9	3.4	6.6
			C4	8.6	10.0	8.0	3.1	9.9	3.6	6.6
Intersection Sites										
Caltrans	15	38	C4	8.2	10.0	8.8	8.8	9.4	2.6	6.9
Illinois EPA	8	39	C4	8.5	9.9	8.1	6.7	9.2	3.7	7.0
NO_2 Site										
US SPA	6	30	C4	8.4	9.9	7.7	7.9	6.9	5.7	7.5

NOTE: C3 = CALINE3 and C4 = CALINE4.

difficulty in predicting these trends. However, prediction of temporal variations at a given site was much more difficult. Temporal changes are influenced by more variables, some of which may interact in ways that are not clearly understood.

The values of F_6 are, in most cases, the lowest of the individual figures of merit. F_6 is a function of the ratio between rms paired differences, S_6, and the average measured concentration. As this ratio increases, F_6 decreases. Paired differences for low measured concentrations usually decrease S_6 less than they decrease the average concentration, disproportionately influencing the statistic. The result is a much lower value of F_6 for the combined data reported in Table 1 than for most values computed individually by location. For example, F_6 values of 5.4 and 4.5 for the GM and Caltrans studies, respectively, are obtained for CALINE4 by averaging individual values of F_6 computed by location.

Scatter plots of the CALINE4 results, displaying predicted versus measured SF_6 concentrations for the GM and Caltrans studies, are presented in Figure 2. A line of perfect agreement and factor of 2 envelope defined by $P = 2M$ and $P = M/2$ are superimposed to assist in interpreting the results. The number of observations (n) and the least squares linear regression intercept (a), slope (b), and correlation coefficient (r) are also given.
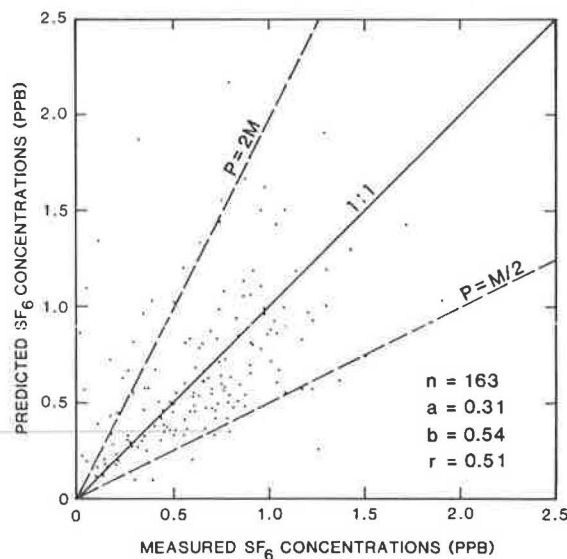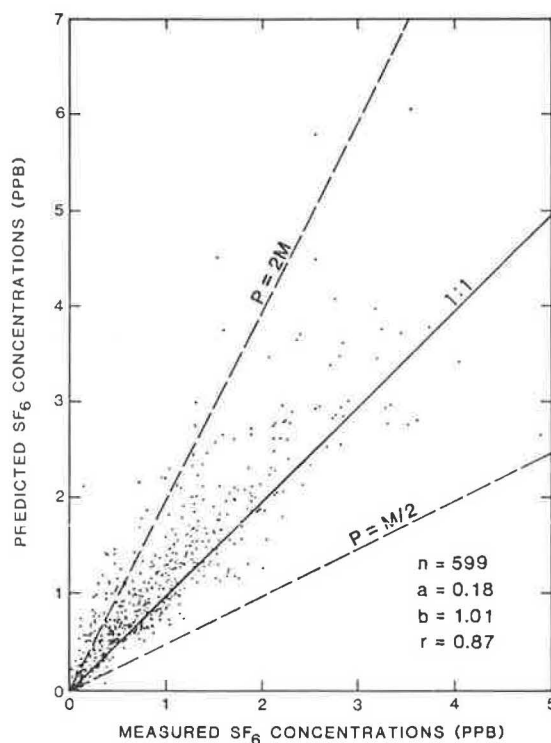

FIGURE 2   Scatter plot showing CALINE4 predictions and measured results for the Caltrans U.S.-99 study.

