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DEVELOPMENT AND EVALUATION OF A MODEL FOR DISPERSION OF EMISSIONS FROM ROADS

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Abstract: LSDM is a line source model based on the dispersion formulations incorporated in AERMOD. The model has been evaluated with data from two field studies, one next to a highway in Raleigh, NC, and the other at a test ground in Idaho Falls. The evaluation with the Raleigh data indicated the need to modify the formulation used in LSDM to describe concentrations under wind meandering at low wind speeds. The results of model evaluation with the Idaho Falls data suggest the need to reformulate the vertical spreads in the Gaussian version of the line source dispersion model. Equations (7) and (8) represent one possible reformulation that describes the observed concentrations.

Key words: *Line source model, near road air quality, surface layer dispersion, vertical plume spread*

INTRODUCTION
Pollutant emissions from motor vehicles influence the temporal and spatial patterns of air concentrations of air toxics within urban areas. Air quality monitoring studies conducted near major roadways have detected elevated concentrations, compared to overall urban background levels, of motor-vehicle-emitted toxics, such as benzene, butadiene, and toluene. These results from air quality and health effects studies motivated two comprehensive field studies, conducted by the U.S. EPA, to characterize the influence of traffic-generated emissions on the temporal and spatial variability in air pollutant concentrations in the near-road environment (Baldauf et al., 2008; Finn et al., 2010). This paper describes the evaluation of a line source model with data from these two field studies. The line source model, referred to as the Line Source Dispersion Model (LSDM), treats a line source as a set of point sources, and the contributions of these sources to concentrations at receptorsare evaluated numerically using an efficient Romberg integration scheme. Venkatram et al. (2007) describes the model and its evaluation with path averaged NO concentrations measured in a field study conducted next to a highway in Raleigh, NC. The evaluation only considered cases when the receptors were downwind of the highway. We now extend the evaluation to cases when relatively high concentrations of pollutants were observed upwind of the highway, primarily during low wind speeds when the horizontal velocity fluctuations were comparable to the mean wind speed. The paper also describes the evaluation of the vertical dispersion parameterizations in LSDM with data from a tracer study conducted in Idaho Falls.

FIELD STUDIES
The first field study was conducted from July 27 to August 10, 2006, adjacent to U.S. Interstate 440 (I-440), in Raleigh, North Carolina. The study was designed to obtain highly time-resolved measurements of traffic activity, meteorology, and air quality at varying distances from the road (Baldauf et. al., 2008). Selected air quality parameters represented the complex mixture of pollutants emitted by motor vehicles. In addition to real-time air quality monitoring, selected time integrated measurements allowed for detailed chemical speciation and the evaluation of particle toxicity.

Onsite meteorological measurements were collected at downwind sites at 5, 20, and 100 m using sonic anemometers (Model 81000 Ultrasonic Anemometer, R.M. Young Company, Traverse City, MI, USA). At the 20-m site, two sonic anemometers measured wind speed and direction at heights of 4and 8m above ground. Comparison of the data at the 5 and 20-m sites provided information on the horizontal and vertical extent of the turbulent mixing zone from the highway. Air quality monitors measured pollutant concentrations at multiple distances from the road. Measurements of regulated gases, particulate matter, and air toxics provided information on the concentration of these pollutants during changing traffic and environmental conditions.

The second field study was conductedin 2008 near NOAA's Grid 3 diffusion grid at the Department of Energy's Idaho National Laboratory (INL). The Grid 3 area on the INL is located across a broad, relatively flat plain on the western edge of the Snake River Plain in southeast Idaho. The primary and reference control experiments both had a 54 m long (9H) SF_6 tracer line source positioned 1 m above ground level (AGL) representing pollution sources from a roadway. In the primary experiment, the line source was positioned 1 meterupwind of a 6m high barrier with a gridded array of bag samplers downwind of the line source and barrier for measuring mean 15-min concentrations. The control experiments (conducted at an adjacent location and simultaneous to the primary) include identical source and concentration sampling but without the barrier in the array. An array of six 3-d sonic anemometers was deployed for making wind and turbulence measurements, 5 on the primary experiment and 1 on the control experiment.

