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Modeling dispersion of emissions from depressed roadways

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ABSTRACT

This paper presents an analysis of data from a wind tunnel (Heist et al., 2009) conducted to study dispersion of emissions from three depressed roadway configurations; a 6 m deep depressed roadway with vertical sidewalls, a 6 m deep depressed roadway with 30° sloping sidewalls, and a 9 m deep depressed roadway with vertical sidewalls. The width of the road at the bottom of the depression is 36 m for all cases. All these configurations induce complex flow fields, increase turbulence levels, and decrease surface concentrations downwind of the depressed road compared to those of the at-grade configuration. The parameters of flat terrain dispersion models are modified to describe concentrations measured downwind of the depressed roadways. In the first part of the paper, a flat terrain model proposed by van Ulden (1978) is adapted. It turns out that this model with increased initial vertical dispersion and friction velocity is able to explain the observed concentration field. The results also suggest that the vertical concentration profiles of all cases under neutral conditions are best explained by a vertical distribution function with an exponent of 1.3. In the second part of the paper, these modifications are incorporated into a model based on the RLINE (Snyder et al., 2013) line-source dispersion model. While this model can be adapted to yield acceptable estimates of near-surface concentrations ($z < 6$ m) measured in the wind tunnel, the Gaussian vertical distribution in RLINE, with an exponent of 2, cannot describe the concentration at higher elevations. Our findings suggest a simple method to account for depressed highways in models such as RLINE and AERMOD through two parameters that modify vertical plume spread.

1. Introduction

Living and working near major roadways has been associated with increased risk of respiratory complications, cardiovascular disease, and other adverse health effects (Health Effects Institute, 2010). Several configurations have been suggested to mitigate the near-road impact of vehicle emissions. These configurations include depressed and elevated roadways, and roadways with sound walls and/or vegetation barriers.

A relatively small number of studies have examined dispersion of emissions from depressed roadways. A notable field study was conducted in the Los Angeles Air Basin by the California Department of Transportation (CalTrans) to collect data to understand dispersion of primary pollutants emitted from freeways with various configurations, including at-grade, depressed, and elevated roads (Bemis et al., 1977). Air pollutants sampled included CO, reactive and unreactive hydrocarbons, NOx, O_3, SO_2, and H_2S. Particulate sampling was also conducted to obtain total particulates and lead.

The data from the CalTrans field study (Bemis et al., 1977) were used to develop the depressed road model in the California Line Source Dispersion Model (CALINE2). CALINE, which is used to estimate air pollutant concentrations near roadways, accounts for the effects of road depression by enhancing the initial vertical plume spread relative to those used for equivalent at-grade sites (Bemis et al., 1977; Benson, 1992).

Feeney et al. (1975) measured aerosols and particulate lead concentrations in the vicinity of several road configurations, including a depressed roadway. Samplers were placed 20 m upwind of a freeway and at several distances downwind of the freeway ranging from 27 m to approximately 160 m from the median strip. They found that the mass concentrations of traffic-derived lead were generally lower downwind of the depressed roadway relative to that predicted by a dispersion model that assumed that the emissions occurred at road level.

Heist et al. (2009) conducted a comprehensive wind-tunnel study on dispersion of emissions from model depressed roadways. The studied configurations included a flat roadway, a 6 m and a 9 m deep depressed roadway with vertical sidewalls, a 6 m deep depressed roadway with

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30° sloping sidewalls, and a 6 m deep depressed roadway with 30° sloping sidewalls with two 6 m solid barriers on top of the road. They observed that all these configurations alter the flow field, increase downwind dispersion, and reduce downwind surface concentrations relative to the flat terrain case. The level of reduction in concentrations depended on the particular configuration.

Baldauf et al. (2013) conducted a field study in Las Vegas, Nevada, to investigate the effects of a depressed roadway on local-scale air quality downwind of the depression. They measured CO and NO_x concentrations along a complex urban highway at two sections; a section at-grade with the surroundings and another section that was depressed. The vertical height from the roadbed to the top of the surroundings was 5 m, and the slope of the sidewalls was approximately 20°. The stationary monitors located 20 m from the downwind edge of the freeway at both sections showed that the maximum concentrations occurred at the at-grade site. However, during some mid- and low-concentration events, the stationary monitor downwind of the cut section observed higher concentration levels than that of the at-grade section. The mobile monitoring data collected along the at-grade and cut section transects indicated that the concentrations at the at-grade transect were greater than those at the cut section transect at 35 m from the downwind edge of the freeway, with concentrations then becoming similar along both gradients further downwind of the highway. They also conducted a wind tunnel simulation of the study site to examine the flow field and the concentration distributions in the vicinity of the highway. The wind tunnel simulations revealed that the cut section reduced concentrations of pollutants measured at breathing-level height by 15–25% relative to the flat terrain case for receptors located approximately 20 m from the downwind edge of the highway. Although the field data were not conclusive, the data collected under the controlled conditions of the wind tunnel indicated that depressed roadways led to reductions in downwind near-surface concentrations relative to those next to at-grade roadways.

