Computational fluid dynamics modeling to assess the impact of roadside barriers on near-road air quality

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ABSTRACT: Near-road air quality is an issue of emerging concern, with field studies consistently showing elevated air pollutant concentrations adjacent to major roads, usually decreasing to background levels within several hundred meters. Roadside barriers, both vegetative and structural, are expected to alter the dispersion patterns of traffic-related emissions and the resulting ambient air pollutant concentrations. In order to understand the influence of roadside barriers on near-road air quality, an idealized computational fluid dynamics (CFD) model of a roadway was developed and simulated using FLUENT. The CFD turbulence model selection and surface roughness parameters were based on comparison with previous wind tunnel experiments. The model includes a six-lane highway and a single-lane access road parallel to the highway which are separated by a solid noise wall. The noise wall is finite in length, allowing the impact of barrier edges to be observed. Downwind normalized air pollutant concentrations (Chi) and turbulent kinetic energy (TKE) are compared for barrier versus no-barrier road segments. The presence of a roadside barrier was observed to significantly impact the horizontal and vertical profiles of Chi and TKE under neutral stability conditions. In addition, the evaluation of barrier-impacted emissions dispersion under oblique wind directions is discussed.

1 INTRODUCTION

Traffic-related emissions on major roadways has long been a focus of research regarding regional air quality, often identified as a significant contributor to the brownish haze common to populated urban areas. Currently, traffic contributions to air pollution are receiving additional attention due to numerous studies reporting an increased risk of adverse health endpoints associated with proximity to major roadways (HEI, 2010). Field studies have established concentration gradients of many traffic-related pollutants (e.g., carbon monoxide, particulate matter, oxides of nitrogen), with high roadside concentrations typically reducing to background levels within several hundred meters of a major roadway (Zhu et al., 2002).

The design of roads, including roadside structures, has been shown to be important in altering the transport of traffic-related emissions and resulting near-road pollution concentrations (Heist et al., 2009, Wang and Zhang, 2009). A recent field study in Raleigh, North Carolina put forth the concept that roadside barriers may serve to mitigate traffic-related emissions impact on near-road air pollution. Field measurements were conducted behind a 6 m noise barrier and in a clearing at approximately 15-20 m from the highway, finding concentrations of carbon monoxide and particulate matter reduced by 15-50% when downwind of a busy roadway (Baldauf et al., 2008). A modeling study of this field site, utilizing the Quick Urban and Industrial Complex model, also simulated reductions in ground-level pollution in barrier-protected areas during downwind conditions (Bowker et al., 2007). In order to better understand how barriers may serve as a mitigation option for near-road air pollution, an idealized computational fluid dynamics roadway model was developed and compared to data from a roadway wind tunnel model. Model simulations will evaluate how traffic-related emissions disperse in the presence of a road barrier, under a variety of wind directions and barrier heights.

2 METHODS

To investigate the effect of a noise barrier on downwind dispersion of traffic-related emissions, a computational fluid dynamics (CFD) model was employed to simulate a noise barrier located on one side of a six lane roadway. Data from wind tunnel experiments were used to evaluate the performance of the CFD model using a k-ε turbulence models with a range of variations. Following the completion of the model development, a number of model scenarios were designed to study the sensitivity of near-road air pollutant concentrations to barrier height, additional emissions due to an access road, and wind direction.

2.1 *Numerical Model Design*

Using a commercial CFD code, FLUENT (www.fluent.com), an idealized highway CFD model was developed that generally parallels an existing wind tunnel model (Figure 1). The CFD model consists of a six-lane divided highway as the primary source for emissions and traffic-induced turbulence, as well as a single lane access road on one side of the highway, which serves as an optional additional emissions and turbulence source. The access road emissions range was set at 0-10% relative to the total highway emissions, after comparison of actual traffic volume between highway and access roads located in Durham, North Carolina (NCDOT Annual Average Daily Traffic). In addition to the line sources, a solid roadside barrier is located on one side of the roadway between the highway and access road and spans 750 m along the highway, with regions lacking any roadside structures located at either end for comparison. This model design was selected to observe the effect of barrier endpoints on downwind concentrations, as well as to allow immediate comparison of barrier-obstructed and unobstructed traffic-related emissions dispersion. The barrier was positioned at 10 m from the nearest lane of traffic and the single lane access road was positioned at 20 m from the nearest traffic lane.

