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Field investigation of roadside vegetative and structural barrier impact on near-road ultrafine particle concentrations under a variety of wind conditions

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ABSTRACT

Roadside barriers, such as tree stands or noise barriers, are prevalent in many populated areas and have been shown to affect the dispersion of traffic emissions. If roadside noise barriers or tree stands are found to consistently lower ground-level air pollution concentrations in the near-road environment, this may be a practical strategy for reducing exposures to air contaminants along populated traffic corridors. This study measured ultrafine particle (UFP) concentrations using an instrumented mobile measurement approach, collecting data on major roadways and in near-road locations for more than forty sampling sessions at three locations in central North Carolina, USA. Two of the sampling sites had relatively thin tree stands, one evergreen and one deciduous, along a portion of the roadway. The third sampling site had a brick noise wall along a portion of the road. At 10 m from the road, UFPs measured using a mobile sampling platform were lower by approximately 50% behind the brick noise wall relative to a nearby location without a barrier for multiple meteorological conditions. The UFP trends at the vegetative barrier sites were variable and the barrier effect is uncertain. In some cases, higher concentrations were observed behind the vegetative barrier, with respect to the clearing, which may be due to gaps in the thin tree stands allowing the transport of traffic-related air pollution to near-road areas behind the vegetation. On-road sampling revealed no consistent difference in UFP levels in on-road portions of the road with or without a roadside barrier present. These findings support the notion that solid roadside barriers may mitigate near-road impact. Given the co-benefits of vegetative barriers in the urban landscape, research regarding the mitigation potential of vegetative barriers of other configurations (e.g., greater density, wider buffer) is encouraged.

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1. Introduction

Near-road air quality is a pressing issue of concern for densely developed urban regions worldwide. In response to field studies documenting significant increases in air pollutant concentrations in the roadside environment relative to areas several hundred meters downwind (Karner et al., 2010 and references therein), a number of health-advocacy groups have issued recommendations to reduce exposure risk. For example, the state of California advises a distance of 500 ft (~150 m) from urban roadways with more than 100,000 vehicles per day or rural roadways with over 50,000 vehicles per day for locating new schools (California Environmental Protection Agency, 2005). The American Academy of Pediatrics has also issued a policy statement suggesting that new school and childcare facilities should take proximity to roadways into account (Shannon et al., 2004). Implementing such recommendations may lower the risk of exposure to high concentrations of traffic-related pollutants; however, this strategy can have limited utility for existing developments and may encourage environmentally-unfriendly urban sprawl, longer commutes for children attending school at locations far from their neighborhoods, and other unintended consequences.

One practical potential mitigation strategy undergoing investigation through field and modeling studies is the reduction of near-road air pollution by roadside barriers, such as solid noise barriers or tree stands. Noise barriers and tree stands are already appreciated as mechanisms of noise control and aesthetic improvement in urban landscapes. In addition, even relatively sparse vegetation has been documented to provide a number of benefits to health; views of greenery have been related to faster healing (Ulrich, 1984), improved cognitive development (Wells, 2000), and reduced domestic violence (Sullivan and Kuo, 1996) and aggression (Moore and Arch, 1981). Urban vegetation can also provide shade, reducing the urban heat-island effect as well

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as building energy costs and greenhouse gas emissions from air conditioning. Near-road vegetative buffers can also filter and slow polluted stormwater runoff from roadways. These and potential near-road air quality benefits may be offset by potentially undesirable effects such as pollen production and habitat for invasive pest species.

Roadside barriers may augment near-road air quality through altering dispersion as well as by capturing air pollutants. Past research studying roadside barrier effects on local air pollution has generally focused on two types of road configurations — (1) street canyon environments typical of highly populated cities with densely located tall buildings and (2) open street environments that have lower density single- to triple-story buildings and are common urban sprawl layouts found in moderate-sized cities or suburban areas of large cities in the United States. While this present research is focused primarily on open street configurations, it is important to point out that the findings may not be simply translated to complex street canyon environments. For example, a recent modeling study found that trees within a street canyon environment may have a positive or negative effect on within-canyon pedestrian air quality, depending on the placement of the trees and on which side of the road the pedestrians are located (Buccolieri et al., 2009). Meanwhile, past field and modeling studies evaluating the open street environment have consistently estimated lower air pollutant concentrations in roadside zones (0–50 m) in the lee of a solid noise barrier (Bowker et al., 2007; Baldauf et al., 2008a, b; Finn et al., 2010; Ning et al., 2010; Hagler et al., 2011a); however, the comparison between barrier-protected versus open roadsides was inconsistent among studies at distances further away from the road.

