Estimating near-road pollutant dispersion: a model inter-comparison

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ABSTRACT

A model inter-comparison study to assess the abilities of steady-state Gaussian dispersion models to capture near-road pollutant dispersion has been carried out with four models (AERMOD, run with both the area-source and volume-source options to represent roadways, CALINE, versions 3 and 4, ADMS and RLINE). Two field tracer studies are used: the Idaho Falls tracer study and the Caltrans Highway 99 tracer study. Model performance measures are calculated using concentrations (observed and estimated) that are paired in time and space, since many of the health related questions involve outcomes associated with spatially and temporally distributed human activities. All four models showed an ability to estimate the majority of downwind concentrations within a factor of two of the observations. RLINE, AERMOD-V, and ADMS, also have the capability to predict concentrations upwind of the roadway that result from low-speed meandering of the plume. Generally, RLINE, ADMS, and AERMOD (both source types) had overall performance statistics that were broadly similar, while CALINE 3 and 4 both produced a larger degree of scatter in their concentration estimates. The models performed best for near-neutral conditions in both tracer studies, but had mixed results under convective and stable conditions.

Key Words: Air quality modeling; near-road; pollutant dispersion; mobile sources; model comparison.

1 Introduction

There is a growing international consensus on elevated health risks for near-road populations. Air quality models provide a deterministic relationship between the spatial and temporal variability of traffic-related pollutants and emissions, meteorology, and roadway design. Air quality and exposure models help establish epidemiological associations between pollution and health. Models, however, require detailed input data (e.g. traffic activity, temporal allocation factors, emission rates, meteorology) to provide reliable estimates. Additionally, improvements are needed in dispersion modeling algorithms, such as plume meandering in light wind speed conditions and the effects of complex roadway configurations (e.g. noise barriers and depressed roadways).

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Here we present results of a model inter-comparison to assess the ability of four models to simulate air pollutant concentrations near highways: CALINE, a model developed by the California Department of Transportation; AERMOD, a US Environmental Protection Agenciy's (EPA) recommended regulatory dispersion model; ADMS-Urban (v3.1), a model for estimating impacts in urban areas developed in the UK by Cambridge Environmental Research Consultants; and RLINE, a new research model under development by the US EPA. All models considered are based on the steady-state Gaussian diffusion equation. Two experimental databases are used in this model inter-comparison exercise: the Idaho Falls tracer study and the Caltrans Highway 99 tracer study.

2 Dispersion models

CALINE

CALINE4 is a line source Gaussian-based dispersion model developed by the California Department of Transportation for estimating air pollution levels within 500m of roadways (Benson, 1989; 1992). It represents a line source as a series of finite length elements each oriented perpendicular to the wind. To improve computational efficiency, the length of each element is determined based on its distance from the receptor of interest. The model uses Pasquill Gifford categories to characterize the stability of the atmosphere and uses a modified version of the Pasquill-Smith vertical dispersion curves (Benson, 1982) and horizontal dispersion estimates based on Draxler (1976). CALINE4 has algorithms to model the effects of the mixing zone over the roadway and certain aspects of roadway geometry such as depressed and elevated sections, among others. CALINE3 (Benson, 1979) and its variants CAL3QHC and CAL3QHCR are the series of the CALINE models that have been recognized as appropriate for regulatory use in specific roadway applications for CO and PM. The primary differences in the model formulations of CALINE3 and CALINE4 are related to the lateral dispersion curves and the introduction of vehicle-induced turbulence in CALINE4. Because there may be differences in the results obtained from the two versions of the model both are included.

AERMOD

AERMOD is US EPA's preferred and recommended steady-state plume model for use in demonstrating compliance with environmental regulatory programs. AERMOD is a comprehensive model for sources of various types including point, area, and volume-type sources in stable and convective atmospheric conditions using Monin-Obhukov similarity theory to vertically scale the winds and turbulence (Cimorelli et al., 2005; Perry et al., 2005). There are two approaches to simulating line-type sources in AERMOD: representing the line as an elongated area source or as a series of volume sources evenly spaced along the length of the line. Guidance on the spacing and initial dispersion of the volume sources to best represent the lines is given in the AERMOD User Guide (US Environmental Protection Agency, 2004). Both the area and volume approaches are used in this analysis and are referred to as AERMOD-A and AERMOD-V. The AERMOD-A approach is simpler to set up since a roadway segment can be represented as a single area (or a few areas if the user wishes to distinguish between traffic lanes of a road segment). The AERMOD-A approach does not allow for the simulation of low-speed plume meander, since this is not an option with area-type sources in AERMOD. The AERMOD-V approach does allow for plume meander. In AERMOD-V, the line source emissions are simulated as a series of evenly spaced volume sources. The model requires an adequate number of these volume sources to simulate a near-continuous release along the roadway. For example, for a 3.6 m wide lane of traffic, the volume sources should be separated from each other by no more than 7.2 m.

ADMS

This is a general purpose dispersion model capable of modeling point, line, area and volume source types in a variety of atmospheric conditions (Carruthers et al., 1994; McHugh et al., 1997). It uses Monin-Obukhov similarity to define the structure of the boundary layer and computes steady state Gaussian solutions (non-Gaussian in the vertical for convective conditions as with AERMOD) to describe the diffusion of pollutants. For line sources such as roadways, ADMS decomposes the source into a series of elements whose spacing depends on the source-receptor distance. Each element's contribution to the concentration at a given receptor is approximated by a finite line source aligned perpendicular to the wind direction. To improve computational speed, portions of the line that are sufficiently far laterally from the receptor are ignored. An integrated input module processes meteorological data to produce parameters required to run the model. ADMS-Roads, the version of ADMS designed for simulating traffic sources, includes algorithms that account for traffic-produced turbulence, and the presence of roadside noise barriers, and has an integrated street canyon model (ADMS-Roads User Guide, 2011). It also includes modules which account for the spatial variation of terrain height and surface roughness, NO_x and sulphate chemistry, and dry and wet deposition of pollutants. The modeling for this study was carried out with ADMS-Roads version 3.1, which will be referred to throughout the paper as ADMS.

RLINE

This is a research dispersion modeling tool under development by the US EPA's Office of Research and Development (Snyder et al, 2013; Venkatram et al., 2013). The model is based upon a steady-state Gaussian formulation and is designed to simulate line-type source emissions (e.g. mobile sources along roadways) by numerically integrating point source emissions. RLINE is currently formulated for near-surface releases, contains new (field study and wind tunnel based) formulations for the vertical and lateral dispersion rates, simulates low wind meander conditions, includes Monin-Obukhov similarity profiling of winds near the surface and selects plume-weighted winds for transport and dispersion calculations. The model uses the surface meteorology provided by the AERMET model (the meteorological preprocessor for AERMOD; Cimorelli, 2005) and simplified road-link specifications. The model computes concentrations by integrating point sources along a source line and has been formulated for appropriate simulation for receptors very near the source line. The current beta version of the model is designed for flat roadways (no surrounding complexities), though the model framework is designed to accommodate future algorithms for simulating the near-source effects of complex roadway configurations (noise barriers, depressed roadways, etc).