Until recently, CALINE3 (and more refined models such as CAL3QHC and CAL3QHCR) had been recommended by the United States Environmental Protection Agency (U.S. EPA) to be used to estimate the impact of vehicular emissions on near-road air concentrations. The situation changed in 2016 when the U.S. EPA replaced CALINE3 with American Meteorological Society/U.S. EPA Regulatory Model (AERMOD) for Transportation Related Air Quality Analyses (U.S. Environmental Protection Agency, 2016). However, AERMOD designed primarily for point, area, and volume-type pollutant sources does not simulate the line-type sources explicitly; line sources are represented as elongated area sources or a series of volume sources evenly spaced along the length of the lines (Heist et al., 2013). AERMOD is also not currently configured to model concentrations downwind of roadways with complex geometries.

In an effort to develop a comprehensive line source dispersion model, the U.S. EPA formulated the Research LINE source model (RLINE) (Snyder et al., 2013). The model framework is designed to facilitate the inclusion of algorithms for complex road geometries, therefore providing a suitable testbed for potential depressed roadway approaches. This study provides results that can be used to incorporate depressed roadways in RLINE.

In this study, we analyze the concentrations and turbulence levels measured in the wind tunnel study downwind of at-grade and depressed road configurations (Heist et al., 2009) to gain insight into the processes that govern dispersion of pollutants from a depressed highway. Wind tunnel studies can provide more information on the processes than field studies can because the governing inputs are controlled and details of the flow fields can be measured. Although they do have the disadvantage of being unable to simulate the effects of atmospheric stability, they provide information that is vital to the development of models for situations in which the effects of source geometry on the flow field are dominant. For example, the wind tunnel results (Heist et al., 2009) on dispersion of pollutants downwind of the roadways with different configurations have been incorporated into several dispersion and CFD models (Ahangar et al., 2017; Amini et al., 2017, 2016; Ghasemian et al., 2017; Hagler et al., 2011; Schulte et al., 2014; Steffens et al., 2014).

Based on the insight from the wind tunnel study, we propose a method to incorporate the dominant effects of the depressed roadway into a flat terrain model. These effects are first parameterized in a model proposed by van Ulden (1978) which not only provides a good description of ground-level concentrations but also the vertical profiles (Nieuwstadt and van Ulden, 1978a; b) measured during the Prairie Grass experiment (Barad, 1958). We then suggest how our findings can be incorporated into a model based on the formulation of RLINE, a Gaussian dispersion model, with emphasis on near-surface concentrations.

2. Wind tunnel experiments

2.1. Experiment description

Heist et al. (2009) performed an experimental study in the U.S. EPA's Meteorological Wind Tunnel (Snyder, 1979) to explore the effects of different road configurations on the dispersion of traffic-related pollutants downwind of roads. The wind tunnel test section is 3.7 m wide, 2.1 m high, and 18.3 m long. A simulated atmospheric boundary layer was generated using three truncated triangular (Irwin, 1981) spires mounted near the entrance to the test section. To maintain the boundary layer, the floor of the test section downwind of the spires was covered with roughness blocks. The position of spires and roughness blocks are shown in Fig. 1. There are no roughness blocks in the proximity of the line sources where turbulence and concentration measurements are conducted. The modeled freeway is a six lane divided highway at 1:150 scale. The width of the modeled freeway is 36 m full scale. The origin of the coordinate system is at the center of the roadway on the wind tunnel floor, with the positive *x* in the stream wise direction, *y* along the axis of the roadway, and *z* vertically upward. The wind-tunnel study examined twelve roadway configurations. In this paper, we focus on three depressed roadway configurations and compare the results to those of a flat roadway.

The configurations that were studied in this paper are shown in Fig. 2. We examine a 6 m deep depressed roadway with vertical sidewalls (D690), a 6 m deep depressed roadway with 30° angled sidewalls

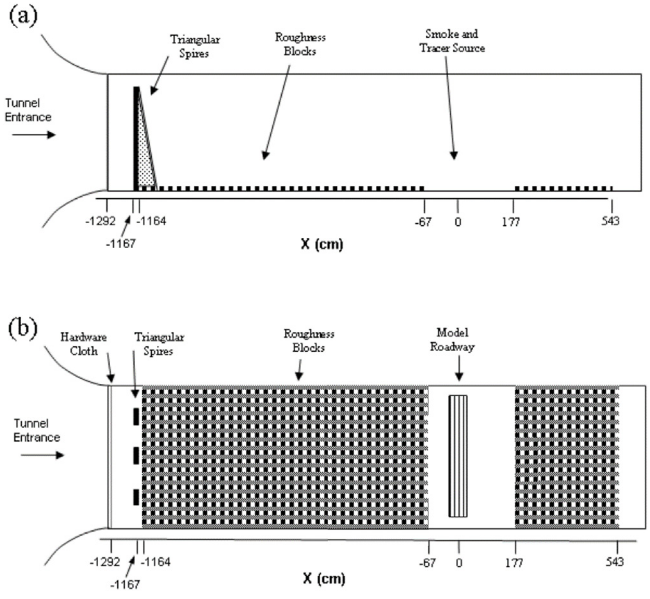

Fig. 1. Schematic of near roadway wind tunnel setup: a) elevation and b) plan view.