There are several key unknowns regarding barrier effects in open street configurations, where field data in particular are lacking. One unknown is the effect of wind direction on the dispersion of traffic emissions — the majority of research to date has focused primarily on solid barrier effects under winds perpendicular to the road. The effect of roadside vegetation on near-road air pollution has received less attention and may be even more difficult to quantify given the added complexities of vegetation type and seasonal effects in addition to physical characteristics such as height, width, and length. Baldauf et al. (2008b) showed measurable reductions in UFP number concentrations when mature and extensive vegetation was present along with a noise barrier compared with a noise barrier-only section of the roadway; however, the site configuration prevented the vegetation effect alone from being isolated. In agriculture environments, vegetation has been used as natural windbreaks and demonstrated to reduce the length of livestock odor plumes by 22% (Lin et al., 2007). In addition, the capacity of urban trees to capture ambient air pollutants has been documented in multiple locations (e.g., Beckett et al., 1998; Nowak et al., 2006) as well as in wind tunnel experiments (Beckett et al., 2000; Lin and Khlystov, 2012). These past findings, as well as previous research regarding roadside structural barriers, provide a basis for hypothesizing that near-road vegetation in open street environments may capture vehicular air pollutants as well as enhance dilution.

This study presents results from a recent field study quantifying the impact of a narrow roadside tree stand or a solid noise barrier on near-road and on-road air pollution, expanding on previous findings in several ways: 1) exploring whether vegetative barriers (trees, hedges) alone lower air pollutant concentrations in the roadside environment, 2) quantifying the impact of both structural and vegetative barriers under multiple wind conditions, and 3) exploring whether on-road concentrations are significantly different with barriers present.

2. Methods

2.1. Field campaign locations and schedule

This field study, named the Triangle Area Barriers Study (TABS), took place at three roadside locations in central North Carolina, located in the southeastern United States (Fig. 1). The road sampling sites were selected based on roadside barrier properties: a stretch of roadway having a vegetative buffer or structural noise wall as well as an adjacent roadside area without a barrier for comparison and moderate to heavy traffic during morning commute periods. In addition, relatively thin vegetative buffers were sought (<10 m in thickness) in order to relate the results of this study most closely to the utility of vegetative buffers in mitigating near-road impact for developments located immediately adjacent to roadways. A final site requirement was a low degree of side road traffic, so that the effect of the barrier on highway emissions impact could be isolated.

The three sites sampled include Mebane, which had a primarily deciduous tree stand and was located along an interstate highway (I-40/I-85 combined) that connects several major population centers of North Carolina; Chapel Hill, which had a primarily evergreen tree stand and was located along an expressway (U.S. Route 15–501); and, Raleigh, which has a brick noise barrier and is located along an interstate highway (I-440) that loops around the city of Raleigh. All sites were characteristic of a typical open street environment; Mebane and Chapel Hill roadways were bordered by residential zones with one- and two-story houses, while the Raleigh site had a mixture of one- and two-story residential and commercial buildings in the near-road area. Further details on each site are provided in Table 1 and a closer look at the sampling locations is available in Fig. 1. The Chapel Hill and Raleigh side roads measured for barrier/clearing comparisons were at-grade with the highway of interest. The Mebane side road adjacent to the highway had slight rolling hills, with the clearing position approximately 1 m above the highway and the barrier position approximately 2 m above the highway, estimated by the mobile car's global positioning system (GPS) elevation data. At all sites, background areas were designated as residential locations with minimal traffic and located at least 200 m from the major roadway (Fig. 1). While these are the first near-road measurements conducted at the Mebane and Chapel Hill locations, the Raleigh site had been previously used to study barrier effects on near-road air pollution and is further described in other studies (Bowker et al., 2007; Baldauf et al., 2008a, b).

Sampling was conducted using instrumented vehicular platforms — one mobile electric vehicle (Li-Ion Motors Corp), one parked sports utility vehicle with on-board battery supply, and one parked van with on-board battery supply and a mast allowing for sampling at heights up to 7 m. The electric vehicle driving route and stationary sampling locations are shown in Fig. 1. Sampling was conducted during the early-fall to winter, 2008, with the three vehicles sampling at each location during weekday morning commute periods (7–9 AM) for a consecutive series of approximately 6–10 days over a two week period. Two sampling sessions were conducted for each of the vegetative barrier sites – in the early-fall and then again in the late-fall/winter – to observe the impact of reduced leaf coverage on near-road air pollution. One sampling session was conducted at the Raleigh site with the brick noise barrier during the mid-fall season.

