Using a Line Source Model to Estimate Near-Surface Concentration

Yifan Ding

1. Introduction

To simulate dispersion from road ways, a few models have been developed such as ADMS-ROADS, CALINE4, and the AERMOD. However most model for dispersion of roadway emissions are analytical approximation which may lead to large errors when the winds are light and variable, or when the wind direction is close to parallel to the road. Therefore, the current RLINE is based on Romberg numerical integration of the contribution of point sources along a line.

RLINE includes new formulations for the vertical and horizontal plume spread of near surface releases based on Prairie Grass data and Idaho Falls data. Additionally, the model contains a wind meander algorithm that accounts for dispersion at light and variable winds. The objective of this report is to reproduce the RLINE for all the cases and estimate the surface concentration with Idaho Falls data.

2. The Line Source Model

The Concentration of a line source in RLINE is found by approximating the line as the sum of a series of point sources. Each point source is simulated using a Gaussian plume formulation. The solution is a function of distance from the source line to the receptor.

2.1 Meteorological Inputs

The plume is transported at an effective velocity given by

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

where the $\bar{z}$ is the mean plume height given by

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

and $U(\bar{z})$ is the wind speed evaluated at the mean plume height using similarity theory

$$U = \frac{u_*}{0.35} \ln\left(\frac{z}{z_0}\right) - \psi(\zeta) \qquad (3)$$

where the dimensionless height ζ is defined as

$$\zeta = z/L$$

where $\psi(\zeta)$ is given by

$$\psi = 2\ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right) - 2\arctan(x) + \pi/2 \qquad \text{for } L \leq 0$$

with $x = (1 - 15\zeta)^{\frac{1}{4}}$

$$\psi = -4.7\zeta \qquad \text{for } L \geq 0$$

The lateral turbulent wind component is computed as

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

2.2 Numerical Line Source Approximation

The line source formulation is the sum of elemental point sources which contains plume components and meandering contributions. The concentration at (x_r,y_r) after coordinate rotation due to the line becomes

$$C(x_r, y_r) = \int_{yb}^{ye} \frac{q\,dy}{U_e \cos\theta} VERT\left[(1 - f_r) \cdot HORZ_{pl} + f_r \cdot HORZ_m\right] \qquad (4)$$

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

$$VERT = \frac{1}{\sqrt{2\pi}\sigma_z}\left(\exp\left[-\frac{1}{2}\left(\frac{z - z_s}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z + z_s}{\sigma_z}\right)^2\right]\right) \qquad (5)$$

The horizontal plume component is found by

$$HORZ_{\mathrm{pl}} = \frac{1}{\sqrt{2\pi}\sigma_y} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \qquad (6)$$

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. Assuming the horizontal plume spreads equally in all directions when wind speed approaches zero. The horizontal meander component has the form

$$\mathrm{HORZ_m} = \frac{1}{2\pi R} \qquad (7)$$

where R is the distance between receptors and the source line, which applies an approximation of x_d.This point is discussed in Section 2.3.

$$R = x_d \qquad (8)$$

The weight for the random component is taken to be

$$f_r = \frac{2\sigma_v^2}{{U_e}^2} \qquad (9)$$

2.3 Application Cases

When applying RLINE formulations, there is slight difference due to different receptor locations. Therefore all the cases are listed below

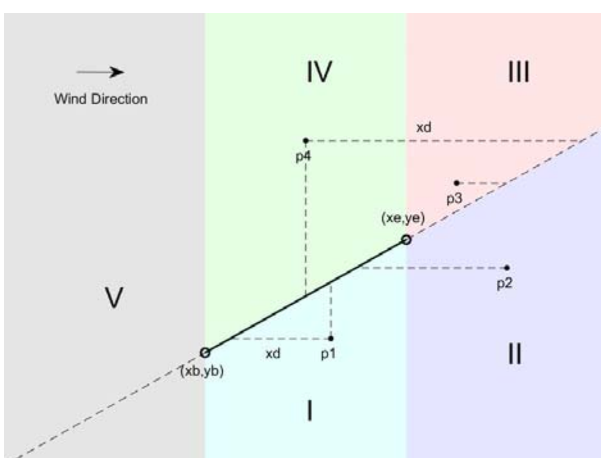

Figure 1: Coordinate after rotating of the source line

In the coordinate after rotating, there are four typical receptors named as p1, p2, p3, and p4 in the different area I, II, III, and IV respectively. (x_b, y_b) and (x_e, y_e) are the beginning and ending point of the source line. x_d is an approximation of the distance between receptors and the source line which is showed in horizontal dashed line.

