RLINE: A Line Source Dispersion Model for Near-Surface Releases

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ABSTRACT

This paper describes the formulation and evaluation of RLINE, a Research LINE source model for near-surface releases. The model is designed to simulate mobile source pollutant dispersion to support the assessment of human exposures in near-roadway environments where a significant portion of the population spends time. The model uses an efficient numerical integration scheme to integrate the contributions of point sources used to represent a line-source. Emphasis has been placed on estimates of concentrations very near to the source line. The near-surface dispersion algorithms are based on new formulations of horizontal and vertical dispersion within the atmospheric surface layer, details of which are described in a companion paper (Venkatram et al. 2013), This paper describes the general formulations of the RLINE model, the meteorological inputs for the model, the numerical integration techniques, the handling of receptors close to the line source, and the performance of the model against developmental data bases and near-road concentrations from independent field studies conducted along actual highway segments.

KEYWORDS

Near-surface dispersion, near-road concentrations, surface releases, similarity theory, meteorological measurements, urban dispersion, Idaho Falls experiment, RLINE

1 Introduction

Growing concern about human exposure and related adverse health effects near roadways motivated an effort by the U. S. Environmental Protection Agency to reexamine the dispersion of mobile source related pollutants. Studies have shown that living near roadways is implicated in adverse health effects including respiratory problems (e.g. McCreanor et al. 2007), birth and developmental defects (Wilhelm and Ritz 2003), premature mortality (e.g. Krewski et al. 2009), cardiovascular effects (Peters et al. 2004; Riediker et al. 2004) and cancer (Harrison et al. 1999; Pearson et al. 2000). These studies of traffic-related health effects have included both short-term (e.g., hourly) and long-term (e.g., annual) exposures. (Krewski et al. 2009; McCreanor et al. 2007)

Estimating exposure to roadway emissions requires dispersion modeling to capture the temporal and spatial variability of mobile source pollutants in the near-road environment. The model needs to account for the variability in mobile emissions across a myriad of urban and suburban landscapes, while considering factors (depending on pollutant and application scenario) such as vehicle induced turbulence, roadway configurations (e.g. depressed roadways and noise barriers), local meteorology, surrounding terrain and buildings, pollutant chemistry, deposition, and others.

There are several models in the literature that have been developed to simulate dispersion from roadways. Examples include HIWAY-2 (Petersen 1980), UCD (Held et al. 2003), CAR-FMI (Harkonen et al. 1995), GM (Chock 1978), OSPM (Hertel and Berkowicz 1989), ADMS-ROADS (McHugh et al. 1997), CFD-VIT-RIT (Wang and Zhang 2009) and the CALINE series of models (Benson 1989, 1992). Because urban areas typically contain a large number of road segments, computational efficiency is an important factor in formulating a line source dispersion model. As a result, most models for dispersion of roadway emissions are analytical approximations to the integral associated with modeling a line source as a set of point sources. However, these approximations can lead to large errors when the winds are light and variable, when the wind direction is close to parallel to the road and when the source and receptor are at different heights (Briant et al, 2011). So the current version of RLINE is based on Romberg numerical integration of the contributions of point sources along a line (road segment). This approach allows us to incorporate the governing processes without introducing errors associated with approximating the underlying model framework.

The point contributions along the line source are computed with the Gaussian, steady-state plume formulation. This is consistent with models currently recommended by the U. S. EPA for regulatory applications e.g. CALINE3 (Benson 1992) and AERMOD (Cimorelli et al. 2005).

RLINE is designed to simulate primary, chemically inert pollutants with emphasis on near surface releases and near source dispersion. The model has several features that distinguishes it from other models. It includes new formulations for the vertical and horizontal plume spread of near surface releases based on historical field data (Prairie Grass, Barad, 1958) as well as a recent tracer field study (Finn et al. 2010) and recent wind tunnel studies (Heist et al. 2009). Details of the formulations are found in the companion paper by Venkatram (2013). Additionally, the model contains a wind meander algorithm that accounts for dispersion in all directions during light and variable winds. To facilitate application of the model, its meteorological inputs are consistent with those used by the AERMOD model (Cimorelli et al., 2005). In addition to evaluation against the Finn et al., 2010 tracer data, the model has been compared with measurements from two independent field studies performed along actual highway segments covering a wide range of meteorological conditions (Baldauf et al. 2008; Benson 1989). The current version of RLINE applies for flat roadways. However, the model framework is designed to facilitate the inclusion of algorithms for depressed roadways and roadways with noise barrier. These complex roadway algorithms will be included in a near future version of the model.

This paper describes the general formulations of the RLINE model including new horizontal and dispersion formulations. the handling of receptors very close to the source, and the meteorological inputs for the model. Then, we evaluate performance of the model against both a developmental data base and near-road concentrations from two independent field studies

2 The Line Source Model

The concentration from a finite line source in RLINE is found by approximating the line as a series of point sources. The number of points needed for convergence to the proper solution is determined by the model and, in particular, is a function of distance from the source line to the receptor. Each point source is simulated using a Gaussian plume formulation. Here we explain the implementation of the point source plume model and the integration scheme used to approximate a line source. We begin with a description of the meteorological inputs needed for the model.