Five tests were conducted during the study, each spanning a 3-h period broken into 15-min tracer sampling intervals. Test 1 was conducted on October 9, 2008 from 1230-1530 hours Mountain Standard Time (MST) in neutral stability conditions. Winds were generally well in excess of 5 m s^{-1} and skies were heavily overcast. Test 2 was conducted on October 17, 2008 from 1300-1600 hours MST in unstable conditions. Skies were clear and sunny throughout the test period and winds were light from 1 to 3 ms^{-1}. Test 3 was conducted on October 18, 2008 from 1600-1900 hours MST in weakly stable conditions. The wind direction was very close to ideal until the last hour of the experiment when a transition in the wind field occurred. Skies were clear throughout the experiment. Test 4 was conducted in moderately to strongly stable conditions but was not used because the wind direction was unfavourable with respect to the barrier and sampler grid orientation.Test 5 was conducted on October 24, 2008 from 1800-2100 hours MST in moderate to strongly stable conditions.

Each of the two sampling grids had 58 sampler locations marked by metal fence posts. The sampler density was greatest near the sources and decreased in the downwind direction. Two of the samplers were deployed upwind of the release line at x = -1H and x= -2H to check for possible upwind tracer dispersion, where H=6m. All bag samplers were attached to the metal fence posts at approximately 1.5 m AGL. In addition to the 58 regular samplers on each grid, an additional 9 samplers were deployed for quality control purposes. These included field duplicates, field controls, and field blanks.

A single tracer line source was used to simulate roadway emissions for the primary and control experimental grids. The tracer release system was engineered to simultaneously release SF_6 from two independently controlled release systems and dissemination lines, one for each grid.The SF_6 tracer was simultaneously released from the line source for each grid beginning 15 min before the sampler measurements started to establish a quasi-steady state concentration field and continued until the end of each test. Tracer release rates ranged from 0.02 to 0.05 g s^{-1}.

EVALUATION OF LSDM

The dispersion formulations in LSDM are adapted from AERMOD (Cimorelli et al., 2005). The vertical spreads, σ_z, aregiven by (Venkatram, 1992):

$$\sigma_z = \sqrt{\frac{2}{\pi}}\frac{u_* x}{U}\left(1 + 0.7\frac{x}{L}\right)^{-\frac{1}{3}} \quad for\ L > 0 \qquad (1)$$

and

$$\sigma_z = \sqrt{\frac{2}{\pi}}\frac{u_* x}{U}\left(1 + 0.006\left(\frac{x}{|L|}\right)^2\right)^{\frac{1}{2}} \quad for\ L < 0. \qquad (2)$$

where L is the Obukhov lengthdefined by$L = -\frac{T_0}{g}\frac{u_*^3}{kQ_0}$, where $Q_0$is the surface kinematic heat flux, $u_*$is the surface friction velocity, g is the acceleration due to gravity, $T_0$is a reference temperature, and κ is the Von Karman constant taken to be 0.40. Equations (1) and (2)are semi-empirical formulations in which the parameters were obtained by fitting estimates from the equations with crosswind-integrated concentrations measured during the Prairie Grass experiment (Barad, 1958). The vertical mixing induced by traffic is accounted for through an initial sourceheight, h_o=2 m. The horizontal spread, σ_y,of the plume was computed using the measured value of the horizontal velocity fluctuations, σ_v, in the formula incorporated in AERMOD (Cimorelli et al., 2005):

$$\sigma_y = \frac{\sigma_v x}{U}(1 + 78X)^{-0.3} \qquad (3)$$

where

$$X = \frac{\sigma_v X}{z_i U}. \qquad (4)$$

and z_i is the mixed layer height.

The observed mean wind U and σ_w are fit to similarity profiles to obtain u_* and L required in the formulations for plume spread. The roughness length, z_o, is taken to be 0.2 m for the Raleigh site and 0.053 m for the Idaho Falls site. The displacement height is given byd_h=5z_o based on Britter and Hanna (2003).

