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# Effects of roadway configurations on near-road air quality and the implications on roadway designs

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## HIGHLIGHTS

- We investigate the impacts of elevated and depressed roadways, and roadside barriers.
- All configurations reduce ground-level air pollutant concentrations near roadways.
- The elevated roadway leads to reduction in both on-road and near-road concentration.
- Adding multiple features offers diminishing returns in concentration reduction.
- The effects of design features damp out <15 multiples of the characteristic height.

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## ABSTRACT

This paper presents an analysis of wind tunnel experiments of twelve different roadway configurations and modeling of these configurations using a Large-Eddy Simulation (LES) model, aiming at investigating how flow structures affect the impact of roadway features on near-road and on-road air quality. The presence of roadside barriers, elevated fill and depressed roadways, and combinations of these configurations all reduce ground-level air pollutant concentrations immediately downwind of roadways. However, all of these cases, except the elevated fill configuration, increase pollutant concentrations on the roadway itself. For a roadside barrier with finite length, higher concentrations than those without a barrier are present in a small region near the edge of the barrier, influenced by complex flow in that region which we term "Edge Effects". The inclusion of multiple roadway features often result in lower downwind pollutant concentrations than those with single roadway features; however, adding features typically offers diminishing returns in concentration reduction. Generally, the effects on concentration, both beneficial and adverse will damp out within 15 multiples of the characteristic height, be it the barrier height or the elevation/depression height of the roadway. Thus, evaluating the trade-off between the air pollutant reductions near the ground and the air pollutant increases on the roadway and elevated above the ground will be important in designing a sustainable transportation system.



## 1. Introduction

Living and working near major roadways has been linked to increased risk of respiratory complications, cardiovascular disease, and other adverse health effects (HEI, 2010). While increasingly stringent tailpipe emission regulations have resulted in drastic reductions in the net amount of traffic-related emissions, the expansion of metropolitan areas and the rise in motor vehicle ownership have led to an increase in the number of people living, working and going to school near highways or other large roads. Therefore, there is a pressing need to develop additional mitigation strategies to protect public health besides those targeting reduced emissions from individual vehicles.

There are potential opportunities for mitigating near-road air pollution in roadway design options that affect pollutant transport and dispersion such as road configurations and the presence of

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roadside barriers (Baldauf et al., 2008, 2009; Wang and Zhang, 2009). To incorporate those options into actual design practices, a mechanistic understanding of the fate and transport of the traffic-related air pollutants is required but is currently lacking. The overall objective of this paper, along with our previous efforts (Wang and Zhang, 2009; Steffens et al., 2012, 2013; Tong et al., 2012), is to bridge this gap, and provide design guidance to urban, transportation and environmental planners.

Our general approach is to develop and apply numerical modeling tools to analyze and supplement existing experimental data. There are two major benefits to using this approach. While experiments provide essential empirical evidence, they do not directly reveal the underlying physical mechanisms, which can be studied by comparing modeling results against measurements; Experiments are often costly and time intensive to cover a wide range of road, traffic and meteorological conditions, which can be investigated by a validated model based on fundamental principles. Several researchers applied this approach to study the effects of barriers on dispersion of pollutants near roadways. Steffens et al. (2012) studied the effects of a vegetation barrier on near-road particle size distributions, and Steffens et al. (2013) investigated the effects of a solid barrier on tracer dispersion under different atmospheric stability conditions (Steffens et al., 2013). Similar approaches have been taken to study pollutant dispersion in street canyon environments (Chang and Meroney, 2003; Xie and Castro, 2009; Neophytou et al., 2011). Hagler et al. (2011) employed a k-ε Reynolds-averaged Navier–Stokes (RANS) turbulence model to simulate *two of the twelve* configurations in the wind tunnel experiment described in Heist et al. (2009) that include a solid barrier, and investigated the sensitivity of simulated near-road air pollution to roadside barrier height, various wind directions, and secondary road emission. Steffens et al. (2013) showed that Large-Eddy Simulation (LES) turbulence model has a clear advantage over RANS in capturing the flow fields near barriers, especially in regions affected by flow recirculation.

In this paper, we apply our approach to simulate the wind tunnel experiment conducted by Heist et al. (2009), which characterized the 3-D concentration gradients of a tracer gas under twelve different roadway configurations, the most comprehensive to date. Here, we substantially advance the work by Hagler et al. (2011) by adopting an LES turbulence model, and comparing the modeling and experimental results for *all twelve* roadway configurations, providing a detailed evaluation for a wide variety of road design scenarios.

