



The effects of roadside vegetation characteristics on local, near-road air quality

Parikshit Deshmukh¹ · Vlad Isakov² · Akula Venkatram³ · Bo Yang⁴ · K. Max Zhang⁴ · Russell Logan¹ · Richard Baldauf^{2,5}

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Abstract

Roadside vegetation has been shown to impact downwind, near-road air quality, with some studies identifying reductions in air pollution concentrations and others indicating increases in pollutant levels when vegetation is present. These widely contradictory results have resulted in confusion regarding the capability of vegetative barriers to mitigate near-road air pollution, which numerous studies have associated with significant adverse human health effects. Roadside vegetation studies have investigated the impact of many different types and conditions of vegetation barriers and urban forests, including preserved, existing vegetation stands usually consisting of mixtures of trees and shrubs or plantings of individual trees. A study was conducted along a highway with differing vegetation characteristics to identify if and how the changing characteristics affected downwind air quality. The results indicated that roadside vegetation needed to be of sufficient height, thickness, and coverage to achieve downwind air pollutant reductions. A vegetation stand which was highly porous and contained large gaps within the stand structure had increased downwind pollutant concentrations. These field study results were consistent with other studies that the roadside vegetation could lead to reductions in average, downwind pollutant concentrations by as much as 50% when this vegetation was thick with no gaps or openings. However, the presence of highly porous vegetation with gaps resulted in similar or sometimes higher concentrations than measured in a clearing with no vegetation. The combination of air quality and meteorological measurements indicated that the vegetation affects downwind pollutant concentrations through attenuation of meteorological and vehicle-induced turbulence as air passes through the vegetation, enhanced mixing as portions of the traffic pollution plume are blocked and forced over the vegetation, and through particulate deposition onto leaf and branch surfaces. Computational fluid dynamic modeling highlighted that density of the vegetation barrier affects pollutant levels, with a leaf area density of $3.0 \text{ m}^2 \text{ m}^{-3}$ or higher needed to ensure downwind pollutant reductions for airborne particulate matter. These results show that roadside bushes and trees can be preserved or planted along highways and other localized pollution sources to mitigate air quality and human health impacts near the source if the planting adheres to important characteristics of height, thickness, and

Highlights

- Mobile monitoring measured near-road air quality impacts of a vegetation barrier.
- Downwind concentration reductions of up to 50% occurred behind the barrier.
- Gaps in the vegetation led to increased downwind pollutant concentrations.
- Vegetation characteristics determine the effects on near-road air pollution.

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✉ Richard Baldauf
Baldauf.Richard@epa.gov

¹ Jacobs Technology Inc., Durham, NC, USA

² Office of Research and Development, U.S. Environmental Protection Agency, Durham, NC, USA

³ Department of Mechanical Engineering, University of California-Riverside, Riverside, CA, USA

⁴ Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY, USA

⁵ Office of Transportation and Air Quality, U.S. Environmental Protection Agency, Ann Arbor, MI, USA

density with full coverage from the ground to the top of the canopy. The results also highlight the importance of planting denser vegetation and maintaining the integrity and structure of these vegetation barriers to achieve pollution reductions and not contribute to unintended increases in downwind air pollutant concentrations.

Keywords Roadside vegetation · Near-road · Air quality · Traffic · Mitigation

Introduction

Public health concerns related to near-road air quality have become a pressing issue due to the increasing number of health studies linking adverse health effects to populations spending significant amounts of time near high-traffic roads (Health Effects Institute 2010). These effects have been attributed to significantly increased concentrations of particulate matter and gaseous air pollutants emitted by vehicle activity on the nearby road (Karner et al. 2010; Kimbrough et al. 2018, 2017). The adverse health effects experienced by urban populations all over the world from exposures to traffic emissions have elevated the call for methods to reduce the concentrations of these pollutants at the local level. While vehicle emission control techniques and programs to reduce air pollutants emissions from transportation sources are vital components of air quality management, these programs often take a long time to fully implement and do not control all emitted pollutants by traffic, such as brake wear, tire wear, and re-entrained road dust. Thus, other mitigation options, including the preservation and planting of roadside vegetation and the construction of roadside structures such as noise barriers, provide some of the few near-term mitigation options available that can be implemented by urban developers and planners for facilities already subject to high pollution levels near roads or from potential future projects (Baldauf et al. 2009). These methods can also complement existing pollution control programs and regulations.

Several studies have investigated the role of vegetation on pollutant concentrations in urban areas employing modeling, wind tunnel, and field measurements (Gallagher et al. 2015; Janhäll 2015; Baldauf 2017; Abhijith et al. 2017). Vegetation has been shown to both reduce and increase local air pollution levels, although the mechanisms and characteristics for these varying effects are often not well understood (Baldauf et al. 2008; Brode et al. 2008; Hagler et al. 2012; Nowak 2005; Nowak et al. 2000; Steffens et al. 2012; Stone and Norman 2006).

Vegetation has been shown to reduce air pollution impacts through the interception of airborne particles (Petroff et al. 2009) or through the uptake of gaseous air pollution via leaf stomata on the plant surface (Smith 1990) in addition to affecting pollutant transport and dispersion as the air passes through the complex leaf/branch structure. Noise barriers combined with mature vegetation have also been found to result in lower ultrafine particle concentrations along a highway transect compared to an open field or a noise barrier alone (Baldauf et al. 2008; Bowker

et al. 2007). Regional particulate and gaseous pollution removal by urban trees has been estimated across the continental United States (U.S.) using the U.S. Forest Service's i-Tree model (Nowak et al. 2006).