Less than 15 percent of the combined results fall outside of the factor of 2 envelope. Of these, 85 percent are overpredictions. For the more significant high concentrations (above 1 ppb), only one serious underprediction occurs for the 762 combined measurements. This particular measurement was made 200 m from the roadway under low wind speed and parallel wind conditions. For the last 10 min of the sampling period, the wind speed dropped to 0.14 m/sec, far below the lower limit for a Gaussian model and the threshold of the meteorological instruments.

The overall scatter of the results is significantly greater for the Caltrans study, as indicated by the lower value of r. Of all

the Caltrans results outside of the factor of 2 envelope, more than 90 percent occurred during sampling periods when either u was less than 1 m/sec or the roadway-wind angle, ϕ, did not exceed 15 degrees. All of the extreme overpredictions ($P/M > 4$) occurred during three sampling periods during which both these conditions existed. The single unusual overprediction for the GM study ($M = 0.17$, $P = 2.13$ ppb) involved an anomalous measurement that was nearly an order of magnitude lower than all concurrent measurements made nearby.

Gaussian model performance deteriorates as wind speed approaches zero because along-wind diffusion, σ_x, is assumed to be negligible when compared to advective dilution. The result is unrealistically high predicted concentrations, typified by the extreme overpredictions presented in Figure 2. Fewer overpredictions occur in Figure 3 because only 10 percent of the GM measurements (versus 40 percent of the Caltrans measurements) were made at wind speeds below 1 m/sec.

FIGURE 3   Scatter plot showing CALINE4 predictions and measured results for the GM study.

Parallel wind conditions make Gaussian line source models much more sensitive to the assumption of steady state, homogeneous wind flow. Field data invariably contain sampling periods during which horizontal plume meander is a significant dispersive mechanism. When the wind direction is parallel or nearly parallel to the roadway, meander can lead to extreme differences between measured and predicted results. This is exacerbated at low wind speeds by the failure of instrumentation to accurately record conditions.

Unfortunately, low wind speeds and horizontal meander often occur together during stable or transitional meteorological regimes. The use of a horizontal dispersion algorithm, such as the one in CALINE4, can help cope with these conditions.

However, the model must still assume that concentrations are normally distributed about a single mean wind direction. If the computed wind direction actually represents two or more distinct distributions, inaccurate predictions can result.

Plots of relative error versus ϕ for four of the GM ground-level sampling locations are given in Figure 4. Relative error, defined as

$$E_r = (P - M)/(P + M) \tag{9}$$

offers a convenient way to plot widely differing residual errors on a single scale. For each of the plots, E_r becomes more erratic as ϕ approaches zero. A general tendency toward overprediction by the model and increased data scatter at more distant locations is also evident. Similar results were obtained for CALINE4 when Caltrans data were used.

A systematic trend toward overpredicting median concentrations during parallel wind conditions can be observed in Figure 4a. In all, 95 percent of the GM and Caltrans median measurements made under parallel wind conditions (ϕ less than 10 degrees) were overpredicted by CALINE4. This is not

surprising, given the empirical nature of the mixing zone model. The model does not attempt to resolve the complex processes of the dispersion within the mixing zone. Instead, it focuses on the net results downwind of the roadway. Assumptions of constants for σ_z and q over the mixing zone and the lack of a mechanism for modeling shear between opposing flows of traffic are probably the reasons for the inaccuracies. Still, 80 percent of the median overpredictions were within the factor of 2 envelope.

Relative error for both the GM and Caltrans tracer data was also studied as a function of u. In general, model performance deteriorated as u decreased. When u was below 1 m/sec, predicted results fell outside the factor of 2 envelope ~25 percent of the time. When u exceeded 1 m/sec, only 10 percent of the predictions were outside.