2.2. Measurements

Air pollution monitoring measurements were collected onboard the two stationary vehicles — the SUV situated in a clearing and the van with a mast situated behind the barrier of interest. In addition, the stationary vehicles each were equipped with three-dimensional (3D) ultrasonic anemometers monitoring wind speed and direction. The vehicle located behind the barrier measured particle number (PN) and wind speed/direction at two heights – 3 m and 7 m – and sampled CO continuously at 3 m. The two sampling heights were selected for an improved observation of the air flow transport with a barrier present. The stationary vehicle located in the clearing continuously measured PN, CO, and wind at 3 m. More information on the instrumentation is

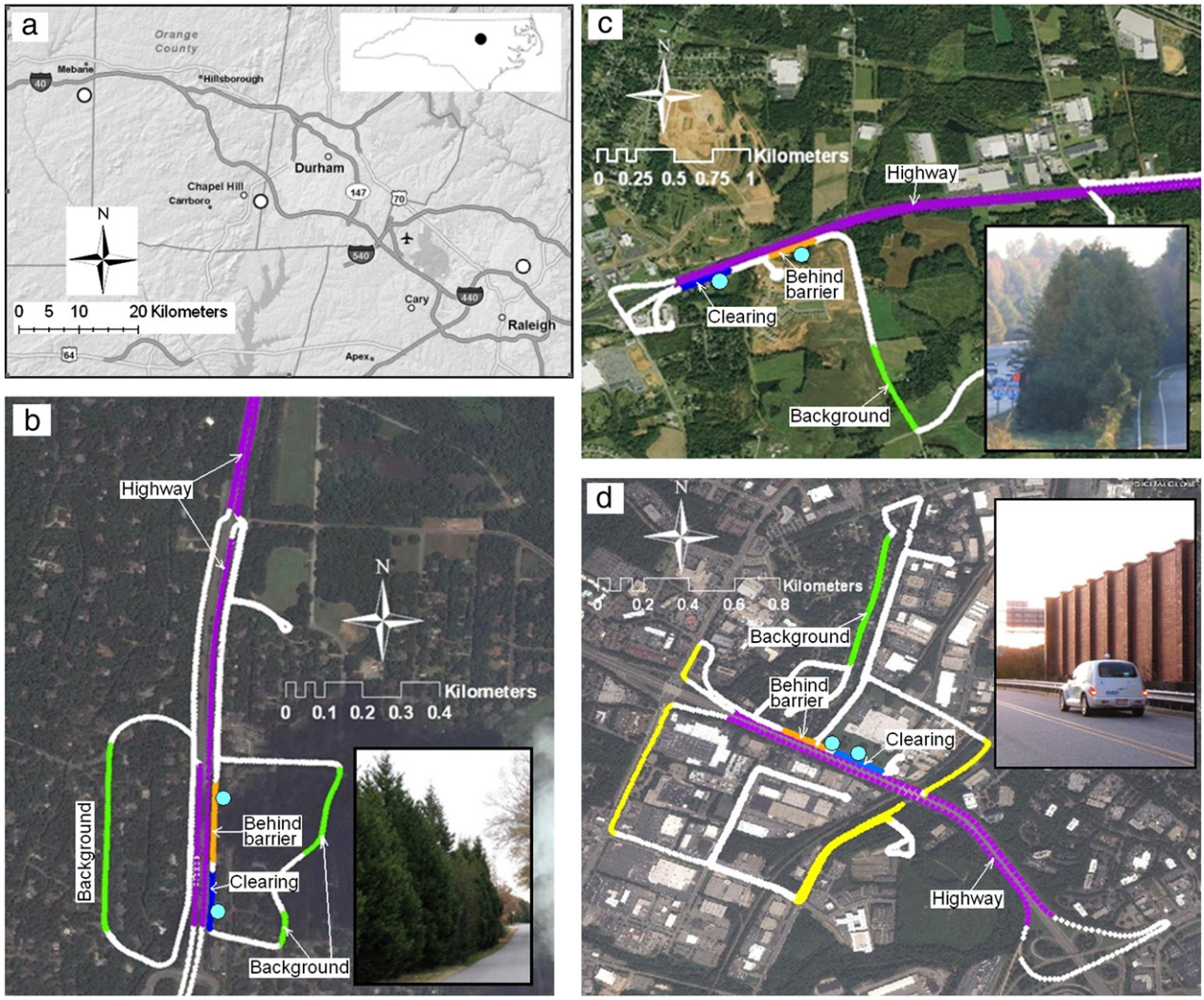

Fig. 1. (a) Sampling locations in the Research Triangle Area of North Carolina, USA, with the sampling locations indicated as white circles on the larger map and general location in the state indicated in the embedded map. A zoom in on the driving routes is shown for Chapel Hill (b), Mebane (c), and Raleigh (d) along with a photograph of the roadside barrier. The stationary sites are marked as light blue circles and the driving route is colored as: highway — purple, high traffic arterial — yellow, background — green, near-road behind barrier — orange, near-road in clearing — blue, uncategorized — white.

provided in Table 2. During sampling, the two stationary vehicles remained with their engines off and used battery-supplied power for the instrumentation during the 2–3 h daily sampling period.