An important factor in modeling the transport of traffic-related emissions is the selection of appropriate surface roughness and turbulence model parameters. The first phase of this study evaluated the CFD base highway model, with either no-barrier or a barrier extending across the entire domain, relative to comparable wind tunnel experimental results. The parameters derived from these results (section 3.1) were used throughout the second phase of research – constructing multiple model scenarios to observe the effect of changing barrier height, wind direction, and access road emissions strength on traffic-related emissions dispersion and resulting near-road air quality. The barrier heights tested ranged 3-18 m (0.5-3 H with H = 6 m), covering both typical noise barrier heights as well as mature tree stands. The wind direction angles ranged from crosswind (+/-90 degrees) to oblique angles (15-75 degrees), all simulated with a constant barrier height of 1H. The access road additional emissions were tested for wind angles of +/-90 degrees and barrier height of 1H.

For the model scenarios that changed the wind angle relative to the roadway, the barrier length and model domain were extended for certain scenarios in order to capture regions unaffected by the barrier, regions affected by the barrier edges, and regions with full air flow obstruction by the barrier. Thus, the overall model domain ranged as follows: 2000-2600 m along the road axis, 700-920 m on a plane crossing the road, and 200 m in height. The barrier span ranged from 750-1000 m. The model has a graduated mesh as shown in Figure 1, with 0.25 m resolution in close proximity to the barrier, increasing with height and distance of the road to 8 m resolution. The overall mesh size ranged from 25.7-29.7 million cells and the model simulations demanded 1300-2800 CPU hours to complete.

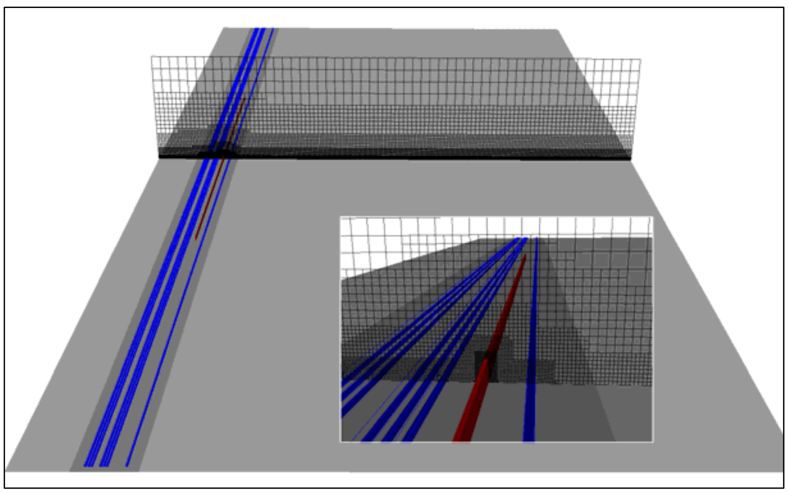

Figure 1. Idealized roadway model for computational fluid dynamics simulations, showing the mesh resolution for a cut-section with cell size ranging from 0.25-8 m.

2.2 *Wind Tunnel Model Configuration*

The US EPA's Fluid Modeling Facility meteorological wind tunnel was utilized to study the effects of a variety of road configurations on traffic-related emissions dispersion. The in-depth methods and results of this study have been previously reported (Heist et al., 2009). Briefly, the road model was designed at a 1:150 scale and included a six-lane, divided roadway. Upwind of the roadway, a boundary layer representative of an urban environment was developed using Irwin spires (Irwin, 1981), followed by a series of roughness blocks (Figure 2). The roadway was oriented orthogonal to the wind direction and the wind speed at the top of the boundary layer was maintained at 4.7 m s^{-1} (measured at a height of 165 cm). Seeding material from a theatrical smoke generator released upwind of the spires was used by the Laser Dopper Velocimeter (LDV) in measuring wind velocities. In addition, tracer gas (ethane) was released along a section of the roadway, with an array of holes simulating six continuous line sources along the roadway. Concentrations downwind of the roadway were measured using Rosemount Model 400A hydrocarbon analyzers. Results of the wind tunnel data, as well of the computational fluid dynamics model, are presented in normalized concentration units (*Chi*), as computed in equation (1) below:

$$Chi = \frac{CU_r L_x L_y}{Q} \quad (1)$$

where C is the background-adjusted concentration, U_r is the reference wind speed measured at a full-scale equivalent of 30 m, Q is the tracer gas emissions rate, and L_x and L_y are the dimensions of the source section (24 cm and 48 cm, respectively). The concentration data was processed to simulate the effect of an infinitely long roadway source (see Heist et al. (2009) for details).