2.1 Meteorological Inputs

The meteorology that drives RLINE is obtained from the surface file output from AERMOD's met processor, AERMET (Cimorelli et al. 2005). AERMET processes surface characteristics (surface roughness, moisture and albedo), cloud cover, upper air temperature soundings, near surface wind speed, wind direction and temperature to compute the surface variables needed by AERMOD. The specific variables that are needed by RLINE include, the surface friction velocity (u_*), the convective velocity scale (w_*), Monin-Obukhov length (L), the surface roughness height (z_o), and the wind speed and direction at a reference height within the surface layer.

Additionally, for light wind, stable conditions, when u_* is generally small, an adjustment is made to the friction velocity based on the work of (Qian and Venkatram 2011). From an examination of stable periods within meteorological field measurements collected in Cardington, Bedfordshire as wind speeds became small Qian and Venkatram found that u_* was much larger than values predicted by those from AERMET. From the formulations in AERMET and assuming a constant value of the temperature scale, $T* = \frac{\overline{w'T'}}{u_*} = 0.08$, where $\overline{w'T'}$ is the mean vertical temperature flux, u_* takes the form

$$u_* = \frac{C_{DN}^{1/2} U_r}{2}\left[1 + (1 - r^2)^{1/2}\right] \tag{1}$$

where

$$C_{DN} = \frac{\kappa^2}{\left(\ln\left(\frac{z_r - d_h}{z_0}\right)\right)^2}, \tag{2}$$

$$r = \frac{U_{crit}}{U_r}, \tag{3}$$

$$U_{crit} = \frac{2u_0}{C_{DN}^{1/4}}, \tag{4}$$

and

$$u_0 = \left(\frac{\beta g (z_r - d_h - z_0) T_*}{T_0}\right)^{1/2} \tag{5}$$

where d_h is the canopy displacement height, κ the von karman constant, U_r is the wind speed measured at the reference height, z_r and T_o is the temperature at reference height.

Qian and Venkatram recommend the following modification to Eqn. 22 for cases of light winds (low u_*) and stable atmospheric conditions (L > 0)

$$u_* = \frac{C_{DN}^{1/2} U_r}{2}\left[\frac{1 + \exp\left(-r^2/2\right)}{1 - \exp\left(-2/r\right)}\right] \tag{6}$$

Once u_* has been adjusted for light wind, then L and all other parameters affected by this adjustment are recalculated using the AERMET methodology for internal consistency.

RLINE has a lower limit for the effective wind speed used in the dispersion calculations that is a function of the lateral turbulence. The horizontal wind energy is composed of a mean component u^2 and two random wind energy components, σ_u^2 and σ_v^2 . Assuming these random components to be approximately equal, when the mean wind goes to zero, the horizontal wind energy will maintain at $2\sigma_v^2$. Therefore, the minimum effective wind speed is set at $\sqrt{2} \cdot \sigma_v$. From (Cimorelli et al. 2005), the lateral turbulent wind component is computed as

$$\sigma_v = \sqrt{(0.6w_*)^2 + (1.9u_*)^2} \tag{7}$$

where w_* is the convective velocity scale.

Therefore, the effective wind speed is:

$$U_e = \sqrt{2\sigma_v^2 + U(\bar{z})^2}. \tag{8}$$

Here the wind speed, U, is evaluated at the mean plume height, $\bar{z}$. The mean plume height depends on the vertical spread of the Gaussian plume, which will be described in section 2.3.1.

2.2 Numerical line source approximation

The mathematical formulation to compute the impact of a line source is simplified by using a coordinate system where the *Y*-axis lies along the line source as shown in Figure 1. The wind direction is oriented at an angle, θ, relative to the X-axis, and the receptor coordinates are given by (X_r, Y_r, Z_r).

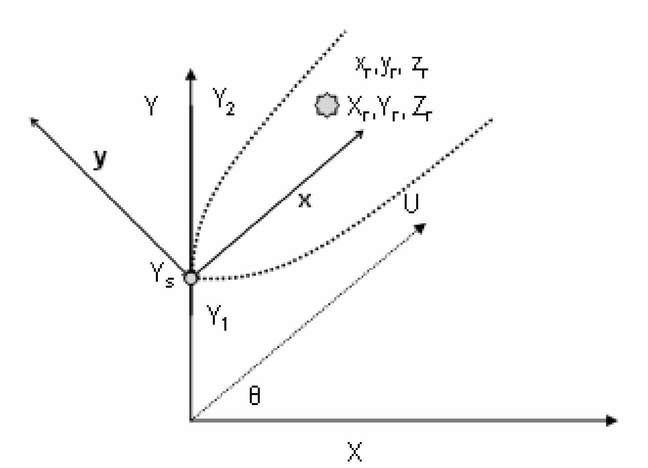

Figure 1: Co-ordinate systems used to calculate contribution of point source at Y_s to concentration at (X_r, Y_r, Z_r). The system x-y has the x-axis along the mean wind direction, which is at an angle θ to the fixed X axis. The dotted line is a representation of the plume.

If L is the length of the source, $Y_2=Y_1+L$. To calculate the concentration at a receptor (X_r, Y_r, Z_r) caused by emissions from the line source characterized by an emission rate of q (mass/(time∗length)), we represent the line source by a set of point sources of strength $q \cdot dY$ along the line Y_1Y_2.