The mobile electric vehicle – the sampling platform that provided data of primary focus for analyses to follow – recorded real-time particulate matter and location data while being repeatedly driven on a specified route (Fig. 1). Particulate matter measurements included black carbon (BC) measured using a portable Aethalometer, size-resolved ultrafine and accumulation mode particle count using an Engine Exhaust Particle Sizer (EEPS), total particle count using a water-based Condensation Particle Counter (CPC), and size-resolved particle count in the fine to coarse mode using an Aerodynamic Particle Sizer (APS). Due to failure of the internal motherboard, the APS data are available only for approximately half of the field sessions, while the other air measurements were successfully collected at all sessions. In addition, for approximately half of the sampling sessions, the EEPS instrument was substituted with a Fast Mobility Particle Sizer (FMPS) which has essentially identical measurements as the EEPS. Additional data collected onboard the electric vehicle included location, using a high-resolution global positioning system, and a forward-facing web camera that recorded each driving session.

A 30-minute intercomparison took place at the end of each sampling day, where the three vehicles were located side-by-side in the clearing and continuously collected data. An example of an extended side-by-side sampling session of an EEPS and an SMPS unit are provided, conducted at the initiation of the study (Fig. 2). These two particle sizing instruments show the similar trends despite the differences in instrumentation and size bin resolution. For analyses to follow, no adjustments were made to the original EEPS data based upon intercomparison, as the barrier/clearing comparison were by location of the mobile sampling vehicle and not between instruments.

Leaf area index (LAI), a metric of leaf area per unit ground area, is one additional parameter measured at the two vegetative barrier sites. The LAI-2000 plant canopy analyzer is a hand-held meter that assesses how solar radiation decreases as it passes through overlying foliage. For the thin vegetative buffers at the Mebane and Chapel Hill sites, this instrument was applied to measure trees or shrubs individually. Prior to and after leaf fall, 10 trees/shrubs were sampled along the roadside vegetative buffer in Mebane and 11 trees/shrubs were sampled in Chapel Hill (Table 1).

Wind speed (U) and direction (θ) measurements were conducted using ultrasonic anemometers that were positioned with the stationary sampling vehicles. The wind data collected in the clearing were used to sort the sampling sessions into meteorological categories based on the 2–3 h sampling period when the mobile sampling vehicle was driven — the roadside barrier upwind of the road, the

Table 1
Site Characteristics and Sampling Schedule.

	Chapel Hill (CH) Vegetative barrier site	Mebane (MB) Vegetative barrier site	Raleigh (RL) Structural barrier site
Location of roadside barrier	Lon: −79.02617 Lat: 35.91338	Lon: −79.26096 Lat: 36.07460	Lon: −78.61496 Lat: 35.82291
Time span	CH1: 9/15–23 (N = 6) CH2: 11/18–23 (N = 10)	MB1: 10/6–16 (N = 9) MB2: 12/8–23 (N = 8)	10/27–11/17 (N = 10)
Barrier type	Evergreen tree stand (Pine, Cedar, Magnolia)	Deciduous tree stand (Maple, Birch, Elder)	Brick noise barrier
Barrier height	6.1 ± 2.3 m[a]	7.2 ± 1.3 m[b]	6 m
Barrier thickness	3.6 ± 1.6 m[a]	4.5 ± 1.0 m[b]	0.5 m
Distance from road to barrier[c]	3.2 ± 0.7 m[a]	7.7 ± 1.7 m[b]	5 m
Leaf area index[d]	Early fall: 3.3 ± 1.0 Winter: 2.8 ± 1.6	Early fall: 3.0 ± 0.8 Winter: 1.0 ± 0.5	n/a
Major roadway traffic (AADT)[e]	38,000	84,000	108,000

[a] Average and standard deviation values measured for 11 trees or shrubs along barrier.
[b] Average and standard deviation values measured for 10 trees or shrubs along barrier.
[c] Distance from edge of road to roadside edge of barrier.
[d] LAI values were measured on two separate days in the fall and in the winter.
[e] Annual Average Daily Traffic (AADT) from North Carolina Department of Transportation 2008/2009 maps.

roadside barrier downwind of the road, winds parallel to the road, low wind speed (mean wind < 0.5 m s^{-1}), and variable winds (wind direction standard deviation, $\sigma_\theta > 50°$). The wind direction standard deviation (σ_θ) was calculated using an approach presented by Yamartino (1984). The threshold limit of 50° was based on viewing associated wind roses and considering the goals of sorting in to general wind categories relative to the roadside barrier and roadway.