Firstly, p2 in area II is the most common case, which x_d and (x_e, y_e) can be used directly. For p1 and p4 in area I and IV, (x_e, y_e) will be shifted to the intersection of the vertical line and the source line because there is no contribution on the right side of the vertical line. For p3, p4 in area III and IV, x_d is negative but there is still concentration from part or whole line. Therefore a new approximation is applied that x_d is assumed to be horizontal distance between the receptors and the midpoint of the source line segment with any contribution. In area V, there is no concentration at all even though x_d is positive in buttom of the area.

2.4 New Dispersion Formulations

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 mean plume height, and the vertical plume spread. By fitting Prairie Grass and Idaho Falls data, the new spread formulations are given by

$$\sigma_z = 0.57 \frac{u_*}{U_e} x \frac{1}{\left(1+3\frac{u_*}{U_e}\left(\frac{x}{|L|}\right)^{2/3}\right)} \qquad \text{for } L \leq 0 \qquad (10)$$

$$\sigma_z = 0.57 \frac{u_*}{U_e} x \left(1 + 1.5\left(\frac{u_*}{U_e}\frac{x}{|L|}\right)\right) \qquad \text{for } L \leq 0 \qquad (11)$$

Using an approach suggested by Eckman(1994), who showed the variation of σ_y with distance could be explained by variation of the effective transport wind speed. Venkatram et al. (2013) use Eckman's equation to derive expressions such that

$$\sigma_y = 1.6 \frac{\sigma_v}{u_*} \sigma_z \left(1 + 2.5\frac{\sigma_z}{|L|}\right) \qquad \text{for } L \leq 0 \qquad (12)$$

$$\sigma_y = 1.6 \frac{\sigma_v}{u_*} \sigma_z \left(1 + \frac{\sigma_z}{|L|}\right)^{-\frac{1}{2}} \qquad \text{for } L \leq 0 \qquad (13)$$

2.5 Determine the Plume Spread Iteratively

From Eq (1), (2), (3), (10), and (11), we notice that there are three iterative equations contains mean plume height, vertical spread, and effective wind velocity. To determine the optimal values of them, the following iterative algorithm is taken into the computation.

Algorithm 1 Determine Mean Plume Height

```
z_new=z_try
for i in range (N) do
  z_old=z_new
  U,Ue=Similarity_Wind(ustar,z_old,z0,L,sigmav)
  sigmay,sigmaz=Reformulation_Sigmayz(x,sigmav,ustar,L,Ue)
  z_new=Mean_Plume_Height(sigmaz,zs)
  if abs(z_new-z_old)/z_old<0.01 then
    break
  end if
end for
Result: z_new,z_old
```

An initial guess height is input to determine the final mean plume height which has the precision that is less than 1%. Then we apply this height into Eq (1), (2), (10), and (11) to evaluate the necessary variables for RLINE.

3. Comparison of Model to Idaho Falls Tracer Study

A line source experiment was conducted near Idaho Falls in 2008(Finn et al. 2010). There are 56 receptors and 5 tests spanning neutral, unstable, and stable conditions. This report analyzes only the center receptors for flat terrain.

