THE IMPACT OF ROADSIDE BARRIERS ON NEAR-ROAD CONCENTRATIONS OF TRAFFIC RELATED POLLUTANTS

Nico Schulte[1] and Akula Venkatram[1]

[1]Mechanical Engineering, University of California, Riverside, USA

Abstract: The emissions from motor vehicles can significantly affect the health of the population. Air quality monitoring studies conducted near major roadways indicate that these health effects are associated with elevated concentrations, compared with overall urban background levels, of motor-vehicle-emitted compounds. Roadside barriers can be one of the most practical methods of reducing near road concentrations. We develop two models of dispersion in the presence of barriers. Comparison with field and wind tunnel data shows that the models capture the major effects of barriers on concentrations. A sensitivity study of the models shows that the concentration reduction due to a barrier extends farthest downwind during stable atmospheric stability conditions. As the barrier height is increased, concentrations are reduced the most during stable conditions.

Key words: *barrier, near-road, dispersion, traffic*

INTRODUCTION

The emissions from motor vehicles can significantly affect the health of the population. One comprehensive study conducted by the Health Effects Institute in 2010 concluded that exposure to traffic-generated air pollution, which in this case means living within about 300-500 m of a major road, exacerbates asthma and likely causes onset of childhood asthma, nonasthma respiratory symptoms, impaired lung function, total and cardiovascular mortality, and cardiovascular morbidity (HEI 2010).

Air quality monitoring studies conducted near major roadways indicate that these health effects are associated with elevated concentrations, compared with overall urban background levels, of motor-vehicle-emitted compounds, which include carbon monoxide (CO); nitrogen oxides (NOx); coarse (PM10-2.5), fine (PM2.5), and ultrafine (PM0.1) particle mass; particle number; black carbon (BC), polycyclic aromatic hydrocarbons (PAHs), and benzene.

Roadside barriers can be one of the most practical methods of reducing near road concentrations. We develop two models of dispersion in the presence of barriers and then use these models to examine the impact of barriers with 1 to 12 m height on near road concentrations under neutral, unstable, and stable atmospheric conditions.

We compare the models we developed with data measured in a wind tunnel study conducted at the EPA wind tunnel in 2008 (Heist et al. 2009) and with data measured in a field study (Finn et al. 2010). These studies measured dispersion from simulated roadways in the presence of barriers.

SOURCE-SHIFT MODEL

The wind tunnel study found that the ground-level concentrations beyond a distance of about 10 times the height of the barrier could be modelled as a ground-level source with two modifications: 1) the source is shifted upwind, and 2) the effective rate of vertical plume spread, the entrainment velocity, w_e, relative to the friction velocity, u_*, is increased in the presence of a barrier (Heist et al. 2009).

We parameterize the source shift distance by enforcing the condition that the concentration downwind of the barrier is well mixed over the height of the barrier, an effect we see from measurements in the wind tunnel. Then, the vertical plume spread at the location of the barrier should be proportional to the barrier height. Based on this assumption we can write the shift distance as:

$$\sigma_z\left(\frac{s+x_b}{\beta\cos(\theta)}\right)=\sqrt{\frac{2}{\pi}}H \qquad (1)$$

where s is the shift distance, σ_z is the vertical plume spread, H is the barrier height, x_b is the distance from the physical source to the barrier, □ is the angle between the mean wind direction and the normal to the barrier, and □ is an empirical constant, which we include to calibrate the model.

The vertical plume spread is given by equation 2:

$$\sigma_z(x) = \alpha * 0.57 \frac{u_* x}{U(\bar{z})} \left(1 + 3 \frac{u_*}{U(\bar{z})} \left(\frac{x}{L} \right)^{2/3} \right)^{-1}, L > 0 \tag{2a}$$

$$\sigma_z(x) = \alpha * 0.57 \frac{u_* x}{U(\bar{z})} \left(1 + 2 \frac{u_*}{U(\bar{z})} \frac{x}{|L|} \right), L < 0 \tag{2b}$$

where u_* is the surface friction velocity, U is the wind speed, L is the Monin-Obukhov length, and we include the factor □, which accounts for increased relative entrainment velocity in the barrier models.