2.3. Mobile data processing and analysis

Location and air monitoring data collected onboard the electric vehicle were imported, time-aligned, and analyzed using mathematical software, MATLAB R2010B. In addition, $PM_{2.5}$ and PM_{10} concentrations were estimated from the APS data – original bin ranges of 0.542–2.458 (22 bins) and 0.542–9.647 μm (41 bins) – by assuming the particles were spherical, applying the bin range median as the diameter, and applying a 1.5 g cm^{-3} particle density. The $PM_{2.5}$ and PM_{10} values should thus be considered estimates of the relative range of concentrations at these sites and not considered comparable to federal reference method (FRM)-derived values or ambient air quality standards.

Two key data processing steps were applied to the mobile monitoring data. First, the Aethalometer Optimized Noise-reduction Algorithm (ONA), was applied to the black carbon data. This algorithm considers the internal particle loading rate of the instrument, maintaining the native high time resolution of the data during higher particle loading periods and adaptively setting longer averaging periods for low particle loading periods (Hagler et al., 2011b). More details on applying ONA to the mobile monitoring black carbon data are in Appendix A. Second, a screening algorithm was developed to detect and flag time periods of exhaust impact. This algorithm is a variation on a method that was recently published by Hagler et al. (2010), where sudden spikes in real-time carbon monoxide concentrations were used as indicators of vehicle exhaust. The method used in this study also detects sudden spikes in a fresh exhaust indicator (UFPs, in this case), but uses a modified running coefficient of variation as the exhaust indicator. The concept behind this approach is that direct impact from exhaust will have both high and highly variable concentrations over a few seconds. This procedure is an improvement over the Hagler et al. (2010) method as it is more transferable, does not require sophisticated programming to employ, and is tied to the variable nature of concentrations encountered during direct exhaust impact. Applying this procedure flagged 2% of data on average (range of 1–5%), with the majority of the flagged events occurring at traffic lights and entrance and exit ramps. More information on this algorithm is provided in Appendix A.

Following preliminary data processing steps, all air monitoring data were time-aligned with the GPS location and location codes were assigned to identify target time periods of data. The "roadside clearing" and "roadside behind barrier" target longitude/latitudes were selected to avoid the first 20 m of distance from the barrier edge. For greatest spatial accuracy, the highest time-resolution and most complete data – UFPs (particle number count under 100 nm) quantified by the EEPS or FMPS instrument – were used to compare the behind barrier to clearing zones. For example, the car driving at 30 km/h moves 8 m per second, thus 5 s BC data have a spatial uncertainty of 42 m while the 1 s PN data have an 8 m uncertainty. Meanwhile, for larger zone assignments where 5 + s of data would not blur classification (i.e., background, highway, arterial), all air monitoring data were used to evaluate concentration trends.

3. Results

3.1. Example mobile sampling time series and local meteorology observations

An example of the time series data recorded by the mobile and stationary platforms during a sampling session in Chapel Hill is provided (Fig. 3). This example gives a sense for the repetitive nature

Table 2
Air monitoring and meteorology data.

	Data[a]	Instrument	Rate	CH1[b]	CH2	MB1	MB2	RL
Stationary vehicle — barrier	UFPs (3, 7 m)	SMPS (with DMA Model 3081 and CPC Model 3010, TSI)	120 s		●	●	●	●
	CO (3 m)	CO analyzer, Teledyne API	60 s		●	●	●	●
	Wind (3, 7 m)	3D ultrasonic anemometer, Model 81000, RM Young	1 s		●	●	●	●
Stationary vehicle — clearing	T, RH	HOBO temperature/relative humidity sensor	60 s		●	●	●	●
	UFPs (3 m)	SMPS Model 3936NL85 with CPC Model 3785, TSI	120 s	●	●	●	●	●
	CO (3 m)	CO analyzer, Model 48i-TLE, Thermo	60 s	●	●	●	●	●
	Wind (3 m)	3D ultrasonic anemometer, Model 81000, RM Young	1 s	●	●	●	●	●
Mobile monitoring vehicle	UFPs	EEPS (Model 3090) or FMPS (Model 3091), TSI	1 s	●	●	●	●	●
	PN	CPC (Model 3781), TSI	1 s	●	●	●	●	●
	BC	Portable Aethalometer (AE42), Magee Scientific	5 s	●	●	●	●	●
	$PM_{2.5}$, PM_{10}	APS (Model 3321) TSI	1 s		●		●	●
	Location	GPS, Hemisphere R100	1 s	●	●	●	●	●
Other	Leaf Area Index	LAI2000, Li-Cor	–	●	●	●	●	n/a

[a] Sampling heights are indicated in parentheses.
[b] CH1 = Chapel Hill, early fall; CH2 = Chapel Hill, late fall; MB1 = Mebane, early fall; MB2 = Mebane, winter; RL = Raleigh.

