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# Re-formulation of plume spread for near-surface dispersion

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## HIGHLIGHTS

- Historically, plume spread was based on the Prairie Grass study (Barad, 1958).
- The Idaho Falls (Finn et al., 2010) dataset indicates need for spread reformulation.
- Spread equations are reformulated from eddy diffusivity & mass conservation.
- New plume spread formulations are evaluated with new and historical datasets.
- Model results are improved with the new surface plume spread formulations.

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## ABSTRACT

Recent concerns about effects of automobile emissions on the health of people living close to roads have motivated an examination of models to estimate dispersion in the surface boundary layer. During the development of a new line source dispersion model, RLINE (Snyder et al., 2013), analysis of data from a tracer field study led to a re-examination of near-surface dispersion resulting in new formulations for horizontal and vertical plume spread presented in this paper. The equations for vertical spread use the solution of the two-dimensional diffusion equation, in which the eddy diffusivity, based on surface layer similarity, is a function of surface micrometeorological variables such as surface friction velocity and Monin–Obukhov length. The horizontal plume spread equations are based on Eckman's (1994) suggestion that plume spread is governed by horizontal turbulent velocity fluctuations and the vertical variation of the wind speed at mean plume height. Concentration estimates based on the proposed plume spread equations compare well with data from both the Prairie Grass experiment (Barad, 1958) as well as the recently conducted Idaho Falls experiment (Finn et al., 2010). One of the major conclusions of this study is that the plume spreads as well as the wind speed used to estimate concentrations in a dispersion model form a set of coupled variables.



## 1. Introduction

New interest in modeling dispersion from surface releases has been sparked by recent studies showing that people living and working near roadways are exposed to elevated levels of pollution and are at increased risk of respiratory problems (e.g., Nitta et al., 1993; McConnell et al., 2006), birth and developmental defects (e.g., Wilhelm and Ritz, 2003), premature mortality (e.g., Finkelstein et al., 2004; Jerrett et al., 2005), cardiovascular effects (e.g., Peters et al., 2004; Riediker et al., 2004), and cancer (e.g., Harrison et al., 1999; Pearson et al., 2000). The near roadway pollutants originate primarily from automobiles and trucks, which are near surface releases.

In response to this concern with the health effects, the USEPA initiated a program to examine the many factors that influence the dispersion of mobile source emissions and develop a line source model, RLINE (Snyder et al., 2013), to model roadway impacts. The model development program included a tracer field study (Finn et al., 2010) in Idaho Falls to provide new data for examining near-surface dispersion from a line source. An analysis of the Idaho Falls data indicated that currently used dispersion curves (Briggs, 1982; Venkatram, 1992), based on the Prairie Grass field study

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(Barad, 1958) do not provide a satisfactory description of both the new and historical data. This led to a reformulation of the plume spread equations, which is the primary topic of this paper.

## 2. Current plume spread formulation and evaluation

Vertical dispersion in the surface layer is well understood. The underlying theory has a long history (e.g., Chaudhry and Meroney, 1973; van Ulden, 1978), and has been evaluated extensively with data from field studies and wind tunnel experiments. This theoretical understanding has been translated into formulations for plume spreads that are used in dispersion models such as AERMOD (Cimorelli et al., 2005). These formulations are functions of micrometeorological variables, such as surface friction velocity and Monin–Obukhov length, and have been evaluated with data from the Prairie Grass field study (Barad, 1958). Examples are those proposed by Venkatram (1982) and Briggs (1982). A version of this equation is included in AERMOD (Cimorelli et al., 2005).

The equations for plume spread are evaluated within the framework of the Gaussian dispersion model for estimating the concentration at a receptor, $(x, y, z)$,

$$\frac{C(x,y,z)}{Q} = \frac{1}{2\pi\sigma_z\sigma_y U}\left(exp\left[-\frac{1}{2}\left(\frac{z-z_s}{\sigma_z}\right)^2\right]+exp\left[-\frac{1}{2}\left(\frac{z+z_s}{\sigma_z}\right)^2\right]\right) \times exp\left(-\frac{y^2}{2\sigma_y^2}\right), \quad (1)$$

where $\sigma_y$ and $\sigma_z$ are a measure of plume spread in the horizontal and vertical, respectively, $Q$ is the emission rate, $U$ is the near surface wind speed, and $z_s$ is the source height.

