Ruhnke for providing traffic and transit information, and Ken Pinkerman for serving as a technical consultant on instrumentation.

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Evaluation of the CALINE4 Line Source Dispersion Model for Complex Terrain Application

PAUL E. BENSON, WILLIAM A. NOKES, and ROBERT L. CRAMER

ABSTRACT

CALINE4, the latest version of the California Line Source Dispersion Model, is evaluated for use in complex terrain. Data from air-quality studies connected with a transportation improvement project along State Route 203 at Mammoth Lakes, California, are used for this purpose. A comprehensive tracer gas release experiment performed after completion of the project is described. Based on comparisons with the CALINE3 model and previous results for CALINE4 in flat terrain, model performance for receptors near the roadway in complex terrain is judged adequate for impact assessment purposes. Predictions for more distant receptors are much less reliable.

The California Line Source Dispersion Model, CALINE3 (1), is used throughout the country as a tool for evaluating the potential microscale air-quality impacts of transportation projects. The U.S. Environmental Protection Agency (EPA) has approved the model for general use with the provision that it not be used for studying projects in complex terrain (2). This restriction is made because of the assumptions on which the model is based.

CALINE3 uses a quasi-empirical Gaussian solution

Transportation Laboratory, California Department of Transportation, 5900 Folsom Boulevard, Sacramento, Calif. 95819.

to the Fickian diffusion equation to model pollutant dispersion. This approach assumes a homogeneous wind flow field (both vertically and horizontally), steady-state conditions, and negligible along-wind diffusion. These assumptions can never be met exactly in any real-world application. However, for sites in relatively flat terrain and wind speeds above 0.5 m/sec, they are considered reasonable and yield answers that compare favorably with measured results (1). In this paper the extent to which these assumptions are satisfied for applications in complex terrain is examined.

A significant fraction of transportation projects is built in complex terrain. Because of difficulties

in obtaining the requisite amount and quality of input data, three-dimensional, finite-difference models are rarely used for assessing air-quality impacts of these projects. Instead, a Gaussian model such as CALINE3 is applied. This approach is subject to a request from the reviewing agencies for a site-specific verification of the model. The California Air Resources Board carried out this type of verification study in 1981 for applications of CALINE3 in the vicinity of South Lake Tahoe (3). They concluded that the model predictions were slightly higher than observed values but were in good agreement with the measured hour-by-hour trends in air quality at most locations.

The South Lake Tahoe findings could not be extrapolated to other complex terrain sites, however. South Lake Tahoe's topography is representative of a large and relatively flat mountain basin. Projects were being proposed in much more complex locations. Questions remained about the model's ability to accurately predict impacts at such locations.

The planning and construction of a transportation improvement project along State Route 203 in the ski resort community of Mammoth Lakes, California, provided an opportunity to answer these questions. A comprehensive pre- and postconstruction monitoring program for carbon monoxide (CO) was conducted in connection with the project. The results of this work are described in a companion paper by Benson et al. in this Record. A series of experiments involving the release of tracer gas was also carried out after construction of the project.

The results of these experiments were used to evaluate the latest version of the California Line Source Dispersion Model, CALINE4 (4). CALINE4 is based on the same limiting assumptions as CALINE3 but contains improved algorithms for modeling vertical and horizontal dispersion. It has already proved superior to CALINE3 for flat terrain applications (4), and it was hoped that the improved dispersion algorithms would also enhance its performance in complex terrain.

EXPERIMENT PROCEDURES

The tracer gas release experiments were conducted during the winter of 1983-1984 along sections of State Route 203 and Lake Mary Road in Mammoth Lakes (Figure 1). The terrain is uneven, generally sloping downhill from the west. Strip commercial development is prevalent along Route 203, whereas the surrounding residential properties are interspersed among stands of mature conifers. Roadside snowbanks 1 to 6 m high are common during the winter months.