CALINE4 performed significantly better than CALINE3 at speeds below 1 m/sec, achieving a 66 percent reduction in rms error. An examination of the data revealed that virtually all of this improvement occurred for near-parallel winds with significant horizontal meander. Because CALINE4 was better able to cope with these conditions, the allowable lower limit
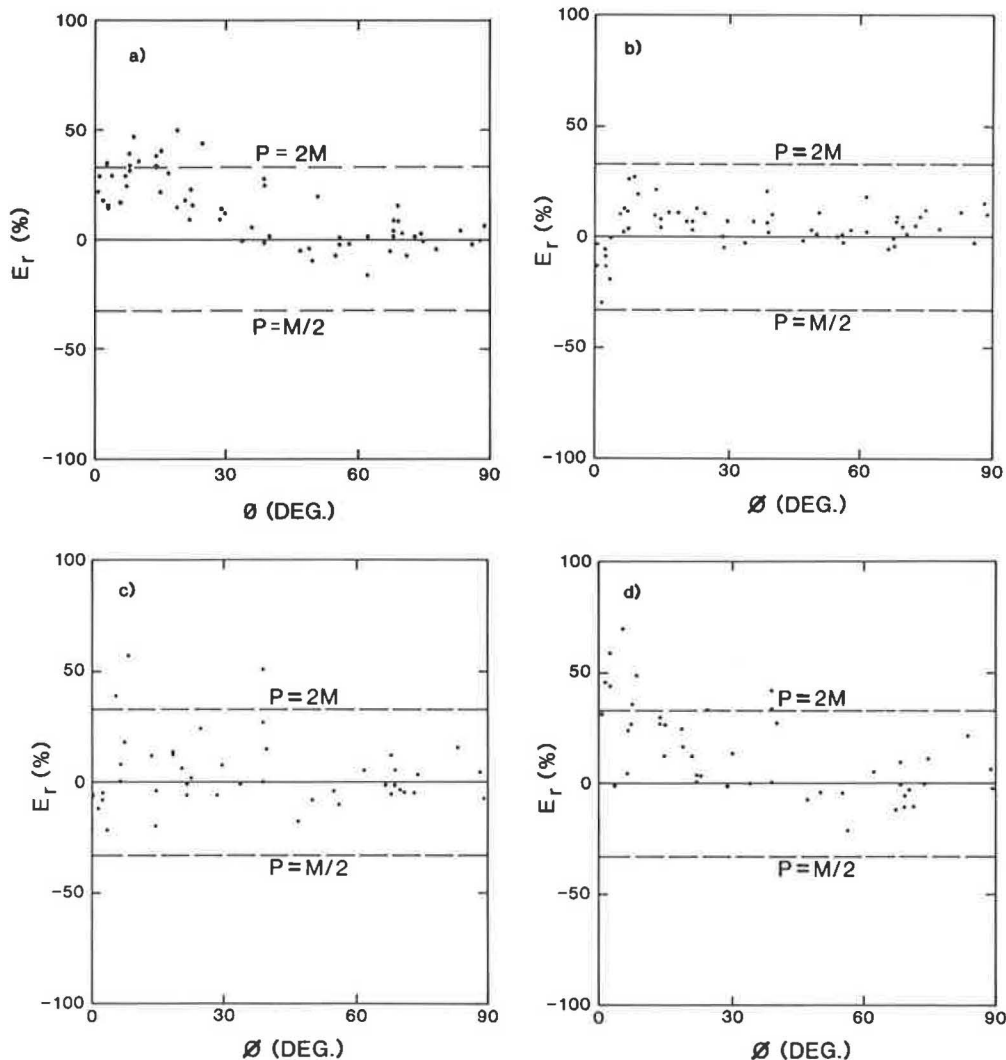

FIGURE 4 Relative error E_r versus roadway-wind angle ϕ for GM ground-level sampling locations at four distances from the roadway centerline: (a) 0 m (at median); (b) 15 m, (c) 43 m, and (d) 113 m.

for u has been reduced from the 1 m/sec value used by CALINE3 to 0.5 m/sec.