In this paper, we adopt the plume spread equations incorporated in AERMOD (Cimorelli et al., 2005; Venkatram, 1992) to be representative of formulations in current use. The vertical spread, $\sigma_z$, of a surface release is estimated from

$$\begin{aligned}\sigma_z &= \sqrt{\tfrac{2}{\pi}}\,\tfrac{u_* x}{U}\left(1+0.7\tfrac{x}{L}\right)^{-1/3} L > 0.0 \\ &= \sqrt{\tfrac{2}{\pi}}\,\tfrac{u_* x}{U}\left(1+0.0006\left(\tfrac{x}{L}\right)^2\right)^{1/2} L < 0.0\end{aligned} \quad (2)$$

where $L$ is the Monin–Obukhov length defined by $L = -T_0 u_*^3/(\kappa g Q_0)$, $Q_0$ 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 $\kappa$ is the von Karman constant taken to be 0.40.

The horizontal spread of the plume used in Equation (1) is a purely empirical equation that fits the data from Prairie Grass (Cimorelli et al., 2005):

$$\begin{aligned}\sigma_y &= \tfrac{\sigma_v x}{U}(1+78X)^{-0.3} \\ \text{where } X &= \tfrac{\sigma_v x}{U z_i}\end{aligned} \quad (3)$$

and $\sigma_v$ is the standard deviation of the horizontal velocity fluctuations and $z_i$ is the mixed layer height.

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. We account for meandering by adopting the approach in AERMOD (Cimorelli et al., 2005) which assumes 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 horizontal distribution in Equation (1) is replaced by:

$$H(x,y,) = f_r\frac{1}{2\pi r} + (1-f_r)\frac{1}{\sqrt{2\pi}\sigma_y}exp\left(-\frac{y^2}{2\sigma_y^2}\right), \quad (4)$$

where the first term represents the random state in which the plume spread covers $2\pi$ radians, and $r$ is the distance between the source and receptor. The second term is the plume state corresponding to the Gaussian distribution.

The plume is transported at an effective velocity given by

$$U_e = \left(\sigma_u^2+\sigma_v^2+U(\bar{z})^2\right)^{1/2} = \left(2\sigma_v^2+U(\bar{z})^2\right)^{1/2}, \quad (5)$$

where $U(\bar{z})$ is the wind speed evaluated at the mean plume height and the expression assumes that $\sigma_v \approx \sigma_u$. The mean plume height, $\bar{z}$, a function of vertical spread, is formulated in Section 3. Note that the effective velocity is non-zero even when the mean velocity is zero. The minimum value of the effective velocity, $U_e$, is $2\sigma_v$.

The weight for the random component in Equation (4) is taken to be

$$f_r = \frac{2\sigma_v^2}{U_e^2}, \quad (6)$$

This ensures that the weight for the random component goes to unity when the mean wind approaches zero. The success of this meandering correction depends on measurements of $\sigma_v$, 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 (see Cimorelli et al., 2005).

The need to specify an effective wind speed, $U_e$, in Equations (1)–(6) highlights a problem with the application of the Gaussian dispersion equation to releases in the surface layer, where the wind speed varies rapidly with height. However, if the source height and the receptor height are close to zero, and the receptor is close to the line source, the ground-level concentration is insensitive to the choice of the height to evaluate the wind speed because the ground-level concentration is inversely proportional to the product $\sigma_z U$ (see Equation (2)), which is independent of $U$. When the release and receptor heights are non-zero, the concentration becomes more sensitive to $U$. This point is discussed in detail in Section 3.

We first examine the performance of current formulations for plume spread using data from the two field studies described next.

### 2.1. Evaluation with Prairie Grass field study

In each experiment of the Prairie Grass Project (Barad, 1958) the tracer, $SO_2$, was released from a point location at a height of 0.46 m, for an interval of 10 min, and the concentration was sampled along five semi-circular arcs at distances of 50, 100, 200, 400, and 800 m from the release. The samplers on the arcs were spaced at 2° intervals on the first four arcs, and at 1° on the 800-m arc for a total of 545 sampler locations. Roughly half of the 70 experiments were conducted under stable conditions, which covered both low and high wind-speed conditions. The mean wind was measured at 8 levels ranging from 0.125 m to 16 m. The standard deviation of the horizontal wind direction and vertical velocity fluctuations used in this study were derived from bivane measurements at a height of 2 m. The micrometeorological inputs, $u_*$ and $L$, computed by fitting M–O velocity and temperature profiles to tower measurements, are taken from van Ulden (1978). Lee and Irwin (1997) fitted Gaussian distributions to the concentrations along each arc and derived horizontal spreads and peak concentrations for each arc.