H13-12
A NEW LINE SOURCE MODEL FOR AIR QUALITY IMPACTS OF ROADWAY TRAFFIC

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Abstract: Roadway traffic may adversely impact air quality and it is essential to be able to predict the pollutant concentrations associated with vehicle emissions.

A standard approach to model atmospheric dispersion consists in using a Gaussian plume model, which means using an analytical Gaussian formula to represent atmospheric dispersion from point sources. This representation of sources is well adapted to model chimneys for instance but not to model roads. Indeed a road needs to be discretized with a huge number of point sources, which makes the computational time excessive. On the other hand, using a line source Gaussian formula could be an efficient alternative but this formula is only exact when the wind is perpendicular to the road.

The solution presented here combines both approaches in an optimal fashion, thus decreasing the computational burden while maintaining good accuracy. The model performance (computational time and precision) is evaluated against an exact solution as well as with observations obtained near a freeway in eastern France.

Key words: *Roadway traffic, Gaussian plume model, Point sources, Line sources.*

INTRODUCTION

Roadway traffic may adversely impact air quality and it is essential to be able to predict with reasonable accuracy the pollutant concentrations associated with vehicle emissions. A new model that combines analytical and numerical solutions to the atmospheric diffusion equation is presented here and applied to a case study.

Gaussian plume models are widely used to model atmospheric dispersion. They are based on an analytical formula to model dispersion from pollution sources represented by points. To model a line emission such as a road, the use of point sources implies to discretize it and to use a large number of points. The precision of the results is related to the discretization step which means that the more point sources per road section we use, the more precise the concentration will be. Because the computational time required for a simulation increases linearly with the number of sources, such an approach may become cumbersome for a large road network.

Using a line source Gaussian formula would then be an efficient alternative because we would have only one source per road section. However, the analytical solution for a line source is only exact when the wind direction is perpendicular to the road (Yamartino, 2008). Indeed, the approximation required to be able to compute an analytical formula for a line source, induces some significant error when the wind direction becomes parallel to the road.

We present here a new solution that combines both approaches in an optimal fashion, thus decreasing the computational burden while maintaining good accuracy. The model performance is evaluated against an exact solution as well as with observations obtained near a freeway in eastern France.

GAUSSIAN PLUME MODEL USING LINE SOURCES

Gaussian models in general require some hypotheses in order to lead to an analytical formula. We first assume that the emission rate and meteorological parameters are constant so that the plume is at steady state and doesn't change with time. Then we assume that the wind is strong enough so that the turbulent diffusion in the wind direction is not significant compared with the advection (slender plume approximation) (Arya 1999; Seinfeld and Pandis 1998).

The Gaussian analytical formula used to compute concentrations (C in $g.m^{-3}$) at a receptor point due to a line source is obtained by solving equation (1). It represents the integral along the line source of a continuous point source.

$$C(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(\frac{-z^2}{2{\sigma_z}^2}\right) \int_{y_1}^{y_2} \exp\left(\frac{-(y_{wind}-s)^2}{2\sigma_y(s)^2}\right) ds \qquad (1)$$

- x, y, z: coordinate of the receptor point in the reference system of coordinates (m).
- Q: emission rate ($g.s^{-1}$).
- u: wind speed ($m.s^{-1}$).
- y_1 and y_2: ordinates of source extremities (m).
- σ_y and σ_z: the dispersion coefficients along y and z axes (m).
- y_{wind}: coordinate y in the wind system of coordinates (m).
- s: variable of integration representing all points of the line source.

To solve this equation for cases when the wind is not perpendicular to the road, another approximation is required. Here we selected the HV approximation (Venkatram and Horst, 2005). It consists in using the effective distance between the receptor and the source in the wind direction, to compute dispersion coefficients. This simplifies equation (1) and makes it possible to solve it by the use of a variable change, equation (2).

$$C(x,y,z)=\frac{Q}{2\sqrt{2\pi}u\cos\theta\sigma_z}\exp\left(\frac{-z^2}{2\sigma_z{}^2}\right)\left[erf\left(\frac{(y-y_1)\cos\theta-x\sin\theta}{\sqrt{2}\sigma_{y_1}}\right)-erf\left(\frac{(y-y_2)\cos\theta-x\sin\theta}{\sqrt{2}\sigma_{y_2}}\right)\right] \quad (2)$$

- θ : the angle between the normal to the source and the wind direction (rad).

