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Effects of solid barriers on dispersion of roadway emissions

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HIGHLIGHTS

- Roadside barriers mitigate the impact of vehicular emissions on near road air quality.
- The concentration reduction is largest during stable conditions.
- The primary effect of barriers is to mix pollutants over the barrier height.
- A simple model that incorporates enhanced mixing describes observations.

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ABSTRACT

Several studies have found that exposure to traffic-generated air pollution is associated with several adverse health effects. Field studies, laboratory experiments, and numerical simulations indicate that roadside barriers represent a practical method of mitigating the impact of vehicle emissions because near road concentrations are significantly reduced downwind of a barrier relative to concentrations in the absence of a barrier. These studies also show that the major effects of barriers on concentrations are: 1) the concentration is well mixed over a height roughly proportional to the barrier height, and this effect persists over several barrier heights downwind, 2) the turbulence that spreads the plume vertically is increased downwind of the barrier, 3) the pollutant is lofted above the top of the barrier. This paper ties these effects together using two semi-empirical dispersion models. These models provide good descriptions of concentrations measured in a wind tunnel study and a tracer field study. Their performance is best during neutral and stable conditions. The models overestimate concentrations near the barrier during unstable conditions. We illustrate an application of these models by estimating the effect of barrier height on concentrations during neutral, stable, and unstable conditions.

1. Introduction

A comprehensive study conducted by the Health Effects Institute (2010) concluded that living within about 300–500 m of a major road is associated with several adverse health effects such as impaired lung function and cardiovascular mortality (HEI, 2010). Air quality monitoring studies conducted near major roadways indicate that these health effects are associated with elevated concentrations, compared with overall urban background levels, of motor-vehicle-emitted compounds, which include carbon monoxide (CO); nitrogen oxides (NO_x); coarse ($PM_{10\text{-}2.5}$), fine ($PM_{2.5}$), and ultrafine ($PM_{0.1}$) particle mass; particle number; black carbon (BC), polycyclic aromatic hydrocarbons (PAHs), and benzene (Hitchins et al., 2000; Kim et al., 2002; Zhu et al., 2002; Kittelson et al., 2004).

Several approaches have been suggested to mitigate the near road impact of vehicle emissions, including optimized roadside noise barriers, roadside vegetation, elevated or depressed roadways, road canopies in combination with methods to treat the pollutants trapped in the canopies (McCrae, 2010), catalytic coatings on barriers to convert NO_2 to nitrate (McCrae, 2010), and dynamic traffic management based on forecasts of conditions that might lead to poor air quality (McCrae, 2010). It turns out that one of the most practical mitigation methods is the use of roadside barriers.

We summarize the effects of barriers on near road concentrations by reviewing results from field studies, laboratory experiments, and numerical simulations using Computational Fluid

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Dynamics (CFD). We then propose two semi-empirical models that capture the essential features of the results from these studies. These models are designed to provide guidance on the design of barriers to mitigate exposure to vehicle related pollutants. We illustrate their application by estimating the impact of barrier height on near road concentrations under neutral, unstable, and stable atmospheric conditions.

2. Recent studies on barrier effects

Heist et al. (2009) studied dispersion of roadway emissions in a 1:150 scale model of a 6 lane divided highway. 12 road configurations were simulated: one with flat terrain with no barrier, six with flat terrain and upwind or downwind barriers, one with an elevated roadway, three with depressed roadways, and one with a depressed roadway with both upwind and downwind barriers.

Finn et al. (2010) examined the effect of a barrier on the dispersion of SF_6 tracer gas from a line source. The tracer was released from two identical 54 m long line sources. One source was located 6 m upwind of a 90 m long, 6 m high solid barrier and the other had no structures next to it. Tracer concentrations were measured simultaneously on identical sampling grids downwind of the sources. Six sonic anemometers measured turbulence around the barrier and atmospheric parameters were measured with other instruments.

Baldauf et al. (2008) conducted a field study in the vicinity of interstate I-440, Raleigh, North Carolina, to measure concentrations of NO_x, particulate matter, and air toxics behind a 1 km long noise barrier. Concentrations were measured using fixed sampling instruments and a mobile laboratory measuring PM size distributions at varying locations. This mobile laboratory was used to make measurements without a barrier, with a barrier, and with a barrier and vegetation. Ning et al. (2010) measured particulate and gas concentrations near the I-710 and I-5 freeways. Two sites were measured near each freeway, one with a noise barrier present and one with no barrier. A mobile platform sampled PM size distributions as well as black carbon, CO, and NO_2, concentrations.