Under low wind speeds, horizontal meandering of the wind spreads the plume over large azimuth angles, which might lead to concentrations upwind relative to the vector averaged wind direction. AERMOD (Cimorelli et al., 2005), and other currently used regulatory models (ADMS, Atmospheric Dispersion Modelling System, Carruthers*et al.*, 1994), attempt to treat this situation by assuming that when the mean wind speed is close to zero, the horizontal plume spread covers 360°. Then, the concentration is taken to be a weighted average of concentrations of two possible states: a random spread state, and a plume state. In the random spread state, the release is allowed to spread radially in all horizontal directions. Then, the weighted horizontal distribution is written as:

$$H(x,y) = f_r\frac{1}{2\pi r} + (1 - f_r)\frac{1}{\sqrt{2\pi}\sigma_y}\exp\left(-\frac{y^2}{2\sigma_y^2}\right). \qquad (5)$$

where the first term on the right represents the random state in which the plume spread covers 2π radians, and $r$is the distance between the source and the receptor. The second term is the plume state corresponding to the Gaussian distribution. The plume is transported at an effective velocity given by

$$U_e = (2\sigma_v^2 + U^2)^{\frac{1}{2}} \qquad (6)$$

where$U$is the mean vector velocity, and the expression assumes thatthe effective velocity is non-zero even when the mean vector velocity is zero.

The weight of the random component in Equation (5) corresponds to that used in AERMOD: $f_r = 2\sigma_v^2/{U_e}^2$. The success of this meandering correction in AERMOD depends on measurements ofσ_v , which presumably reflect meandering when the wind speed is close to zero. If measurements are not available, we have to estimate$\sigma_v$from other meteorological variables.

EVALUATIONOF DISPERSION MODEL

LSDM was used to estimate the 10-min averaged concentrations measured during the Raleigh study t at 7.6-m and 17.6m from the edge of the paved road. The performance of the models in explaining observations is quantified using the geometric mean (m_g) and the standard deviation (s_g) of the ratios of the predicted to observed concentrations. The estimated NO concentrations compared well with observed concentrations at the two measurement sites when these sites are downwind of the road (Venkatram et al., 2007). However, the results deteriorated when the receptors were upwind of the highway. The scatter was larger, and the residual plot showed a trend with the friction velocity. The results improved when the random fraction in Equation (5) was modified as follows: $f_r = \frac{3p}{1+3p}\ where\ p = \frac{2\sigma_v^2}{U_e^2}$. Figures 1 and 2 show the performance of the model with this modification.

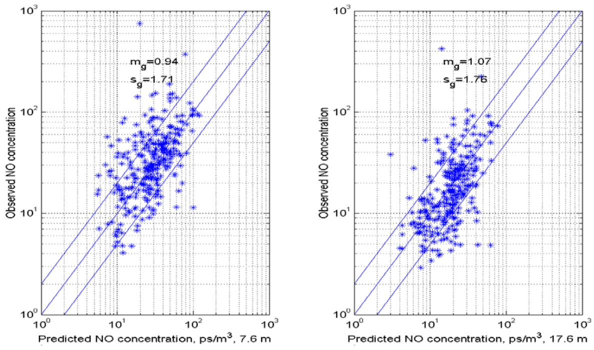

Figure 1: Comparison of model estimates of NO concentrations with corresponding observations for receptors upwind of the highway.

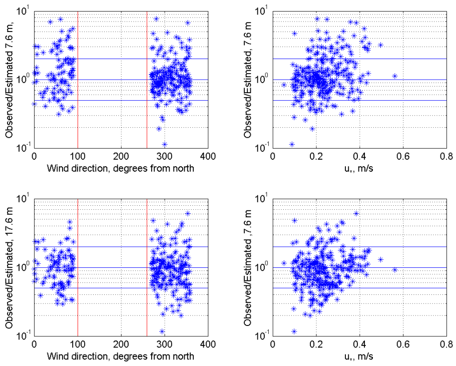

Figure 2: Plot of ratios of model estimates of NO concentrations to observations against model inputs for receptors upwind of the highway. Receptors are north of the highway. Points outside the vertical red lines indicate wind directions when the receptors are upwind of the highway. Random fraction uses modified formulation.