Intersection Sites

Emission factors and traffic parameters for the two intersection sites were estimated by using the best available information for each site. The distribution of vehicles by operating mode was assumed to follow the national average (21 percent cold start, 27 percent hot start). The percentages of vehicle types were based on vehicle classification counts. Acceleration rates, vehicle delay, turn movements, and other needed traffic parameters were estimated from floating car surveys and representative traffic counts.

Because of the difficulty in accumulating the input data needed to run the intersection link option, only a fraction of the intersection data was used in the verification analysis. For each data base, ~30 randomly selected hours were combined with the 10 hours of highest concentration to form a verification data set. The CALINE3 model was not run on the intersection or NO_2 data bases because it was not designed for those kinds of applications.

Model performance for intersection sites actually exceeded the performance for highway sites on the basis of the FOMs in Table 1. Two possible reasons for this are the higher wind speeds that were experienced during the intersection sampling and the elimination of parallel winds as a critical condition.

NO$_2$ Option

The verification analysis for the CALINE4 NO_2 option was performed by using the EPA NO_2/O_3 sampler siting study data base. From the data base, 30 time periods were chosen to represent a variety of traffic and meteorological conditions. Photolysis rate constants were determined by using a method that incorporated the effects of cloud cover (33). Emission factors were determined by using a California emission factor model (34) and assuming representative distributions of vehicle type and operating mode. The resulting individual and overall FOMs are given in Table 1.

The model performance is actually better than the results presented for the relatively inert species, SF_6 and CO. However, the improvement is due to the nature of the site, not the use of the NO_2 option. Prevailing winds were perpendicular to the highway alignment and were steady in speed and direction. For the 30 time periods studied, the roadway-wind angle was never less than 60 degrees, and the average wind speed never dropped below 1.4 m/sec. Under these conditions, the CALINE4 model gives its best performance. Because of the assumptions involved, application of the NO_2 option is not recommended for parallel winds unless measured results are available for calibrating the model.

CONCLUSIONS

The comparisons between CALINE3 and CALINE4, summarized in this paper, indicate that modest improvements in accuracy can be expected from the newer version of the model. It is assumed that these improvements are attributable to the use of σ_θ in CALINE4 to estimate horizontal dispersion,

a method recommended by others as the best practical solution for near-field dispersion in flat terrain (35–37), and the addition of a vehicle-induced heat flux algorithm. No other significant differences in dispersion mechanisms exist between the models.

The problem of accurately predicting pollutant concentrations near line sources during conditions of low wind speed and parallel wind is not, however, fully solved by σ_θ methodology. Shifts in wind direction over time or distance make the parallel wind case the most difficult to model successfully with a Gaussian plume approach, especially at low wind speeds. Fortunately, model predictions are usually conservative under such conditions. Because measured results are usually integrated over an arbitrary time interval, during which adverse meteorological conditions might not persist, the conservative model prediction may actually be a better estimate of the true maximum concentration.

The ability of CALINE4 to handle a greater variety of problems in a more flexible manner is just as important as its enhanced accuracy. This is particularly true with regard to the intersection link option. Accurate predictions of microscale air quality effects near intersections can only be obtained by a realistic spatial allocation of the modal emissions. This is exactly what CALINE4 is designed to do.

Verification analyses for both the intersection link and NO_2 options were based on limited field data and multiple assumptions about emissions. Additional laboratory work on modal emissions and field studies, incorporating either better documentation of pertinent traffic parameters or tracer gas controls, is needed. As better estimates of modal emission rates become available, they can easily be incorporated into the CALINE4 intersection link option.

Modifications of the NO_2 option for parallel wind conditions (not tested in this analysis) would be much more difficult because of the restrictive assumptions employed. It is quite possible, however, that crosswind conditions cause higher NO_2 concentrations near the roadway than do parallel winds. The abundant supply of upwind O_3 available to react with roadway-generated NO during crosswind conditions may raise the NO-to-NO_2 conversion rate to much higher levels than occur under parallel winds, leading to higher downwind NO_2 concentrations.

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