Trees and bushes can also act as buffers between pollutant sources and nearby populations, although the complexity and variability of vegetation structures can lead to varying effects on downwind pollutant concentrations as shown by Hagler et al. (2012) for ultrafine particles (UFP). This variability is due to a number of confounding factors. The complex and porous structure of trees and bushes can modify near-road concentrations via pollutant capture onto plant surfaces or through altering air flow, which can result in either reduced dispersion through the reduction of wind speed and boundary layer heights (Nowak et al. 2000; Wania et al. 2012) or in enhanced dispersion due to increased air turbulence and mixing (Bowker et al. 2007). Recirculation zones have also been observed immediately downwind of forested areas with a flow structure consistent with an intermittent recirculation pattern (Detto et al. 2008; Frank and Ruck 2008). Vegetation type, height, and thickness can all influence the extent of mixing and pollutant deposition experienced at the site. Air pollution near a highway increased in the presence of highly porous vegetation and scattered, ornamental trees with open space under the canopy compared to measurements at a similar area with no vegetation (Yli-Pelkonen et al. 2017; Tong et al. 2015). Alternatively, downwind air pollution decreased when the vegetation was thick, tall, and completely covered the height from the ground to the top of the canopy (Brantley et al. 2014; Al-Dabbous and Kumar 2014). The built environment also matters greatly; air flow and impacts of trees on local air pollution can be substantially different for a street canyon environment than an open highway environment, although similarities in the characteristics of vegetation and the corresponding effect on near-road air pollution exist (Buccolieri et al. 2009; Gromke et al. 2008; Gromke et al. 2016).

In addition to positive and negative impacts on air quality, roadside vegetation can have other varying effects which need to be considered when planning to preserve or plant a vegetation barrier (Baldauf 2017). For example, trees and bushes along roads can improve aesthetics, increase property values, reduce heat island effects, control surface water runoff, and limit noise pollution if dense and thick. However, roadside vegetation can also affect driver sight lines, protrude into safety clear zones along highway right-of-ways, contribute to debris on roads, present fire hazards, and be pathways for pests and invasive species

(Baldauf et al. 2011; Baldauf et al. 2013). Thus, the benefits and potential concerns of roadside vegetation need to be considered for any application, although this paper focuses on air quality impacts.

A research effort was initiated to evaluate the effectiveness of planted vegetation barriers as a potential mitigation strategy to reduce exposure to traffic-related pollutants. The study was conducted to determine whether planted roadside bushes and trees could reduce downwind pollutant concentrations near a large highway and how different characteristics of the vegetation affected pollutant transport and dispersion in order to reconcile the differences observed in previous field studies and provide guidance toward the development of best management practices for roadside vegetation.

Methods

Site location

The field study consisted of air quality measurements during the summer season in Woodside, California, USA near a

highway with vegetation planted along the roadside. The location included a segment of open area with no obstructions to air flow and a long segment of roadside vegetation along the same stretch of limited-access highway (Interstate-280). This highway supported approximately 125,000 vehicles per day during the study. An access road parallel to the highway and behind the vegetation had less than 200 vehicles per day during the study. Figure 1 shows an aerial view of the site. As shown at the bottom of Fig. 1, six locations (labeled “Stops”) were identified with differing vegetation characteristics. Table 1 lists the Stop numbers, descriptors, and details on the vegetation characteristics corresponding to the locations shown in Fig. 1.

As described in Table 1, Stop 1 (CLEARING) was an open area with the vegetation consisting of only low grass and isolated bushes less than 1 m in height and width and no other major obstructions to air flow. The vegetative barrier beyond Stop 1 consisted of a mixture of planted hedges and oleander bushes with scattered trees growing among the bushes. The porosity of the vegetation varied along the study area. The majority of the vegetation had low porosity, as shown for Stops 2 (BUSHES/EDGE), 4 (BUSHES), and 6 (BUSHES/