The simplest formulation for α would be to set it to a constant. During neutral conditions α is about 1.25 to 1.5 in the wind tunnel and about 2 in the field study. The difference between the necessary choices of α in the wind tunnel and field study may be explained by the difference in the upstream boundary layer turbulence and surface roughness. Similarity parameters for the flow over a barrier include the upstream turbulent intensity (Raine et al. 1977; Ogawa et al. 1980) and the height above ground level relative to the surface roughness length (Raine et al. 1977). The wind tunnel study has a larger surface roughness than the field study (0.78 m and 0.27 m vs. 0.051 m) and a larger turbulent intensity, so the value of α may be different between the wind tunnel and field study data.

MIXED-WAKE MODEL

The mixed-wake model is based on the Gaussian plume formulation, but the vertical concentration distribution is modified to account for the effect of the barrier. Equation 3 describes the surface concentration C_s when the concentration below the barrier height is well-mixed:

$$C_s = \frac{q}{\gamma U(H/2) + U(\bar{z})\sqrt{\pi/2}\,\sigma_z(x)} \tag{3}$$

where q is the emission rate, U is the wind speed, $\bar{z}$ is the effective plume centreline height, and □ is an empirical constant that we include to calibrate the model.

There are two important wind speeds in this formulation (which are included in equation 3): the wind speed at half the barrier height and the wind speed at the effective plume centerline height. The pollutant mass that is mixed below the barrier height is advected with the wind speed at half the barrier height, and the rest of the plume is advected with the wind speed at the effective plume centerline height. We make a modification to the velocity profile used to calculate the wind speed at half the barrier height: when we calculate the velocity for a boundary layer with a nonzero displacement height we set the displacement height equal to zero. This may be physically correct because the flow in the wake of the barrier may not experience the same displacement as the upstream boundary layer (Counihan et al. 1974).

We make an additional modification to both the source-shift and mixed-wake models: in both models we modify the plume spreads given by equation 2 by setting $L=\infty$ when the atmosphere is stable ($L>0$). This improves the model predictions during stable conditions. For the factor α, we use values of 1.5 and 1.15 for NRTS08 and the wind tunnel, respectively.

COMPARISON WITH DATA

The model performance is expressed quantitatively by the geometric mean and standard deviation of the residuals between the log-transformed observations and predictions, by the fraction of data points that are within a factor of two of the observations, and by the correlation coefficient between the data. A perfect correspondence between observations and predictions will produce m_g and s_g equal to 1. If m_g is less than 1 the observations are on average smaller than the model predictions.

Wind Tunnel

Table 1 shows the performance of the source-shift and mixed-wake models at explaining the concentrations measured in the wind tunnel. Two wind tunnel simulations were conducted with a barrier downwind of the road, one with a smooth approach flow and one with a rough approach flow. The smooth approach flow velocity profile has zero displacement height, while the rough approach flow, intended to be typical of an urban environment, has a displacement height of *8.1 m.* The mixed-wake model underestimates concentrations near the barrier in the smooth case, and the source-shift overestimates concentrations near the barrier in the rough case. The mixed-wake model residuals have a smaller standard deviation than that of the source-shift.

Table 1: Performance of source-shift (Shift) and mixed-wake (MW) models at explaining concentrations measured in the wind tunnel.

	m_g		s_g		r^2	
Boundary Layer	**Shift**	**MW**	**Shift**	**MW**	**Shift**	**MW**
Smooth	1.04	1.42	1.31	1.17	0.82	0.96
Rough	0.69	1.03	1.40	1.13	0.92	0.97

Field study

Figure 1 show the performance of the source-shift model at explaining crosswind maximum concentrations measured in the field study. The model was run with □ = *0.5,* and □ = *1.5.* The model performs best during neutral and slightly stable conditions and worst during the very stable conditions of day 5. The source-shift model tends to underestimate concentrations far from the barrier, especially during unstable conditions. During unstable conditions the source-shift model overestimates concentrations which were measured at receptors located within a distance of about 5H from the barrier.

