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Modeling the impact of solid noise barriers on near road air quality

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HIGHLIGHTS

- Developed a dispersion model algorithm for noise barriers in unstable meteorology.
- Account for the lofting of the plume above the height of the barrier.
- Simulate the entrainment of the elevated plume into the cavity behind the barrier.
- Model compared to field measurement data in Phoenix, Arizona, USA.
- Model predicted reductions similar, but slightly lower, than field measurements.

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ABSTRACT

Studies based on field measurements, wind tunnel experiments, and controlled tracer gas releases indicate that solid, roadside noise barriers can lead to reductions in downwind near-road air pollutant concentrations. A tracer gas study showed that a solid barrier reduced pollutant concentrations as much as 80% next to the barrier relative to an open area under unstable meteorological conditions, which corresponds to typical daytime conditions when residents living or children going to school near roadways are most likely to be exposed to traffic emissions. The data from this tracer gas study and a wind tunnel simulation were used to develop a model to describe dispersion of traffic emissions near a highway in the presence of a solid noise barrier. The model is used to interpret real-world data collected during a field study conducted in a complex urban environment next to a large highway in Phoenix, Arizona, USA. We show that the analysis of the data with the model yields useful information on the emission factors and the mitigation impact of the barrier on near-road air quality. The estimated emission factors for the four species, ultrafine particles, CO, NO_2, and black carbon, are consistent with data cited in the literature. The results suggest that the model accounted for reductions in pollutant concentrations from a 4.5 m high noise barrier, ranging from 40% next to the barrier to 10% at 300 m from the barrier.

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1. Introduction

With a growing number of studies linking population exposures to nearby traffic emissions with adverse health effects (e.g. summary by Health Effects Institute, 2010), interest has increased in identifying methods to mitigate these impacts. One approach that has received recent attention is the use of roadway design to reduce near-road pollution concentrations. The designs include roadside noise barriers, roadside vegetation, and elevated or depressed roadways (Baldauf et al., 2009). Field measurements have shown that solid roadside noise barriers have the potential to reduce downwind pollutant concentrations (Baldauf et al., 2008; Ning et al., 2010; Hagler et al., 2012). Wind tunnel simulations (Heist et al., 2009); computational fluid dynamics modeling (Hagler et al., 2011); and tracer gas studies (Finn et al., 2010) also indicated that solid roadside barriers represent practical mitigation

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methods that can result in substantial reductions in pollutant concentrations caused by line source emissions, such as those from traffic, relative to those in the absence of barriers.

Schulte et al. (2014) initially developed a semi-empirical dispersion model to estimate the impact of solid barriers on pollutant transport and dispersion using data from the tracer study described by Finn et al. (2010). This paper uses a modified version of the Schulte et al. (2014) model to interpret data from a field study conducted in the vicinity of an urban highway in Phoenix, Arizona, USA (Baldauf et al., 2016). The field study in Phoenix provides a real-world evaluation of solid barrier effects, where we expect a multitude of confounding factors that are absent in a controlled tracer study. The Phoenix data was collected during daytime using a mobile platform that measured concentrations of several pollutants on the highway and at distances of up to 300 m away from the road, both with and without a solid barrier present. The reductions in concentrations associated with the 4.5 m high noise barrier ranged from 40% to 50% relative to concentrations measured along the same stretch of highway in the absence of the barrier.

2. Modified barrier model

Wind tunnel observations (Heist et al., 2009) and computational fluid dynamics modeling (Hagler et al., 2011) indicate that the major effects of solid barriers on downwind pollutant concentrations are: 1) pollutants emitted from the road become well-mixed in a zone extending from the ground to the barrier height and this mixing persists downwind over several barrier heights 2) turbulent velocities are increased downwind of the barrier, and 3) the pollutant plume is lofted above the top of the barrier, which results in a concentration maximum above the top of the barrier.

Schulte et al. (2014) developed a semi-empirical dispersion model that incorporated some of the observed effects induced by barriers on dispersion. The model assumes that the pollutant is well mixed below the height of the wall. This assumption coupled with the increase in turbulence by the wall provided an adequate description of the data from the wind tunnel (Heist et al., 2009) and tracer studies Finn et al. (2010) during near neutral conditions. However, the model overestimated concentrations close to the barrier under unstable conditions.

