Atmospheric Environment 45 (2011) 4099–4107

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

An improved line source model for air pollutant dispersion from roadway traffic

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ARTICLE INFO

Article history:
Received 12 August 2010
Received in revised form
10 November 2010
Accepted 10 November 2010

Keywords:
Gaussian plume model
Line source
Polyphemus

ABSTRACT

Gaussian plume models, which are widely used to model atmospheric dispersion, provide an exact analytical solution for line sources such as roads only when the wind direction is perpendicular to the road. Some approximations have been developed to provide an analytical formula for a line source when the wind direction is not perpendicular to the road; however, such formulas lead to some error and the solution diverges when the wind direction is parallel to the road. A novel approach that reduces the error in the line source formula when the wind direction is not perpendicular to the road is presented here. Furthermore, a combination of analytical and numerical line source solutions is used to better represent cases where the wind direction becomes parallel to the road. The improved model was implemented in the Polyphemus modeling platform and it was successfully evaluated against a reference solution as well as observations obtained near a roadway in eastern France.

1. Introduction

Atmospheric dispersion models are used to estimate the air quality impacts of road traffic emissions for many purposes, such as attainment of ambient air quality standards, health risk assessment and decision support. It may be used for instance to assess the effect of emission control measures or to help select a new road location. It is thus essential to be able to predict with reasonable accuracy the pollutant concentrations associated with vehicle emissions. To that end, analytical models have been developed to simulate the effect of atmospheric dispersion on pollutant concentrations based on an emission rate from a roadway. In open terrain, Gaussian dispersion models are the most commonly used (e.g., Levitin et al., 2005; Berger et al., 2010; Venkatram et al., 2009; Chen et al., 2009). Although the Gaussian dispersion formula provides an exact solution to the atmospheric diffusion equation for the dispersion of a pollutant emitted from a point source given some assumptions on stationarity and homogeneity (Csanady, 1973), the Gaussian dispersion formula provides an exact solution for the emissions of a pollutant from a line source only in the case where the wind is perpendicular to the line source (Yamartino, 2008). It is, therefore, necessary to develop approximations to model atmospheric dispersion from a line source using a Gaussian formulation. Several solutions are used by state-of-the-art Gaussian models. In the CALINE series of models (Benson, 1992), the roadway is represented by a series of short road sections placed perpendicular to the wind; the number of segments (and the computational cost) increases as the wind becomes more parallel to the road. In the original formulation of the AERMOD model (Cimorelli et al., 2005), no line source formulation was available and a simulation of nitrogen dioxide (NO_2) concentrations due to roadway traffic in Atlanta required the use of the area source formulation and the discretization of the roadways in a very large number of area sources (EPA, 2008), thereby leading to very large computational costs. Another similar approach consists in representing the line source by a series of point sources with initial diameters commensurate with the road width (Karamchandani et al., 2009). This approach also becomes rapidly cumbersome computationally. There is, therefore, a need to develop approximate, yet reasonably accurate formulations based on the Gaussian dispersion formula that are computationally efficient. One example of such a formulation is that of Venkatram and Horst (2006) (see description below). We propose here an extension of that formulation that further minimizes the error due to the Gaussian formulation for a line source without significantly increasing the computational requirements. After a brief overview of that Gaussian formulation (Section 2), a description of the method used to develop the improved line source model is presented (Section 3). Next, a thorough comparison with an exact solution, given by a discretized source, is presented (Section 4). It provides a quantitative assessment of the decrease in the error obtained with the improved model as well as the remaining error. Finally, this model is included in the Gaussian

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doi:10.1016/j.atmosenv.2010.11.016

plume model of Polyphemus (Korsakissok and Mallet, 2009) and the model is evaluated against measurements made in the vicinity of a roadway (Section 4.4).

2. Gaussian plume formulations for line sources

The Gaussian formulation of the concentration field for a pollutant emitted from a point source is as follows, neglecting reflexion terms for simplicity (Csanady, 1973; Arya, 1999):

$$\mathrm{C}(x,y,z) = \frac{\mathrm{Q}}{2\pi \mathrm{u}\sigma_y\sigma_z}\exp\left(-\frac{y^2}{2\sigma_y^2}-\frac{z^2}{2\sigma_z^2}\right) \quad (1)$$

where C is the pollutant concentration in g m^{-3} at location (x, y, z), x is the distance from the source along the wind direction in m, y and z are the cross-wind distances from the plume centerline in m, u is the wind velocity in m s^{-1}, Q is the emission rate in g s^{-1}, and σ_y and σ_z are the standard deviations representing pollutant dispersion in the cross-wind directions in m. They are computed here with Briggs's parameterization (Equation (2); Briggs, 1973) where coefficients α, β and γ depend on the Pasquill stability classes and the x parameter represents the distance from the source (Appendix A).

$$\sigma_y(x) = \frac{\alpha x}{\sqrt{1+\beta x}} \quad ; \quad \sigma_z(x) = \alpha x(1+\beta x)^{\gamma} \quad (2)$$

Turbulent diffusion in the downwind direction is neglected here; this slender plume approximation (Seinfeld and Pandis, 1998) is justified because the along-wind dispersion of the plume is small compared with advection, assuming that receptors are not too close to the source and the wind velocity is not too low. To obtain the concentration field due to emission from a line source, Equation (1) is integrated over the line source to obtain the following integral equation:

$$\mathrm{C}(x,y,z) = \int_{y1}^{y2} \frac{\mathrm{Q}}{2\pi \mathrm{u}\sigma_y(s)\sigma_z(s)}\exp\left(\frac{-z^2}{2\sigma_z^2(s)}-\frac{(y-s)^2}{2\sigma_y^2(s)}\right)\mathrm{d}s \quad (3)$$

where y_1 and y_2 the ordinates of the source extremities.