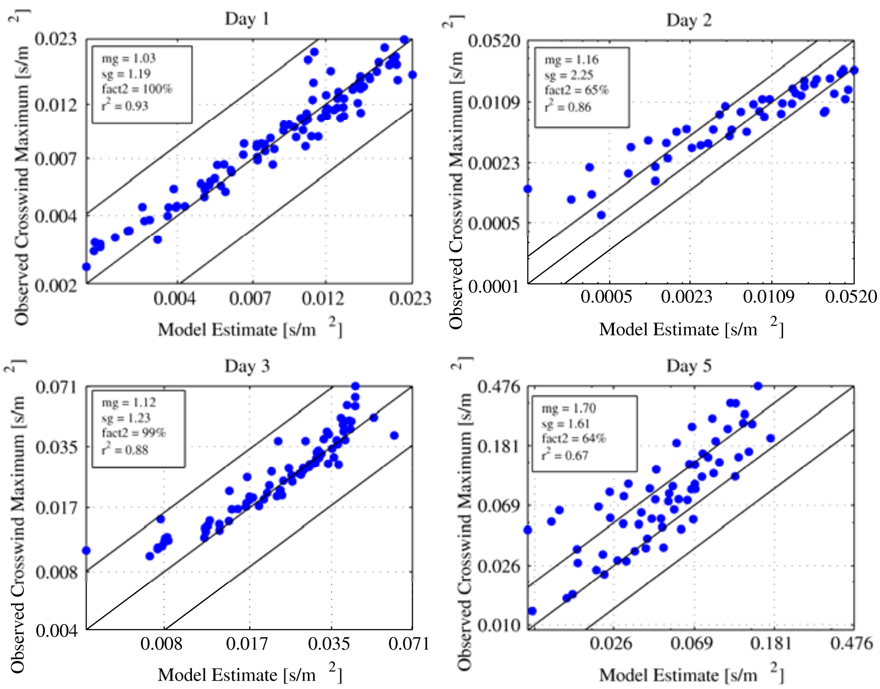

Figure 1: Scatterplots comparing the source-shift with mean crosswind maximum concentrations observed during NRTS08. The model was run with □=*0.5.* The model performs best during neutral conditions and worst during very stable conditions. The model slightly overestimates during day 3, and tends to underestimate concentrations far from the barrier.

Figure 2 shows scatterplots comparing the mixed-wake model with NRTS08 crosswind maximum concentrations. The model was run with □=*1.3.* The mixed-wake model performs best during neutral and slightly stable atmospheric conditions. The mixed-wake model overestimates concentrations near the barrier during unstable conditions, but it doesn't underestimate far from the barrier and the standard deviation of residuals during unstable conditions is smaller for the mixed-wake model than for the source-shift (1.76 vs. 2.25). Overall the performance is similar to the source-shift, except during day 2, where the mixed-wake model has a smaller spread.

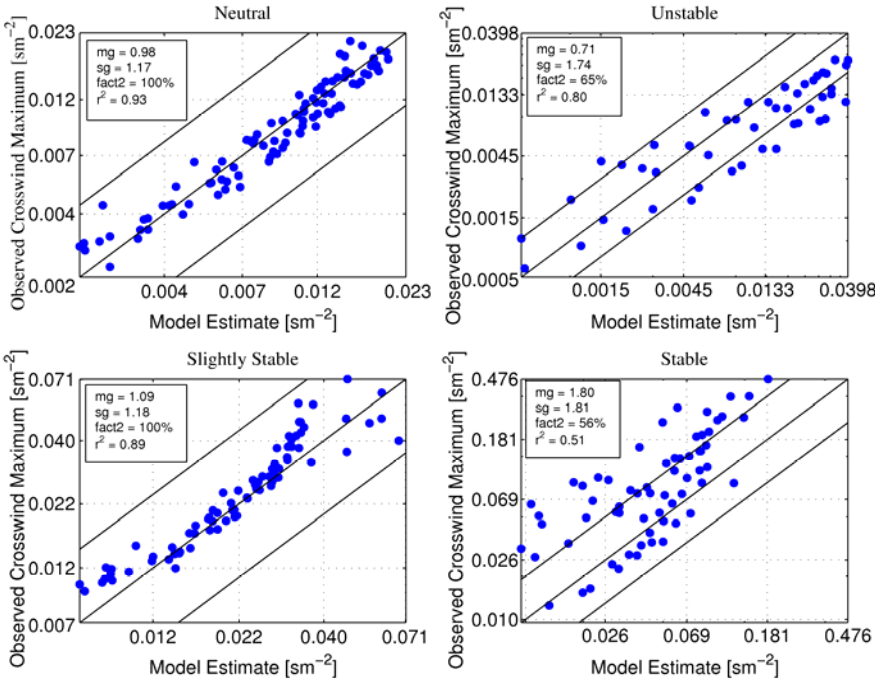

Figure 2: Comparison of mixed-wake model crosswind maximum concentrations with NRTS08 crosswind maximum concentrations. The model was run with □=*1.3.* The model performance is similar to the source-shift, except during day 2, when the model performs better than the source-shift.