In this paper, we modify the model of Schulte et al. (2014) to reduce the overestimation close to the barrier. First, we loft the plume maximum above the wall as observed in the wind tunnel. Second, we reduce the entrainment of the elevated plume into the wake of the wall through a function that depends on stability characterized by the Monin-Obukhov length.

The model is based on the Gaussian plume formulation for the concentration $C(x,z)$ from an infinite line source:

$$C(x,z) = C_{\max}\left[\exp\left(-\frac{1}{2}\left(\frac{z-h_p}{\sigma_z}\right)^2\right) + \exp\left(-\frac{1}{2}\left(\frac{z+h_p}{\sigma_z}\right)^2\right)\right] \tag{1}$$

where h_p is the effective plume height. Equation (1) defines the profile of the concentration above the well mixed region that extends below the wall height, h_w. Below h_w, the concentration is well mixed and is denoted by C_s,

$$C_s = f_m C(x, z = h_w), \tag{2}$$

where h_w is the wall height, and f_m is an entrainment coefficient we will parameterize later.

We compute C_{max} by conserving the horizontal flux of material:

$$\left(U_w C_s h_w + U_e \int_{h_w}^{\infty} C(x,z)dz\right)\cos\theta = q, \tag{3}$$

Where q is the emission rate of the line source, U_w is the velocity in the well mixed region, which is taken to be the value at $z = h_w$, U_e is the effective transport velocity of the plume material above the wall height and θ is the angle between the mean wind and the normal to the line source. Note that σ_z in Equation (1) is evaluated at $x/cos\theta$, where x is the perpendicular distance of the receptor from the line source. The vertical spread,σ_z, and the effective velocity, U_e, are estimated using the formulations described in Schulte et al. (2014).

The first term on the left hand side of Equation (2) is the mass being transported below the wall, and the second term is the mass transported above the wall. Substituting Equations (1) and (2) into (3) yields the expression for C_{max},

$$C_{\max} = q\Big/\left(\cos\theta\left(h_w U_w f_m\left(\exp\left(-p_1^2\right) + \exp\left(-p_2^2\right)\right) + U_e\sigma_z(2 - erf(p_1) - erf(p_2))\right)\right), \tag{4}$$

where erf is the error function, and

$$p_1 = \left(\frac{h_w - h_p}{\sqrt{2}\sigma_z}\right),\ p_2 = \left(\frac{h_w + h_p}{\sqrt{2}\sigma_z}\right). \tag{5}$$

Then, C_s, the ground-level concentration can be calculated from Equation (2) once the entrainment factor, f_m, is specified.

In Schulte et al. (2014), we took $f_m = 1$ in Equation (2), and the plume height, $h_p = h_w$, which implies that the plume concentration decreases above the wall. In the modified model, we loft the plume above the wall by taking $h_p = h_w + \sigma_z/2$, where the plume properties correspond to the modified micrometeorology after the wall. We now allow f_m to be small next to the wall to reduce the wall's mixing effect during unstable conditions. The entrainment factor is parameterized as

$$f_m = f_c + (1 - f_c)(1 - \exp(-x/L_s)), \tag{6}$$

where the entrainment factor, f_c, at $x = 0$ is taken to be a function of the Monin-Obukhov length, L_{MO},

$$f_c = \exp(-L_s/|L_{MO}|), \tag{7}$$

Equation (6) is designed to allow the entrainment factor to approach unity over a length scale, $L_s = 10h_w$. The factor, f_c, ensures that the entrainment into the cavity behind the wall decreases as $|L_{MO}|$ decreases: the entrainment decreases as the surface layer becomes more unstable.

We account for the effect of the finite length of the source using the approximation described in Venkatram and Horst (2006). In applying the model to a highway, we assume that the center of each lane is a line source, and the traffic flow is distributed equally among the lanes.

3. Evaluation with Idaho Falls field study

The set of parameterizations described here were obtained by comparing model estimates to observations made in the Idaho Falls tracer experiment, details of which are described in Finn et al. (2010). In brief, the field study was conducted in 2008 near NOAA's Grid 3 diffusion grid at the Department of Energy's Idaho

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