From the east boundary of the tracer release to the Lake Mary Road intersection, Route 203 has two lanes in each direction with a two-way left-turn lane between. From the Lake Mary Road intersection to the north and west boundaries, there is one lane in each direction with no median. Average daily traffic in the study area is 15,700 vehicles with a peak hourly volume on Route 203 of 3,100 vehicles.

Sulfur hexafluoride (SF_6) was used as the tracer gas. It is a highly inert gas, detectable at extremely low concentrations. SF_6 does not occur naturally and its presence in ambient air samples is negligible (5).

The SF_6 was released from two specially equipped 1970 Matador sedans. Each sedan had an on-off flow control switch mounted on the dashboard and a strip-chart recorder to monitor the flow status. The gas was contained in a cylinder secured in the trunk of the sedan. It was carried by copper tubing through the trunk floor to the tailpipe and released directly into the exhaust stream.

The tracer gas flow rates were checked before and after each test with a bubblemeter. The nominal flow rate, controlled by a needle valve, was 0.5 L/min. The measured flow rates typically varied no more than 20 percent from the nominal value over the course of a test. Tests were 2 1/2 hr in duration, with samples being taken only during the last 2 hr. The 1/2-hr delay was made to avoid sampling during the transient build-up phase of the release. A total of 13 tests were conducted at various times between 5:00 a.m. to 8:00 p.m.

The vehicles released SF_6 along the test section indicated in Figure 1. The SF_6 flow was turned off at each turnaround point as the vehicles left the test section. On the four-lane portion of the route, vehicles were assigned separate lanes. The distribution of the vehicles was controlled at a staging area by spacing departures at 4-min intervals. The drivers were instructed to try to maintain a speed between 30 and 35 mph. When stopped at the
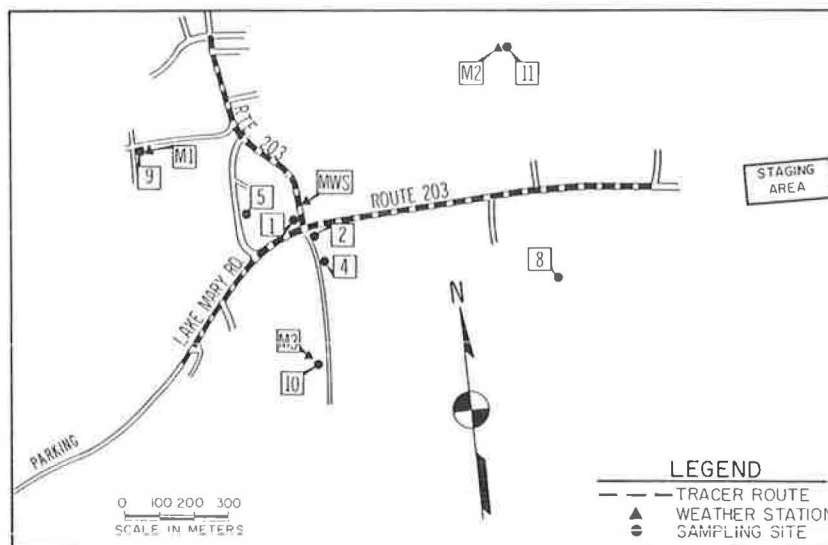

FIGURE 1 Tracer study sampling site location map.

intersection, the vehicles continued to release gas. Event markers recorded the location and duration of these releases on the strip chart.

Sampling sites were selected to represent three zones surrounding the Route 203-Lake Mary Road intersection. Their locations are shown in Figure 1. Sites 1 and 2 were located immediately adjacent to the intersection. These were designated as Zone 1 sites. The Zone 2 sites, Sites 4 and 5, were located 80 and 135 m from the intersection, respectively. Sites 8 through 11 ranged approximately 300 to 600 m from the intersection and were no closer than 190 m to the tracer release route. These were considered Zone 3 sites.

All samples were taken at a height of 1 m above the ground. They were collected in tedlar bags by using EMI AQS III samplers equipped with positive displacement pulse pumps. The samples represented 30-min integrated concentrations. They were analyzed on a Perkin-Elmer Sigma 2 gas chromatograph with electron capture detector. This instrument was calibrated with a Dasibi Model 1005 CE-2 flow dilution system and a National Bureau of Standards traceable cylinder of 5 ppm SF_6.

