Atmospheric Environment 155 (2017) 1–10

Contents lists available at ScienceDirect

Atmospheric Environment

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

Reduction of air pollution levels downwind of a road with an upwind noise barrier

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HIGHLIGHTS

- Upwind barrier reduces downwind near-road pollutant concentrations.
- Dispersion model accounts for upwind barrier.
- Recirculation behind barrier pushes emissions upwind.
- Can be as effective as downwind barrier.
- Increases impact of downwind barrier.

ARTICLE INFO

Article history:
Received 13 July 2016
Received in revised form
1 February 2017
Accepted 2 February 2017
Available online 3 February 2017

Keywords:
Dispersion modeling
Noise barrier
Near-road concentration
Air pollution
Recirculation zone

ABSTRACT

We propose a dispersion model to estimate the impact of a solid noise barrier upwind of a highway on air pollution concentrations downwind of the road. The model, based on data from wind tunnel experiments conducted by Heist et al. (2009), assumes that the upwind barrier has two main effects: 1) it creates a recirculation zone behind the barrier that sweeps the emissions from the highway back towards the wall, and 2) it enhances vertical dispersion and initial mixing. By combining the upwind barrier model with the mixed wake model for a downwind barrier described in Schulte et al. (2014), we are able to model dispersion of emissions from a highway with noise barriers on both sides. The model provides a good description of measurements made in the wind tunnel. The presence of an upwind barrier causes reductions in concentrations relative to those measured downwind of a road with no barriers. The reduction can be as large as that caused by a downwind barrier if the recirculation zone covers the width of the highway. Barriers on both sides of the highway result in larger reductions downwind of the barriers than those caused by a single barrier either upwind or downwind. As expected, barrier effects are small beyond 10 barrier heights downwind of the highway. We also propose a tentative model to estimate on-road concentrations within the recirculation zone induced by the upwind barrier.

1. Introduction

Several field and laboratory studies indicate that noise barriers next to roads reduce near-road concentration of pollutants emitted by vehicles. Because these barriers are designed to reduce the impact of road noise on adjacent residential areas, they can be located on both sides of the road or only on one side. In this paper, we refer to a barrier as "upwind" if the road is downwind of the barrier when the wind blows across the road. It is referred to as "downwind" otherwise.

A field study near interstate I-440, Raleigh, North Carolina, showed that the presence of a downwind noise barrier can reduce concentrations of CO and PM number by up to 50% downwind of the barrier (Baldauf et al., 2008). A study at the Idaho National Laboratory that released a tracer gas, sulfur hexafluoride, from a line source upwind of a barrier (Finn et al., 2010) showed similar reductions in tracer concentrations downwind of the barrier under all meteorological conditions. A wind tunnel study examined the effect of different configurations including downwind solid barriers, upwind barriers, depressed highways, and elevated highways on near-road pollutant concentrations and found that all of these configurations result in reductions of near-road concentrations

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http://dx.doi.org/10.1016/j.atmosenv.2017.02.001

compared to those for a flat roadway with no barriers except for an elevated highway where the source is elevated on a sloped embankment. (Heist et al., 2009).

These results from field and laboratory studies are supported by simulations using a Computational fluid dynamics (CFD) model, which shows that downwind roadside barriers result in reduced concentrations behind the barrier (Hagler et al., 2011). Steffens et al. (2014) developed a CFD model based on Large-Eddy Simulation and found that roadside barriers, elevated highways, depressed highways, and combinations of these configurations reduced near-road concentrations. Schulte et al. (2014) developed a semi-empirical model to estimate concentrations in the presence of a downwind barrier and evaluated it with data from the Idaho Falls experiment (Finn et al., 2010) and wind tunnel data (Heist et al., 2009). However, none of these modeling studies examined the impact of single barriers upwind of the road, or barriers on both sides of the road.

In this paper, we propose a semi-empirical model to estimate the effects of upwind barriers on near-road pollutant concentrations. The impact of barriers on both sides of the highway is modeled using the upwind barrier model in combination with the mixed-wake model (Schulte et al., 2014) formulated to estimate the effect of a downwind barrier. The models are evaluated using the data collected by Heist et al. (2009) in a wind tunnel study. These semi-empirical models are useful because they capture the fundamental physics governing the effects of solid barriers on the dispersion of pollutants, and yet are anchored to observations through frameworks that facilitate application to real-world situations.