3 Model comparison performance measures

Model estimates of concentration from the four models were compared to on-site measurements made during the two field studies described below. The performance of the models has been quantified using performance measures, defined below, calculated using the BOOT statistical model evaluation software (Chang and Hanna, 2004). In addition, model performance is assessed qualitatively with scatter plots to reveal systematic differences between the models.

The quantitative model performance measures used are the fractional bias (FB), the normalized mean square error (NMSE), the correlation (R), and the fraction of estimates within a factor of two of the measured value (FAC2). The definitions of these quantities are:

$$FB = \frac{\left(\overline{C_o} - \overline{C_p}\right)}{0.5\left(\overline{C_o} + \overline{C_p}\right)} \qquad (1)$$

$$NMSE = \frac{\overline{\left(C_o - C_p\right)^2}}{\overline{C_o}\,\overline{C_p}} \qquad (2)$$

$$R = \frac{\overline{\left(C_o - \overline{C_o}\right)\left(C_p - \overline{C_p}\right)}}{\sigma_{C_o}\sigma_{C_p}} \qquad (3)$$

and
FAC2: Fraction of model estimates that satisfy

$$0.5 \leq \frac{C_p}{C_o} \leq 2.0 \qquad (4)$$

where C is the concentration, either observed (subscript 'o') or predicted ('p'), the overbar indicates an arithmetic average and σ is the standard deviation. FB is a measure of the systematic bias of the model and is ideally equal to zero. NMSE measures the mean relative scatter and is smaller for better model performance (= 0, ideally). The correlation coefficient can range from -1 and +1 and reflects the linear relationship between the observed and predicted values (= +1, ideally). Finally, FAC2 measures the fraction of estimates within a factor of two of the observations (= 1, ideally).

In computing these performance measures and in the scatter plots, observed and predicted concentrations are paired in time and space. Time and space pairing is relevant because models such as those examined are being considered for applications in support of health studies (Gauderman et al, 2007; Wu et al., 2011) in which the pollutant concentration at the time and location where a study participant is exposed is of importance. Generally this creates much more of a demand on the accuracy of the models than typical regulatory evaluations of concentration distributions unpaired in time or space, with emphasis only on the highest end of the distribution. The statistics used are applied to the entire range of conditions (and thus concentrations) found in the databases. Future epidemiology studies could use such models to address the importance of spatial and temporal components of overall concentration variance.

4 Model evaluation field studies

Idaho Falls tracer study

A tracer study of dispersion from a near ground-level line source was carried out in 2008 near Idaho Falls, ID on an open-field test site designed for transport and dispersion tracer studies (Finn, 2010). In this study, two parallel sites were set up, one with a noise barrier and one without. Tracer releases were performed simultaneously at both sites. In each case, sulfur hexafluoride (SF_6) was released uniformly along a 54 m long source, positioned 1m above ground level, beginning 15 minutes before the first sampling period and continuing through a 3 hour experiment consisting of 12 consecutive 15-min sampling periods. Background levels of SF6 at the study site were measured to be between 6 and 8 pptv, whereas measurements in the center of the grid were the order of thousands or tens of thousands of pptv. Only data from the non-barrier site were used in the present model inter-comparison. Experimental data are available from four separate days, capturing a wide range of atmospheric stabilities and wind speeds (see Table 1; MST is Mountain Standard Time; L_{mo} is the Monin-Obhukov length).

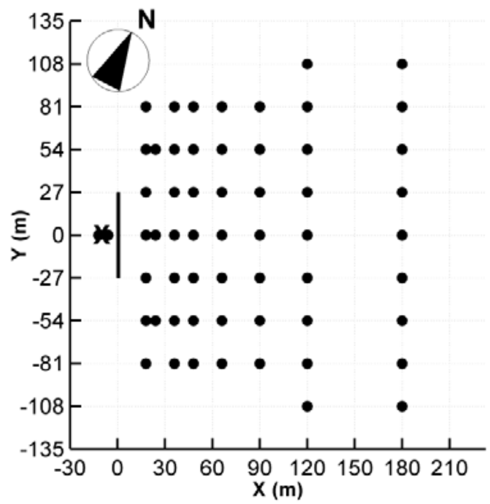
Test Day	Date	Time (MST)	Stability/ L_{mo} range	Wind speed range (m s^{-1})	Wind direction range (departure from perpendicular to source, degrees)	Notes
1	9-Oct	12:30 – 15:30	near-neutral, convective/ -500 to -180	5.5 to 8.1	-15 to 20	overcast
2	17-Oct	13:00 – 16:00	convective/ -30 to -1.7	0.7 to 2.5	9 to 24	light SW winds, clear skies, sunny
3	18-Oct	16:00 – 19:00	weakly stable/ 35 to 50	3.2 to 3.6	4 to 11	clear skies
5	24-Oct	18:00 – 21:00	moderate to strongly stable/ 7 to 18	1.6 to 2.4	-18 to 19	high cirrus clouds thinning throughout the experiment, mostly clear by the end

Table 1. Experimental conditions during the 2008 Idaho Falls tracer experiment

A grid of 56 samplers mounted 1.5 m above ground level was arrayed downwind of the source with an additional two receptors upwind to capture the dispersion pattern from the line segment source (Figure 1). The bag samplers were programmed to acquire 15-minute samples that were later analyzed by gas chromatography to produce concentrations. Meteorological instruments arrayed in the experiment area included six sonic anemometers, one of which was located within the sampler array on the non-barrier site, five on the barrier site, a 30 m meteorological tower with cup and vane anemometers between the two sites and radar wind profiler with radio acoustic sounding system (RASS) to characterize the mixing layer at the sites.

Meteorological inputs for the models were derived from the on-site instrumentation as follows. Mean wind speed, friction velocity, temperature and surface heat flux were computed from sonic anemometer measurements at a 3 m height on the non-barrier site. The roughness length scale was determined to be 0.053 m using velocity profiles based on Monin-Obhukov similarity and mean wind and shear stress measurements from the 3 m high sonic anemometer during the near-neutral conditions of test day one. Heat flux measurements from the sonic anemometer were used in the calculation of the convective velocity scale and the temperature scale (w^* and ϑ^*) using methods outlined in Cimorelli et al. (2005). The convective mixing height was estimated from the RASS data, while the mechanical mixing height was estimated as 2300 $u_*^{1.5}$ (Venkatram, 1980).