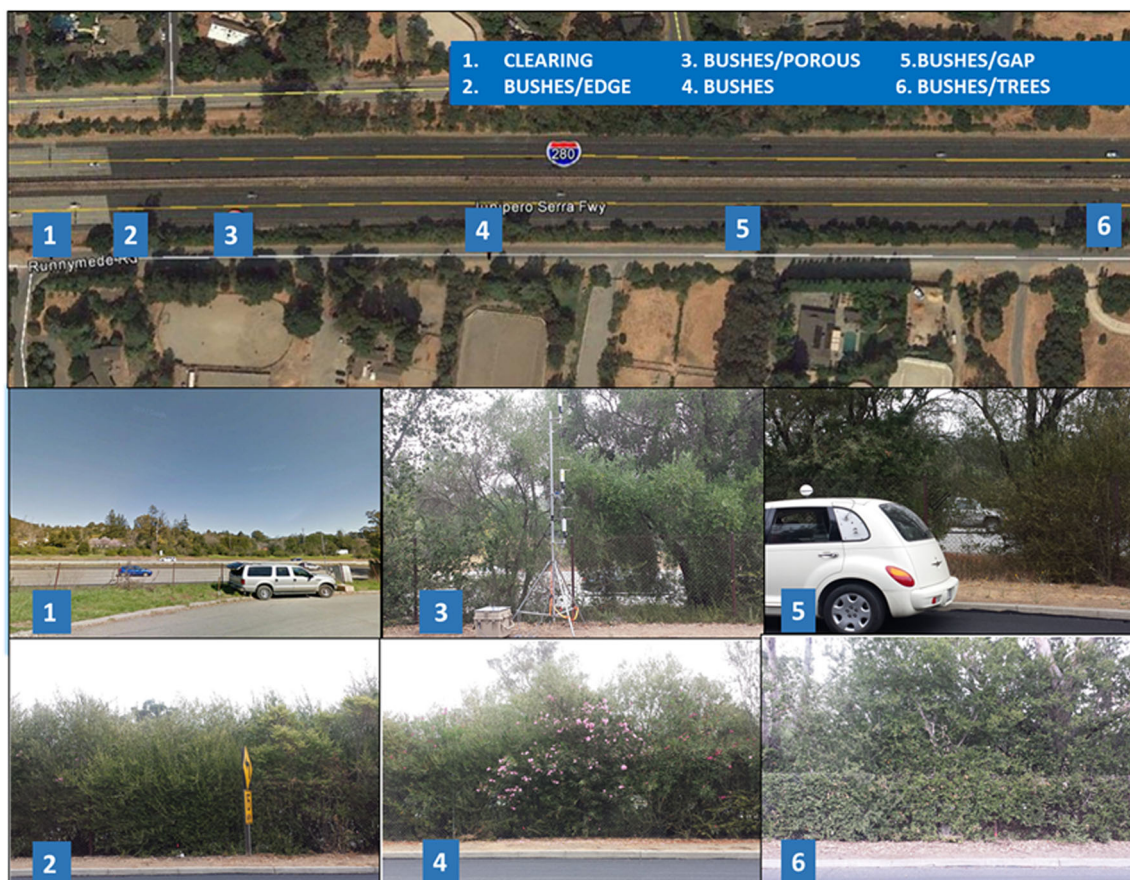


Fig. 1 Aerial view of the study location including Interstate-280, the parallel access road, and the neighborhood to the south of the highway. The inserts at the bottom show a view of the vegetation characteristics at

each measurement location, which correspond to the estimates of vegetation porosity at each location as listed in Table 1

Table 1 Vegetation characteristics at each stop

Stop	Descriptor	Height (m)	Width (m)	Porosity ^a	Notes
1	CLEARING	< 1	< 1	100	Grass and low bushes only; no obstruction to air flow
2	BUSHES/EDGE	3	5	25	Bushes only; located approximately 20 m from clearing
3	BUSHES/POROUS	5	5	50	Porous vegetation with bushes and trees, including large gaps with limited or no vegetation
4	BUSHES	4	10	10	Mix of thick bushes and flowering oleanders
5	BUSHES/GAP	5	10	25/90	Bushes (25% porosity) on either side of an approximately 1.5 m wide, gap (90% porosity)
6	BUSHES/TREES	10	10	10	Mix of bushes approximately 2 m tall with trees extending above to approximately 10 m

^a Porosity estimated visually from pictures as shown in Fig. 1

TREES) in Fig. 1; however, two locations, Stops 3 (BUSHES/POROUS) and 5 (BUSHES/GAP), had large spacing within and between the bushes, where the vegetation either grew sporadically or did not grow at all. The open section and vegetative barrier sections were at-grade (± 2 m) with the highway along the area of all six locations. An access road parallel to Interstate-280 was present along both the clearing and vegetation sections. This road provided access to measure air pollution concentrations at the same distance from the highway for the clearing and behind barrier segments. The access road led to a small residential area, so fewer than 200 vehicles per day were estimated to use this road based on video surveillance collected during the study.

As noted in Table 1, porosities were visually estimated for the vegetation at each of the measurement locations. Quantitative porosity measurements were not obtained for this study due to site limitations. Leaf Area Index (LAI), a common technique used to estimate porosity in a tree canopy setting (Bréda 2003; Weiss et al. 2004; Jonckheere et al. 2004), could not be safely measured accurately due to the characteristics of the vegetation and the surrounding land use. One factor inhibiting the measurement of LAI or other quantitative porosity estimates was the coverage of the vegetation from the ground to the top of the canopy. Under these conditions, porosity measurements could not be taken through the vegetation vertically with the sky as a constant background. In addition, vertical LAI or porosity does not indicate the likelihood of roadside vegetation to reduce downwind pollutant concentrations; rather, the porosity of the vegetation along the horizontal plane from the highway to the downwind receptor affects pollutant deposition and dispersion. Obtaining a horizontal estimate of porosity was also limited at this location since a consistent background was not available horizontally in either direction, from the highway or from the access road. The pictures for Stops 3 (BUSHES/POROUS) and 5 (BUSHES/GAP) highlight the lack of consistent background in the horizontal direction when looking toward the highway since the background changes with changing traffic conditions. Similar background

inconsistencies were present when viewing the vegetation from the highway side toward the residential area. As a result, only visual estimates of porosity could be used for this study.

No other major sources of air pollution were identified within a 5-km radius of the study location. The main sources of pollutants that could confound the measurements of impacts from Interstate-280 were vehicles operating on the access road. In previous studies, to aid in identifying the influence of side road traffic, major short-term spikes in concentrations in the second-by-second mobile monitoring measurements were identified using the procedure described by Hagler et al. (2010). This procedure utilized short-term fluctuations in either CO or UFP concentrations as indicators of exhaust from a nearby vehicle on the access road. For most of the study area, these brief concentration spikes indicating localized impacts from access road vehicles were rare but may have influenced some short-term measurements.

Sampling methods

This study deployed two mobile monitoring vehicles equipped with air monitoring analyzers and portable sonic anemometers for meteorological measurements. Table 2 provides a summary of all measurement methods used in this study. One mobile monitoring vehicle was an electric car equipped with real-time location (with a global positioning system), black carbon (BC), particulate matter count (PM), nitrogen dioxide (NO₂), and carbon monoxide (CO) instruments that drove along the access road and measured air quality at each of the six fixed-site Stops as shown in Fig. 1. For each day, the electric vehicle drove approximately five to seven continuous laps along the access road and on Interstate-280. After the last lap, the sampling vehicle parked for 10 min at each of the six fixed-site Stops shown in Fig. 1. All air quality instruments used in mobile monitoring measured at 1-s sampling intervals, resulting in a spatial resolution of approximately 10 m at typical access road driving speeds (e.g., 30 km/h) and 25 m at highway driving speeds (e.g.,

