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Using models to interpret the impact of roadside barriers on near-road air quality

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HIGHLIGHTS

- Roadside barriers produce effective mitigation of the impact of emissions.
- Real-world barrier effects can be described with simple model.
- Roadside barrier effects are equivalent to shifting source upwind.
- Model can be used to design roadside barriers.
- Model can be used to estimate UFP emission factors.

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ABSTRACT

The question this paper addresses is whether semi-empirical dispersion models based on data from controlled wind tunnel and tracer experiments can describe data collected downwind of a sound barrier next to a real-world urban highway. Both models are based on the mixed wake model described in Schulte et al. (2014). The first neglects the effects of stability on dispersion, and the second accounts for reduced entrainment into the wake of the barrier under unstable conditions. The models were evaluated with data collected downwind of a kilometer-long barrier next to the I-215 freeway running next to the University of California campus in Riverside. The data included measurements of 1) ultrafine particle (UFP) concentrations at several distances from the barrier, 2) micrometeorological variables upwind and downwind of the barrier, and 3) traffic flow separated by automobiles and trucks. Because the emission factor for UFP is highly uncertain, we treated it as a model parameter whose value is obtained by fitting model estimates to observations of UFP concentrations measured at distances where the barrier impact is not dominant. Both models provide adequate descriptions of both the magnitude and the spatial variation of observed concentrations. The good performance of the models reinforces the conclusion from Schulte et al. (2014) that the presence of the barrier is equivalent to shifting the line sources on the road upwind by a distance of about HU/u_* where H is the barrier height, U is the wind velocity at half of the barrier height, and u_* is the friction velocity. The models predict that a 4 m barrier results in a 35% reduction in average concentration within 40 m (10 times the barrier height) of the barrier, relative to the no-barrier site. This concentration reduction is 55% if the barrier height is doubled.

1. Introduction

The majority of the studies (Gallagher et al., 2015) conducted to date indicate that solid barriers placed next to roads have a mitigating effect on near-road air quality. The physics that governs this effect has been elucidated through several studies, such as the wind-tunnel study conducted by Heist et al. (2009). Through measurements of wind flow patterns and concentration distributions around a 1:150 scale model of a 6 lane divided highway with roadside barriers they showed that the mitigating impact of barriers is governed by two mechanisms: the plume from the road becomes elevated by being forced over the barrier, and vertical dispersion is enhanced by the turbulence created in the wake of the barrier. King et al. (2009) suggest that even a low wall (~1 m) on the leeside of a road can shield pedestrians from exposure to pollutants swept upwind by the reverse flow induced by buildings on the

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windward side. This mechanism is not examined in this paper.

The results from the wind tunnel were confirmed in a tracer study conducted by Finn et al. (2010). They studied the effects of a barrier by releasing SF_6 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 flow around the barrier. Carefully controlled experiments showed that the barrier reduced downwind concentrations over a wide range of atmospheric stabilities.

Field studies conducted next to roadways confirm that barriers mitigate the impact of vehicle-related emissions. For example, Hagler et al. (2012) found that UFP concentrations at 10 m behind the 6 m barrier were about 50% less than those measured at this distance downwind of road sections without a barrier. Baldauf et al. (2008) found that CO and PM concentrations were reduced by 15%–50% within 50 m of the 6 m barrier. 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 measurements from the wind tunnel and tracer experiments have been described with a variety of mechanistic models. Hagler et al. (2011) and Steffens et al. (2014) used computational fluid dynamics (CFD) models to produce adequate descriptions of the data from the wind tunnel (Heist et al., 2009). Bowker et al. (2007) used the Quick Urban & Industrial Complex (QUIC) flow model coupled with a Lagrangian particle dispersion model to produce concentration patterns that were roughly consistent with observations from Baldauf et al. (2008).

Schulte et al. (2014) developed a semi-empirical dispersion model to describe data from the wind tunnel and the tracer studies. This model parameterizes the major features of the flow and dispersion effects induced by a barrier to avoid the computational burden of mechanistic CFD models, which have their own set of parameterizations. It is designed to be incorporated into routinely used models such as AERMOD (Cimorelli et al., 2005) or RLINE (Snyder et al., 2013). In this paper, we evaluate the model with field data collected next to a real world roadside barrier to answer the question: Can a model developed with data from controlled experiments conducted with well-characterized sources and meteorology be used to estimate the impact of a road-side barrier next to a multilane highway on which the magnitudes of the distributed sources are highly uncertain?