A study (Hooghwerff et al., 2010; McCrae, 2010) conducted in Putten, the Netherlands, between 2007 and 2009 measured PM, NO_x, and NO_2 concentrations behind 9 different barriers next to a major freeway. Measurements were taken for 3 months for each barrier. A 4 m tall barrier was chosen as a reference and a 7 m tall barrier and seven other "optimized" 4 m tall barriers were tested. The optimized barriers included barriers with TiO_2 coatings, vegetated barriers, porous barriers, and barriers with a T-shaped top.

In all these studies, the ground level concentration immediately behind a 6 m barrier was 15–50% lower than the concentration with no barrier when the wind direction was close to perpendicular to the barrier, although the Idaho Falls study (Finn et al., 2010) found some concentration deficits greater than 50%. Concentrations were typically less than about 50% of the non-barrier concentrations in the wake zone of the barrier, although in some cases concentrations were as low as 20% of the non-barrier concentrations. This is similar to the concentration reduction found in the wind tunnel study by Heist et al. (2009). The Raleigh study (Baldauf et al., 2008) found that concentrations downwind of the barrier were decreased by 15–50% when the wind blew from the road. PM concentrations were reduced by up to 50%, with an average reduction of 20%. The effect of the barrier persisted up to at least 20 times the barrier height in these studies, after which the concentration approached the value that would occur without a barrier.

The wind tunnel study (Heist et al., 2009) found that the ground level concentrations beyond a distance of about 10 times the height of the barrier could be modeled as a ground level source with two modifications: 1) the source is shifted upwind, and 2) the effective rate of vertical plume spread, the entrainment velocity, w_e, relative to the friction velocity, u_*, is increased in the presence of a barrier (Heist et al., 2009). The upwind shift in source location depends on the particular geometry, with larger shifts necessary when multiple physical effects are combined. The study also found that the entrainment velocity depends on the surface friction velocity and the road geometry, with larger entrainment velocities occurring for cases with barriers rather than flat terrain and for rougher boundary layers (greater surface friction velocity).

Hagler et al. (2011) and Steffens et al. (2013) used CFD codes to study the effects of barriers on the flow field and the associated concentration distributions. Hagler et al. (2011) simulated dispersion from a six lane divided highway with a 750 m long barrier next to the road. They found that a 3 m barrier reduced concentrations by 20% immediately downwind of the barrier while an 18 m barrier reduced the concentrations by about 70%. The horizontal extent of the barrier effect was about 30 times the barrier height.

The simulated vertical concentration profiles (Hagler et al., 2011) show that the barriers and elevated roadways shift peak concentrations vertically upward. This is consistent with the results from the wind tunnel (Heist et al., 2009), which are discussed in more detail in a later section on model development. Steffens et al. (2013) show that the recirculating flow behind the barrier controls the concentrations close to the barrier.

An important question is whether barriers can increase roadside concentrations. As far as we are aware, only one study, conducted by Ning et al. (2010), showed that mass and number concentrations of particulate matter were small immediately behind the barrier, increased with distance from the barrier, reaching peaks at distances of 80–100 m, and then decreased. The peak concentrations were about twice those observed at the same distance in the absence of the barrier. The occurrence of this peak concentration is attributed to the effective elevation of the emissions by the barrier. However, the field and wind tunnel studies indicate that the recirculating flow downwind of the barrier mixes the concentrations both in the horizontal and vertical directions, thus eliminating the peak.

In summary, the major effects of barriers on concentrations are: 1) the concentration is well mixed in a zone extending from the ground to the barrier height, and several barrier heights downwind, 2) the turbulence spreading the plume is increased downwind of the barrier, 3) the pollutant is lofted above the top of the barrier, which increases the concentration near the top of the barrier.

3. Framework for the barrier models

The physical features described earlier are the basis of the source-shift and mixed-wake models proposed here. These models are based on the Gaussian plume formulation for a point source, which gives the concentration as:

$$C(x,y,z) = \frac{Q}{\sqrt{2\pi}\sigma_y(x)} \exp\left(-\frac{y^2}{2\sigma_y(x)^2}\right) F_z(x,z) \tag{1}$$

where x, y, and z are the downwind distance from the source, crosswind distance, and height of the receptor, Q is the emission rate, σ_y is the horizontal plume spread, and F_z is the vertical distribution function. For the Gaussian formulation F_z is:

$$F_z(x,z) = \frac{1}{U(\bar{z})\sqrt{2\pi}\sigma_z(x)} \left[\exp\left(-\frac{(z-h)^2}{2\sigma_z(x)^2}\right) + \exp\left(-\frac{(z+h)^2}{2\sigma_z(x)^2}\right)\right] \tag{2}$$