A meteorological tower 12 m high was located approximately 3 km east of the test course in an open area. It was equipped with a horizontal wind vane, two low-threshold (0.3 m/sec) cup anemometers, and a pair of self-aspirated temperature sensors. Information from this tower was used to estimate atmospheric stability by Golder's method (6).

A mechanical weather station was located in the northeast quadrant of the Route 203-Lake Mary Road intersection at a height of 10 m. Measurements from this device were used to determine wind direction and directional variability. Mechanical weather stations were also set up at Sites 9, 10, and 11 at a height of 1.5 m to measure surface winds. Wind speed was estimated as the average of these three measurements.

MODEL VERIFICATION

A statistical method developed through the National Cooperative Highway Research Program (7) was used to evaluate the performance of CALINE3 and CALINE4 on the Mammoth Lakes data. The method uses an overall figure of merit (FOM) based on six separate statistics. These statistics are defined as follows:

S_1 = the ratio of the highest 5 percent of the measured concentrations to the highest 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 paired measured and predicted concentrations,

S_4 = the temporal component of Pearson's correlation coefficient for paired concentrations,

S_5 = the spatial component of Pearson's correlation coefficient for paired concentrations, and

S_6 = the root mean square of the difference between paired measured and predicted concentrations.

Statistic S_1 measures the model's ability to predict high concentrations. Statistic S_2 measures how well the model predicts the frequency of exceeding an air-quality standard or threshold. Statistics S_3, S_4, and S_5 correlate the model's response to changing conditions with real-world response. Statistic S_4 considers changes over time (wind speed, atmospheric stability), whereas S_5 is associated

with changes over space (source-receptor distance, topography). Statistic S_3 represents a combined measure of both factors. Statistic S_6 measures the overall error attributable to both modeling and measurement processes.

Each of the six statistics is converted into an individual FOM (F_1, F_2, F_3, etc.) based on a common scale from 0 to 10. An overall FOM is computed by weighting and summing the individual values as follows:

$$FOM = \{[(F_1 + F_2)/2] + [(F_3 + F_4 + F_5)/3] \\ + F_6\}/3 \qquad (1)$$

No standard value for FOM has been established to differentiate between "good" and "bad" model performance. A relative measure of model accuracy is used in this paper to compare CALINE3 and CALINE4 results in complex terrain and to contrast those results with performance in flat terrain.

Two graphical verification methods are also used to evaluate model performance. The first method is a scatterplot showing predicted versus measured concentrations. The second is a plot of relative error E_r by zone with E_r defined as

$$E_r = [(P - M)/(P + M)] * 100 \qquad (2)$$

where P equals the prediction and M the measurement. E_r is a symmetric form of the residual error P - M normalized to 100 percent. It provides a convenient way to graph widely differing residual errors on a single scale.

Of the 13 tracer tests conducted during the study, only 4 were judged suitable for the verification analysis. The dates and times of these tests are shown in Table 1. Tests 1 and 4 were performed during downslope wind conditions, whereas Tests 2 and 3 coincided with upslope winds. These tests were selected because of their low wind speeds (below 2 m/sec) and lack of major discontinuities in wind direction over the 2 1/2-hr release period. SF_6 concentrations for the tests omitted from the analysis were usually low because of prevailing high winds or unsteady wind direction.