Table 2 Measurement methods used at each monitoring site

Measurement location	Measurement parameter	Sampling approach	Instrument make/model	Sampling height (above ground)	Sample type and frequency
Clearing (SUV) Site (at-grade section; 20 m from highway)	Carbon monoxide (CO)	Nondispersive infrared Chemiluminescence Engine exhaust particle sizer Micro-aethalometer Sonic anemometer Quantum cascade laser Cavity attenuation phase shift Engine exhaust particle sizer Single-channel aethalometer Global positioning system Webcam Micro-aethalometer Sonic anemometer	Model 48i-TLE Thermo Scientific Model 200A API TSI, Inc., Model 3090 Magee Scientific, AE-51 RM Young 81000 Aerodyne Research, Inc. Aerodyne Research, Inc. TSI, Inc., Model 3090 Magee Scientific, AE-42 Crescent R100, Hemisphere GPS Magee Scientific, AE-51 RM Young 81,000	2 m	Continuous, 1-s averages
	Oxides of nitrogen (NO/NO ₂ /NO _x)				
	Particle number concentration (size range 5.6–560 nm, 32 channels)				
	Black carbon (BC)				
	Wind speed and direction				
	Carbon monoxide (CO)				
	Nitrogen dioxide (NO ₂)				
	Particle number concentration (size range 5.6–560 nm, 32 channels)				
	Black carbon (BC)				
	Longitude and latitude				
Mobile monitoring vehicle	Video	Webcam		1.5 m	Continuous, 1-s averages
	Black carbon (BC)	Micro-aethalometer	Magee Scientific, AE-51	2, 4, 5 m	Continuous, 1-s averages
Behind barrier portable monitoring tower site (20 m from highway)	Wind speed and direction	Sonic anemometer	RM Young 81,000	2, 4, 5 m	Continuous, 1-s averages

100 km/h). Hagler et al. (2010) describe the vehicle setup and sampling methods used in the mobile monitoring platform. Calibration of the instruments occurred each day prior to sampling. The instruments used in this study represent research-grade, real-time monitoring equipment and low-cost, portable air quality sensors.

In addition to mobile monitoring, meteorological measurements were made approximately 20 m from the nearest travel lane of Interstate-280. Meteorological measurements using three-dimensional (3-D) sonic anemometers provided information required to interpret the concentration measurements and evaluate the impacts of the vegetation barrier relative to the clearing location. One sonic anemometer was located at the clearing location approximately 2 m above ground, while three sonic anemometers were located on a tower behind the vegetative barrier at heights of 2, 3, and 5 m above ground. The location of this tower was rotated among each of the behind vegetation fixed sites each day. Thus, each location/vegetation barrier characteristic was monitored for 4 days.

A sport utility vehicle (SUV) was parked at Stop 1-CLEARING (approximately 20 m from the highway) and continuously collected air quality measurements, including CO, NO, NO₂, and PM at 1-min time intervals during this study. The measurements from the SUV in the clearing provided continuous comparisons between concentrations in the clearing and concentrations measured behind the vegetation with the electric vehicle. Batteries located within the vehicle powered these samplers, so the vehicle's engines could be turned off during all sampling times. Instrument calibrations were also performed each day before sampling began. At the end of each sampling day, the SUV and electric vehicle parked together to conduct co-located air monitoring for a minimum of 30 min. Comparison of the collocated electric vehicle and SUV measurements showed highly correlated data collection, with r^2 values above 0.95.

Results and discussion

The combination of mobile and fixed-site monitoring provided information on the variability of downwind, near-road pollution concentrations in the presence of differing roadside vegetation characteristics. As discussed in the "Introduction," previous field studies have provided inconsistent results, with some studies showing vegetative barriers can decrease downwind concentrations and other studies showing increased downwind concentrations in the presence of roadside vegetation. To evaluate the potential differences in the results of these previous studies, air quality measurements were conducted behind vegetation with differing characteristics, notably changes in height, porosity, and bush/tree combination.

A summary of the key statistics from the measurements collected at each Stop location shown in Fig. 1 can be found in the Supplemental Information, Table SII. The highest mean and median downwind pollutant concentrations generally occurred at Stop 1 (CLEARING) or behind Stop 3 (BUSHES/POROUS) where the vegetation had high porosity and gaps due to larger trees that limited or restricted the growth of surrounding bushes. The locations behind thick bushes, Stops 2 (BUSHES/EDGE), 4 (BUSHES), and 6 (BUSHES/TREES) had lower relative downwind pollutant concentrations. Stop 5 (BUSHES/GAP) also experienced lower mean and median concentrations than the Stop 1 (CLEARING) and Stop 3 (BUSHES/POROUS) locations even with the presence of an approximately 1-m-wide gap. Maximum concentration measurements were highest at the clearing (Stop 1, CLEARING) for all pollutants except NO_2 . For NO_2 , the maximum concentration measurement occurred behind the vegetation (Stop 3, BUSHES/POROUS), suggesting the potential for increased residence time or other influences from upwind sources allowing for secondary reactions of NO to NO_2 when winds were not from the road at this location. Average concentrations were equal or higher at Stop 3 (BUSHES/POROUS) compared to all other stops, while, for median values, NO_2 and CO were higher downwind of Stop 3 (BUSHES/POROUS) and BC and UFP were higher downwind of Stop 1 (CLEARING). The standard error of the mean for this

dataset suggests that the concentration differences at each stop were statistically significant, although the table also shows that these distributions were slightly skewed, with means always higher than the median concentration values.

Figure 2 compares median air pollutant concentrations at each fixed-site Stop as an estimate of the percentage reductions experienced downwind of the vegetation barrier. Normalizing the measurements reduces the influence of outlier readings which may have been influenced by individual vehicles on the access road or changes in the region's background pollution levels. Concentrations at each location normalized to the average at Stop 1 (CLEARING) highlight the reduction or increase in downwind concentrations depending on the vegetation characteristics at each Stop. This figure also compares the concentrations measured with mobile monitoring on Interstate-280 (listed as "On-Road") to provide an estimate of pollutant reductions due solely to distance from the road.

The results in Fig. 2 indicate that the thick vegetation barrier resulted in lower median downwind concentrations under all wind conditions. The lowest concentrations for all pollutants occurred behind Stop 6 (BUSHES/TREES), with average reductions of approximately 30% across all pollutants and 50, 27, 20, and 19% for UFP , BC , NO_2 , and CO , individually. As shown in Fig. 1, Stop 6 (BUSHES/TREES) had the highest and thickest vegetation and was the furthest from the clearing.