It should be noted that the Idaho Falls data set was instrumental in the formulation of the vertical dispersion curves in the RLINE model (Snyder et al., 2013), however, for that formulation work the finite line source data were processed to simulate the effect of an infinite line source (see Heist et al., 2009, for an example of this procedure) so that only the vertical dispersion algorithm was influenced by the Idaho Falls data. In this model inter-comparison, the original finite line source data were employed with all of the downwind receptors to test the ability of the models to estimate lateral dispersion as well as vertical.

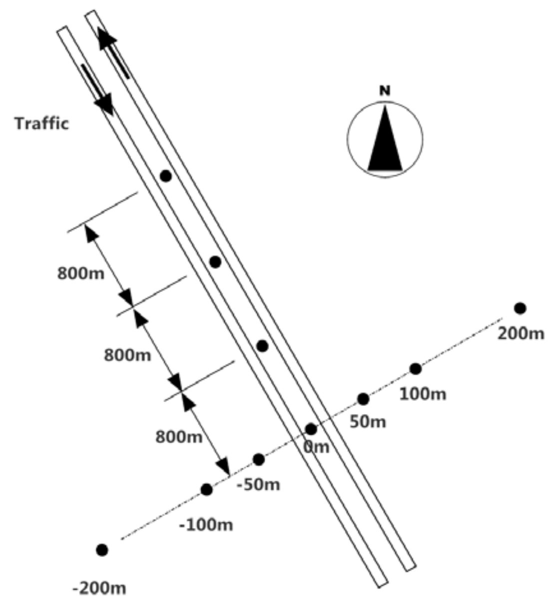


Note: Circles indicate the locations of the bag samplers. An 'X' indicates the location of a sonic anemometer. The source was located at x = 0 and spanned 54 m between y = -27 m and y=+27 m.

Figure 1. Sampler array for the Idaho Falls field experiment.

Caltrans Highway 99 tracer experiment

Another tracer study was performed in the early 1980's using SF_6 released from the tailpipes of eight specially modified automobiles traveling with traffic on Highway 99 outside Sacramento (Benson, 1989). The study was conducted along a straight segment of the highway aligned from northwest to southeast consisting of four lanes and a 14 m wide median. The highway carried approximately 35,000 vehicles daily. The surrounding terrain was fairly flat and nearby land use consisted of open park land, fields and scattered residential developments. Eight automobiles releasing the tracer circulated up and down a 4 km segment of the highway beginning one hour before sampling started. Half of the modified vehicles were driven in the right hand lane and the other half in the left to distribute emission evenly across the lanes of the highway. SF_6 monitors were arrayed on both sides of the road (spaced at 50, 100 and 200 m from the center of the road) and at four locations along the median (spaced approximately 800 m apart) (Figure 2). Samplers were positioned 1 m above ground level. Samples were collected in Tedlar bags for four consecutive 30-minute periods and analyzed using gas chromatography. Two cup and vane anemometers were installed on a 12 m meteorological tower near the sampling array at heights of approximately 6.5 m and 11.4 m.



Note: The locations of the samplers are indicated with filled circles. Not to scale.

Figure 2. Layout of Caltrans highway 99 tracer study.

Sampling took place on fourteen separate days covering a range of meteorological conditions including stable and unstable conditions, wind directions ranging from near parallel to near perpendicular and wind speeds from 0.2 m s^{-1} to 6 m s^{-1} (at the 11.4 m height). Stability was reported in Pasquill-Gifford stability categories and ranged from class B through to class G.

Meteorological inputs for the models were derived from the on-site instrumentation as follows. Mean wind speed and direction were taken from the 11.4 m anemometer. A roughness length scale of 0.1 m was assumed to represent the study area consisting of a mix of open fields and scattered residential developments (based on the “roughly open” category in Table 1, Britter and Hanna, 2003). The Monin-Obhukov length was estimated using the curves developed by Liu and Durran (Randerson, 1984) that relate stability class as a function of roughness length to L_{mo}. The friction velocity (u_*) was estimated from the Monin-Obhukov similarity relationships for wind speed. The mechanical mixing height was estimated identically to the Idaho Falls experiment described above. No information was provided for the convective mixing height, so an estimate of 100 m for morning hours and 500 m for afternoon hours was used. The sensible heat flux (H_s) was estimated from the definition of L_{mo} as $H_s = -\rho\ C_p\ T\ u_*^3/(0.4\ g\ L_{mo})$ and the convective mixing velocity was calculated from $w_* = (g\ H_s\ z_{ic}\ /\ (-\rho\ C_p\ T))^{1/3}$ (Cimorelli, 2005) (ρ, T and C_p are the density, temperature and heat capacity of the air, g is the gravitational acceleration). Finally, for low wind speed conditions, an adjustment in the friction velocity and the variables that depend on it (e.g., H_s, w_*) was made according to the method of Qian and Venkatram (2011).