TABLE 1   Meteorological Data During Tracer Tests

Time	Wind Speed (m/sec)	Wind Direction (degrees)	Sigma Theta (degrees)	Temperature (°C)	Stability Class
Test 1, 1/12/84					
6:00-6:30 a.m.	0.47	330	5.0	−5.9	F
6:30-7:00 a.m.	0.36	330	5.0	−5.9	F
7:00-7:30 a.m.	0.40	330	5.0	−5.6	F
7:30-8:00 a.m.	0.39	330	5.0	−5.6	F
Test 2, 1/12/84					
12:00-12:30 p.m.	1.5	210	27.5	−0.4	C
12:30-1:00 p.m.	1.5	210	32.5	−0.4	C
1:00-1:30 p.m.	1.5	240	27.5	−0.5	C
1:30-2:00 p.m.	1.6	210	28.3	−0.5	C
Test 3, 2/7/84					
10:00-10:30 a.m.	0.67	120	40.0	8.9	C
10:30-11:00 a.m.	0.81	90	30.0	8.9	C
11:00-11:30 a.m.	0.88	135	25.0	9.9	C
11:30-12:00 p.m.	0.95	120	30.0	9.9	C
Test 4, 3/22/84					
6:00-6:30 p.m.	0.73	320	12.5	4.0	E
6:30-7:00 p.m.	0.68	315	12.5	4.0	E
7:00-7:30 p.m.	0.68	300	15.0	1.7	G
7:30-8:00 p.m.	0.78	310	7.5	1.7	G

Results from the four sampling periods for each test were examined for anomalous values. SF_6 concentrations near the intersection for the first sampling period of Test 1 were abnormally high. Levels of 43 ppb at Site 2 and 20 ppb at Sites 1 and 4 were 10 times higher than any other measurements made during the study. A review of 10-min integrated samples revealed a significant drop in concentrations at these sites during the first hour of Test 1 (Figure 2). The change was most dramatic during the
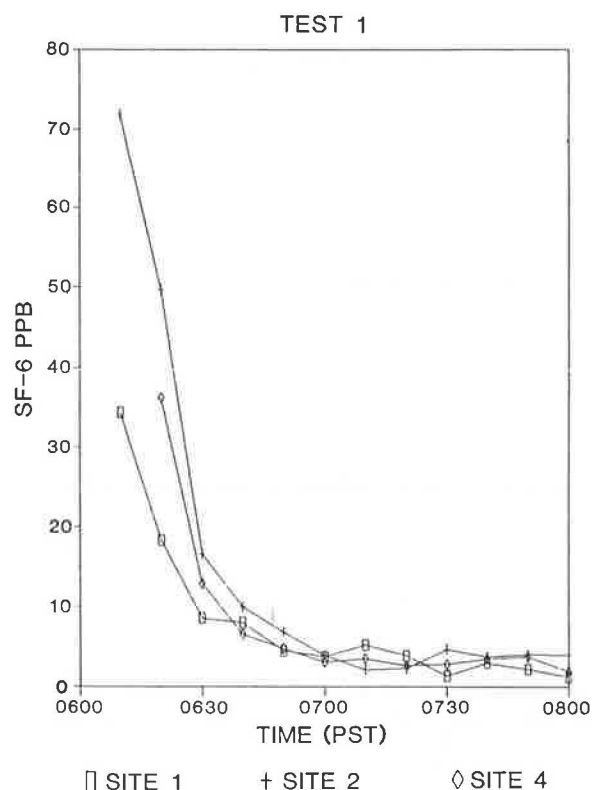
FIGURE 2 Test 1: 10-min integrated samples.

TABLE 2 CALINE3 and CALINE4 FOMs for Mammoth Lakes Tracer Study

Site No.	Zone	No. of Periods	Model	F_1	F_2	F_3	F_6	Overall FOM
1	1	7	C3	1.6	9.0	8.0	0.1	4.5
			C4	6.3	9.3	8.0	4.2	6.7
2	2	8	C3	2.1	10.0	8.6	0.1	4.9
			C4	7.8	10.0	8.3	2.1	6.4
4	2	7	C3	2.0	9.6	8.5	0.1	4.8
			C4	7.9	9.6	8.2	3.1	6.7
5	2	8	C3	1.2	7.5	0.0	0.1	1.5
			C4	3.8	10.0	2.5	0.7	3.4
8	3	8	C3	3.2	8.6	5.2	1.7	4.3
			C4	1.3	8.3	2.9	1.2	2.9
9	3	8	C3	0.9	10.0	7.6	0.0	4.4
			C4	2.8	10.0	9.6	0.1	5.4
10	3	8	C3	8.2	7.9	4.7	1.5	4.8
			C4	1.3	8.2	0.6	1.2	2.2
11	3	8	C3	2.3	10.0	6.9	0.1	4.4
			C4	7.6	10.0	9.5	3.4	7.2

Note: C3 = CALINE3, C4 = CALINE4.