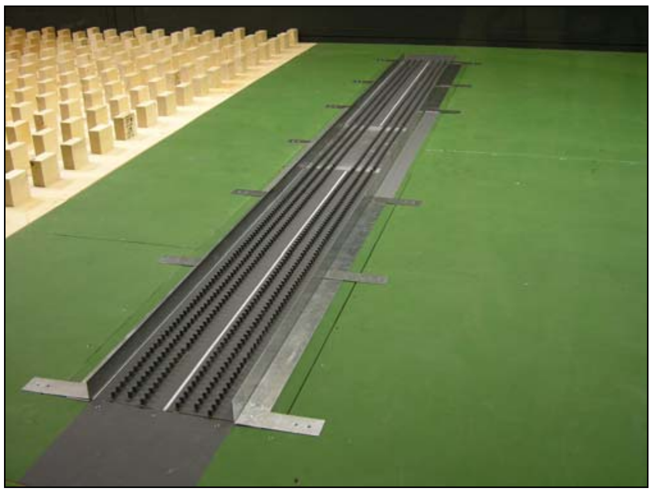

Figure 2. The roadway model for a case with noise barriers on both sides of the roadway installed in the meteorological wind tunnel. Roughness elements are visible upwind of the model and on the roadway surface.

3 RESULTS

3.1 *Comparison of Numerical and Wind Tunnel Data*

Among the various turbulence models in FLUENT code, *k*-ε model is widely used for simulating short-range atmospheric dispersion. Available variations include the standard *k*-ε model, RNG *k*-ε model, and Realizable *k*-ε model. In order to evaluate which *k*-ε model was most appropriate for near-road studies, CFD model simulations using the three *k*-ε turbulence models were compared against wind tunnel data for both flat terrain and roadside barrier cases. For the Realizable *k*-ε model, several different turbulent Schmidt numbers, a parameter relating to mass diffusion, were used to evaluate a best-fit value. Results were compared in terms of normalized concentration profiles (*Chi*), mean velocity and turbulent kinetic energy (TKE) profiles. Some example results are provided in Figure 3. Measurements of concentration were not made on or upwind of the roadway in the wind tunnel simulations, hence, the absence of data upwind of the barrier in the wind tunnel data shown in Figure 3.

The results of the wind tunnel to CFD model comparison show that the various turbulence models are in reasonable agreement with the general trend of plume vertical lift in the presence of a barrier and downwind attenuation with distance from a road (Figure 3). Detailed evaluation of the various models and range of Schmidt values, for both no-barrier and 1H barrier models, lead to the selection of the Realizable model with Schmidt value of 1.0 for the second phase of simulations. Although a constant value for the turbulent Schmidt number through the modeling domain may be a simplification of the physical processes involved (Kastner-Klein and Federovich, 2002; Koeltzsch, 2000), these comparisons show that this assumption produces results useful for investigating the effect of noise barriers on near-road dispersion.