The major objective of the Idaho Falls experiment was to understand the effects of roadside barriers on dispersion from roads. As the first step towards this objective, we evaluated LDSM with tracer data corresponding to the no barrier cases. Figure 3 indicates that LSDM underestimates concentrations at small$\overline{x} = x/|L|$, and overestimates concentrations under strongly unstable conditions. We can formulate vertical spreads that can explain the observed concentrations at Idaho Falls (IF) better than the spreads derived from the Prairie Grass (PG) data. The modified spreads, which provide an adequate description of the data, are:

$$\sigma_z = 0.57\frac{u_* x}{U}(1+\bar{x})^{-0.25}(1+0.25\,\bar{x})^{0.15} \quad for \quad L > 0 \tag{7}$$

and

$$\sigma_z = 0.57\frac{u_* x}{U}(1+\bar{x})^{-0.25}(1+0.5\,\bar{x}^2)^{0.5} \quad for \quad L < 0 \tag{8}$$

Note that the leading terms of both equations are the same, and start out proportional to$\bar{x}$, transition to$\bar{x}^{0.75}$, before approaching their far field behavior. Under stable conditions, $\sigma_z \sim\bar{x}^{0.9}$at large$\bar{x}$, while under unstable conditions, $\sigma_z \sim\bar{x}^{1.75}$. The use of Equations (7) and (8) in LSDM produces results shown in 4. We see that the underpredictions of the near neutral Tests 1 and 3 have largely disappeared, and there is little bias in the stable case, Test 5. The concentrations are slightly overestimated in the highly stable case, Test5, at large$\bar{x}$.

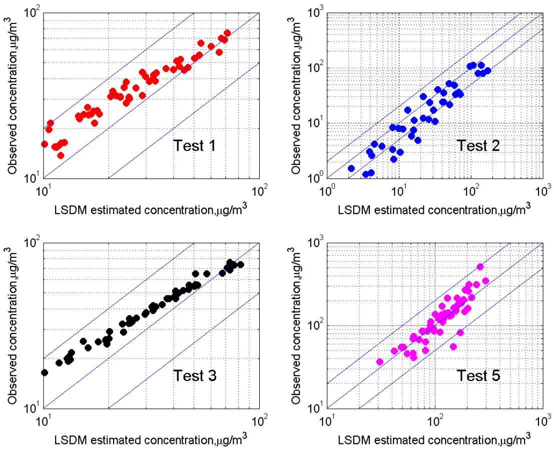

Figure 3: Comparison of results from LSDM with observed concentrations when wind speed is specified at mean plume height.

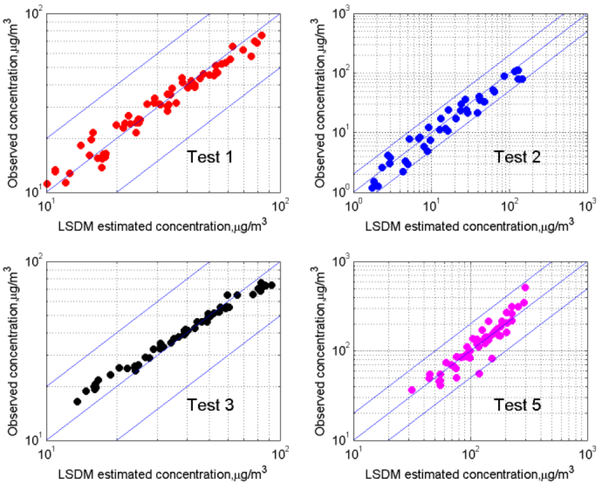

Figure 4: Comparison of observed concentrations with results from LSDM using modified vertical spread formulations of Equation (7) and (8).

CONCLUSIONS

LSDM is a line source model based on the dispersion formulations incorporated in AERMOD. The model has been evaluated with data from two field studies, one next to a highway in Raleigh, NC, and the other at a test ground in Idaho Falls. The evaluation with the Raleigh data indicated the need to modify the formulation used in LSDM to describe concentrations under wind meandering at low wind speeds.

