LARGE EDDY SIMULATION OF POLLUTION DISPERSION FROM HIGHWAYS WITH NOISE BARRIERS

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Abstract: The impact of noise barriers on gaseous air-pollution dispersion was examined using the high-resolution CLMM (Charles University LES (Large Eddy Simulation) Microscale Model). The dispersion of a scalar was computed, providing the simulation in which wind direction is approximately perpendicular to the noise barriers. The barriers were assumed to be straight and infinitely long, with a height of 3 m. Dispersion of scalar was modeled for situations with no noise barriers along the highway, barriers on both sides, and for a single barrier on the upwind and downwind sides of the highway. The modelling results are presented and discussed in relation to previous studies and the implications of the results are considered for pollution barriers along highways.

Key words: *LES modelling, Noise barriers, Traffic air-pollution, Air-pollution transport and dispersion.*

INTRODUCTION

This study examines the role of noise barriers as traffic pollution shields for the areas adjacent to busy roads by means of computer modelling using the LES (Large Eddy Simulation) approach. There have been few previous studies in which the transport and dispersion of air pollution have been assessed using LES modelling, particularly for air pollution produced by vehicles. Computational Fluid Dynamic (CFD) approaches have been used in previous studies, and results have been compared with measured data (e.g., Bowker et al., 2007 or Hagler et al., 2011). However, such studies used less sophisticated parameterization of turbulence than that used in this study.

The remainder of this manuscript is organized as follows. A brief description of the LES model is presented in Section 2, and the geometry of the problem, together with the boundary and initial conditions, are outlined in Section 3. The results of numerical simulation are presented and discussed in Section 4. Finally, concluding remarks are provided in Section 5.

NUMERICAL MODEL

The CLMM (**C**harles University **L**ES **M**icroscale **M**odel) has been developed at the Department of Meteorology and Environment Protection, Faculty of Mathematics and Physics at Charles University in Prague. Examples of previous use include study of the very stably stratified atmospheric boundary layer in Fuka, Brechler, 2011 and mathematical simulation of the transport and dispersion of aerosol air pollution, see Fuka, Brechler, 2012.

The basic set of model equations comprises an incompressible continuity equation, the Navier–Stokes equations (possibly for thermally stratified flow), and a transport equation(s) for a passive scalar(s). It is possible to include chemical reactions between different types of pollutants or transformation processes in the model. However, as the aim in this case is to simulate small-scale dynamics in high resolution, completed chemical reactions are likely to be minimal. Consequently, air pollution is denoted as NO_x (a mix of NO and NO_2) and is considered as a non-reacting passive scalar with constant composition.
The set of filtered model equations is as follows:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0, \quad (1)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \overline{u_i u_j}}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{2\nu \bar{S}_{ij}}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j}, \quad (2)$$

$$\frac{\partial \bar{c}}{\partial t} + \frac{\partial \overline{u_j c}}{\partial x_j} = -\frac{\partial}{\partial x_j} s_j, \quad (3)$$

where the overline indicates filtered quantities. The symbol τ_{ij} denotes the turbulent sub-grid stress components, q_j and s_j are turbulent heat and air-pollution fluxes, respectively and these terms have to be modelled using the LES approach.

To model these sub-grid quantities, the concept of turbulent (or eddy) viscosity is used, namely using the Vreman model (Vreman, 2004).

GEOMETRY OF THE PROBLEM, AND THE BOUNDARY AND INITIAL CONDITIONS

The modeled section of road is a straight, four-lane highway, with two lanes in each direction. The lanes are separated in the middle by a median strip 1 m wide. Each lane is 6 m wide (4 m of the lane itself and 2 m wide emergency stopping lane on the outer side of each lane). The total road width (and distance between barriers where present) is 25 m. After consultation with the Road and Motorway Directorate of the Czech Republic (http://www.rsd.cz/en), the height of the noise barrier(s) was set to 3 m in suburban areas. The terrain near the road is assumed to be flat on both sides, and the road is level. When the impact of barriers is modeled, it is assumed that they are of infinite length—the impact of the end of the barrier on air-pollution dispersion has not been modeled. The road emmisions were modeled as 2 m high and 4 m wide continuous volume sources. The traffic induced turbulence is not considered, but the emmisions are assumed to be well mixed in the source volume.

On the solid surfaces (bottom boundary and walls of the noise barrier(s)) the no slip boundary condition was applied. At the top of the domain, the free-slip condition was used, together with a 100-m-thick sponge layer immediately below this boundary. The wind direction is perpendicular to the axis of the road, and flow is fully developed on the inflow boundary using the approach outlined in Xie, Castro, 2008. At the outflow, a Neumann type boundary is applied for flow directed normal to the boundary. Additional 100-m-thick buffer zone is added to the domain immediately in front of the outflow boundary. The geometry of the problem allowed for periodic boundaries on the side of the domain, parallel to the incoming wind direction.