IMPACT OF BARRIERS ON NEAR ROAD CONCENTRATIONS

Figure 3 shows the sensitivity of the mixed-wake model predictions to variations in the barrier height, plotted as a function of non-dimensional distance x/H, where H is the barrier height and x is the distance from the barrier. As expected, the largest impact of the change in barrier height occurs close to the barrier, and this impact decreases with distance as vertical mixing by atmospheric turbulence becomes more dominant relative to that induced by the barrier.

The change in barrier height has its greatest impact during stable conditions. This is significant because the largest concentrations occur during stable conditions corresponding to early morning, late evening, and night time periods.

During unstable conditions (upper right) the concentration for all the barrier heights is within 20% of the flat terrain concentration at a downwind distance of *30H*, while during very stable conditions (bottom right) the concentrations for the *3 m, 6 m, and 12 m* barriers are still significantly different from the flat terrain concentration beyond $x = 300H$. Note that for a *3 m* barrier, *300H* is almost *1 km.*

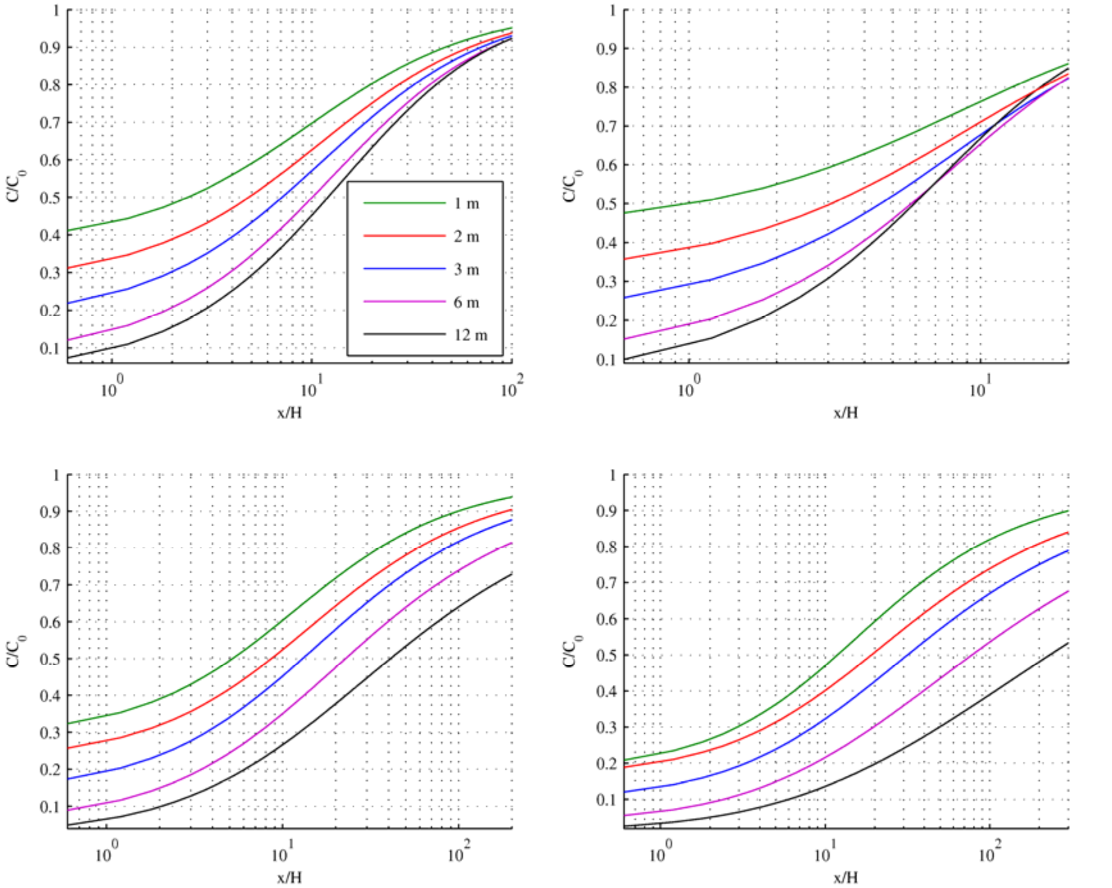

Figure 3: Sensitivity of mixed-wake model predicted concentrations to changes in barrier height vs. downwind distance for meteorology representing neutral (top left), unstable (top right), slightly stable (bottom left), and strongly stable (bottom right) atmospheric conditions. The barrier height, H, takes values of 1 m, 2 m , 3 m, 6 m, and 12 m. Note the different horizontal scale.

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