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Authors
Isakov, Vlad
Venkatram, Akula
Baldauf, Richard
et al.

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Evaluation and development of tools to quantify the impacts of roadside vegetation barriers on near-road air quality

Vlad Isakov[*],
Office of Research and Development, National Exposure Research Laboratory, US Environmental Protection Agency, 109 TW Alexander Drive, Research Triangle Park, NC 27711, USA

Akula Venkatram[*],
Bourns College of Engineering, University of California, Bourns Hall A343, Riverside Riverside, CA 92521, USA

Richard Baldauf,
Office of Research and Development, Office of Transportation and Air Quality, US Environmental Protection Agency, 109 TW Alexander Drive, Research Triangle Park, NC 27711, USA

Parikshit Deshmukh, and
Jacobs Technology Inc., 109 TW Alexander Drive, Research Triangle Park, NC 27711, USA

Max Zhang
Sibley School of Mechanical and Aerospace Engineering, Cornell University Ithaca, NY 14853, USA

Abstract

Traffic emissions are associated with the elevation of health risks of people living close to highways. Roadside vegetation barriers have the potential of reducing these risks by decreasing near-road air pollution concentrations. However, while we understand the mechanisms that determine the mitigation caused by solid barriers, we still have questions about how vegetative barriers affect dispersion. The US EPA conducted several field experiments to understand the effects of vegetation barriers on dispersion of pollutants near roadways (e.g., 2008 North Carolina study and 2014 California study) that indicate the reduction of near-road pollutant concentrations can be up to 30% due to the barrier effects. The results of these field studies are being used to develop and evaluate dispersion models that account for the effects of near-road vegetative barriers. These models can be used for evaluating the effectiveness of vegetation barriers as a potential mitigation strategy to reduce exposure to traffic-related pollutants and their associated adverse health effects. This paper presents the results of the analysis of the field studies and discusses dispersion models being used to describe the data in order to simulate the effects of near-road barriers and to develop recommendations for model improvements.

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[*] Corresponding author: Isakov.Vlad@epa.gov.

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Keywords

roadways; barriers; vegetation; dispersion; models

1 Introduction

There is a strong international consensus on elevated health risks for populations living, working, or going to school near large roadways. The health concerns have been linked to elevated levels of air pollution caused by traffic emissions (see Health Effects Institute, 2010). Public health concerns have raised interest in methods to mitigate these traffic emission impacts. Traditionally, transportation and land use planning options have been focusing on vehicle emission standards and reduction in vehicle activity, and also establishing buffer or exclusion zones. These options are typically ‘long-term’ since emission reductions take long to implement and planning and zoning is involved in rerouting and reducing vehicle miles travelled as well as establishing buffer zones. Other options to mitigate the impacts of traffic emissions focus on roadway design and urban planning that includes road location and configuration, and roadside solid barriers and vegetation (Baldauf et al., 2009). The advantage of the roadside barriers option is that it provides an opportunity for a ‘short-term’ solution. In addition, roadside features may already be present and affecting nearby population exposures. Also, the roadside barriers often have other positive benefits. Thus, appropriately selected and planted roadside vegetation may reduce traffic-related air pollution concentrations by providing a way of reducing exposures to traffic emissions. However, barriers may also cause increases in air pollution due to confinement effects, especially in urban canyons (Janhäll, 2015). While roadside vegetation barriers have shown the potential to reduce near-road air pollution concentrations, the characteristics of these barriers needed to ensure pollution reductions are often not well understood. Therefore, models and more supporting field measurement data are needed to fully assess these impacts. The US EPA has initiated studies to examine how roadside vegetation barriers affect near-road air pollutant exposures. The studies used a combination of modelling and monitoring to characterise the impact of roadway features on near-road air quality.