The contribution of the plume originating at Y_s to the receptor concentration is most conveniently expressed in a co-ordinate system, x-y, with its origin at $(0, Y_s)$, and the x-axis along the direction of the mean wind; the x-axis is rotated by an angle θ relative to the fixed X-axis.

The horizontal co-ordinates of the receptor in the along-wind coordinate system, *(*x_r*,* y_r*,* z_r*)*, can be expressed as

$$\begin{aligned} x_r &= X_r \cos\theta + (Y_r - Y_s)\sin\theta \\ y_r &= (Y_r - Y_s)\cos\theta - X_r \sin\theta \end{aligned} \qquad (9)$$

The vertical coordinate remains unchanged so that $z_r = Z_r$.

Then, the concentration at (x_r, y_r) due to the line becomes

$$C(x_r, y_r) = \int_{Y_1}^{Y_1+L} dC_{pt}\,, \qquad (10)$$

where dC_{pt} is the contribution from an elemental point source.

The point-source Gaussian plume formulation is the sum of plume components (horizontal and vertical with subscript *pl*) and meandering contributions (with subscript *m*). The plume component centerline follows the wind direction, as in Figure 1, and the meandering component, accounting for the random component of the wind, spreads the plume material radially outward from the source equally in all directions. The two components are added using a weighting factor, *f*, based on the magnitudes of the lateral turbulence and the mean wind.

$$dC_{pt} = (1 - f)\cdot dC_{pl} + f \cdot dC_m \qquad (11)$$

where

$$f = \frac{2\cdot\sigma_v^2}{U_e^2} \qquad (12)$$

Because U_e has a minimum value of $2\sigma_v^2$, f is limited to between 0 and 1.

The plume concentration is broken into the vertical and horizontal components,

$$dC_{pl} = \frac{q dY_s}{U_e}\left[VERT \cdot HORZ_{pl}\right], \qquad (13)$$

where q is the emission rate.

The meander component is given by

$$dC_m = \frac{q dY_s}{U_e}\left[VERT \cdot HORZ_m\right] \qquad (14)$$

The vertical component of the plume and meander concentrations is found by

$$VERT = \frac{1}{\sqrt{2\pi}\sigma_z}\cdot\left[\exp\left(-\frac{1}{2}\left(\frac{z_s - z_r}{\sigma_z}\right)^2\right) + \exp\left(-\frac{1}{2}\left(\frac{z_s + z_r}{\sigma_z}\right)^2\right)\right], \qquad (15)$$

where the vertical spread, σ_z, will be described in section 2.3.1.

The horizontal plume component is found by

$$HORZ_{pl} = \frac{1}{\sqrt{2\pi}\sigma_y} \exp\left(-\frac{1}{2}\left(\frac{y_r - y_s}{\sigma_y}\right)^2\right), \tag{16}$$

where the horizontal spread, σ_y, will be described in section 2.3.2.

Under low wind speeds, horizontal meander tends to spread the plume over large azimuth angles, which might even lead to concentrations upwind relative to the vector averaged wind direction. Adopting the approach in Cimorelli et al. (2005) we assume that as the wind speed approaches zero, the horizontal plume spreads equally in all directions. Thus the horizontal meander component in Equation (15) has the form

$$\begin{aligned} HORZ_m &= \frac{1}{2 \cdot \pi \cdot R} \\ R &= \sqrt{(x_r - x_s)^2 + (y_r - y_s)^2} \end{aligned} \tag{17}$$

In the Gaussian point source formulation the concentration goes to infinity as the distance between the source and the receptor goes to zero (since σ_y and σ_z also go to zero). Therefore, for receptors very near the source, the model sets the minimum distance (along the wind direction) between the receptor and the line source to one-meter.

2.3 New dispersion formulations

Near surface dispersion has been studied extensively since the 1950s. The Prairie Grass experiment (PG) (Barad 1958), provided a comprehensive data base that has been used by several authors to formulate dispersion models for near surface releases (e.g. Briggs 1982; van Ulden 1978; Venkatram 1992). A new tracer study (Finn et al. 2010) examining dispersion from a near surface line release provided an opportunity to re-examine the formulations of σ_z and σ_y in Equations (16) and (17). The companion paper (Venkatram et al. 2013) provides an detailed reformulation of the dispersion parameters. The resultant formula incorporated into RLINE are included here.

2.3.1 Vertical Spread

The starting point of the vertical spread reformulation is the solution of the eddy diffusivity based mass conservation equation proposed by van Ulden (1978). Venkatram et al. (2013) proposes an interpolation between the limits of very stable and neutral conditions to establish a relationship between the mean plume height, $\bar{z}$, and the vertical plume spread, σ_z. In <u>stable conditions</u>, the vertical spread is given by

$$\sigma_z = a\frac{u_*}{U_e}x\frac{1}{\left(1 + b_s\frac{u_*}{U_e}\left(\frac{x}{L}\right)^{2/3}\right)}, \tag{18}$$

where the constants, *a* and b_s, are obtained empirically. Similarly, for <u>unstable conditions</u> the vertical spread is found to be

$$\sigma_z = a\frac{u_*}{U_e}x\left(1 + b_u\left(\frac{u_*}{U_e}\frac{x}{L}\right)\right). \tag{19}$$

where b_u is an empirical constant for unstable conditions. Note that these expressions for σ_z are implicit because the wind speed, U_e, on the right hand side of the equation is a function of $\bar{z}$, which in turn is a function of σ_z. Note also that the expressions for stable (Equation 18) and unstable (Equation 19) conditions reduce to the same neutral limit for large L.