Neutral vertical temperature stratification was chosen for the simulation. The wind speed was set to 5 ms^{-1} at the anemometric height (10 m above the terrain. The wind speed at the inflow boundary followed a logarithmic profile with a roughness length on the order of 10^{-2} m.

The emission rate of NO_x used in this model was set to 0.2255 $g.s^{-1}.km^{-1}$ per lane of traffic, as suggested by the Road and Motorway Directorate. The composition of NO_x corresponds to 70% NO_2 and 30% NO, and this remains constant over the time and distance modeled.

RESULTS AND DISCUSSION

Figs. 1-4 show the spatial distribution of NO_x concentrations (in $\mu g.m^{-3}$) in the four obstacle layouts. All parameters, except the noise barriers positions are unchanged. There is clearly an area of trapped air with high concentrations with the wall in front of the road, but also there is some effect on the far field concentrations.

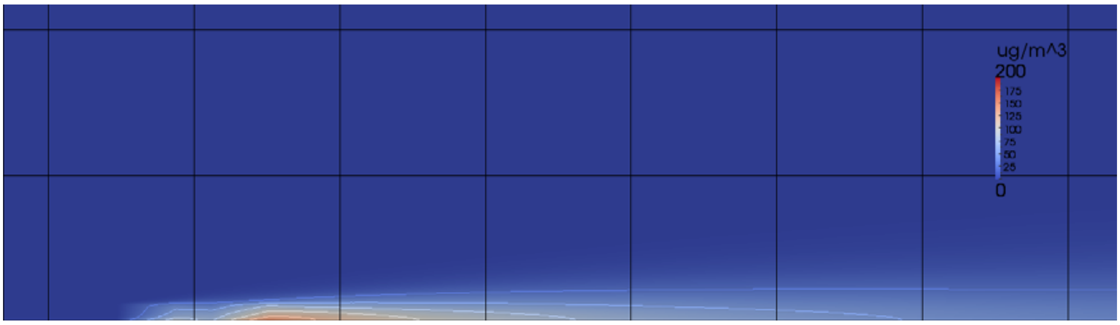

Figure 1. Time averaged concentrations without the barriers. Gridlines denote every 20 m.

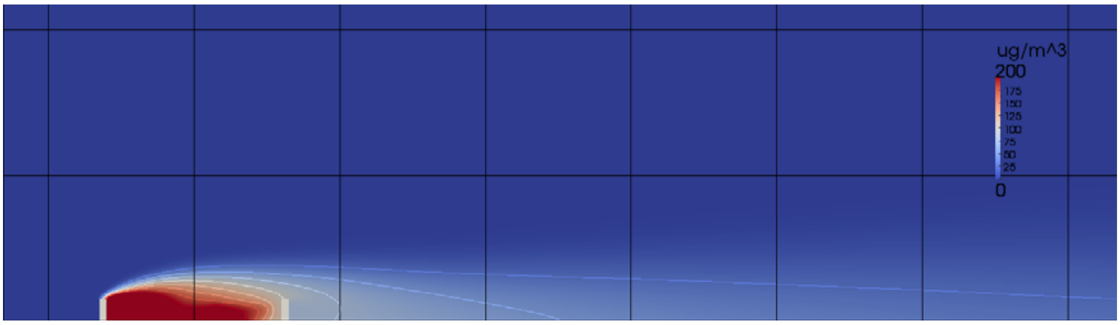

Figure 2. Time averaged concentrations with both upwind and downwind barriers. Gridlines denote every 20 m.

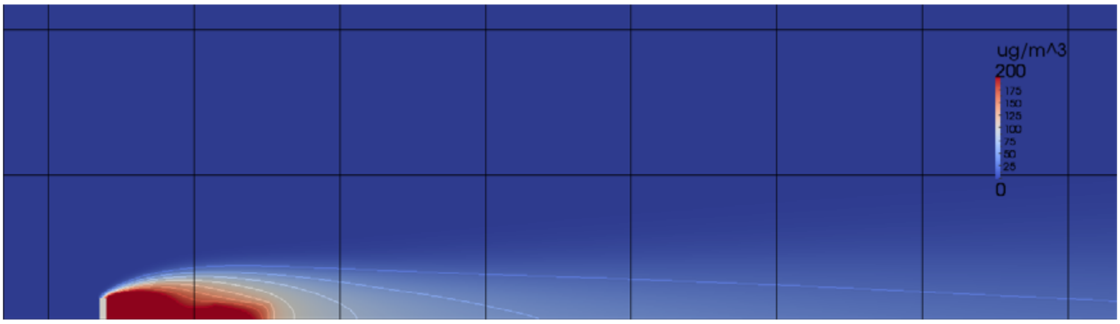

Figure 3. Time averaged concentrations with the upwind barrier. Gridlines denote every 20 m.