2 Roadside barrier field studies

The US EPA has conducted two field studies to examine how roadside vegetation barriers affect near-road air pollutant exposures – in Chapel Hill, North Carolina and Woodside, California. The Chapel Hill study was conducted in fall of 2008 along a four-lane highway (US Route 15–501). The geospatial monitoring of air pollution (GMAP) electric car provided real-time mapping of PM, NO2, and CO by repeatedly driving a specified route at each study site (Hagler et al., 2010). Thus, mobile monitoring provided spatially-resolved air quality data behind the barrier and in the clearing. The vegetation barrier consists of around 10% of deciduous trees (Maple tree) and 90% of coniferous trees (Leyland Cypress and Morella cerifera) approximately 4–8 m in height and 2–5 metres thick. We have a combination of measurement and modelling to evaluate the impact of the vegetation barriers and developing recommendation for improved dispersion modelling algorithms based on solid barrier algorithms to be applicable for vegetation barriers. We used the comprehensive turbulent aerosol dynamics and gas chemistry (CTAG) model with large eddy simulation (LES) to simulate the impacts of vegetation barriers on dispersion of ultrafine particulates near roadways and evaluated model results against the Chapel Hill field study data (Tong et al., 2016). Next, we used the model to explore the effects of vegetation barriers on near-road particle concentrations using six common near-road configurations: for vegetation and solid barriers. The modelling suggests two potentially viable design options as a potential mitigation option for near-road particulates:

1. a wide vegetation barrier with high leaf area density
2. vegetation-solid barrier combinations, i.e., planting trees next to a solid barrier.

However, these recommendations for vegetation barrier designs are based on model simulations for a few generic configurations, and therefore future implementation needs to take into account site-specific characteristics, given the complexity of urban landscapes. The recommendations were considered in the design of the California 2014 field study.

The California Roadside Vegetation Barrier study was conducted to determine the influence of vegetation barriers with various characteristics on near-road pollutant concentrations. The study was conducted in the San Francisco Bay area along Interstate-280 near Woodside, CA. Measurements were collected near a roadway with varying vegetation types – bush/tree combinations with varying porosity and manicured hedges. The study was conducted for approximately one month, from late August until late September 2014 for approximately three hours each day during either morning or afternoon time periods. Data collected included traffic counts and speed, meteorology, and air quality for multiple pollutants. Concentrations of NO2, CO, ultrafine particles (UFP), and black carbon (BC) were measured using the GMAP electric car and fixed sites along two limited-access stretches of highway that contained a section of the vegetation barrier and a section with no noise barrier at-grade with the surrounding terrain. The terrain is mostly flat with a few low-level buildings, and there are no other major sources of air pollution which were identified within a 5 km area around the study sites.

The GMAP measurements were conducted across six locations behind the barrier with different characteristics:

Stop 1	clearing
Stop 2	behind bushes
Stop 3	gap with trees
Stop 4	behind thick oleander bushes
Stop 5	gap with trees
Stop 6	behind thick bushes and trees (Figure 1).

The porosity of the vegetation varied along the study area. The majority of the vegetation had low porosity, as shown in Figure 1; however, a couple of areas had gaps and openings where the bushes did not grow (stops 3 and 5). Quantitative porosity measurements, such as leaf area index (LAI), could not be obtained at this site due to safety concerns with making these measurements from the highway and no locations available with a consistent background contrast horizontally, which is needed for this type of measurement. The bushes/

trees ranged from 4 to 6 m in height and 3 to 5 m in thickness along the monitored route. The GMAP measurements were made right behind the vegetation barriers, approximately 20 m from the nearest travel lane of Interstate-280.

In addition to GMAP monitoring, onsite meteorological measurements were made using three-dimensional RM Young 81000 sonic anemometers at the clearing location, and behind the vegetative barrier (approximately 20 m from I-280) at heights of 2, 3 and 5 metres above ground. The locations of sonic anemometer were rotated among the behind vegetation fixed sites each day, so each location/vegetation barrier characteristic was monitored for four days. The onsite measurements indicate low winds (below 3 m/s), predominantly from North-East. A wind rose based on all sonic observations at six stops at 5 m height is shown in Figure 1.

The results of GMAP measurements at the Woodside location for BC, CO, NO2 and UFP are shown in Figure 2. Distributions of observed concentrations from all 1-second measurements in Woodside are compared across six locations behind the barrier with different characteristics. Each distribution is based on roughly ten thousand observations during the entire field campaign. Thus, the distributions represent a longer-term exposure over the range of varying meteorological conditions. The results indicate reduction in concentrations behind the barrier. The median values of the distribution behind the barrier with different characteristics (stops 2 and 3 – bushes, stops 5 and 6 – bushes and trees) are generally lower than in the clearing. One exception is stop 3, which is a gap in the barrier.