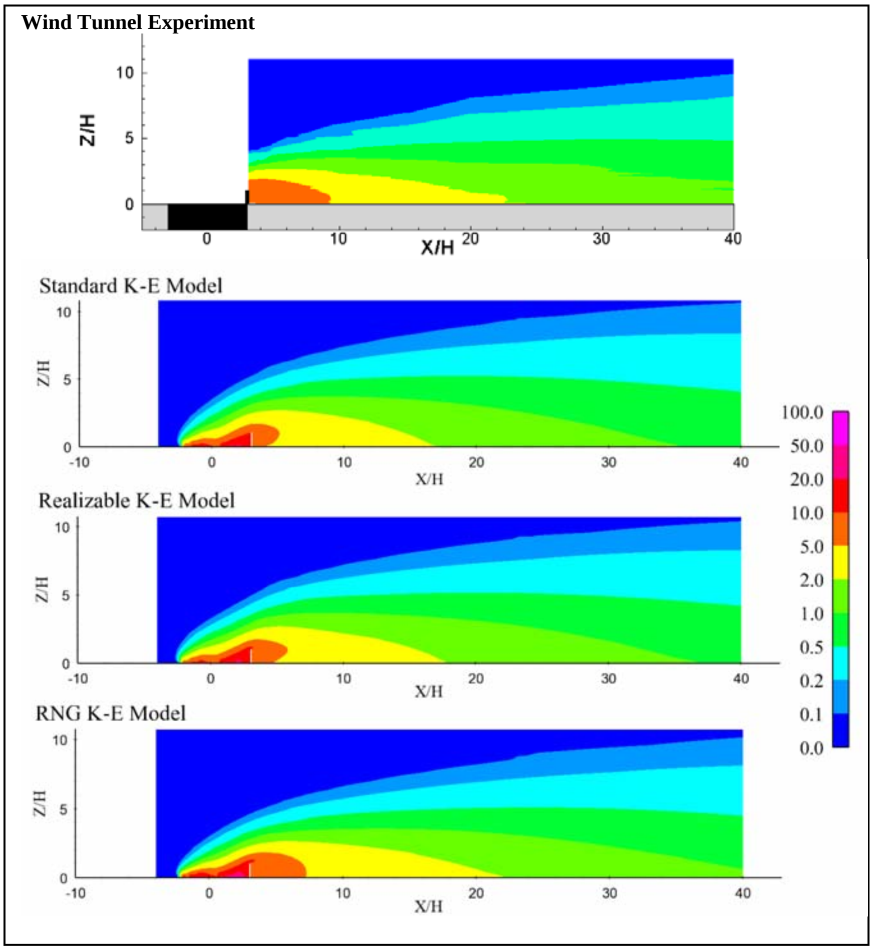

Figure 3. Example Chi results of wind tunnel results (top figure) compared with CFD models using three different turbulence models (bottom three figures). For all cases the wind direction is perpendicular to the road, with the barrier downwind of the roadway. X/H position of 0 represents the center of the roadway.

3.2 *Evaluation of Barrier Impact*

Model results for the base case scenario – barrier height of a typical noise barrier (6 m), winds orthogonal to the road, and no emissions from the access road – reveal the influence of near-road barriers on highway traffic-related emissions dispersion. Figures 4 and 5 show several Y-Z cross-sections of the modeling plane, including at the center of the barrier (Y = 0 m), at the barrier edge (Y = 375 m), and in the clearing (Y = 750 m).

Figure 4 shows the modeled turbulence related to the road traffic as well as the significant additional turbulence generated by the barrier. The highest TKE levels are observed at the height of the barrier top, with low TKE immediately behind the barrier.

The presence of the 6 m barrier causes traffic-related emissions to accumulate on the road and then disperse with a greater plume height, with the increased vertical dispersion leading to reduced Chi values behind the barrier region relative to the clearing. The breathing height (2 m) Chi levels are observed to be significantly reduced in the barrier-protected region. The greatest difference is observed in close proximity to the road – at 20 m, the Chi at 2 m height is 24% less behind the barrier than in the clearing. At increasing distances from the road, the difference reduces to 18% at 100 m and 13% at 200 m. It is important to note that numerous studies have established an exponential decrease in traffic-related air pollutant concentrations with increasing distance from the road (e.g., Zhu et al., 2002). Thus, a 24% reduction at 20 m from the roadway relates to a substantial decrease in air pollutant concentrations, while the 13% reduction at 200 m may be a very slight decrease in absolute terms.

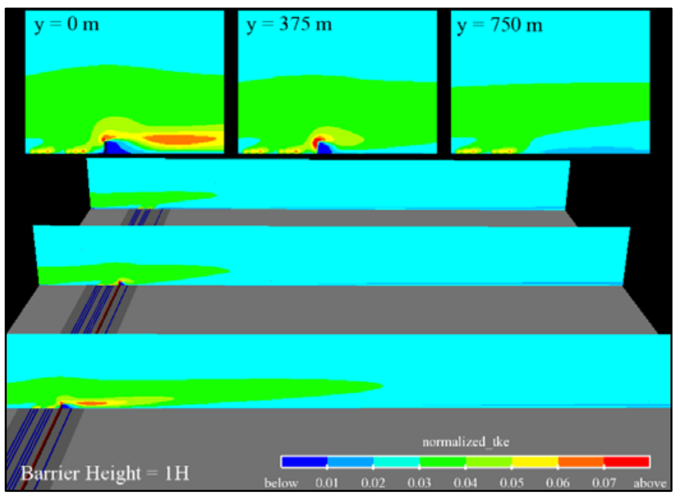

Figure 4. Modeled turbulent kinetic energy for winds orthogonal to the roadway, with cut-sections displaying TKE values at the center of the barrier (0 m), at the edge of the barrier (375 m), and in a clearing (750 m).