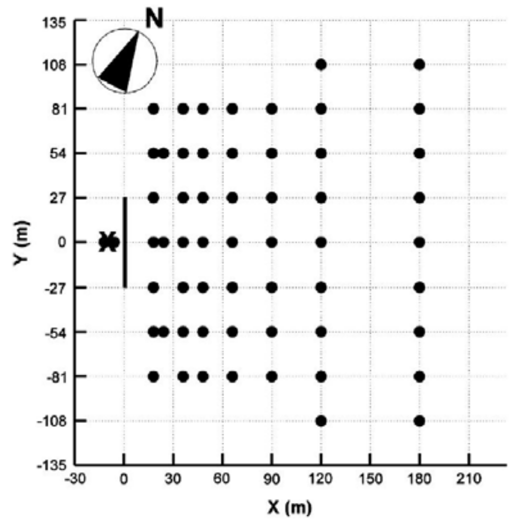

Figure 2: Schematic map of the sampling grid

Figure 3 shows the finite line source model predictions vs. the observed concentrations for the neutral, convective, weakly stable and stable cases in Idaho Falls.

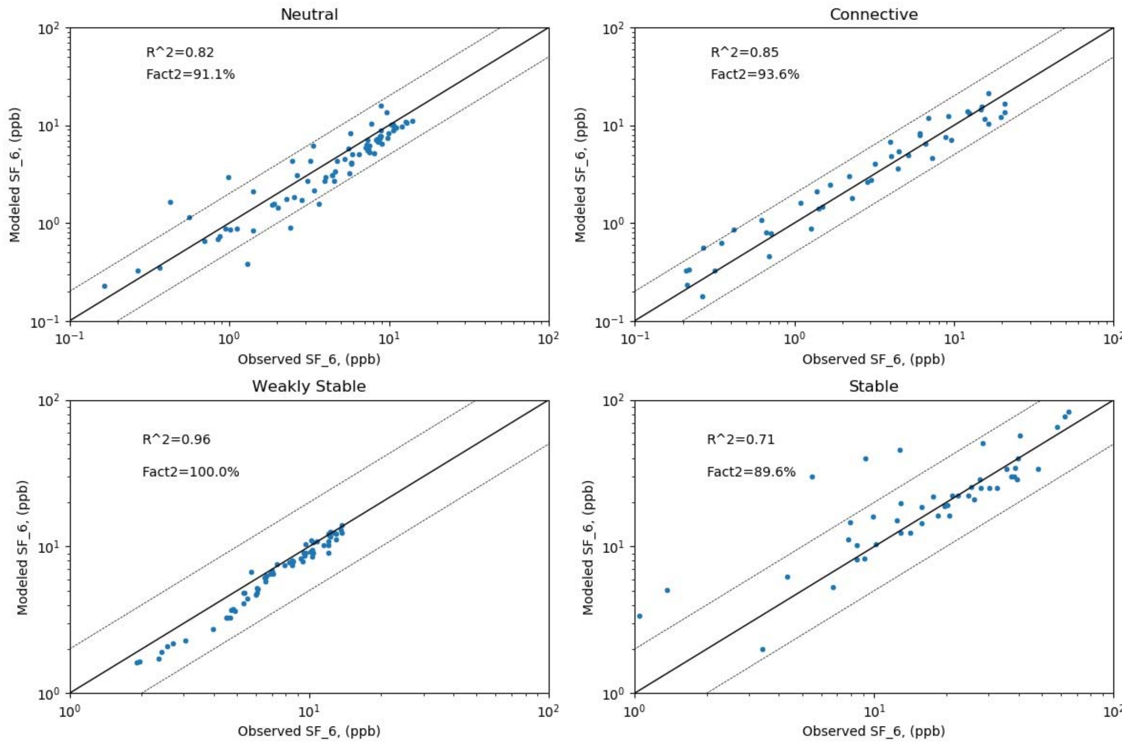

Figure 3: Scatter-plot of modeled and observed concentration

We can see RLINE performs very well except for stable case, which means the meander component should be improved in the future.

4. Summary

RLINE, a steady-state, line-source dispersion model, has been developed for near-surface applications. A line is simulated as the sum of the contributions from elemental point sources.

There are different approximation methods when receptors are at different locations, but we need more upwind data to examine the model completely.

An iterative algorithm is introduced to determine the plume spread and effective wind velocity. And the mean plume height is varying from 2-10m in entire experiment.

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