2. Wind tunnel measurements

Heist et al. (2009) conducted a wind tunnel study to examine the near-road impact of emissions from a simulated six-lane divided highway modeled at 1:150 scale. They considered twelve roadway configurations (Table 1), including seven with solid noise barriers at different heights and locations, Five of the seven barrier cases are used in this examination of upwind barrier effects. The study was conducted in the meteorological wind tunnel at U.S. EPA's Fluid Modeling Facility (Snyder, 1979). The wind tunnel test section measures 370 cm wide by 210 cm high and 1830 cm long (Fig. 1). The boundary layer wind profile was generated with a combination of Irwin spires (Irwin, 1981) at the inlet and roughness blocks arrayed on the floor to condition the flow to simulate a typical atmospheric boundary layer profile. The typical barrier height, H, at full scale was 6 m. Four cases, G, L, J, and K, involved only upwind barriers. Case I examined two 6 m barriers, one on each side of the highway. All of the cases used a neutral boundary layer with a surface roughness, $z_0 = 0.52\ cm$ (0.78 m full scale), and a friction velocity, $u_* = 0.3\,\frac{m}{s}$ and a displacement height $d = 5.4\ cm$ (8.1 m full scale). A near-neutrally-buoyant tracer gas (ethane) was released from six lines along the roadway, and downwind concentration samples were collected through tubes mounted on the wind tunnel carriage system. Tracer concentrations were measured using hydrocarbon analyzers (flame ionization detectors) to form concentration profiles. Velocity measurements were obtained with a two-component laser Doppler velocimetry (LDV) system.

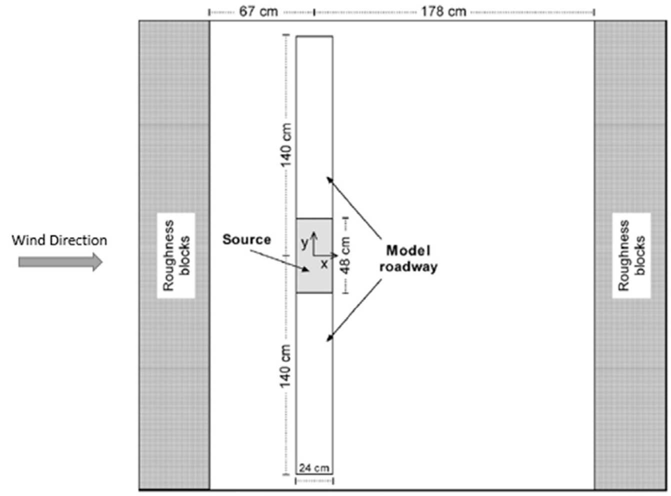

Fig. 1. Layout of the wind tunnel study (Heist et al., 2007).

Table 1
Case descriptions in the wind tunnel study.

Case	Description
A	Flat terrain
B	Elevated source, 1H, 30° walls
C	Depressed source, 1H, 90° walls
D	Depressed source, 1.5H, 90° walls
E	Depressed source, 1H, 30° walls
F	Depressed source, 1H, 30° walls with noise barriers, 1H tall at upwind and downwind edges.
G	Noise barrier, 1H tall, at upwind edge of the road
H	Noise barrier, 1H tall, at downwind edge of the road
I	Noise barriers, 1H tall, at upwind and downwind edges of the road
J	Noise barrier, 1.5H tall, at upwind edge of the road
K	Noise barrier, 1H tall, 1H upwind of upwind edge of the road
L	Noise barrier, 1H tall, 2H upwind of upwind edge of the road

2.1. Upwind barrier cases

Fig. 2 shows the configuration of each upwind barrier case modeled in Heist et al. (2009). Dimensions are in full scale.

Fig. 3, which depicts the velocity profiles for the two single barrier cases, G and H, shows that the length of the recirculation zone behind the barrier is about 6 barrier heights. Note that H corresponds to a single barrier located downwind of the road. As expected, the velocity field around a single barrier does not depend on its location.

However, as Fig. 4 shows, the recirculation zone extends 4 barrier heights behind the upwind barrier when there are two barriers on both sides of the highway. This observation is used in formulating the model for dispersion in the presence of two barriers. This is consistent with studies (Becker et al., 2002; Schulman et al., 2000) that show that the extent of the recirculation zone depends on the height of the barrier, the width of the road, the aspect ratio, and the type of boundary layer.

3. Barrier models

3.1. Upwind barrier model

We see from the wind tunnel measurements, shown in Figs. 3 and 4, that the flow in the recirculation zone is directed towards the upwind barrier close to the highway surface. This flow transports the pollutants emitted within the recirculation zone towards the barrier in the upwind direction. This feature is also observed in street canyons on the leeward side of the street and is incorporated in the Operational Street Pollution Model (OSPM, Berkowicz, 2000). In the proposed model, we assume that the emissions on the highway that are covered by the recirculation zone originate from a