3 Comparisons with simplified modelling approach

We can quantify the effect of vegetation on reducing near-road concentrations by estimating the height of a solid barrier that would result in the same reduction. The primary effect of a solid barrier is to increase vertical dispersion of the pollutants emitted from the road. A simple model of this effect adds the height of the barrier to the vertical dispersion (Schulte et al., 2014). Then, if we assume that the emissions from the road are distributed over the width of the road, W, the concentration at a distance, d, from the edge of the road is described by equation (1) (Venkatram et al., 2007).

$$C = \sqrt{\frac{2}{\pi}}\frac{q}{\sigma_w W}\ln\left(1 + \frac{W}{d + \frac{h_0 U}{\sigma_w}}\right), \quad (1)$$

In equation (1), q is the emission rate per unit length of the road, h0 is the initial spread of the plume induced by vehicle turbulence, σw is the standard deviation of the vertical velocity fluctuations, and U is the near surface wind speed. We can adapt this equation to dispersion in the presence of solid barriers by assuming that the barrier induces vertical spread h0 = H, where H is the height of the barrier. This approximation simulates solid noise barrier impacts on downwind pollutant concentrations for a field tracer study (Schulte et al., 2014) and a real-world field study in Phoenix, Arizona, USA (Venkatram et al., 2016).

If we assume that vehicle induced turbulence enhances the vertical spread by 2 m, we can derive an expression for the solid barrier height that would have resulted in the observed concentration reduction, R, seen by the vegetative barrier relative to the open section. This expression is described by equation (2). In equation (3), R is the ratio of the concentration behind the vegetative barrier to the concentration in the open section, and h0 = 2 m corresponds to vehicle induced turbulence in the open section.

$$H = \frac{\sigma_w}{U}\left(\frac{W}{p-1} - \mathrm{d}\right), \quad (2)$$

where p is given by

$$p = \left(1 + \frac{W}{d + \frac{h_0 U}{\sigma_w}}\right)^R \quad (3)$$

Table 1 presents results for the measurements made in Woodside. Here, R refers to the mean of the observed concentration reductions of the four species at each of the stops. The variables σw and U were derived from the sonic measurements made at a 3 m height in the open area. All the variables used in deriving averages correspond to the wind direction blowing the emissions towards the measurement stops.

We see that the computed solid barrier heights, in the last column, are consistent with the heights of the vegetation and their coverage. This suggests that it might be possible to estimate the equivalent height of a barrier using the actual height of the vegetative barrier multiplied by its porosity. This would allow us to compute the effect of a vegetative barrier under different meteorological conditions using more established models for dispersion behind a solid barrier (Schulte et al., 2014). This approach would not account for potential removal of particulate by diffusion or impaction.

4 Further thoughts

A roadside vegetation barrier can affect downwind pollutant concentrations in several ways:

1. enhance vertical dispersion by forcing the flow over the barrier
2. remove pollutants from the flow passing through the barrier through dry deposition
3. inhibit vertical dispersion of the pollutants passing through the barriers by reducing turbulent velocities in the flow.

While mechanisms (1) and (2) will reduce downwind concentrations, the third mechanism can increase downwind concentrations relative to those in the absence of a barrier if the plume embedded in the flow going through the vegetative barrier dominates the plume going over the barrier. The relative roles of these mechanisms, which depends on the physical structure including the porosity of the barrier, are not well understood. Thus, while roadside bushes and hedges can result in improved near-road air quality if designed properly, some configurations might not enhance dispersion or could even increase concentrations behind the barrier relative to those in flat terrain.

Our analysis of the field data suggests that the following barrier configurations could help mitigate near-road exposures to traffic pollution:

1. complete coverage from ground to top of the vegetation canopy
2. no gaps, dead tree areas or high porosity (original planting and maintenance of vegetation)
3. sufficient length for protecting sensitive populations/land uses.

It is clear that more field studies accompanied with modelling analysis are required to elucidate the processes that govern the impact of vegetative barriers on near-road air pollution.

