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# Atmospheric dispersion modeling near a roadway under calm meteorological conditions

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A B S T R A C T

Atmospheric pollutant dispersion near sources is typically simulated by Gaussian models because of their efficient compromise between reasonable accuracy and manageable computational time. However, the standard Gaussian dispersion formula applies downwind of a source under advective conditions with a well-defined wind direction and cannot calculate air pollutant concentrations under calm conditions with fluctuating wind direction and/or upwind of the emission source. Attempts have been made to address atmospheric dispersion under such conditions. This work evaluates the performance of standard and modified Gaussian plume models using measurements of $NO_2$, $PM_{10}$, $PM_{2.5}$, five inorganic ions and seven metals conducted near a freeway in Grenoble, France, during 11–27 September 2011. The formulation for calm conditions significantly improves model performance. However, it appears that atmospheric dispersion due to vehicle-induced turbulence is still underestimated. Furthermore, model performance is poor for particulate species unless road dust resuspension by traffic is explicitly taken into account.



## Introduction

Studies have shown that populations spending large amounts of time near major roadways have an increased incidence and severity of health problems that may be related to air pollution from roadway traffic (Baldauf et al., 2008). Health effects include reduced and impaired lung function, asthma and other respiratory symptoms, cardiovascular effects, low birth weight, cancer, and premature death (e.g., Garshick et al., 2003; Janssen et al., 2002; Gauderman et al., 2005; Heinrich et al., 2005; McConnell et al., 2006; Pirjola et al., 2006). Therefore, it is essential to estimate population exposure near roadways in support of exposure and epidemiological studies as well as for impact studies of future roadway projects. To that end, one needs to select traffic, emission, and air quality models relevant to the given case study. Traffic models can be classified as static or dynamic models according to spatio-temporal scales. However, in many studies, traffic data are

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available from measurements that can be used directly as inputs for emission models. Emission models use traffic data (fleet composition, vehicle speed, etc.) and other relevant data (e.g., road gradient, ambient temperature) to estimate traffic-related emissions of air pollutants, which are used as inputs to an atmospheric dispersion model. A variety of atmospheric dispersion models are available to simulate the concentrations of air pollutants as a function of time and space, with different levels of details (Holmes and Morawska, 2006; Zannetti, 1990; Sportisse, 2009). Eulerian and Lagrangian models are typically used for large domains, ranging from urban to global scales. At local scales (i.e., near emission sources), different models are used depending on topography. Gaussian dispersion models are typically used for cases without obstacles or with obstacles of simple geometry. Street-canyon models may be appropriate for cities with high buildings, although for cases with complex geometries computational fluid dynamics (CFD) models may be required.

In this work, we use a Gaussian dispersion model to simulate air pollutant concentrations near a roadway. Actual traffic data are used as input to estimate air pollutant emissions. Concentrations of pollutants were measured near the roadway for a two-week period. Local meteorological measurements were also available. During that period, wind speeds were mostly low and the prevailing wind direction was such that the measurement site was located mostly upwind of the roadway. Most Gaussian dispersion models are designed for receptors located downwind of the roadway and for conditions with a significant wind speed (Benson, 1989; Zhang and Batterman, 2010; Kenty et al., 2007). However, conditions with calm meteorological conditions and upwind locations are also relevant to population exposure. Therefore, this study examines the performance of a Gaussian model with and without modification for calm meteorological conditions using the measurements conducted near a roadway. First, the formulation of the atmospheric dispersion model is briefly presented. Then, the field campaign is described. Finally, the model simulation results are presented and discussed.

## Model description

The emission and atmospheric dispersion models must be selected such that they are consistent in terms of level of detail, input requirements, and spatial and temporal resolution. An emission model based on average vehicle speed is appropriate here considering the available traffic data.

Two steady-state models are used here to simulate the atmospheric dispersion of pollutants: a Gaussian plume model for roadway sources (Briant et al., 2011, 2013) and this plume model augmented with a formulation suitable for conditions with light winds (Venkatram et al., 2013).

### *Gaussian plume formulation for roadway sources*

The Gaussian dispersion model used here for the atmospheric dispersion of pollutants emitted from a roadway is that of Briant et al. (2011, 2013). The concentration field is calculated with an equation that minimizes the error when the wind direction is not perpendicular to the roadway:

$$C_p(x,y,z) = \frac{qF(z)}{2\sqrt{2\pi}u\cos\theta\sigma_z(d_{eff})} \times [erf(t_1) - erf(t_2)] \times \left(\frac{1}{L(x_{wind})+1}\right) + E(x_{wind}, y_{wind}, z) \tag{1}$$

where, $t_i = \frac{(y-y_i)\cos\theta - x\sin\theta}{\sqrt{2}\sigma_y(d_i)}$; $F(z) = \left(\exp\left(-\frac{(h_s-z)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(h_s+z)^2}{2\sigma_z^2}\right)\right)$; $d_{eff} = \frac{x}{\cos\theta}$; $d_i = (x - x_i)\cos\theta + (y - y_i)\sin\theta$.

$C$ is the pollutant concentration in g m$^{-3}$ at the location of the receptor ($x$, $y$, $z$), $x$ 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, $x_i$ and $y_i$ are the coordinates of the source (road segment) extremities, $u$ is the wind velocity in m s$^{-1}$, $q$ is the emission rate per unit length of the line source in g m$^{-1}$ s$^{-1}$, and $\sigma_y$ and $\sigma_z$ are the standard deviations representing pollutant dispersion in the cross-wind directions in m. $L$ and $E$ are analytical functions that minimize the error when the wind direction is not perpendicular to the line source. The standard deviations $\sigma_y$ and $\sigma_z$ are computed here with the Briggs parameterization (Briggs, 1973). The effective distance $d_{eff}$ is used to compute $\sigma_z$ and $d_i$ is the distance from each extremity of the line source section in the wind direction used to compute $\sigma_y$. This equation applies when the angle $\theta$ between the wind direction and the normal to the road segment ranges from 0° to 80°.

When the wind is parallel or nearly parallel ($80° \leqslant \theta \leqslant 90°$) to the roadway, the concentration, $C$, is calculated as a combination between Eq. (1) and a numerical solution ($C_{\text{discretized}}$) obtained by discretizing the line source as a series of point sources:

$$C = (1-\alpha)C_p + \alpha C_{\text{discretized}} \tag{2}$$

The coefficient $\alpha$ varies linearly from 0 to 1 when $\theta$ vary from 80° to 90°.

This model was successfully evaluated against a reference solution as well as against observations obtained over a large road network in France (Briant et al., 2013). The overall spatial correlations for nitrogen dioxide ($NO_2$) concentrations measured and modeled at 242 sites were between 0.74 and 0.79, which indicates that the model explains more than half of the spatial variability observed in the monthly-averaged observations. Although the results for spatial variability were satisfactory, the ability of the model to reproduce temporal variability could not be evaluated in this previous work (Briant et al., 2013) because of a lack of hourly-averaged data. However, the temporal correlations between observed and modeled concentrations are typically poor for many models. For example Misra et al. (2013) obtained a correlation of hourly