CALINE4 at six of the eight sites. At Sites 8 and 10, better performance by CALINE3 is indicated. As will be seen later, this is primarily due to more suspiciously high results from Test 1. The overall FOMs for CALINE3 and CALINE4, respectively, were 4.4 and 6.0 for Tests 1 and 4 (downslope) and 4.4 and 6.2 for Tests 2 and 3 (upslope). These results indicate that CALINE4 performed somewhat better than CALINE3 at the site with complex terrain.

FOM values based on previous studies of CALINE4 in flat terrain range from 6.4 to 6.8 (4). The overall values of 6.0 and 6.2 for this study fall just below that range. As indicated in Table 2, CALINE4 results for half of the sites (1, 2, 4, and 11) meet or exceed model performance in flat terrain. Results from Sites 5, 8, and 10 indicate extremely poor performance. Although there is no clear trend, the average FOM by zone decreases with distance from the intersection.

Scatterplots of CALINE4 predictions versus measured SF_6 concentrations at downwind sites are shown by zone in Figures 3 through 5. CALINE3 re-
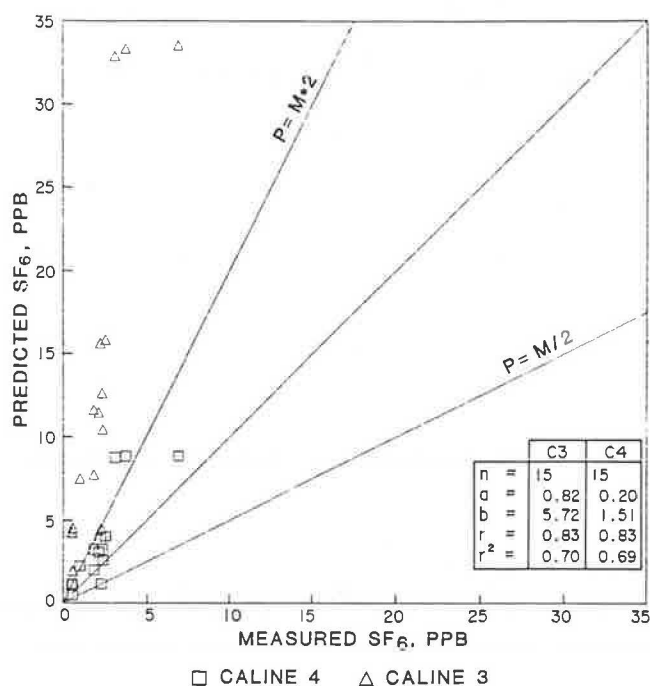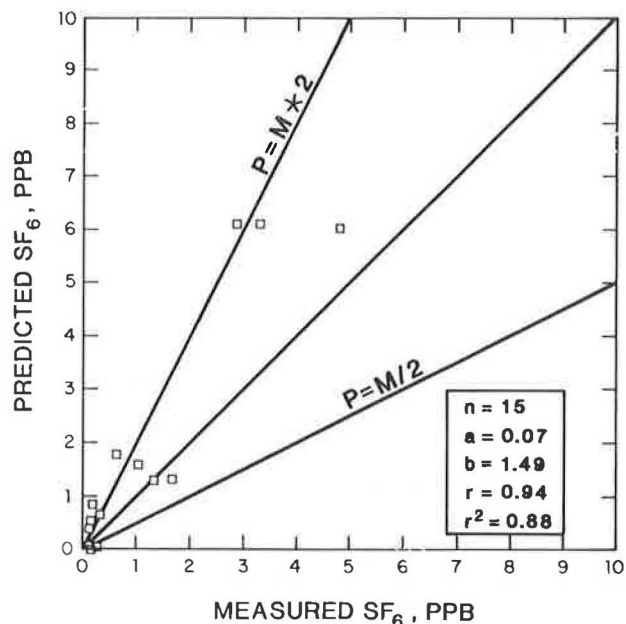
6:00–6:30 a.m. sampling period. Records were checked to see whether an accidental release of SF_6 might have occurred during the initial flow calibration procedure or the preliminary release period. No indications of an accidental release were found. Strip charts from the ground-level weather stations were examined for stagnant conditions sometimes associated with drainage winds in forested terrain (8–10). This may have caused the heavier-than-air tracer to create a "puddle" of SF_6 near the intersection. Although wind speeds were very low near the ground, the charts indicated that they were steady in direction and speed.