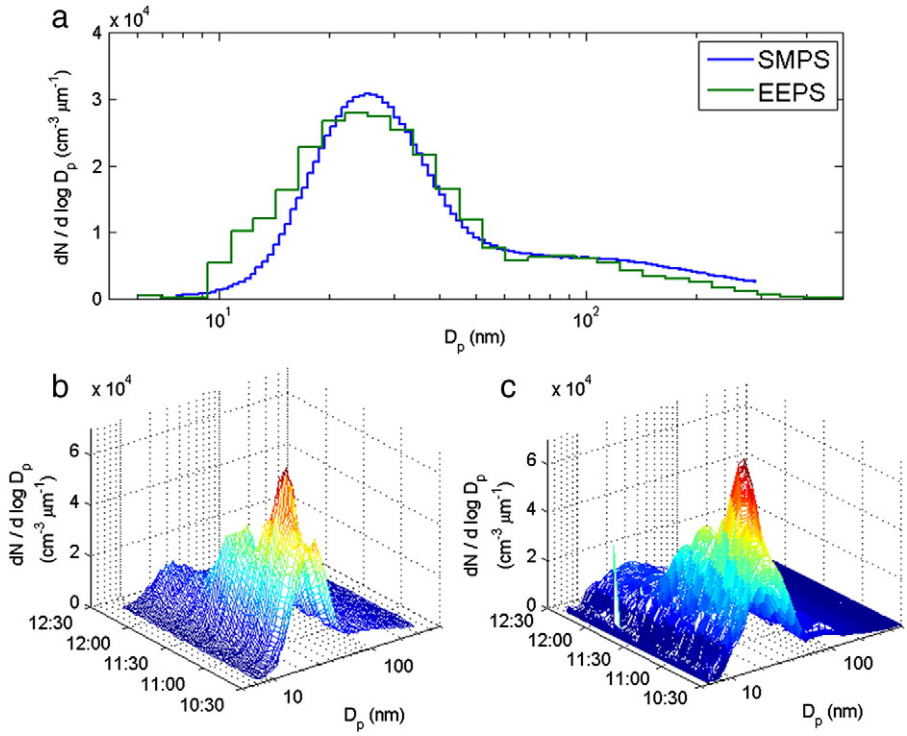

Fig. 2. Example of collocated measurements for an engine exhaust particle sizer (EEPS, 1 s data) and scanning mobility particle sizer (SMPS, 2 min data): (a) 2-hour average size distribution, (b) real-time size distributions for the SMPS, (c) real-time size distributions for the EEPS. Normalized number size distributions are shown as a function of particle diameter (Dp).

of the mobile sampling, where the clearing, behind barrier, and background locations were sampled repeatedly over a sampling sessions. The very high time resolution (1 s) PN data of the instrument onboard the mobile vehicle also has significant fluctuations in the near-road zone relative to the 2 min integrated measurements, while the mobile data in the background locations have much lower variability. It should be noted that the mobile vehicle data represents a stretch of roadway behind the vegetative barrier (Fig. 1) whereas the stationary vehicle represents a fixed location.

Throughout the sampling sessions conducted, most morning commute periods at the three locations in North Carolina had relatively low wind speeds measured in the clearing location, lower than 2 m s^{-1} for 38 out of the 43 sampling sessions (Table 3). Comparing the mean wind speed and direction against the threshold levels of 0.5 m s^{-1} and 50°, respectively, morning commute periods had either low speeds and/or highly variable winds for 6 of the 17 periods in Mebane, 12 out of the 16 periods in Chapel Hill, and 3 out of the 10 periods measured in Raleigh. This is important to note, as near-road studies commonly consider air pollution impact in the context of winds crossing over the roadway in a steady fashion (Karner et al., 2010 and references therein), whereas for this study we encountered approximately 50% of the sampling cases with wind either too variable or low-speed to be assigned a directional category. It should be noted that, for analyses of the continuous data recorded in stationary locations, more directional categorization may be possible on shorter timeframes than the 2–3 h that were averaged to match the mobile vehicle sampling sessions.