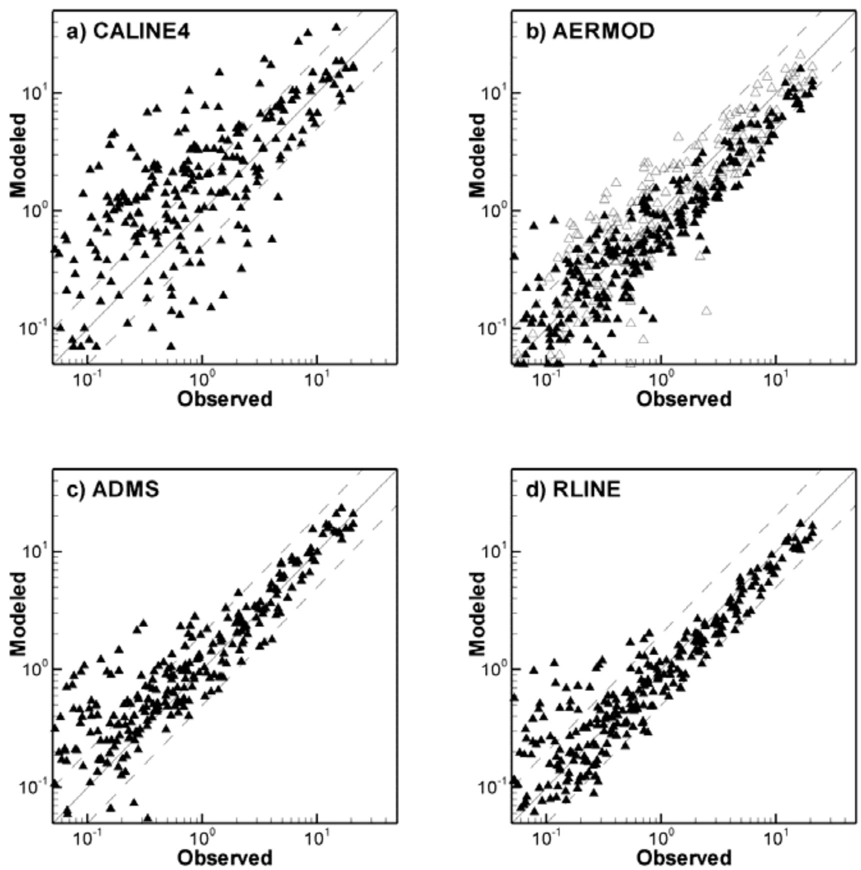
5 Results

Idaho Falls tracer study

Although the Idaho Falls tracer study was performed on an open-field, and therefore without any effects of traffic-induced turbulence, this study offers a wide range of atmospheric conditions over which to test the models, ranging from strongly stable through neutral to strongly convective. As expected, the highest concentrations measured during the experiment occurred on test day five during strongly stable conditions with relatively light winds (wind speeds between 1.6 and 2.4 m s^{-1}). On the fifth day, the concentrations gradually increased throughout the duration of the experiment as winds speeds slowed and atmospheric stability increased. In contrast, on test day one, the winds were relatively strong (greater than 5 m s^{-1}) and concentrations were relatively low, falling off by roughly a factor of four between the maxima at receptors on the lines closest to and farthest from the source. The greatest drop off in concentration with downwind distance occurred on test day two, when the atmospheric conditions were convective. On the convective day, the winds were lighter than on the neutral day, ranging from 0.7 to 2.5 m s^{-1}. On the third test day with weakly stable conditions and steady wind speeds between 3 and 4 m s^{-1}, concentrations were similar in magnitude to those on test day two (convective), but fell off more slowly with downwind distance.

For the model runs shown, we only considered cases when the mean wind direction for the sample period was within ±25 degrees of perpendicular to the line source. When wind directions were outside this range, the observations showed that the plume was not well captured by the grid of samplers.

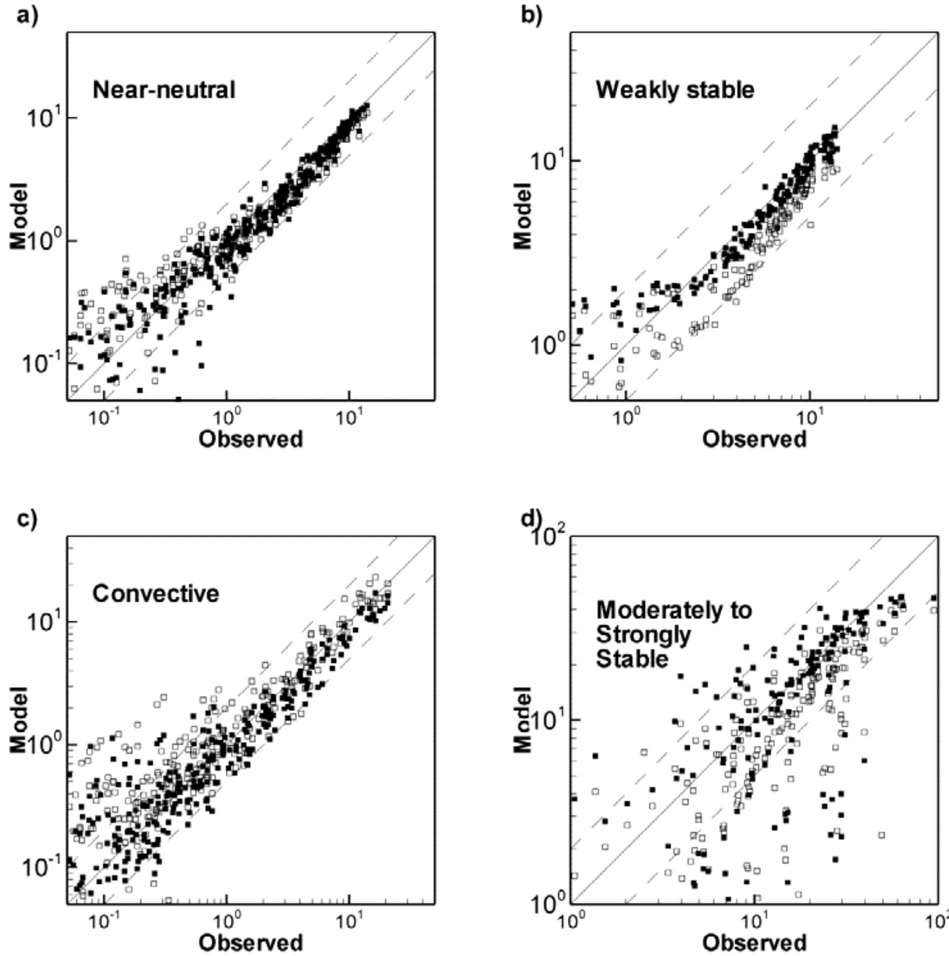
To begin the examination of model performance against observations, Figure 3 shows estimates versus observations for the four models for test day two when atmospheric conditions were convective and winds were light. For higher concentrations measured during this test day, the RLINE and AERMOD-V models tend to under-predict the observations, while remaining largely within the factor of two lines. For this concentration range, AERMOD-A and ADMS are relatively unbiased, and CALINE4 tends to over-predict. All models tend to show an increase in scatter as the concentration decreases (i.e., as the plume moves downwind from the source). This scatter is greatest for the CALINE4 model. The RLINE, ADMS and AERMOD models are mostly within a factor of two of the observations for concentrations above 1 ppb, but with decreasing concentrations a greater proportion of the data lie outside the factor of two lines. The difference between AERMOD-A and AERMOD-V is shown in Figure 3b. The inclusion of the effect of meander to the calculation in AERMOD-V has the tendency to reduce the higher concentrations as the lateral spread is enhanced. For lower concentrations, especially on the edges of the plume, the concentration may be higher when meander is included as can be seen in some of the data in the low end of the plot.



Note: Test 2 (convective atmospheric conditions). a) CALINE4, b) AERMOD-V (black symbols) and AERMOD-A (grey symbols), c) ADMS and d) RLINE. The solid and dashed lines are the 1:1 and factor of two lines. Each symbol represents a 15 minute average.

Figure 3. Estimates versus observations (in ppb) for Idaho Falls non-barrier case.