For some reason that is still not clear, SF_6 concentrations at Sites 1, 2, and 4 did not reach a reasonable state of equilibrium before the first 30-min sampling period of Test 1. The anomalous measurements were therefore removed from the verification data base because they did not conform with the model requirement for steady-state conditions.

The edited data base was used to develop FOMs for CALINE3 and CALINE4. A summary of the site-by-site results with zone and number of sampling periods noted is given in Table 2. Only downwind locations were used for computations. The threshold value for computing F_2 was 1.0 ppb SF_6.

The FOM results indicate superior performance by

FIGURE 3 Zone 1 predicted versus measured SF_6 levels.

FIGURE 4 Zone 2 predicted versus measured SF$_6$ levels.

n = 15
a = 0.07
b = 1.49
r = 0.94
r^2 = 0.88
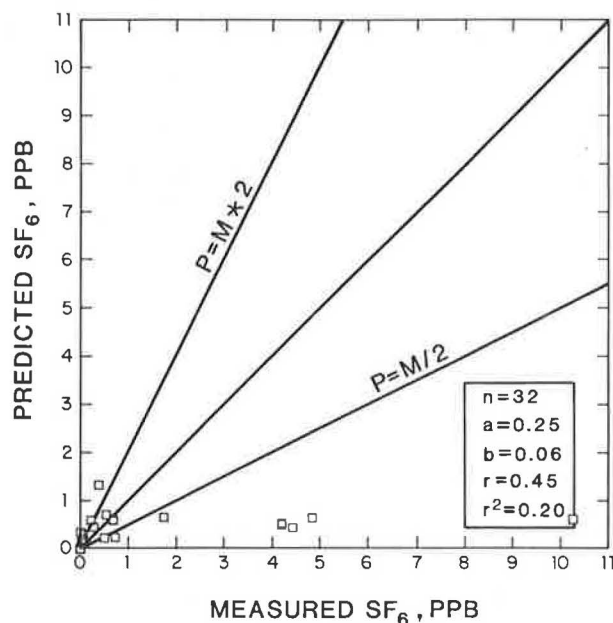
FIGURE 5 Zone 3 predicted versus measured SF$_6$ levels.

n = 32
a = 0.25
b = 0.06
r = 0.45
r^2 = 0.20

sults are included in the Zone 1 plot (Figure 3). A line of perfect agreement and factor-of-2 envelope highlight the results. Points falling inside the envelope represent predictions within plus or minus a factor of 2 of the measured concentrations, a frequently used minimum criterion for judging model performance. The number of points (n), intercept (a), slope (b), and correlation coefficient (r) for a linear least-squares regression are also given.

The number and magnitude of overpredictions by CALINE3 for Zone 1 sites indicate model performance inferior to that of CALINE4. Most of the overpredictions occur at wind speeds below the model's nominal limit of 1 m/sec. CALINE4 is better able to handle these conditions because of its ability to address wind meander through an improved horizontal dispersion algorithm. Nevertheless, Figures 3 and 4 also

indicate an excess of overpredictions by CALINE4. Considering measured values of 0.5 ppb SF$_6$ and above, all the CALINE4 results that fall outside of the factor-of-2 envelope, approximately 30 percent of the total, are overpredictions. This is somewhat higher than the 13 percent and 22 percent reported for similar studies in flat terrain (4). The conservative pattern of overpredictions is similar, however.