We notice that when the wind direction is parallel to the road, the computed concentration is infinite ($\cos\theta = 0$). Therefore we assume that the solution can then be approximated by that for $\theta = 89°$. When the wind is perpendicular to the road, equation (2) becomes identical to the basic analytical solution.

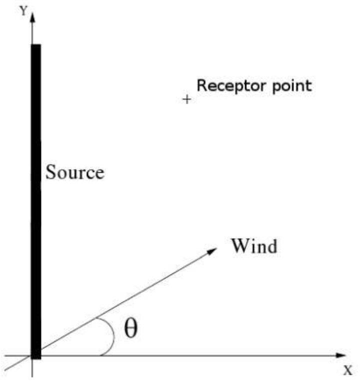

Figure 2. θ is the angle between the wind direction and the direction perpendicular to the road.

We wish to compare the solution of equation (2) to an "exact" solution. This reference solution was obtained by representing the line source by a very large number of point sources until convergence was obtained (i.e., when doubling the number of point sources did not lead to a significant change in the solution). To estimate the error, we assume heteroscedasticity and the error between the line source analytical formula and the exact solution is computed as in equation (3). Equation (3) computes a relative error so that it does not depend on the multiplicative factor in front of the equation (e.g., emission rate, wind speed and σ_z).

$$Error(x,y,z)=\frac{C_{line}(x,y,z)-C_{discretized}(x,y,z)}{C_{discretized}(x,y,z)} \quad (3)$$

- Error: relative error.
- C_{line}: Concentration computed with a line source ($g.m^{-3}$).
- $C_{discretized}$: Concentration computed with a large number of point sources ($g.m^{-3}$).

Line source / Point sources combination

For small wind angles (i.e. when the direction is nearly perpendicular to the road), the error value is small so no correction is needed. The method presented here consists in using both a line source and point sources for angle between 70° and 90° (in the first quadrant) as in equation (4) to compute a corrected concentration ($C_{corrected}$ in $g.m^{-3}$). Then by symmetry, the same method is applied to other quadrants.

$$C_{corrected}(x,y,z)=\alpha C_{line}+(1-\alpha)C_{discretized} \quad (4)$$

- α : coefficient which varies between 1 and 0 as θ varies between 70° and 90°.

This method allows one to compute concentrations with only one line source per road section for wind angles in range of 0° to 70°. Then for wind angles greater than 70° the computation of a discretized source is needed. However, because of the combination between line source and point sources, the number of point sources needed depends on the desired accuracy. It can be lower than for a fully discretized source because the solution is weighted by the line source solution. Therefore additional computational time needed is not too important.

RESULTS

Evaluation of the new model against the reference solution

This new model was implemented into the Gaussian plume model (Korsakissok and Mallet, 2009) of the modelling platform Polyphemus (Mallet *et al*., 2007). We performed some simulations and computed the correlation between the reference results and the line source results with and without the correction. The Figure 2 (left) shows that without the combination, the correlation around 90° and 270° (when the wind is parallel to the road) goes down to 0.46, which is not the case when we apply the combination. Indeed, the Figure 2 (right) shows that, with the combination, the correlation remains between 0.99 and 1.

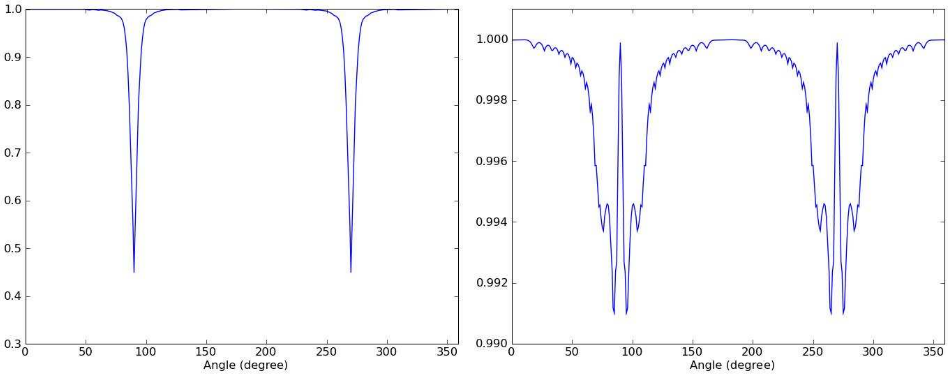

Figure 2. Correlation between the reference results and the line source results with (right) and without (left) the combination, as a function of the wind angle θ (in degree).