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Biographies

Vlad Isakov is a Research Physical Scientist at the US EPA National Exposure Research Laboratory’s Computational Exposure Division where he leads research efforts on the development and testing through applications innovative approaches to model spatially and temporally resolved air quality concentrations in support of exposure and health studies.

Akula Venkatram is a Professor of Mechanical Engineering at the University of California, Riverside. His research interests focus on comprehensive modelling of systems governing air quality, theoretical aspects of small-scale dispersion, application of micrometeorology to dispersion problems, and development of simplified models for complex systems.

Richard Baldauf is a Senior Research Engineer at the US EPA jointly appointed to the Office of Research and Development’s National Risk Management Research Laboratory and the Office of Transportation and Air Quality where he leads research efforts characterising the impacts of transportation sources on local air quality and developing methods to mitigate these impacts on human health and the environment.

Parikshit Deshmukh is a Research Engineer with Jacobs Technology Inc. and works as an on-site consultant with the US EPA. He functions as the Jacobs Project Manager and Lead Engineer on several EPA mobile and stationary air quality monitoring projects around the country.

Max Zhang is an Associate Professor at the Sibley School of Mechanical and Aerospace Engineering of the Cornell University. His research interests focus on energy and the environment. He studies the effects of airborne particulate matters and gaseous pollutants on air quality and climate change, using numerical models and experimental techniques.

References

Baldauf RW, Cahill TA, Bailey CR, Khlystov A, Zhang KM, Cook JR, Cowherd C, Bowker G. Can roadway design be used to mitigate air quality impacts from traffic? Air & Waste Manage Assoc. 2009 Environmental Manager (EM), August edition.

Hagler GSW, Thoma ED, Baldauf RW. High-resolution mobile monitoring of carbon monoxide and ultrafine particle concentrations in a near-road environment. J Air & Waste Manage Assoc. 2010 Mar; 60(3):328–336.

Health Effects InstituteTraffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health EffectsBoston, MA: 2010Jan. Special Report 17[online] https://www.healtheffects.org/publication/traffic-related-air-pollution-critical-review-literature-emissions-exposure-and-health (accessed 14 November 2016)

Janhäll S. Review on urban vegetation and particle air pollution – deposition and dispersion. Atmos Environ. 2015 Mar.105:130–137.

Schulte N, Snyder M, Heist D, Venkatram A. Effects of solid barriers on dispersion of roadway emissions. Atmos Environ. 2014 Nov.97:286–295.

Tong Z, Baldauf RW, Isakov V, Deshmukh P, Zhang KM. Roadside vegetation barrier designs to mitigate near-road air pollution impacts. Science Tot Environ. 2016 Jan.541:920–927.

Venkatram A, Isakov V, Deshmukh P, Baldauf R. Modeling the impact of noise barriers on near road air quality. Atmos Environ. 2016 Sep.141:462–469.

Venkatram A, Isakov V, Thoma E, Baldauf R. Analysis of air quality data near roadways using a dispersion model. Atmos Environ. 2007 Dec.41:9481–9497.

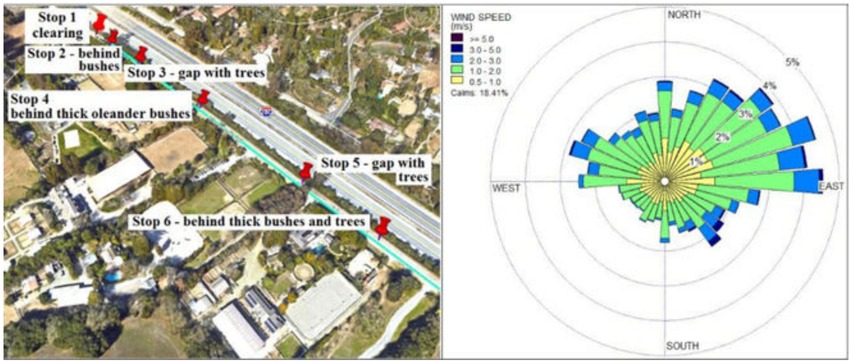

Figure 1.