Based on the evaluation of Equations (18) and (19) against the Prairie Grass and the Idaho Falls tracer experiments, Venkatram et al. (2013) find the following best fit to the coefficients: a = 0.57, $b_s = 3$, and $b_u = 1.5$.

The mean plume height, where U_e is evaluated (see Equation 8), is found to be a function of the vertical spread (Venkatram et al. 2013), and has the form:

$$\bar{z} = \sigma_z \sqrt{\frac{2}{\pi}} exp\left[-\frac{1}{2}\left(\frac{z_s}{\sigma_z}\right)^2\right] + z_s erf\left(\frac{z_s}{\sqrt{2}\sigma_z}\right). \qquad (20)$$

2.3.2 Horizontal Spread

Estimates of horizontal dispersion in the surface layer have largely been based on Taylor's theory (1921) for dispersion in homogeneous turbulence which is based on the Lagrangian time scale and σ_v. Unfortunately, the plume travel time cannot be defined unambiguously because the wind speed varies with height. We avoid this problem by using an approach suggested by Eckman (1994), who showed that the variation of σ_y with distance could be explained by the variation of the effective transport wind speed, even when the standard deviation of the horizontal velocity fluctuations is constant with height Venkatram et al. (2013) use Eckman's equation to derive expressions such that

$$\sigma_y = c\frac{\sigma_v}{u_*}\sigma_z\left(1 + d_s\frac{\sigma_z}{|L|}\right), \text{for stable conditions} \qquad (21)$$

and

$$\sigma_y = c\frac{\sigma_v}{u_*}\sigma_z\left(1 + d_u\frac{\sigma_z}{|L|}\right)^{-1/2}, \text{for unstable conditions} \qquad (22)$$

where c, d_s, and d_u are empirical constants. Based on the evaluation of Equations (21) and (22) against the Prairie Grass data, the best fit values for the constants are: c = 1.6, $d_s = 2.5$, and $d_u = 1.0$. As with the vertical spread, a detailed discussion of the horizontal spread formulation is found in Venkatram et al. (2013).

2.4 Numerical Computation of Concentration

The right hand side of Equation (10) must be integrated numerically because both σ_y and σ_z depend on x_r, which in turn is a function of the integrating variable Y_s (See Equation (9)). This is done in RLINE with an efficient Romberg integration scheme (Press et al. 1992). Convergence of the scheme is assumed when the difference between estimated concentration is below a user specified error limit (recommended $1\text{x}10^{-3}$). When multiple sources are modeled the cumulative concentration is reported, but each source's contribution is calculated with an accuracy of the user defined limit.

In some cases, such as modeling pedestrian or bike-lane exposures it may be necessary to estimate concentrations within a few meters of the source. When the receptor is close to the line source and its concentration in the early steps of the integration scheme is dominated by a single point source or has little or no impact from any point, convergence may occur too quickly. Therefore a minimum number of iterations, j_{min}, is calculated that prevents this premature convergence by ensuring that the spacing between the points used to approximate the line source, dr, is smaller than the distance from receptor to the line. Starting from the fact that for the j^{th} iteration, the number of points representing the line is $2^{j-1} + 1$, we find that:

$$\frac{L}{dr} < 2^{j-1} + 1 \quad (23)$$

$$j_{min} = \left\lceil \frac{\log\left(\frac{2L}{dr\sin\theta} - 2\right)}{\log 2} \right\rceil, \quad (24)$$

where L is the length of the line and $dr \sin\theta$ is the perpendicular distance between the receptor and the line source. The case of receptors very close to the line source is the most computationally time consuming. The minimum number of iterations, j_{min}, can be large when the line source is long and the distance, $dr \sin\theta$, becomes small.

3 Model Applications

Model performance estimates of concentration are compared qualitatively to on-site measurements made during the two field studies described below with the use of scatter plots. In addition, model performance is quantified using the performance statistics as described in Venkatram (2008). The quantitative model performance measures used here are the geometric mean bias (m_g), the geometric standard deviation (s_g) and the fraction of estimates within a factor of two of the measured value (fac2). Venkatram's definition of m_g suggests that a model is over predictive when $m_g < 1$. We have flipped the ratio of observed-to-predicted concentrations here, so that $m_g > 1$ is indicative of a model over-prediction; $m_g < 1$ is indicative of a model under-prediction. The geometric mean bias and standard deviation are found by:

$$m_g = median\left(\frac{C_p}{C_o}\right) \quad (25)$$

$$s_g = exp\left(\frac{\ln(F)}{\sqrt{2}\, erf^{-1}(A_F)}\right), \quad (26)$$

where C is the concentration, either observed (subscript 'o') or predicted (subscript 'p'), F is taken to be 2, A_F is the fraction of the ratio, $C_p/(C_o m_g)$, between $1/F$ and F, and erf^{-1} is the inverse error function. Observed and predicted concentrations are paired in time and space.

3.1 Comparison of Model to Idaho Falls Tracer Study

A line source experiment was conducted near Idaho Falls, Idaho in 2008 (Finn et al. 2010). The study area is located in a broad, relatively flat area on the western edge of the Snake River Plain. Five tests were conducted during the study, each spanning a 3-h period broken into 15-min tracer sampling intervals. One test was conducted in unstable conditions, one in neutral conditions, and two in stable conditions; test 4 was not used since the wind shifted away from the sampler array as the test period began. A brief summary is shown in Table 1.