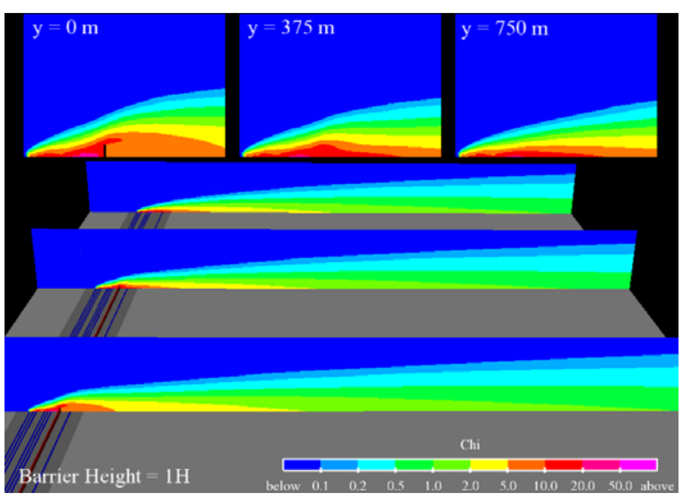

Figure 5. Modeled Chi for winds orthogonal to the roadway, with cut-sections displaying Chi values at the center of the barrier (0 m), at the edge of the barrier (375 m), and in a clearing (750 m).

3.3 *Modeling Challenges for Oblique Winds*

A major benefit of CFD modeling applied to study near-road barrier effects is the ability to easily modify wind direction. However, initial investigations of modeling the barrier effect under multiple wind directions revealed the challenge of pairing a line source with oblique winds. As the wind angle moves from perpendicular to parallel with respect to the roadway, the on-road Chi values begin to increase along the length of the road as emissions accumulate along the road axis. Figure 6 presents the on-road concentrations for the no-barrier section of the highway, starting near the edge of the modeling domain and moving along the wind direction. For the 15 degree wind angle case, the near-parallel wind direction leads to significantly higher on-road Chi relative to the perpendicular (90 degree) wind case and does not level off in the first ~300 m of road. In the case of 45 degree winds, on-road Chi is yet higher than the 90 degree case in absolute terms, but does level off within approximately 100 m of road.

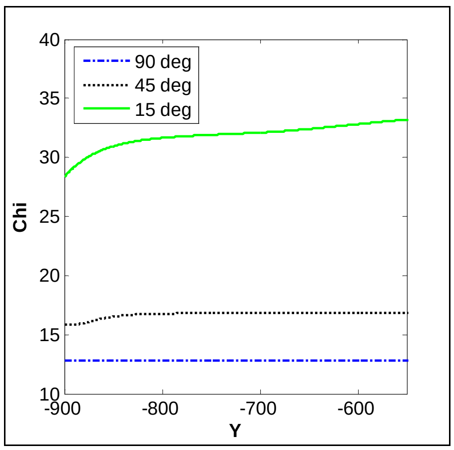

Figure 6. On-road normalized concentrations as a function of distance (m) along the roadway.

It is thus expected that for wind angles greater than 45 degrees, a comparison of relative Chi values for no-barrier to barrier zones with the current model is appropriate, given the selected model section for comparison has ~100 m of along-road distance from either the model edge or barrier edge. However, comparison of absolute Chi values for one oblique wind case to other wind angles, including perpendicular, is inappropriate due to the bias of increasing on-road accumulation of traffic-related emissions with wind angle.

4 CONCLUSIONS

The study of roadside barrier effects on near-road air quality is motivated by recent field research that measured lower ambient air pollution concentrations in barrier-protected areas adjacent to major roads (Baldauf et al., 2008). In order to expand our knowledge of the barrier influence on near-road air quality, this study developed a CFD model simulating a highway with a solid barrier on one side that extends over approximately 50% of the model and is flanked by no-barrier regions on either side. The base road model was evaluated against existing wind tunnel data (Heist et al., 2009), which resulted in the selection of the Realizable k-ε model as the best fit for simulating near-road dispersion. Following this initial evaluation, multiple scenarios of the roadside barrier model were developed. Initial evaluations of a 6 m barrier under perpendicular winds found significant reductions in breathing-height concentrations for behind-barrier areas relative to the no-barrier condition. These findings agree with previous field studies, wind tunnel investigations, and QUIC modeling research observing roadside barrier effects under perpendicular winds from a major road (Baldauf et al., 2008; Bowker et al., 2007; Heist et al., 2009). Variations of this base model will include different barrier heights, wind directions, and additional emissions from an access road paralleling the highway. The initial results for oblique wind angles reveal model limitations for comparison of absolute concentrations from one wind angle to another, although comparison of relative concentrations for no-barrier to barrier regions is possible for near-perpendicular winds.

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