Aerial view of the study site in Woodside, CA showing locations of selected six stops along the vegetation barriers where GMAP measurements were taken (left panel) and wind rose of onsite meteorological observations

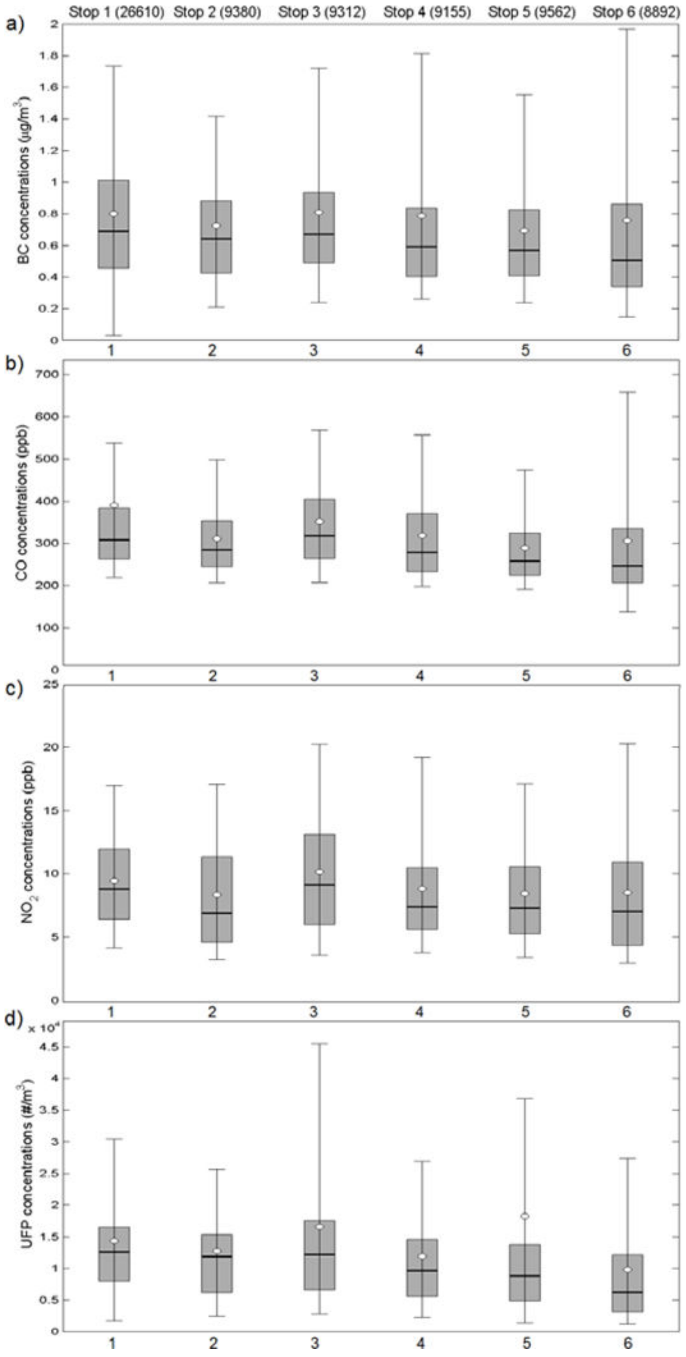

Figure 2.

Distributions of observed, (a) BC (b) CO (c) NO2 and (d) UFP concentrations from all mobile measurements in Woodside

Notes: Each distribution is based on n observations (shown below). The middle line represents the median, the box the 25th and 75th percentiles, and the whiskers the 5th and 95th percentiles. The point represents the mean value of the distribution.

Table 1

Effect of vegetative barriers on concentrations

Stop Description	Stop Description	Observed concentration ratio	Observed height of vegetation (m)	Modelled equivalent barrier height (m)
1	Clear	1	0	2.0
2	vegetation buffer ~6–7 m deep with approx. 75% coverage	0.77	3-4	3.5
3	Wide gap (> 4 m) with highly porous mix of trees and thin bushes (~6–7 m with approx. 50% coverage)	1	3-4	2.0
4	vegetation buffer ~6–7 m with approx. 90% coverage	0.73	3-4	3.9
5	trees ~10 m, thick vegetation buffer ~7 m, and 1m wide gap with little vegetation	0.85	3-4	2.8
6	trees 10–12 m, vegetation buffer ~7m with approx. 90% coverage	0.71	3-4	4.1