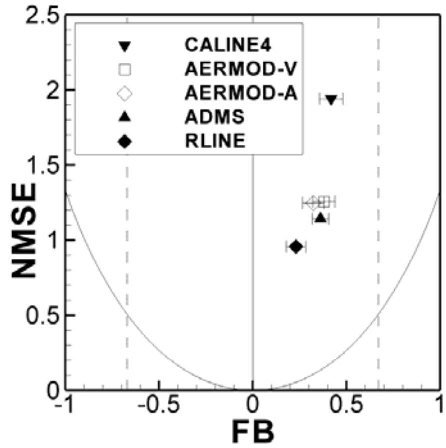
To demonstrate the variation of model performance with atmospheric stability, Figure 4 shows RLINE and ADMS model performance for the four test days. For the near-neutral and weakly stable days, the scatter in the model estimates is the least, with model estimates remaining mostly within the factor of two lines except for the lowest concentrations. The models have a tendency to over-predict the lower concentrations on the neutral and convective days and at the same time have higher amounts of scatter. The concentrations have the highest degree of scatter during the strongly stable hours of Test 5 where the winds were light and variable and plumes were narrow with steep concentration gradients.



Note: a) Near-neutral (Test 1) b) weakly stable (Test 3) c) convective (Test 2), and d) moderately to strongly stable (Test 5). Each symbol represents a 15 minute average.

Figure 4. RLINE (solid symbols) and ADMS (hollow symbols) results for all test days at Idaho Falls.

One way to visualize relative performance of all of the models is with a plot of "NMSE vs. FB." Figure 5 shows relative model performance in this way for all of the test days together. An ideal model would have zero fractional bias and normalized mean square error, so the closer the model is to (0,0) on this plot, the better the performance. All of the models have positive fractional bias, indicating a tendency in the models to underestimate the observed concentrations. It should be borne in mind that the statistics reported are for estimates and observations that are paired in time and space, and thus represent a very stringent test of the models in contrast to the method often employed in a more typical dispersion model evaluation where the distributions of results are used without regard for the location and timing of the measurements. Therefore, the magnitude of the FB and NMSE are larger than is often found for dispersion models. While the FB falls within a fairly narrow range for all of the models, the magnitude of the NMSE ranges from slightly less than 1 (RLINE) to slightly less than 2 (CALINE4). The wide-ranging scatter in Figure 3a is indicative of the higher NMSE produced by the CALINE4 model. Table 2 summarizes these statistics plus the FAC2 and correlation.

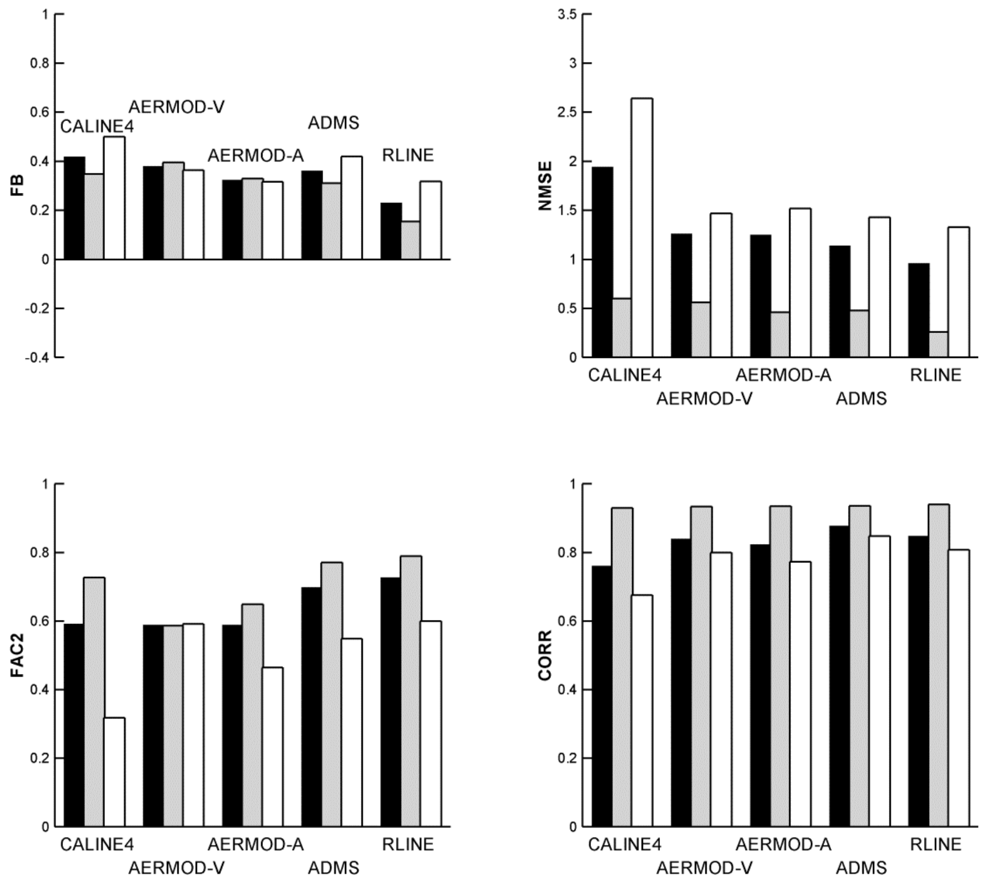


Note: A perfect model would be plotted at (0, 0). The parabola indicates the minimum possible NMSE for a given FB. The horizontal error bars are based on bootstrap re-sampling and indicate the 95% confidence limits on FB. The vertical dashed lines at FB = ±0.67 represent a factor of two bias in predictions.

Figure 5. Normalized mean square error (NMSE) as a function of fractional bias (FB) of the models for the Idaho Falls tracer study.

Model	FB	NMSE	R	FAC2
CALINE4	0.42	1.94	0.76	0.59
AERMOD-V	0.38	1.26	0.84	0.59
AERMOD-A	0.32	1.25	0.82	0.59
ADMS	0.36	1.14	0.88	0.70
RLINE	0.23	0.96	0.85	0.73