Table 1: Summary of the wind conditions during each day of the Idaho Falls 2008 field test.

Test Day	L (m)	u_* (m/s)	Wind Speed (m/s)	Wind Direction (deg)
1 – Neutral/Weakly Convective	-(500-181.8)	0.52-0.88	5.5-8.1	192.7-228.1
2 - Convective	-(29.8-1.7)	0.15-0.34	0.7-2.5	189-203.9
3 – Weakly Stable	+(35.3-62.0)	0.28-0.35	3.2-3.6	202-208.6
5 - Stable	+(4.9-17.3)	0.05-0.19	1.6-2.4	194.1-230.8

The overall purpose of the study was to examine the difference in pollutant dispersion from a line-source (e.g. roadway) in the presence and in the absence of a 90 meter long and 6 meter high (H) noise barrier. Simultaneous measurements were made at the barrier and no-barrier (control) sites. Both sites had a 54 m long SF_6 tracer line source release positioned 1 m above ground level (AGL). In both experiments, a gridded array of bag samplers were positioned downwind of the line source for measuring concentrations.

Mean wind and turbulence was obtained on the control site from a sonic anemometer within the sampler array at a 3 meter height. The roughness length scale, z_0 , for the site was estimated at 0.053 m based on mean wind and sheer stress measurements from the sonic during the near-neutral conditions of test day 1. In the development and evaluation of RLINE as described in this paper we have only used the control experiment (non-barrier) measurements.

Figure 2 shows the infinite line source model predications vs. the observed concentrations for the four cases in Idaho Falls. The infinite line source was constructed from the finite line measurements using the procedure in Heist et al. (2009).

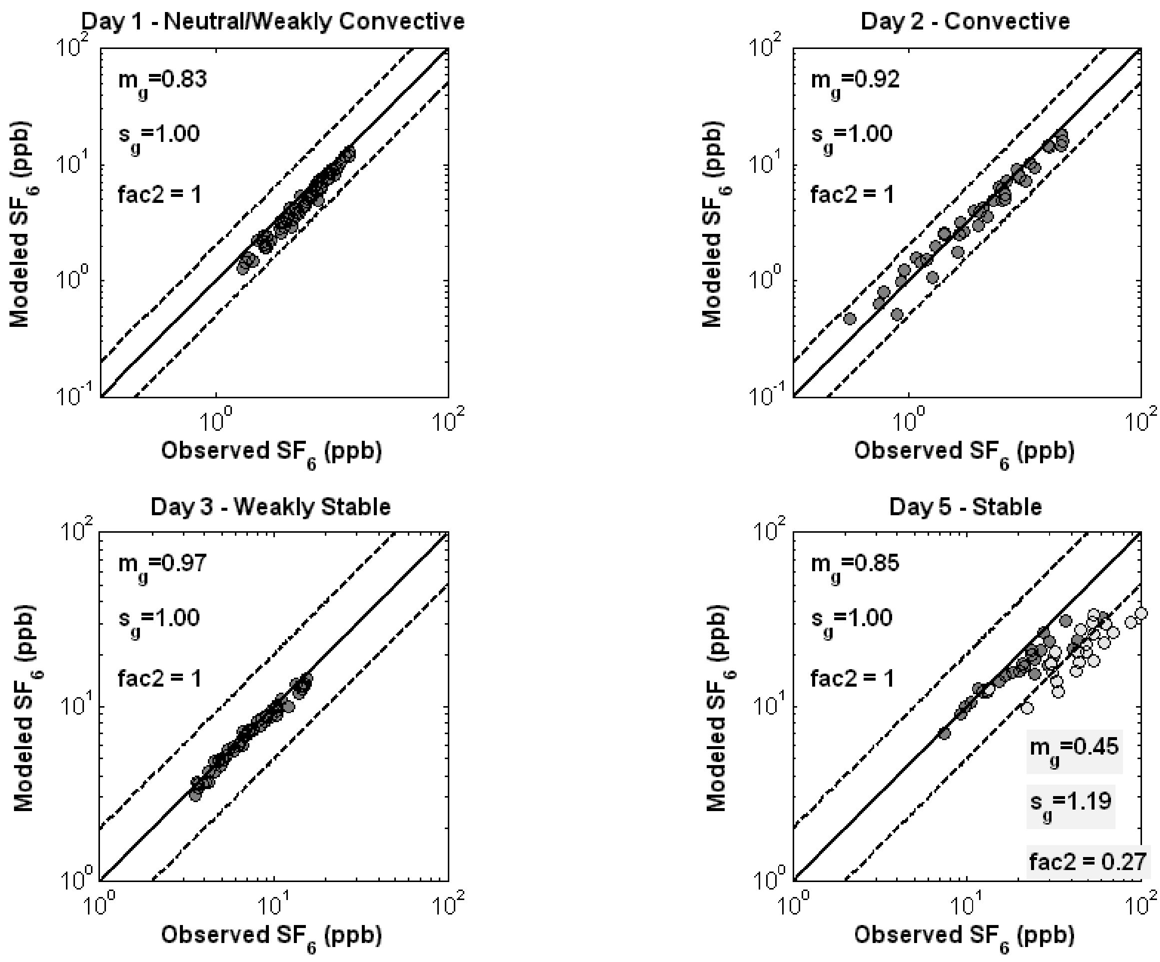

Figure 2: Scatter-plot of the modeled concentration vs. the observed concentration for a crosswind integrated line source during days 1, 2, 3, and 5 of the Idaho Falls 2009 line source field experiment. Grey symbols are for very stable conditions.