The results of model evaluation with the Idaho Falls data suggest the need to reformulate the vertical spreads in the Gaussian version of the line source dispersion model. Equations (7) and (8) represent one possible reformulation that describes the observed concentrations.The differences between the vertical spreads from the Prairie Grass (PG) and Idaho Falls (IF) data are summarized in Figure 5. The IF vertical spreads are smaller than the PG spreads in the near field and become larger in the far field. Under stable conditions, the IF vertical spread is smaller than the PG spread for $x/|L|$ less than 30 and is about 20% larger at $x/|L|=100$. Under unstable conditions, the IF spread is smaller than the PG spread for $x/|L|$ less than 3 and becomes a factor of 2.6 larger at $x/|L|=20$; the ratio of the spreads then decreases to 2 at $x/|L|=100$.

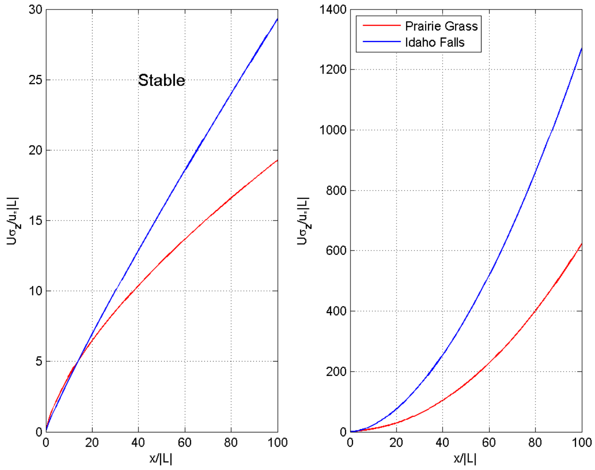

Figure 5: Vertical spreads inferred from the Prairie Grass and the Idaho Falls data as a function of x/|L|. The left panel corresponds to stable conditions and the right to unstable conditions.

REFERENCES

Baldauf, R., E. Thoma, V. Isakov, T. Long, J. Weinstein, I. Gilmour, S. Cho, A. Khlystov, F. Chen, J. Kinsey, M. Hays, R. Seila, R. Snow, R. Shores, D. Olson, B. Gullett, S. Kimbrough, N. Watkins, P. Rowley, J. Bang, D. Costa, 2008: Near road air quality and particle toxicity: summary of methods. *J. A&WMA*.**58**: 865–878

Barad ML (Ed.) (1958) Project Prairie Grass. A field program in diffusion, Geophysical Research Paper No. 59, vols. I (300 pp.) and II (221 pp.), AFCRF-TR-58-235, Air Force Cambridge Research Center, Bedford, MA.

Britter, R.E., and S.R Hanna, 2003: Flow and dispersion in urban areas. *Annual Review of Fluid Mechanics*, 35, 469–496.

Carruthers D. J, R. J. Holroyd, J. C. R. Hunt, W. S. Weng, A. G. Robins, D. D. Apsley, D. J. Thompson, and F. B. Smith, 1994: UK-ADMS: A new approach to modelling dispersion in the earth's atmospheric boundary layer. *J Wind EngIndAerodyn*, 52, 139-153.

Cimorelli, A.J., S.G. Perry, A. Venkatram, J.C. Weil, R.J. Paine, R.B. Wilson, R.F. Lee, W.D. Peters, and R.W. Brode, 2005, AERMOD: A Dispersion Model for Industrial Source Applications. Part I: General Model Formulation and Boundary Layer Characterization. *Journal of Applied Meteorology*, **44**, 682–693.

Finn, D., K. L. Clawson, R.G. Carter, J. D. Rich, R. M. Eckman, S. G. Perry, V.Isakov, and D. K. Heist, 2010: Tracer studies to characterize the effects of roadside noise barriers on near-road pollutant dispersion under varying atmospheric stability conditions. *Atmospheric Environment*, **44**, 204-214

Venkatram, A., 1992: Vertical dispersion of ground-level releases in the surface boundary layer. *Atmospheric Environment*, **26A**, 947-949.

Venkatram, A., V. Isakov, E. Thoma, and R. Baldauf, 2007: Analysis of air quality data near roadways using a dispersion model. *Atmospheric Environment*, **41**, 9481-9497