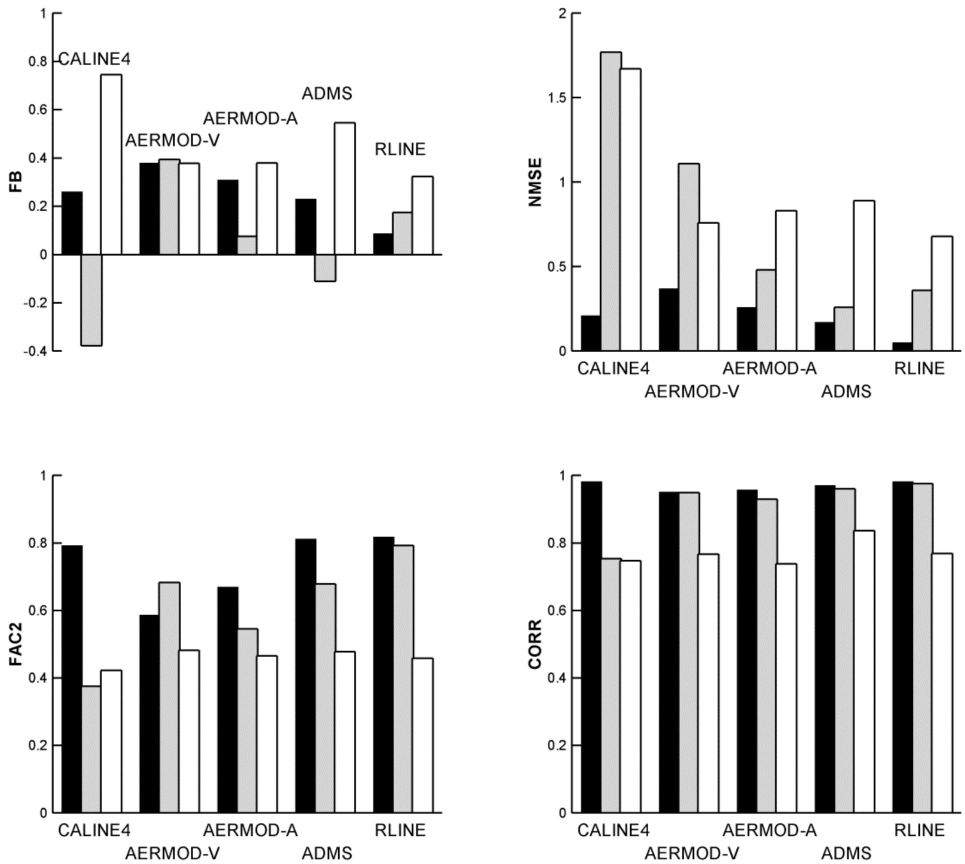
Table 2. Model statistics comparison from all test days for the Idaho Falls tracer study.



Note: Black - all wind speeds, Gray - wind speeds greater than 2 m s^{-1}, White - wind speeds less than 2 m s^{-1}.

Figure 6. Performance statistics for wind speed classes in the Idaho Falls study.

Different wind speed ranges may pose particular challenges to dispersion models. Figure 6 shows model performance statistics for ranges of wind speeds. In all cases, performance is generally better for higher winds than for lighter winds . This is consistent with the scatter plots in Figure 4 for RLINE and ADMS where the two days with higher wind speeds (Test 1 and 3) show better agreement between the model and the observations than the two days with light winds (Tests 2 and 5). In terms of inter-model comparison, the models have similar performance levels although light wind performance for CALINE4 is noticeably worse than for the others.



Note: Black - near neutral (Tests 1 and 3), Gray - strongly convective (Test 2), White - moderate to strongly stable (Test 5).

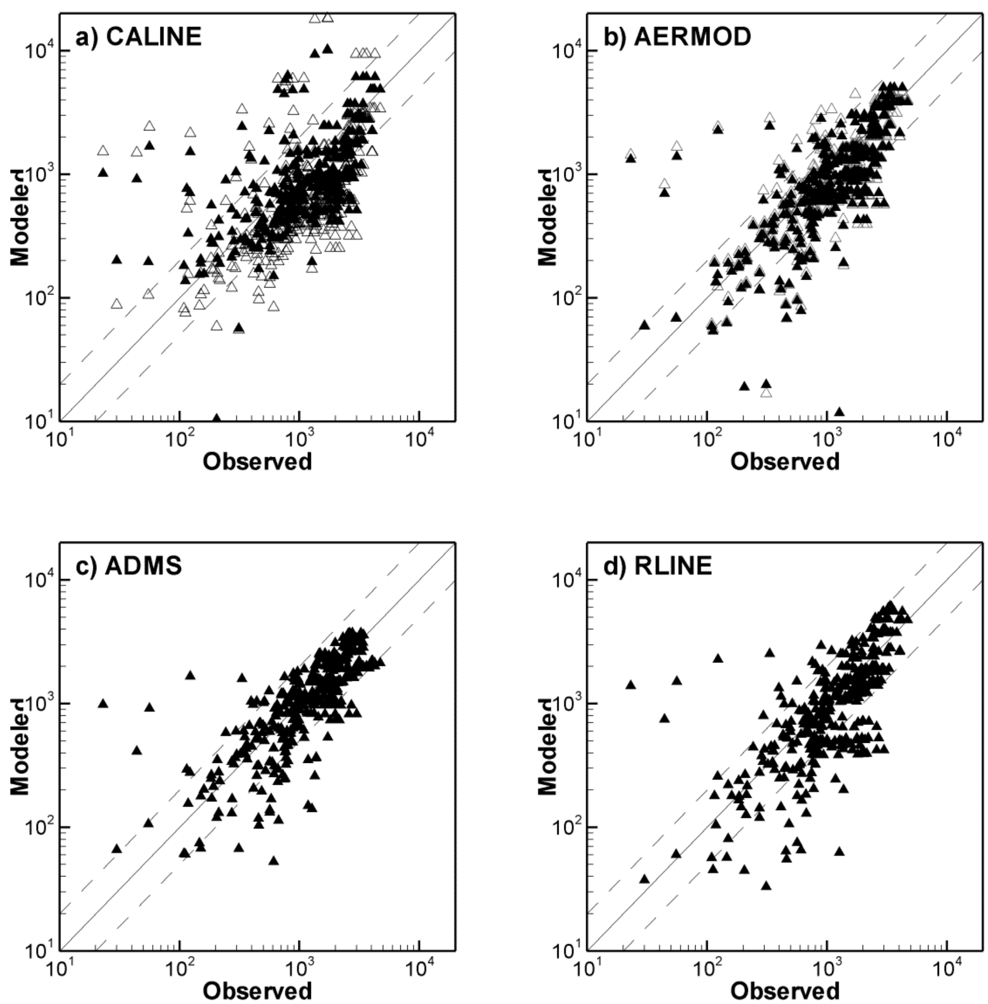
Figure 7. Performance statistics for different stabilities in the Idaho Falls study.

It is also important to examine the performance of the models under different atmospheric stabilities. Figure 7 shows the results for near-neutral (combining Tests 1 and 3), convective (Test 2), and moderate to strongly stable (Test 5). Model performance is generally the best for the near-neutral stabilities (which is also when the winds are the highest) and the most challenged for stable conditions. Differences in the performance of the various models are most evident under the stable and convective regimes especially in terms of NMSE where CALINE4 shows the highest values.