2. Field study

2.1. Site description

The field study was conducted adjacent to CA-60, U.S. Interstate 215 (I-215) in Riverside, California. The highway has a barrier section located on the University of California, Riverside campus (Fig. 1). The freeway has average traffic flow rate of 200,000 vehicles/day. The meteorological data collected from UC Riverside Meteorological Station, which is 1 km away from the barrier site, indicates a dominant wind from west/southwest during the daytime as shown in Fig. 2. Thus, the wind blows close to perpendicular to the freeway during the daytime, which makes it convenient to study barrier effects during daytime unstable conditions. During the night, the wind blows from east, and the barrier is located upwind of the road.

The barrier, which is 3 m away from the edge of the road, is 4.5 m high and 1 km long. There are three lanes and one High Occupancy Vehicle (HOV) lane on the north bound side and four lanes and one HOV lane on the south bound side of the freeway. There is an entrance to the north bound lanes and an exit on the south bound side of the freeway. The lanes are 3.5 m wide and the median is 10 m across. The freeway is at the same level as the adjacent streets. There is no major source of pollution within a 3.5 km radius of the barrier site except the freeway. The heading of the freeway is 140°. Therefore, the wind direction perpendicular to the freeway is 230° true to north. Two parking lots are located behind the barrier, which provide convenient locations for sampling.

The largest obstacles in the parking lots downwind of the barrier are widely scattered trees. There are no other major obstacles within 170 m of the barrier. A 2-lane street, West Campus Drive, runs parallel to the freeway between the parking lots. The street is mainly used to access the parking lots and the traffic is mainly passenger cars travelling during the morning hours, 8 a.m.–10 a.m., and in the evening, 4 p.m.–6 p.m. Another parking lot extends for 300 m west of the freeway. There is no major obstacle in this parking lot and trees are sparser and shorter than in the eastside parking lots.

2.2. Measurements

Ultrafine particles (UFPs) were used as the tracer in this study for several reasons. First, because they have adverse health effects, the levels of UFP concentrations next to a major highway are of public interest. Second, their concentrations next to major highways are well above background levels, and can be measured continuously with readily available instruments. Gidhagen et al. (2005) and Zhang and Wexler (2004) show that at the 100 m scale being considered here, deposition and coagulation play a minor role relative to turbulent dispersion in reducing particle number concentrations. Thus, UFP can be treated as a passive tracer by using particle number concentrations to characterize dispersion. One major problem with using UFP as a tracer is that UFP emission factors from vehicles are highly uncertain. Thus, it is necessary to treat the emission factor as an unknown whose value is obtained by fitting model estimates to measurements. This process is discussed in more detail in a later section.

Fifteen tests were conducted on different days and at different times of day from July 2014 to May 2015 but due to the malfunction of instruments and unfavorable meteorological conditions, only six tests were selected for analysis. Table 1 shows the dates and duration of measurements. The total duration of the 6 tests is 27 h.

2.2.1. Air quality measurements

UFP number concentrations were measured using TSI Condensation Particle Counters (CPC), Model 3022A. The cutoff size of these CPCs is 7 nm. The measured concentration range was $5 \times 10^3 - 10^5$ particles/cm^3. According to the CPC manual, accuracy within this range of concentrations is ±10%. The CPC concentrations were stored on a custom-designed data logger.

Several CPCs were used to measure background UFP concentrations and downwind UFP concentrations at several downwind distances. A CPC was placed at the upwind side of the freeway (assuming that the wind is blowing WSW) to measure background UFP number concentrations. The rest of the CPCs were deployed behind the barrier (Fig. 3). The downwind CPCs were placed at least 250 m away from the barrier edge to avoid barrier edge effects. CPC locations were changed from one test to another to avoid any systematic bias in measurements. The background concentrations were subtracted from the downwind concentrations to estimate contributions from vehicles on the highway.

2.2.2. Meteorology

Campbell Scientific CSAT3 3-D (three dimensional) Sonic