Fig. 2 Median concentration measurements for all mobile and 10-min sampling periods at each location and on Interstate-280 along the study area. The medians are all normalized to the median measurement at Stop 1 (clearing location)

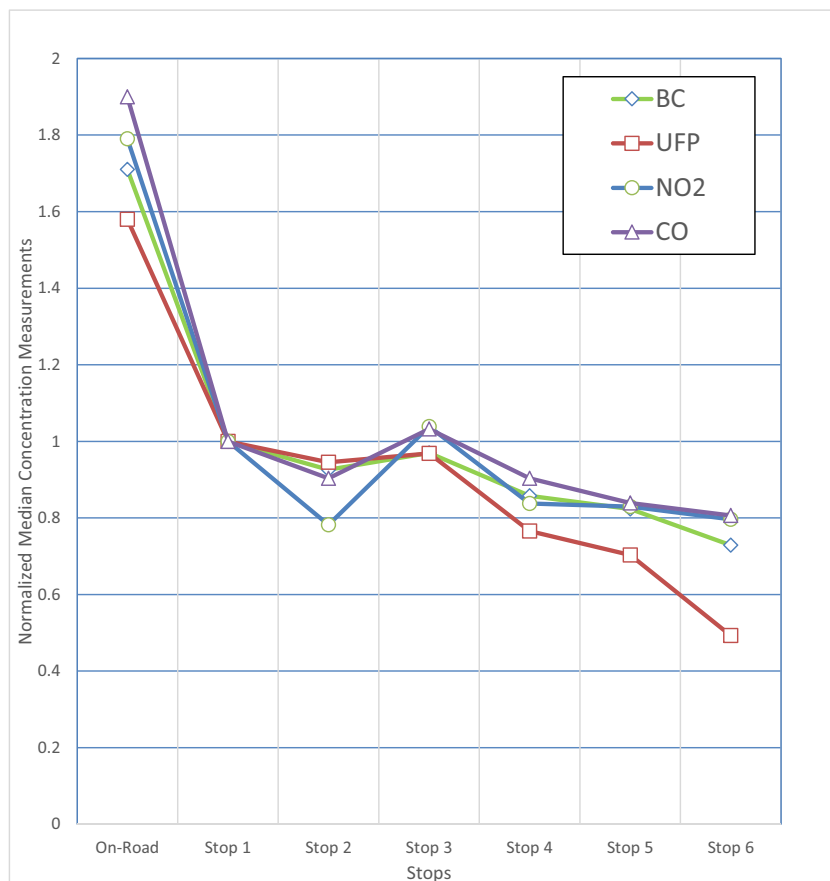


Figure 2 also shows the highest median concentrations for BC and UFP occurred at the clearing (Stop 1), while the highest median concentrations of CO and NO₂ occurred at Stop 3, the location with the highest porosity as shown in Fig. 1. While Stops 2 (BUSHES/EDGE) and 4 (BUSHES) also experienced downwind reductions, these reductions were less than experienced at Stop 6 (BUSHES/TREES). A review of Fig. 1 shows that Stop 2 was located less than 20 m from the clearing (Stop 1) and 30 m from the highly porous vegetation site (Stop 3), so the lower reductions at Stop 2 (BUSHES/EDGE) compared with Stop 6 (BUSHES/TREES) indicate that pollutant wrap-around likely occurred at the vegetation barrier edges, similar to the effects seen for solid noise barriers (Baldauf et al. 2008; Steffens et al. 2014; Steffens et al. 2013; Baldauf et al. 2016). The lower decrease at Stop 4 (BUSHES) compared with Stop 6 (BUSHES/TREES) may be due to the difference in vegetation type, height, and thickness affecting reductions although the distributions were very similar. A surprising result was the decrease seen at Stop 5 (BUSHES/GAP, approximately 1-m gap with thick vegetation on either side). The results at Stop 3 (BUSHES/POROUS) would suggest similar to higher concentrations would occur at Stop 5 (BUSHES/GAP) compared with Stops 4 (BUSHES) and 6 (BUSHES/TREES). However, the average measurements were lower at Stop 5 (BUSHES/GAP) compared all the other Stops except Stop 6 (BUSHES/TREES). This result suggests that the thick vegetation around the gap still resulted in pollution reduction when analyzing all wind conditions.

Since wind direction and speed were highly variable and light during the study, as shown in Fig. 3, an evaluation of

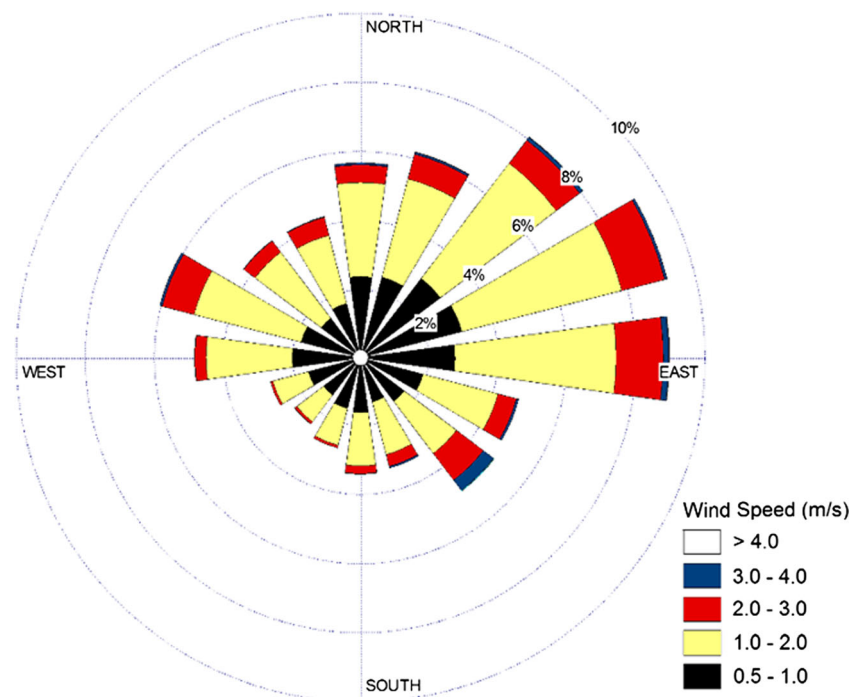
pollutant concentrations downwind of the vegetation was conducted, focusing on winds $\pm 45^\circ$ of normal from the road. Since upwind, background pollutant concentrations were not measured, the impacts of vehicle emissions on the concentration measurements at Stop 1 (CLEARING) were estimated with a model described in the Supplemental Information to understand the difference in concentrations between two sites.