The observations on day 5 are split into two groups. The light grey circles indicate periods of very strong stability. Clearly for these conditions the plume is not well represented by the model. In the presence of strong convection, the model appears to be overestimating the vertical spread.

3.2 Comparisons to Roadway Measurements

Two field study data bases involving free flowing traffic on major highways were selected for comparison with the RLINE model. The first was a tracer study, CALTRANS Highway 99 (Benson 1989), and the other a study of the dispersion of nitrogen oxide near an interstate highway, Raleigh 2006 (Baldauf et al. 2008).

The CALTRANS Highway 99 Tracer Experiment was conducted in the winter of 1981-1982 along a four kilometer section of U. S. Highway 99 in Sacramento, California. During the period of the experiment, the highway carried approximately 35,000 vehicles per day. The surrounding terrain is flat with open fields and parks and scattered residential development. The experiment location had 2 lanes of traffic northbound and two southbound separated by a 14 m median. Tracer concentration measurements were taken at four locations in the highway median and at 50, 100, and 200 m distances perpendicular to the roadway in each direction. Tracer gas, SF_6, was released through the exhaust system of vehicles at specified intervals as they traveled down each side of the highway to simulate a quasi-continuous line release during the measurement periods. All tracer samples were taken at one meter above the local surface and on site measurements of meteorology were taken from a 12 m tower.

Figure 3 shows a comparison of the model estimates to the measurements for cases where the mean wind direction is within 60 degrees of perpendicular to the highway, while distinguishing upwind and downwind concentrations. The model performs well for downwind receptors with over 80% of the estimates within a factor of two of the observations and the geometric mean value showing a slight overprediction at 0.89. The highest observations, not surprisingly, are found at the median locations as are the model estimates. The range of concentrations over all downwind locations for model and observations is approximately the same.

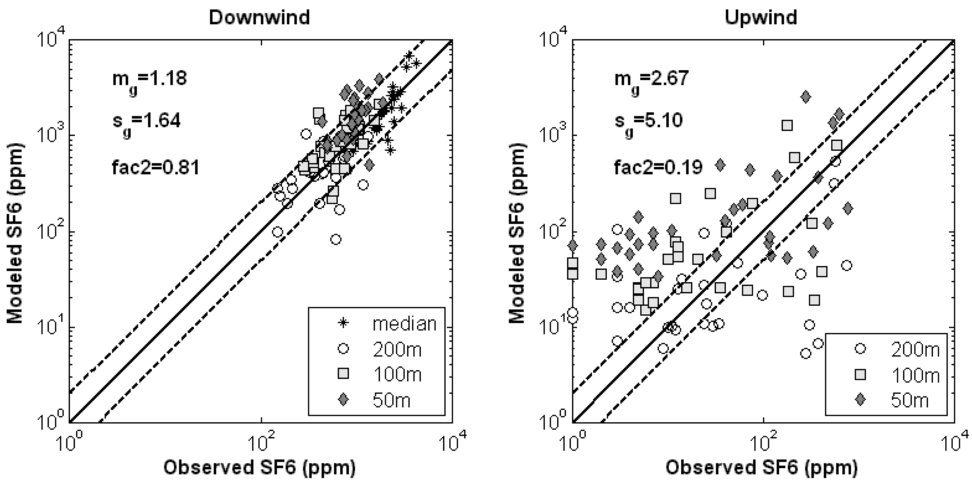

Figure 3: Comparison of RLINE modeled concentrations to those measured during CALTRANS99 for winds within 60 degrees of perpendicular to Highway 99.

For upwind receptors, the scatter is much larger and the performance reduced. The geometric mean suggests an overprediction by about a factor of two and the geometric standard deviation reveals scatter six times larger than that for downwind receptors. In looking at the distribution of the data points, the observations show no distinguishable trend in concentrations with distance from the highway. The model, however, does display a decreasing trend with distance. This suggests that there may be other factors influencing the observed upwind concentrations that are dominating the expected concentration decay with distance from the line source. One possibility may be small plume rise from a heated highway or from hot exhaust that can have a strong influence on the turbulence driven nature of upwind dispersion. These results suggest that further research into the upwind dispersion algorithm is necessary.

Expanding the analysis of the downwind values in Figure 3, the distinction between low and moderate winds is examined. In Figure 4 is displayed the model performance for winds below and above 1.5 ms^{-1}. The values at the median locations match well between model and observations for all wind speeds suggesting that the initial dispersion estimates are good in the model. For moderate to high winds, the model is performing at its best. For light winds, there is a slight degredation of this performance with a slight tendency to overpredict the concentrations particularly at 50 and 100 meters downwind. Light winds are related to more extremes in stability (stable or unstable). Therefore an examination of the dispersion rates for these conditions will be a subject of future work.