When the wind is perpendicular to the line source, the integration of Equation (3) leads to the following analytical solution:

$$\mathrm{C}(x,y,z) = \frac{\mathrm{Q}}{2\sqrt{2\pi}\mathrm{u}\sigma_z(x)}\exp\left(\frac{-z^2}{2\sigma_z^2(x)}\right) \times \left[\mathrm{erf}\left(\frac{y-y_1}{\sqrt{2}\sigma_y(x)}\right) - \mathrm{erf}\left(\frac{y-y_2}{\sqrt{2}\sigma_y(x)}\right)\right] \quad (4)$$

Indeed, in a perpendicular wind case, both source coordinate system and wind coordinate system are identical (Fig. 1). Therefore, the distance of the receptor from the source in the wind direction, needed to compute σ_y and σ_z, does not change with the integration variable so no additional approximation is required. For other wind directions, the dependency of standard deviations on the integration variable makes the integration impossible without approximations. Various approximations can be made (Yamartino, 2008); we use here a formulation recently proposed by Venkatram and Horst (2006).

The Horst–Venkatram (HV) approximation consists in evaluating the integral by approximating the integrand with its behavior near $y_{\mathrm{wind}} = 0$ (see Fig. 1). The effective distance $\mathrm{d_{eff}}$ (Equation (5)) is used to compute σ_z and a distance d_i (Equation (6)) from each extremity of the line source section in the wind direction for σ_y.

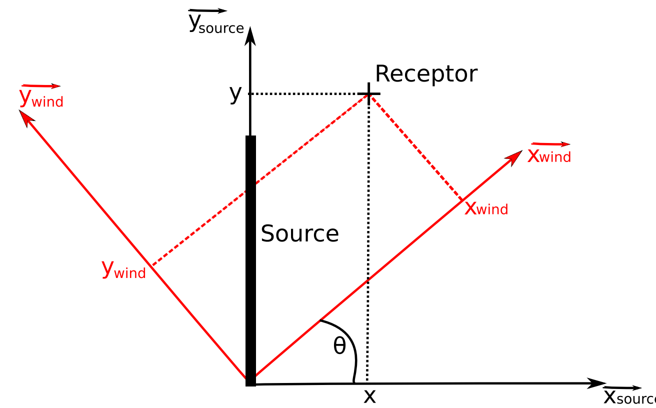

Fig. 1. Schematic representation of the source $(\overrightarrow{x}_{\mathrm{source}}, \overrightarrow{y}_{\mathrm{source}})$ and wind $(\overrightarrow{x}_{\mathrm{wind}}, \overrightarrow{y}_{\mathrm{wind}})$ coordinate systems. The wind angle θ is the angle between the normal to the source and the wind direction.

$$\mathrm{d_{eff}} = x/\cos\theta \quad (5)$$

$$\mathrm{d}_i = (x-x_i)\cos\theta + (y-y_i)\sin\theta \quad (6)$$

where x and y are the coordinates of the receptor and x_i and y_i the coordinates of the source extremity i (with $i = 1$ or 2) in the source coordinate system. The angle θ represents the angle between the normal to the line source and the wind direction.

Solving Equation (3) with the HV approximation leads to Equation (7), which provides the concentration field for all wind directions, except $\theta = 90°$. The term u$\cos\theta$ represents the projection of the wind velocity onto the normal direction to the source. For $\theta = 0°$, Equation (7) becomes identical to Equation (4). However, when the wind is parallel to the line source ($\theta = 90°$), the term $\cos\theta$, on the denominator of the equation, makes Equation (7) diverge.

$$\mathrm{C}(x,y,z) = \frac{\mathrm{Q}}{2\sqrt{2\pi}\mathrm{u}\cos\theta\sigma_z(\mathrm{d_{eff}})}\exp\left(\frac{-z^2}{2\sigma_z^2(\mathrm{d_{eff}})}\right) \times \left[\mathrm{erf}\left(\frac{(y-y_1)\cos\theta - x\sin\theta}{\sqrt{2}\sigma_y(\mathrm{d}_1)}\right) - \mathrm{erf}\left(\frac{(y-y_2)\cos\theta - x\sin\theta}{\sqrt{2}\sigma_y(\mathrm{d}_2)}\right)\right] \quad (7)$$

If d_i, the distance used to compute σ_{y_i} from both extremities is negative, the receptor is not downwind of the extremity i. A receptor can be downwind of an extremity and upwind of the other. In that case, in the HV approximation, a segment of the source is excluded of the calculation by setting the term: $\mathrm{erf}(((y-y_i)\cos\theta - x\sin\theta)/\sqrt{2}\sigma_y(\mathrm{d}_i))$ of Equation (7) to: $-\mathrm{sign}(\sin\theta)$.

This solution to the Gaussian equation for a line source has been shown to lead to small acceptable errors compared to an exact solution (Venkatram and Horst, 2006); nevertheless, some errors remain due to the approximate nature of the solution, especially when the wind is nearly parallel to the line source. The objective of this work is to further improve this solution for the concentration field while retaining a computationally-efficient analytical formulation to the extent possible.

3. Development of the improved line source formula

The approach used to develop an improved version of the HV model consists of (1) quantitatively assessing the error over the modeling domain and (2) approximating this error with analytical