Figure 4 shows the changes in the concentrations relative to Stop 1 computed using Eqs. (S11) to (S17). These changes are computed using the median, the 25th, and the 75th percentiles of the BC and UFP concentrations measured at each of the stops when the wind blows from the road to the receptor within a 90° sector centered on the normal to the road.

Again, the results at Stop 5 (BUSHES/GAP) still showed reductions in downwind pollutant concentrations, suggesting the thickness of the vegetation and small relative width of the gap still result in the dominance of mechanisms such as increased vertical dispersion and pollutant removal. Not enough data points were available with winds directly along the angle of the gap in the vegetation to determine effects under these unique conditions. However, Fig. 4 further highlights the potential for increased downwind pollutant concentrations with highly porous vegetation as shown for the 75th percentile results for Stop 3 (BUSHES/POROUS), which was almost a doubling of the UFP concentration compared with the measurements at Stop 1 (CLEARING). We provide a tentative explanation for this effect.

The increase in concentrations at Stop 3 (BUSHES/POROUS), especially during downwind conditions, appears to be related to the reduction of turbulence in the air that flows

Fig. 3 Wind speeds and directions during all measurement periods of the study



through the vegetation as a result of the combination of the vegetation structure with relatively large spacing, leading to wind stagnation as well as not increasing dispersion by forcing a portion of the air to flow up and over the vegetation barrier. This can be expressed by assuming the concentration downwind of a vegetation barrier, C_v , is a linear combination of the concentration, C_b , associated with the flow that goes over the barrier, and concentration, αC_f , associated with the flow that goes through the barrier. Here, C_f is the concentration in the absence of the barrier, and α is the enhancement caused by the turbulence reduction in the vegetation. Then,

$$C_v = p\alpha C_f + (1-p)C_b \quad (1)$$

where p is the fraction of the flow that goes through the barrier. Dividing both sides of the equation by C_f , we get the expression for the mitigation factor $R_v = C_v/C_f$ in terms of $R_b = C_b/C_f$ provided by the solid barrier,

$$R_v = p(\alpha R_b) + R_b \quad (2)$$

Because $\alpha \geq 1$ in the absence of deposition, $R_v \geq R_b$; the vegetation barrier produces less reduction than a solid barrier would. Also, the concentration can be larger than that without the barrier if α is large enough. If we assume that vegetation can reduce turbulence levels, vegetation on top of a solid barrier can enhance the effect of the solid barrier by reducing entrainment of the pollutant into the wake of the solid barrier, as has been shown by Baldauf et al. (2008) and Lee et al. (2018).

Figure 4 also highlights the potential for downwind pollutant reductions with thick, less porous vegetation, as pollutant concentrations behind the bushes and bush/tree combinations (Stops 2, 4, and 6) were lower for the normal wind conditions as compared to all wind conditions.

As indicated earlier, the analysis leading to the results shown in Fig. 4 provides estimates of the emission factors of BC and UFP. The computed values of emission factors for BC range from 13 mg/(veh·mi) to 34 mg/(veh·mi), which are well within the range of measured values from other studies (Krecl et al. 2015; Miguel et al. 1998). The values for the emission

factors for UFP range from 7.8×10^{13} to 2.5×10^{14} particle numbers/(vehicle·mile), which is consistent with measured values from other studies (Gramotnev et al. 2003; Imhof et al. 2005). This consistency between the emission factors inferred from this study with values from studies designed to estimate emission factors supports the approach described by model in the Supplemental Information represented by Eqs. (SI1) to (SI7).

In principle, the concentration reductions for BC and UFP should be the same at all the Stops in the absence of deposition because the dispersion mechanisms are the same for both species; however, the values differ considerably at Stops 5 (BUSHES/GAP) and 6 (BUSHES/TREES). The reductions in concentrations range from 10% or less at stop 3 (BUSHES/POROUS) to more than 50% at stop 6 (BUSHES/TREES). The results of this field study demonstrate that roadside vegetation affects downwind air pollution concentrations by influencing pollutant transport and dispersion through three primary mechanisms: attenuation of meteorological and vehicle-induced turbulence as air passes through the vegetation, enhanced mixing as the traffic pollution plume is blocked and forced over the vegetation, and, for airborne particles, reduced concentrations through PM removal by diffusion, interception, or impaction onto leaf and branch surfaces depending on particle size and morphology.

To further evaluate the potential effect of the vegetative barrier on concentration reductions, Fig. 5 plots the reduction in average pollutant concentrations at each Stop normalized to the measurements at the clearing (Stop 1) against the ratio of the difference in the average wind speeds between Stop 1 (CLEARING) and the specified Stop (plotted as $\Delta U/\sigma_w$ (ratio)). The difference in average wind speeds is a measure of the blocking effect of the barrier, which results in concentration reduction. On the other hand, the reduction in σ_w due to the barrier relative to that measured at Stop 1 results in an increase in concentration. Thus, $\Delta U/\sigma_w$ (ratio) is a measure of the relative importance of these two competing effects on concentration reduction; the concentration reduction should increase (magnitude decreases) as this ratio increases. For

Fig. 4 Normalized BC (left) and UFP (right) concentration reductions with median, 25th, and 75th percentile concentration measurements for all mobile and 10-min sampling periods at each fixed-site Stop location during downwind ($\pm 45^\circ$) conditions