Figure 4. Time averaged concentrations with the downwind barrier. Gridlines denote every 20 m.

Figure 5 shows concentrations in the height z = 1.5 m. When there are no barriers present, or when there is a barrier on the downwind side of the road only, the peak concentration just above the road is much lower and shifted downwind. However, concentrations up to approximately 100 m from the road are higher when there is only a downwind barrier, or over the whole downwind area when no barrier is present. Most importantly, when there are no barriers or only a leeward side barrier, concentrations of NO_x above the road itself are relatively low, but are higher adjacent to the road. This extends for 100 m when there is a leeward barrier, and over the whole modeled area when there are no barriers. The low concentrations occur as a result of good ventilation in the area above the road. This is slightly lower, but of the same magnitude, as the concentration with one barrier on the upwind side.

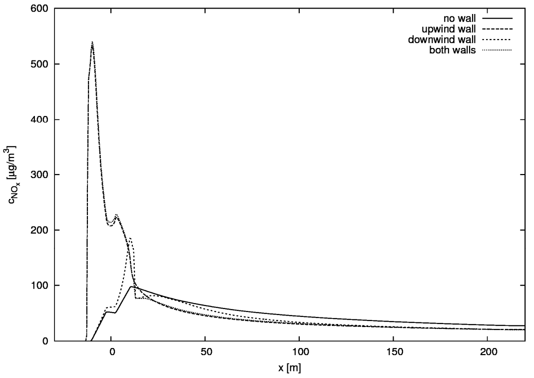

Figure 5. Plot of NO_x concentrations at height z = 1.5 m as a function of distance from the centerline.

The vertical distributions of concentrations at a point located 22.5 m downwind of the road axis are shown in Figure 6. This demonstrates that the presence of any barrier, regardless of location, results in a decrease in concentration at ground level and an increase in the height at which higher concentrations occur, due to blocking effects and recirculation behind the barrier. The highest ground concentrations at this location were recorded when no barriers were present, but this changes at 2.0–2.5 m above the surface.

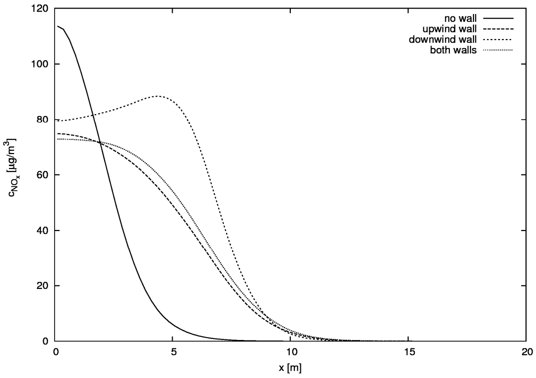

Figure 6. Vertical profiles of concentrations at x = 22.5 m (10 m behind the possible downwind barrier).

It is important to note that throughout the modelling process, the layout of the simulation was simplified, as buildings and vegetation were not taken into account and terrain was assumed to be flat. Furthermore, it was assumed that emissions only originated from traffic on the segment on the road being examined. When a barrier is present, the pollutant distribution is affected by the recirculation zone, primarily occurring on the leeward side of the highway.

CONCLUSIONS

We simulated the impact of noise barriers on air-pollution dispersion. To do this, relatively simple conditions were chosen: a straight section of four-lane highway on flat terrain with no surrounding buildings or vegetation. The wind direction was perpendicular to the highway direction and thermal stratification was neutral.

The results show that barriers, particularly when located on the upwind side or on both sides of a highway, may improve environment conditions. Concentrations of pollutants in the lee of the highway are lower when there are no barriers, or when a barrier is located on the downwind side of the highway. This effect is due to increased mixing. When a barrier is present on the upwind side of the highway, the concentration at and just above the road surface is increased, but lowered on the leeward side of the highway. Recirculation behind the leeward-side barriers also increases the pollutant concentration behind the barrier up to 80 m from the highway side in comparison with barriers on both sides or on the upwind side. When there are no barriers, concentrations at the highway surface and just above are the lowest of all situations due to the increased ventilation. However, a much greater area is subject to increased concentrations of pollutants.

The results show that the use of only one barrier located on the upwind side may provide a good result at a lower cost, assuming the wind direction is relatively constant. If this is not the case, barriers on both sides of the highway may have to be installed to effectively shield the urban population from increased air pollution near highways.

ACKNOWLEDGEMENTS

This work was supported by the Czech Ministry of Education, Youth and Sports under the framework of the research plan MSM0021620860, by the Road and Motorway Directorate of the Czech Republic, and by the company ATEM, s.r.o.

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