3.2. Structural barrier impact under a variety of meteorological conditions

Concentrations of ultrafine particles, measured in the clearing and behind a 6 m brick barrier, were compared for the ten sampling sessions conducted at the Raleigh location. Subtracting out background concentrations, it appears that the barrier led to reduced concentrations immediately behind the barrier, relative to the clearing, for all periods when the roadside concentrations were significantly higher than the background (Fig. 4). With background concentrations accounted for, the highest excess UFP levels in the clearing (10 m from the road) was measured under downwind conditions, followed by variable and parallel wind conditions. During sessions categorized as upwind of the road, the clearing/behind-barrier background-adjusted UFP concentrations were approximately zero or even slightly negative, explained by a slightly higher background average for that case. For the other sessions – categorized as parallel, downwind, or variable winds – concentrations behind the barrier (10 m from the edge of the road) were reduced, relative to the clearing, by 49–53% for downwind cases, 30–61% for the parallel-to-road wind cases, and 33–50% under variable winds. The mean reduction

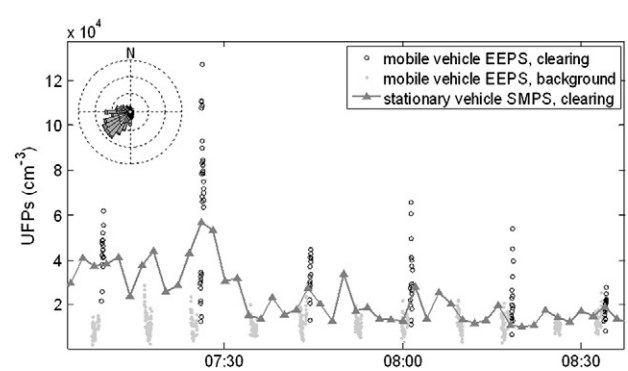

Fig. 3. Example of the UFP estimates recorded for a sampling session in Chapel Hill in the clearing. Data shown are recorded by the FMPS (size range 6–93 nm) onboard the mobile sampling vehicle and SMPS/CPC units (size range 14–98 nm) onboard the stationary vehicle. The mobile sampling levels in the background locations are also shown for comparison. A wind rose is provided at 3 m height for this example sampling period.

Table 3
Wind measurements collected in the clearing location during the sampling sessions[a].

Mebane, NC				Chapel Hill, NC				Raleigh, NC			
Date	U (m s^{-1})	Θ (deg)	σ_Θ (deg)	Date	U (m s^{-1})	Θ (deg)	σ_Θ (deg)	Date	U (m s^{-1})	Θ (deg)	σ_Θ (deg)
6-Oct	0.48	209	49	15-Sep	0.80	206	58	27-Oct	0.63	131	36
7-Oct	1.25	34	38	16-Sep	0.87	347	56	28-Oct	1.83	261	42
8-Oct	0.66	160	40	18-Sep	0.46	186	53	29-Oct	1.14	192	48
9-Oct	0.49	196	61	19-Sep	0.91	6	53	30-Oct	0.70	93	66
10-Oct	0.84	342	46	22-Sep	0.61	349	68	31-Oct	0.57	113	41
13-Oct	0.83	310	36	23-Sep	1.38	4	34	3-Nov	1.73	18	38
14-Oct	0.51	177	12	18-Nov	1.92	2	46	5-Nov	2.19	5	35
15-Oct	0.46	161	13	19-Nov	1.37	116	56	6-Nov	1.46	262	52
16-Oct	0.50	176	25	20-Nov	0.99	241	57	12-Nov	0.71	44	42
8-Dec	0.63	190	42	24-Nov	0.65	197	64	17-Nov	0.67	119	53
9-Dec	0.67	330	54	25-Nov	0.85	226	70				
12-Dec	2.73	301	14	1-Dec	2.35	195	20				
15-Dec	0.35	199	33	2-Dec	0.65	180	51				
18-Dec	0.62	304	52	3-Dec	0.55	216	65				
19-Dec	1.34	174	27	4-Dec	1.69	194	23				
22-Dec	3.37	303	16	5-Dec	2.66	5	23				
23-Dec	0.73	105	50								

[a] Calculated as mean wind speed (U), wind direction (Θ), and standard deviation of wind direction (σ_Θ) for the periods of time the driving-mode vehicle sampled.

of road-attributed concentrations for the non-upwind cases is 47%. The downwind category findings generally agree with what had been reported at the same site several years prior for CO and UFP concentrations (Baldauf et al., 2008a, b). These results also agree with the apparent reduction in near-field concentrations under downwind conditions observed at sites in California (Ning et al., 2010) and tracer study results showing lower behind-barrier concentrations under multiple meteorological stability categories (Finn et al., 2010) .