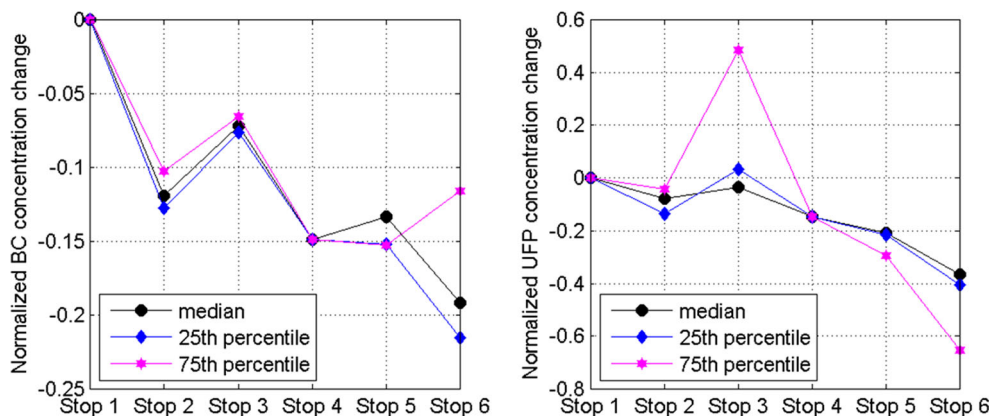


Fig. 5 Comparison of the average pollutant reduction with the ratio of $\Delta U/\sigma_w$ measured for 4 days at each stop location with winds $\pm 45^\circ$ of normal and speeds greater than 1 m/s. The number in the figure indicates the Stop location, with the number of valid measurements meeting the meteorological criteria shown in parentheses. Concentration reductions are calculated using Eqs. (SI1) to (SI7)

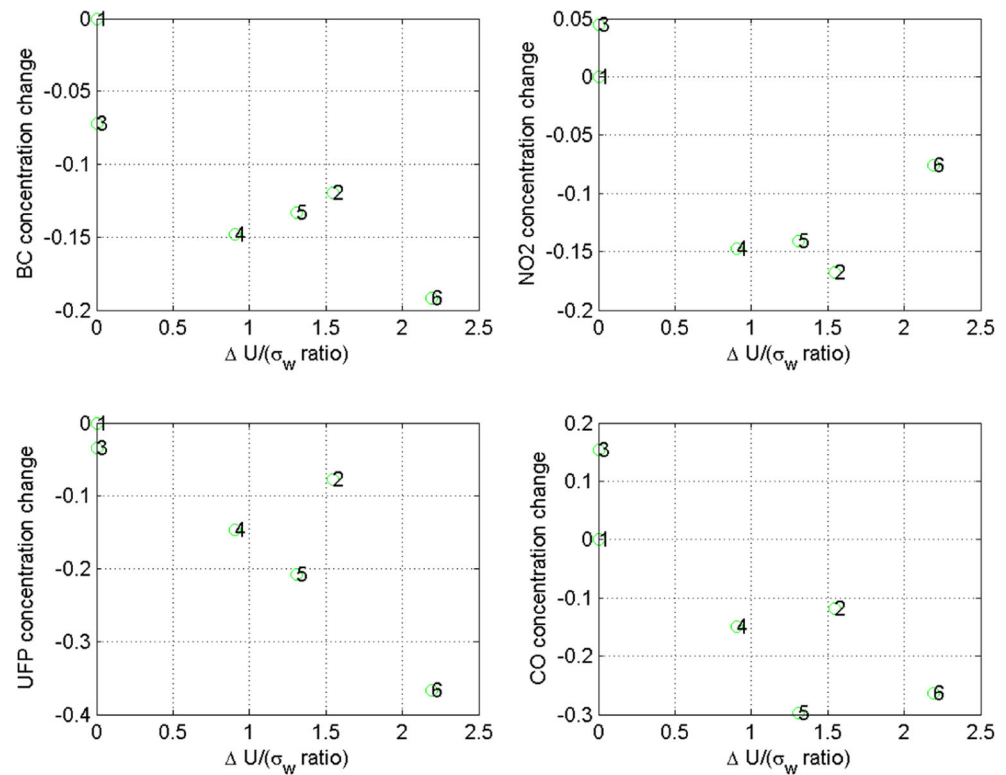


Fig. 5, only winds $\pm 45^\circ$ of normal at speeds greater than 1 m/s were analyzed, and the comparison of wind data at each Stop could only occur on days when the meteorological monitoring tower was placed at that location. Thus, the results presented do not represent simultaneous measurements and the number of data points for each Stop varied since the meteorological monitoring tower was moved each day to a different Stop.

In general, Fig. 5 shows that the Stops behind the thicker, less porous vegetation (Stops 2, 4, and 6) had higher reductions in wind speed relative to reductions in turbulence behind the vegetative barrier resulting in higher $\Delta U/\sigma_w$ ratios associated with higher concentration reductions. This trend is clear for UFP and BC and less evident for CO and NO₂. For Stop 6 (BUSHES/TREES), only 90 s of observations with the required wind speed and direction occurred during the 4 days of sampling at this location (compared with over an hour at the other locations); thus, the results from this Stop may not be as informative as the other locations, especially for NO₂ which showed very different results for this small subset of data compared with the overall dataset.