Caltrans experiment

The Caltrans Highway 99 experiment provides the opportunity to evaluate the models' abilities to estimate concentrations in real highway driving conditions. Figure 8 shows scatter plots for all of the models for the entire period of the experiment with the samplers on the downwind side of the road. For this comparison, the CALINE3 model was also used to assess its ability to simulate this dataset. The upwind monitors were omitted from these scatter plots because it is particularly challenging for dispersion models to predict non-zero concentrations upwind of the source. The RLINE, ADMS and AERMOD model results have similar character, though the AERMOD results tend to be slightly lower than the RLINE results for the highest observations. As with the Idaho Falls results, the change from AERMOD-A to AERMOD-V (and therefore the addition of meander and initial lateral dispersion) generally decreases the model estimates slightly. The CALINE3 and 4 results are biased low, clustering between the 1:2 and 1:1 lines. With all models, the majority of estimates lie within a factor of two of the observations.

The model performance statistics for receptors downwind of the roadway are summarized in Table 3 and the NMSE and FB are plotted in Figure 9 to allow a graphical model-to-model comparison. The FB for all models is between 0.05 and 0.25, indicating that on average, the models underpredicted the observations. The spread in NMSE is larger with the RLINE, ADMS and AERMOD (both "A" and "V") models clustered between 0.20 and 0.34 and CALINE3 and -4 at 2.26 and 0.86. RLINE has the lowest FB at 0.05 and ADMS has the lowest NMSE at 0.20. All models except CALINE3 had at least two-thirds of their estimates within a factor of two of the observations.

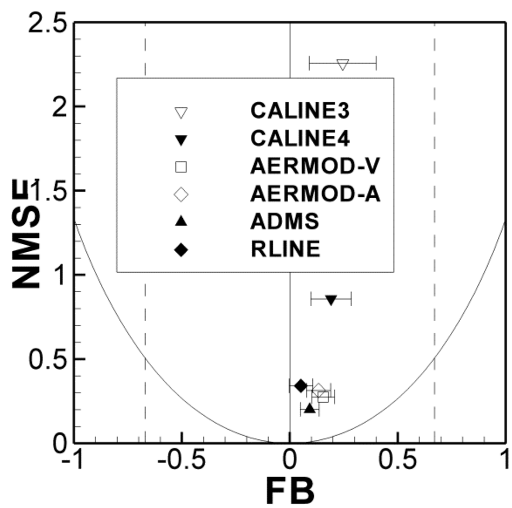


Note: a) CALINE4 (black symbols) and CALINE3 (open symbols), b) AERMOD-V (black symbols) and AERMOD-A (open symbols), c) ADMS and d) RLINE. The solid and dashed lines are the 1:1 and factor of two lines. Each symbol represents a 30 minute average.

Figure 8. Predictions versus observations for the Caltrans Highway 99 tracer study for receptors located downwind of the roadway.

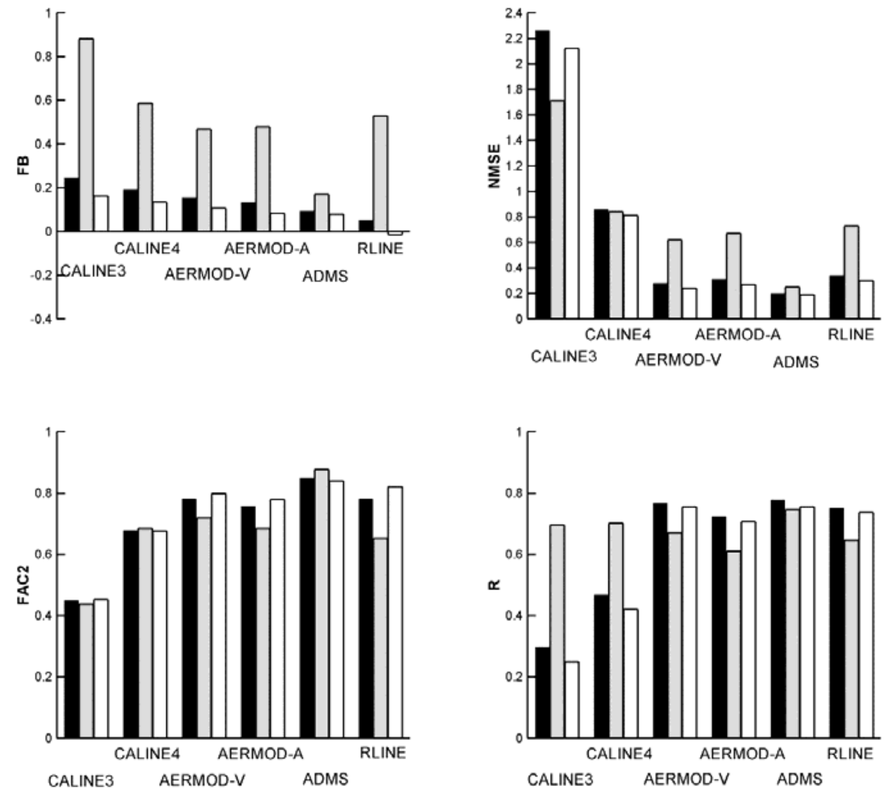
MODEL	FB	NMSE	R	FAC2
CALINE3	0.25	2.26	0.29	0.45
CALINE4	0.19	0.86	0.47	0.68
AERMOD_V	0.15	0.28	0.77	0.78
AERMOD_A	0.13	0.31	0.72	0.76
ADMS	0.09	0.20	0.78	0.85
RLINE	0.05	0.34	0.75	0.78

Table 3. Overall performance of models against the Caltrans Highway 99 data set for receptors downwind of the roadway.



Note: See Figure 5 for explanation.