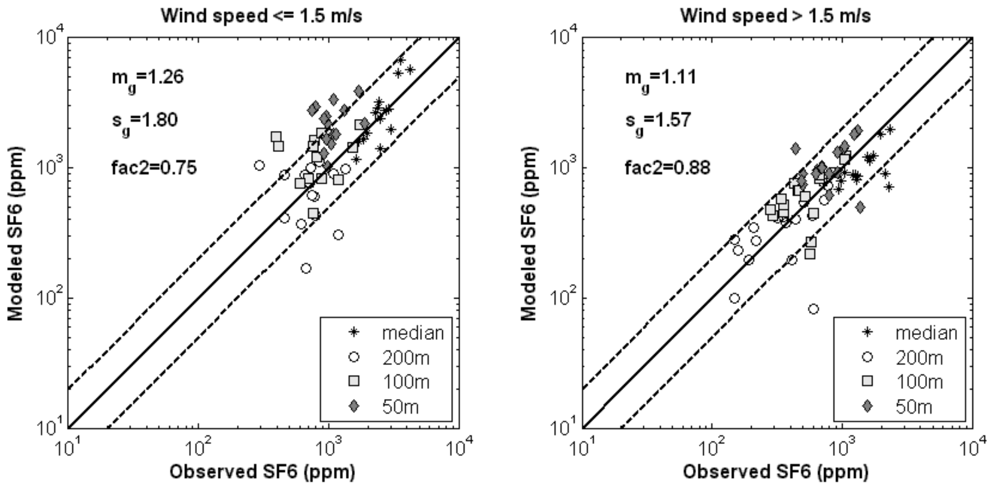

Figure 4: Expansion of the analysis of the downwind concentration comparisons of Figure 4 based on wind speed.

Figure 5 shows the comparison of model estimates to observations at all sampler locations for wind direction within 30 degrees of parallel to the highway. Unlike the cases when winds approach the roadway at an oblique angle, with near parallel winds concentrations become very sensitive to wind direction. In particular, the formulation of the lateral dispersion becomes much more important as does the influence of the meander component. Overall, the model tends to overpredict these conditions by a little less than a factor of two (m_g = 0.56), with half of the estimates within a factor of two of the observations. For the sampler locations within the median of the highway the model is performing particularly well, which adds confidence to the emissions and near-source characterization. The tendency toward overprediction is particularly pronounced for the smaller observed concentrations with a somewhat better performance for the higher concentrations. Overprediction of the smaller concentrations, as in Figure 5, represents an overestimation in the upwind concentration. This outcome suggests that perhaps the meander component may be over estimated.

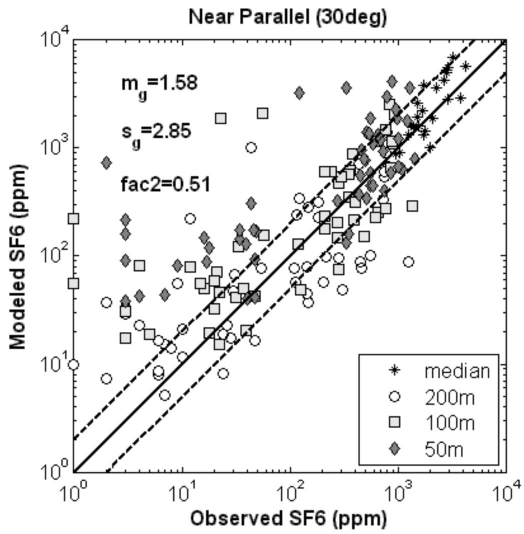

Figure 5: Comparison of RLINE modeled concentrations to those measured during CALTRANS99 for wind that were within 30 degrees of parallel to Highway 99.

In July and August 2006 a roadway study was conducted in Raleigh, NC along a busy section of I-440 supporting approximately 125,000 vehicles per day (Baldauf et al. 2008). This analysis is based on NO measurements collected at 7 m and 17 m from the roadway shoulder (at a height of 2 m). Thoma et al (2008) presents nearly identical time-series measurements NO and NO_2 during this study, thus chemical transformation is negligible in this case. On site measurements of traffic and meteorology were collected along with NO concentrations. We used traffic counts from the study and emission factors as found by Venkatram et al. (2007). Although these emission factors were determined, in part, using dispersion calculations, the comparisons here are an independent test of RLINE's ability to capture the concentration distribution as well as the concentration fall off as a function of distance. Model estimates versus measured concentrations are shown in Figure 6 for the two monitor locations.

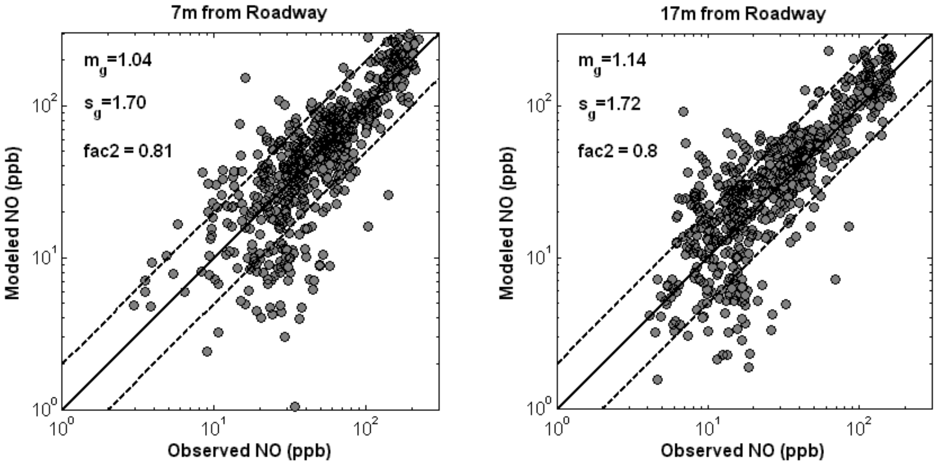

Figure 6: Scatter-plot of Raleigh 2006 NO observed concentration versus the RLINE predicted concentration for each NO receptor.