The results in Figs. 2, 4, and 5 suggest that BC and UFP reductions can be generally greater than the reduction for the gaseous pollutants downwind of the roadside vegetation. Since the field measurements cannot identify the extent particle deposition contributes in pollutant reductions from the roadside vegetation, the Computational Fluid Dynamics (CFD)-based CTAG model, as described by Tong et al. (2016), was employed to estimate these effects, providing

further insights on the influence of vegetation characteristics, particularly porosity, as represented by leaf area density (LAD in units of $\text{m}^2 \text{m}^{-3}$), on downwind pollutant concentrations. The impact of LAD on particle concentrations for 15- and

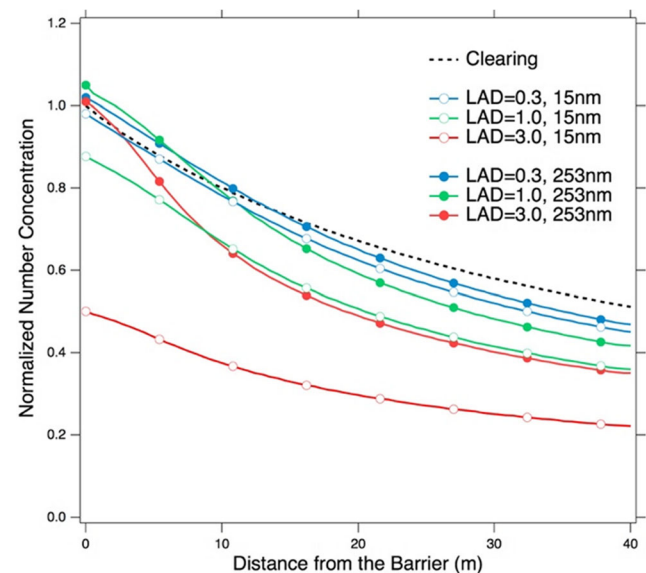


Fig. 6 CFD-based CTAG modeling results for 15- and 253-nm size particles comparing the particle number concentrations for each size at increasing distances from the road for vegetative barriers with different LAD characteristics. The colors represent different LAD: the open marker represents 15 nm and the filled marker represents 253 nm. A LAD of 0 represents the clearing while a LAD of 3.0 represents a very thick vegetative barrier with low porosity

253-nm particles shown in Fig. 6 highlights differences between the influences of vegetation on nano- and accumulation-mode particles, respectively. This model accounted for the reduction in wind speed and turbulence caused by vegetation and the increased mixing due to plume lofting and dispersion as evaluated in Fig. 5. The CTAG model also accounted for potential particle loss due to deposition of the two size fractions analyzed in order to simulate all three mechanisms affecting downwind pollutant concentrations. While a quantitative comparison against the experimental field results cannot be made due to the lack of site-specific LAD and traffic measurements, the modeled conditions presented in the CTAG modeling qualitatively represented those captured by the field experiments.

For the modeled vegetation, the nano-size particles (15 nm), which have high deposition rates (dominated by diffusion), experience concentration reductions at all of the LAD levels evaluated, with removal as high as 50% for vegetation with a LAD of 3.0, although a LAD of 0.3 resulted in only a small concentration reduction for these size particles. The modeling results suggest that denser vegetation (i.e., higher LAD value) resulted in much higher removal of these particles and lower downwind number concentrations. The nano-particle removal indicates that air still passes through the dense vegetation, which has a higher surface area for particle diffusion and removal.

For the 253-nm size particles, which have relatively low deposition rates, the vegetation affected concentrations much differently. Since particles in this size range do not have strong removal mechanisms for diffusion or impaction within the vegetation, these particles generally represent behaviors for inert gases as well. For example, vegetation at the LAD of 3 only resulted in reductions of approximately 15%. However, at the higher porosity/lower LAD values for the vegetation, the 253-nm size particle concentrations increased by a small percentage close to the barrier. The modeling results are qualitatively consistent with those from the field measurements for gaseous species (i.e., CO), suggesting that highly porous vegetation (low LAD) promotes stagnation by lowering wind speeds and decreasing turbulence, leading to higher downwind concentrations than if the vegetation were not present. However, when the porosity is lowered, represented by a higher LAD, the stagnation effect is minimized and offset by the increased dispersion caused by a large portion of the plume forced to loft over the barrier, resulting in lower downwind concentrations. The results for the 253-nm particles in Fig. 6 suggest a LAD of at least 3.0 is needed in order for the increased dispersion to counteract the stagnation effects.

Conclusions

A field study conducted along a stretch of limited-access highway containing a long section of tall bushes and trees as well

as a section with no vegetation or other obstructions to air flow highlighted how roadside vegetation characteristics affect downwind pollutant concentrations in both positive and negative ways. When the roadside vegetation was tall and dense, with low porosity, downwind pollutant reductions averaged approximately 30% across all pollutants and 50, 27, 20, and 19% for UFP, BC, NO₂, and CO individually. However, when the vegetation was highly porous, downwind particle concentrations were similar to those in the clearing while the gaseous pollutants CO and NO₂ experienced slightly higher downwind concentrations than at the clearing. These results demonstrate that roadside vegetation must be dense enough to enhanced mixing by blocking and forcing a portion of the traffic pollution plume over the vegetation; thus, overcoming the potential increase in concentrations due to the attenuation of meteorological and vehicle-induced turbulence as air passes through the vegetation. The CFD-based CTAG modeling suggested that a roadside barrier should have a leaf area density of 3.0 or higher to ensure downwind pollutant reductions. The CFD-based CTAG modeling also demonstrated the importance of particle deposition onto plant surfaces as an additional mechanism for PM removal.

These results demonstrate that roadside vegetation can be planted along highways and other localized pollution sources to mitigate air pollution impacts from nearby source on population exposures and adverse health effects provided the vegetation is thick, tall, and dense and provides coverage from the ground to the top of the canopy in order to promote the physical mechanisms that reduce concentrations and minimize the characteristics that may lead to increased downwind concentrations. The results also highlight the importance of planting denser vegetation and maintaining the integrity and structure of these vegetation barriers to achieve pollution reductions and not result in unintended increases in downwind pollutant concentrations. Roadside vegetation being used as a barrier to mitigate local air pollution concerns must also be long enough since concentrations may be higher near and around the edges.

The results of this study and previous research show that roadside vegetation, alone or in combination with solid barriers, may be used by urban and transportation planners as a tool for reducing the air pollution and health impacts of traffic on nearby roads for local populations. While this study does suggest a minimum leaf area density for this vegetation, additional research is needed on the sensitivity of this value as well as methods for accurately characterizing LAD during the planting and maintenance of these types of barriers. In addition, air dispersion models need to be further developed to quantify the potential benefits, as well as potential increases under certain vegetation characteristics, in local air quality and human exposures.

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