The results for Zone 3 shown in Figure 5 indicate that model performance in complex terrain deteriorates with distance from the source. Considering only measured values equaling or exceeding 0.5 ppb SF$_6$, 7 of the 9 values (78 percent) fall outside of the factor-of-2 envelope. All of these are underpredictions. Five results measured at Sites 8 and 10 during Test 1 exceed an order-of-magnitude difference. Test 1 also contained the anomalous measurements for the first 30-min sampling period at Sites 1, 2, and 4. It is possible that the dense concentration of SF$_6$ measured at the intersection was transported downwind to Sites 8 and 10 in later sampling periods. However, even if these results are omitted from Figure 5, nearly two-thirds of the CALINE4 predictions still fall outside of the factor-of-2 envelope. The model is not able to predict concentrations at the distant Zone 3 sites with any reliability.

A plot of relative error versus zone (Figure 6) further dramatizes this point. The plot contains Test 1 results for Sites 8 and 10 but does not include any results for which either the predicted or measured values equaled zero. The differences in this latter case rarely exceeded 0.01 ppb. The factor-of-2 envelope is represented by the two horizontal lines at E$_r$ = ±33 percent. A progressive deterioration in model performance by zone is clearly evident.
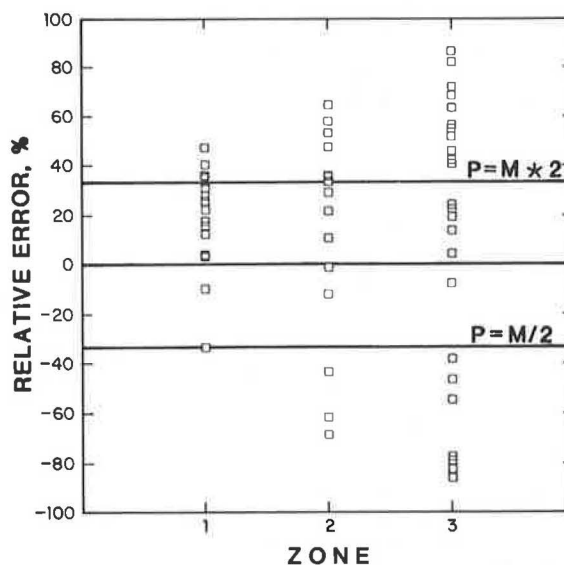
FIGURE 6 Relative error of predicted versus measured SF$_6$ levels versus zonal locations.

DISCUSSION OF RESULTS

It is obvious from the results of the verification analysis that CALINE4 has difficulty handling the temporal and spatial changes in meteorology that are commonplace in mountainous terrain. The model assumes that horizontal and vertical dispersion are adequately described by unimodal, normal distribu-

tions, and that wind direction is uniform over the study area. Real-world processes such as wind shear, channeling, and stagnation cause significant spatial variations in meteorology that clearly violate these assumptions. The model also assumes that the transport and dispersion processes have reached a steady-state condition. Periods of transition between flow regimes (e.g., downslope to upslope winds) cause changes in wind direction and speed that violate this assumption. Such transitions occur more often in complex terrain. Therefore, it is not surprising that the CALINE4 verification results for Mammoth Lakes fall short of results for similar studies in flat terrain.

There were, however, indications ·in the verification analysis that CALINE4 could be used successfully in complex terrain if the application was limited to sites immediately adjacent to the source. Model performance for the Zone 1 sites was comparable with performance in flat terrain because spatial and temporal variations in meteorology were less critical. Tracer gas released near the intersection had little time to disperse before reaching the Zone 1 sites. Concentrations were therefore heavily dependent on the emissions in the immediate vicinity of the intersection. Within this limited area, the effects of topography on meteorology were minimal. By restricting the analysis to a small area, CALINE4 performed better.