Figure 3 shows that the computed concentration is closer to the reference concentration and that the relative error is smaller, with the combination than without.

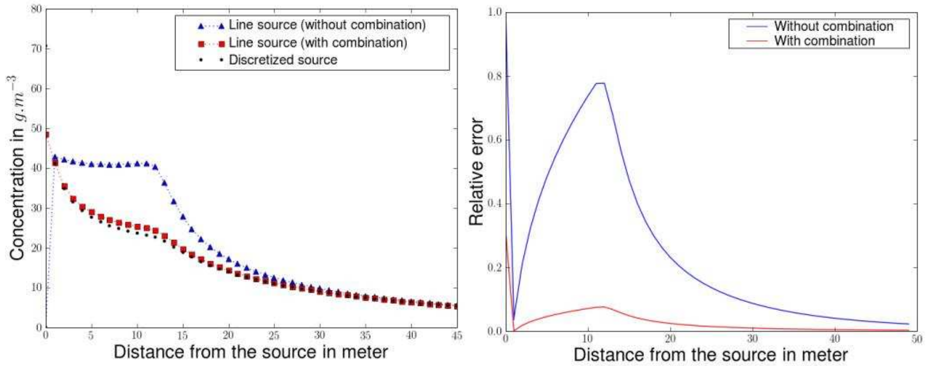

Figure 3. Concentration (left) and relative error (right) as a function of the distance of the receptor from the center of the source (θ = 88°).

In terms of computational time, performing a simulation with one line source, without the combination is equivalent to performing the same simulation with 2 point sources. The combination presented here is applied only for a small range of angles (for angles between 70° and 90° in the first quadrant). It requires computing both line source and point sources which increases the computational time but not as much as with a simulation with only point sources. The number of point sources added is related to the road length and the desired accuracy, which is then reflected in the increase in computational time as well.

Evaluation of the new model against observations

The report by Taghavi *et al*. (2009) summarizes a study conducted in cooperation with the CETE of Lyon. It uses some measurements of cadmium deposition, made during the whole month of February 1997 near a roadway, to evaluate the CFD model Code-Saturn (Milliez and Carissimo 2007), the ADMS model (a British model, widely used in Europe), and the original Gaussian plume model of Polyphemus (with point sources).

Here, we added the Gaussian plume model using line sources of Polyphemus to the comparison made in the report so that it could also be compared to the observations and the other models.

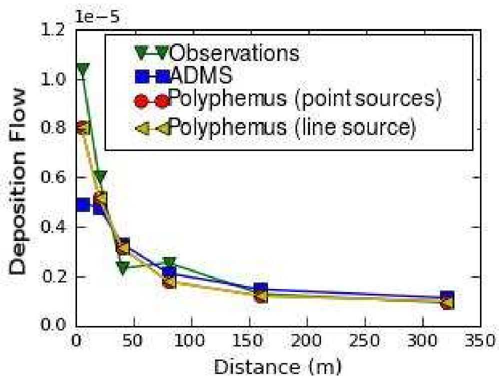

Figure 4. Average corrected cadmium deposition flow (in $\mu g.m^{-2}s^{-1}$) during 19 days of February 1997.

We notice on Figure 4 that all 3 models are close to the observations. However, both Polyphemus models, which give approximately the same results, are closer than the ADMS model to the observations. This discrepancy may be due to the selection of the initial plume height. In terms of precision, both Gaussian plume models are equivalent but in terms of computational time, the Gaussian plume model using line sources is much more efficient (about 10 times faster for this specific simulation, depending of the desired precision)

CONCLUSION

The results presented here are very promising because the correlation between the results and the references is almost equal to 1 for the entire range of angles and the relative error is highly reduced. The computational burden is also reduced because only 1 line source is needed when the combination is not applied and only a smaller number of sources when it is applied.

Ongoing work is now to reduce the computational time even more by adding a corrective term directly into the Gaussian formula. In that way, no combination would be needed and only 1 line source per road section would suffice for the entire range of angles.

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