## 2. Methodology

### 2.1. Wind tunnel experiment

The U.S. Environmental Protection Agency (EPA) performed a wind tunnel experiment detailing the effects of various roadway configurations on the concentration of a tracer gas. The full description of the experiment and methodology employed can be found in the work of Heist et al. (2009). A brief description is presented here.

The experiment was performed using a meteorological wind tunnel (Snyder, 1979) located in the EPA's Fluid Modeling Facility. The wind tunnel test section measures 370 cm wide by 210 cm high by 1830 cm long. The inlet boundary layer profile was created by utilizing three Irwin spires (Irwin, 1981) and the floor downwind of the spires was covered in roughness blocks to maintain and condition the boundary layer to approximate a typical atmospheric boundary layer profile.

Twelve roadway configurations (see Table 1, Section 3.1) including depressed and elevated roadways and roadways with noise barriers were studied based on the prevalence of use along U.S. highways and feasibility for simulation in the wind tunnel. Each was constructed at a scale height of 1:150 of a typical 6 lane divided highway, with the lanes (traffic) running perpendicular to the flow in the tunnel. The right-handed coordinate system used to record and display the results had the origin placed in the center of the roadway with the positive $x$ in the downwind direction, $y$ lateral and $z$ vertical. The roadway extended 18 m (full-scale) in both the $\pm x$ direction at ground level and centered laterally in the tunnel. The distances in the study were normalized by a characteristic length, assumed to be the standard height of a solid roadside barrier of 6 m. This corresponds to a scaled model barrier height of 4 cm. Turbulence generated by the presence of roadway vehicles was simulated by placing a number of small blocks ($6 \times 6 \times 12$ mm) on the roadway. A near-neutrally buoyant tracer gas, ethane, was released from six lines along the roadway at a total emission rate of 1500 cc/min. Tracer concentrations were measured by six Rosemount Model 400A hydrocarbon analyzers. A 20 Hz Laser Doppler Velocimetry (LDV) system was used to measure velocity at various points on, above, and downwind of the roadway.

**Table 1**
Description of Case ID letters for the various roadway configurations with the Normalized Mean Error (*NME*) between the experimental data and simulation results, where *H* is the height of the feature as well as the scaling factor for evaluating the actual distance and elevation of modeled air quality effects; *Fill angle* is the angle from a line extending horizontal from the road surface down to the surface of the fill material; *Cut angle* is the angle from a line extending horizontal from the road surface up to the surface of the depression material.

| Case ID | Description | Dimensions | NME |
|---|---|---|---|
| A | Level roadway and no barriers (base case) | H = 6 m[a] | 0.090 |
| B | Elevated roadway with solid fill underneath | H = 6 m<br>Fill angle = 30° | 0.132 |
| C | Depressed roadway, straight edges | H = 6 m<br>Cut angle = 90° | 0.073 |
| D | Deep depressed roadway, straight edges | H = 9 m<br>Cut angle = 90° | 0.062 |
| E | Depressed roadway, angled edges | H = 6 m<br>Cut angle = 30° | 0.188 |
| F | Depressed roadway with both upwind and downwind barriers | H = 6 m<br>Cut angle = 30° | 0.403 |
| G | Upwind barrier | H = 6 m | 0.128 |
| H | Downwind barrier | H = 6 m | 0.058 |
| I | Upwind and downwind barrier | H = 6 m | 0.077 |
| J | Tall upwind barrier | H = 9 m | 0.147 |
| K | Barrier at 1H upwind of roadway | H = 6 m | 0.125 |
| L | Barrier at 2H upwind of roadway | H = 6 m | 0.157 |

[a] For level road, a value of H = 6 m is used as the scaling factor for comparative purposes, although the actual height of the road is equal to zero.

### 2.2. Model description

The Comprehensive Turbulent Aerosol Dynamics and Gas Chemistry (CTAG) model contains the functionality to resolve the flow field including turbulent reacting flows, aerosol dynamics, and gas chemistry. The modular design of the model allows us to decide which components of the model to run in order to maximize simulation run time efficiency. In this paper, the model will be used to solve the flow field (velocity and turbulence) as well as compute the tracer gas concentration. A full description of the model's theoretical background and implementation is presented in our previous work (Steffens et al., 2013), which evaluated the model against a solid roadway barrier. A condensed description is presented here.

The CTAG model employs a commercial Computational Fluid Dynamics (CFD) software package, ANSYS Fluent (ANSYS Inc., 2009) to compute the velocity and turbulence flow fields. We choose to use a Large Eddy Simulation with the Smagorinsky–Lilly subgrid