As a practical test of the model's ability to predict air quality impacts in complex terrain, model predictions for worst-case CO levels were compared with the highest levels recorded during a companion CO study (paper by Benson et al. in this Record). Sites 1, 2, and 4 of the tracer study were sampled as part of the companion study. The normal procedures recommended by Caltrans for assessing project-level air-quality impacts were followed. Emission factors for CO were generated by running the EMFAC6D program (California's version of MOBILE2) and adjusting results to the elevation of Mammoth Lakes by using EPA methods (11). Vehicle type distributions and traffic volumes were based on actual counts made during peak ski season weekends. Percent hot and cold starts was estimated for each leg of the intersection on the basis of observed travel patterns and a New Jersey Department of Transportation study (12). Recommended worst-case values for meteorology in mountainous terrain and worst-case wind directions were assumed (13). The maximum 1-hr CO concentration of 13.8 ppm sampled 1 km from the intersection was used as a background level (14,15).

The estimates were made for the morning time period (all of the highest measurements at each site were recorded between 7:00 and 10:00 a.m.). The intersection geometry was modified to accommodate four CALINE4 intersection links. Each of these links includes deceleration, idle, acceleration, and cruise components. Traffic and signal parameters were based on surveys conducted during the traffic counts.

Predictions of 1-hr averaged concentrations for CO at Sites 1, 2, and 4 were made. Predictions for a site in the same quadrant as Site 2 but about 5 m closer to the intersection were also made. This site, called A_1, was not included as part of the tracer study. These results and the highest measured values are summarized in Table 3. The measured 8-hr peak values are also included in the table. As can be seen, the predictions for the sites closest to the intersection (Sites A_1 and 1) agree quite well with the measured results. Underpredictions of approximately 10 ppm CO occur for the more distant Sites 2 and 4, however. The pattern of higher concentrations measured further from the intersection suggests the possibility of other significant con-

TABLE 3 Measured and CALINE4-Predicted Worst-Case CO Concentrations for 1982-1983 Mammoth Lakes Air-Quality Monitoring Program

Site	One-Hour Predicted	One-Hour Measured	Eight-Hour Measured
1	27.5	26.1	10.2
2	24.1	36.4	11.4
4	19.4	29.3	10.7
A_1	29.4	30.5	11.0

tributing sources. Sites 2 and 4 were located on the edge of a motel parking lot. It is possible that idling cold-start vehicles or smoke from the nearby model chimney could have contaminated these samples. In any case, the performance of the model and the procedures for estimating the worst-case inputs are certainly reasonable for the receptors closest to the intersection.

The 8-hr peak concentrations were included in Table 3 to give an idea of the kind of persistence factor to be expected in complex terrain near a roadway with a pronounced traffic peak. The persistence factor, which is defined as the ratio of the 8-hr peak CO concentration to the 1-hr maximum, is normally assigned a value ranging from 0.6 to 0.7 (16). Because of the more frequent changes in meteorology typical of complex terrain, it appears reasonable to expect a lower persistence factor. The persistence factors computed from the results in Table 3 range from about 0.3 to 0.4. Applying the higher recommended persistence factors to the estimated 1-hr concentrations would have resulted in overestimates of the 8-hr average as high as 65 percent. This is the primary reason that the California Department of Transportation recommends the use of persistence factors derived from local data whenever possible (13).

CONCLUSIONS

CALINE4 model performance for adjacent receptors in complex terrain is not as good as that for similar modeling situations in flat terrain. However, the differences are not great when compared with the accuracy of many of the estimates that are used as inputs to the model. Predictions for more distant receptors are much less reliable. Model performance clearly deteriorates with distance from the emissions source. The model assumptions of steady-state, quasi-homogenous flow are obviously not satisfied for distant receptors in complex terrain.

On the basis of these findings, it is recommended that CALINE4 applications in complex terrain be restricted to receptors immediately adjacent to the primary source of emissions. For most project-level analyses, this restriction will not pose a problem because worse-case receptor locations are normally chosen at the right-of-way line.

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