Agreement between model and observations is good as suggested by both the geometric mean and the percent within a factor of two. This is true for both sampler locations. The model does show increased scatter for some moderate to low concentrations. Examining the data further, Figure 7 shows two subsets of the data in Figure 6. On the left is shown the model to observation comparisons for mean winds within 60 degrees of perpendicular to the roadway and blowing toward the monitors, i.e. downwind. The right figure shows the same plus or minus 60 degree sector only with the wind direction away from the monitors, i.e. upwind. So the increased scatter noted in Figure 7 is, in fact, mostly related to upwind concentrations where the model is simulating plume meander. For this data base, the model is performing fairly well, on average, in estimating the upwind concentrations, however the distribution of modeled concentrations is clearly much wider than that of the observations. As with the Caltrans 99 data base, there appears to be a need to further examine the meander algorithm in the model with the goal of reducing the scatter.

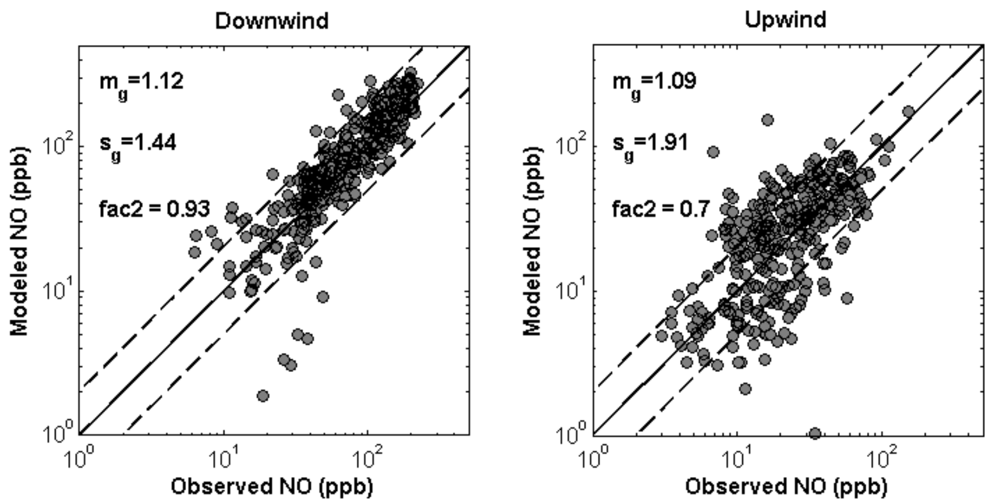

Figure 7: Scatter-plot of Raleigh 2006 NO observed concentration versus the RLINE predicted concentration for both NO receptors (7 and 17 m); a) receptors are downwind of roadway and b) receptors are upwind of roadway.

4 Summary

RLINE, a steady-state, line-source dispersion model, has been developed for near-surface applications with emphasis on simulating impacts from mobile source emissions of primary air pollutants in near-road environments. A line is simulated as the sum of the contributions from point sources, the number determined by the model based on the source to receptor distance and the convergence criteria. Focus has been placed on dispersion within the first few hundreds meters of the source and for releases within the surface layer and near the surface. New dispersion approaches have been formulated from theoretical foundations, with empirical coefficients based on field tracer studies and wind tunnel simulations, and have been tested within the RLINE model platform against independent roadway field study data bases. Plume meander and upwind dispersion are simulated by the model. Adjustments to the atmospheric boundary layer parameters are considered for light wind conditions and lateral turbulence is considered in keeping the wind speed near the surface from reaching an unrealistically small value.

The RLINE model was evaluated with the line source field study conducted in Idaho Falls in 2008 (Finn et al. 2010). The model compared well for most meteorological conditions with a tendency to slightly underpredict. All observations are within a factor of two and geometric mean biases are between 1.04 and 1.21, except for very stable conditions during part of one day of the study. RLINE was also evaluated with near-roadway measurements taken during a tracer study (in Sacramento, CA) and a real emissions study (in Raleigh, NC), both of which were conducted with traffic present on major freeways. Overall, in these studies the model preformed well for receptors downwind of the roadways, with a tendency to slightly overpredict. The model did not perform as well in light wind conditions and for upwind receptors, with a tendency to overpredict in these cases.

The current version of the model is designed for flat roadways (line sources with no surrounding complexities), though the model framework can accommodate future algorithms. Areas of ongoing research are leading to expanded model applicability and development of algorithms for simulating the near-source effects of complex roadway configurations (in particular, noise barriers, depressed roadways, and roadside vegetation) and accounting for the effects of urban areas on both meteorology and dispersion.

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6 Disclaimer

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