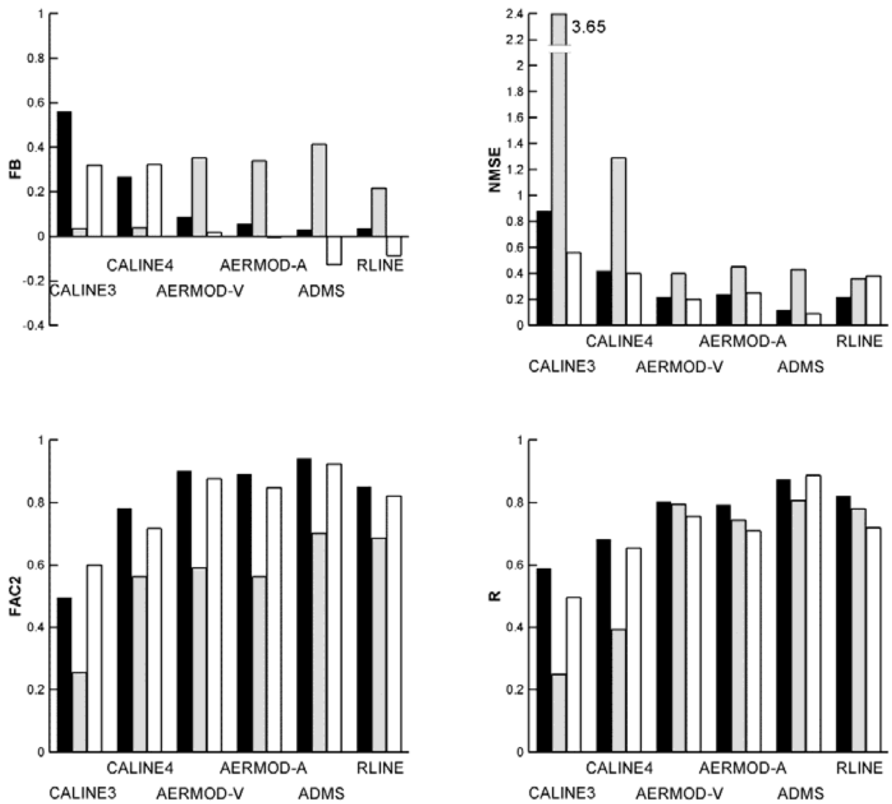
Figure 9. Normalized mean square error (NMSE) as a function of fractional bias (FB) of the models for the Caltrans Highway 99 tracer study for receptors downwind of the roadway.



Note: All downwind receptors. Black - all wind speeds, Gray - wind speeds greater than 2 m s^{-1}, White - wind speeds less than 2 m s^{-1}.

Figure 10. Performance statistics for wind speed classes in the Caltrans Highway 99 study.

With respect to wind speed ranges, the performance of the models was different in the Caltrans experiment than in the Idaho Falls study. For wind speeds above 2 m s^{-1}, model performance generally deteriorated relative to the overall performance as seen by the increased FB and NMSE in Figure 10. One major difference between the two studies is the proximity of the closest receptors to the source. In Idaho Falls the closest measurements were 18 m downwind, whereas in the Caltrans study, there were four samplers located in the median of the highway, approximately 7 m from the nearest edges of the inner lanes of traffic. This close proximity of the receptor to the source requires the model to handle the very near source dispersion well. Another difference between the two studies is that the wind directions in the Caltrans study varied from near-parallel (to the source) to near-perpendicular whereas winds were close to perpendicular in the Idaho Falls study. For near-parallel winds the lateral dispersion parameterizations become more important even though the source is a line.



Note: All downwind receptors. Black - near-neutral, Gray - convective, White - stable.

Figure 11. Performance statistics for Caltrans Highway 99 study.

With monitors on both sides of the road, it is possible to evaluate model performance for upwind meander, where measureable concentrations occur on the upwind side of the roadway due to the slow shifting of the plume especially prevalent in lighter wind conditions. An analysis of the observational data from the Caltrans Highway 99 data set shows that receptors upwind of the road measure on average approximately 10% of the concentration measured at a corresponding distance downwind of the road. The fractional bias for these upwind estimates was -0.10 (RLINE), 0.01 (AERMOD-V), and -0.15 (ADMS); CALINE and AERMOD-A do not compute upwind concentrations. The FAC2 was 0.30 (RLINE), 0.25 (AERMOD-V), and 0.12 (ADMS). While this represents substantially reduced performance compared to that for the downwind receptors, the ability to estimate these upwind concentrations is useful in assessing potential exposures from the traffic related pollutants.

Model performance for atmospheric stability categories is summarized in Figure 11. As with the Idaho Falls data set, the best performance was found for neutral atmospheric conditions for all models considered. Unlike the Idaho Falls data set, however, for the Caltrans tracer study model performance for stable conditions is better than for convective.

6 Conclusions

The performance of four dispersion models (and variants) in simulating the concentrations generated from roadway traffic has been compared using two tracer databases, one simulating traffic emissions with a stationary finite line source and the other emitting tracer from the tailpipes of automobiles moving with traffic. Use of tracer in these field studies eliminates an otherwise large uncertainty in emissions since the release rate of the tracer material is carefully controlled. The four models used in this comparison, RLINE, AERMOD, ADMS, and CALINE, all showed an ability to estimate the majority of downwind concentrations within a factor of two of the observations (except version 3 of CALINE). Three of the models, RLINE, AERMOD-V, and ADMS, also have the capability to predict concentrations upwind of the roadway that result from low-speed meandering of the plume. The FB for these upwind estimates is comparable to that for downwind estimates, though the scatter is significantly greater. Generally, RLINE, ADMS, and AERMOD (-A and -V) had overall performance statistics clustered in a fairly tight range on a “NMSE v. FB” plot, while CALINE3 and 4’s larger degree of scatter resulted in elevated NMSE[1]. For the two databases used, under most conditions, the models under-predicted the observations (the exceptions being under convective conditions in Idaho Falls for CALINE4 and ADMS and under stable conditions in the Caltrans study for ADMS and RLINE).

The models were tested over a range of atmospheric stabilities and wind speed ranges. In both the Idaho Falls and Caltrans Highway 99 tracer studies, the best overall model performance occurred during near-neutral and weakly-stable conditions. The models were most challenged in the Idaho Falls study during stable conditions and in the Caltrans study during convective conditions. One major difference between the studies is the length of the line source – 54 m in Idaho Falls and 4000 m in Caltrans. The shorter length in Idaho Falls puts more emphasis on the ability of the model to predict the edges of the plume well, which may explain the difficulty the models had in stable conditions there. In the Idaho Falls study, the models generally performed better (lower FB and NMSE) for higher wind speeds whereas the opposite was true for the Caltrans study. In terms of FB, however, AERMOD (both -A and -V) performed consistently across wind speeds in Idaho Falls and ADMS performed consistently across wind speeds in the Caltrans study. While RLINE is a model still under development this inter-comparison study with two research-grade databases suggests that it is performing well and generally on the same level as AERMOD and ADMS, but measurably better than CALINE3 or CALINE4.

Acknowledgements and Disclaimer

We thank colleagues within EPA for their constructive suggestions for improving this manuscript. The US Environmental Protection Agency through its Office of Research and Development funded and managed the research described. It has been subjected to Agency’s administrative review and approved for publication.

[1] One possible explanation for the differences may be related to the characterization of dispersion rates. While CALINE 3 and 4 base dispersion rates on the Pasquill-Gifford stability categories, RLINE, ADMS, and AERMOD derive their dispersion rates from the more advanced Monin-Obukhov similarity theory.

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