3.3. Vegetative barrier impact under a variety of meteorological conditions

A comparison of behind-vegetation versus clearing UFP concentrations is provided for both early-fall and winter conditions (Figs. 5–7). The leaf area index (LAI) was not significantly different at Chapel Hill – which has an evergreen vegetative barrier – in the early-fall versus winter (Table 1); therefore, all of the driving sessions here were combined and displayed together in Fig. 5. The deciduous vegetative barrier in Mebane had significant leaf fall, exhibited in a change in LAI from 3.0 to 1.0 in the early fall versus winter. These two sampling series are therefore shown separately (Fig. 6–7).

For the two data sets where the roadside vegetation has LAI values of ~3, the effect of the roadside vegetation on concentrations at 15 m from the road (Chapel Hill) and 20 m from the road (Mebane) is less clear relative to the solid barrier case in Raleigh. In Chapel Hill, all of 3-hour sessions were categorized either as parallel to the road, variable wind direction, or low wind speed; therefore, the anticipated highest impact of downwind conditions was not observed on the two-hour average basis. Under these other wind conditions, the behind-barrier location was lower relative to the clearing for 6 periods, no difference was observed for 5 periods, and concentrations appeared to be higher behind the vegetation for 5 periods. For the Mebane cases with leaf-on conditions, the behind-barrier location had lower concentrations for 5 of the 9 cases, while the remaining 4 cases had elevated concentrations relative to the clearing. For the Mebane downwind cases, 2 had lower levels behind the barrier while 1 had higher — it is of note that the case with elevated levels relative to the clearing occurred on a sampling day (10-Oct) with relatively higher wind direction variability ($\sigma_\theta = 46°$, near the defined threshold of 50) compared to the other sessions categorized as downwind (7-Oct, 13-Oct) as shown in Table 3. During the sampling period in Mebane after leaf-fall (Fig. 7), concentrations between the clearing

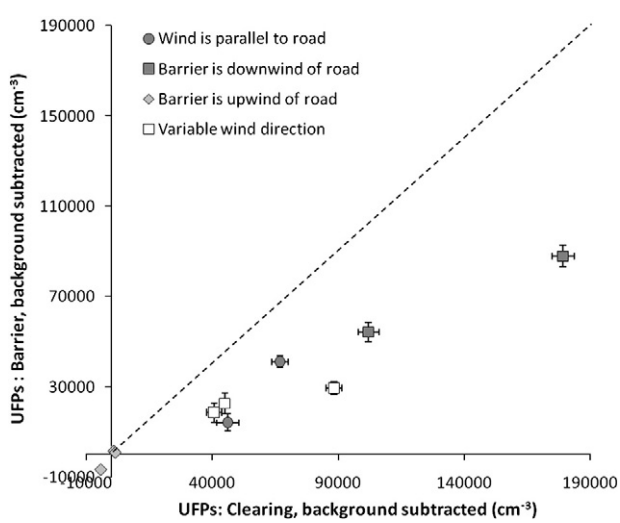

Fig. 4. Comparison of traffic-related ultrafine particle concentrations (<100 nm) measured in a clearing and behind a noise barrier at 10 m from a highway. The error bars indicate the standard error of the mean value — if bars are not visible, then the standard error is smaller than the marker size.

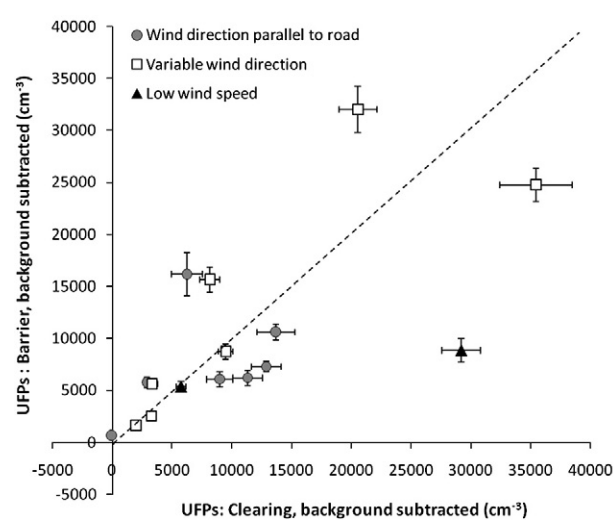

Fig. 5. Comparison of traffic-related ultrafine particle concentrations (<100 nm) measured in a clearing and behind a stand of evergreen trees at 15 m from a major roadway in Chapel Hill. The error bars indicate the standard error of the mean value — if bars are not visible, then the standard error is smaller than the marker size.

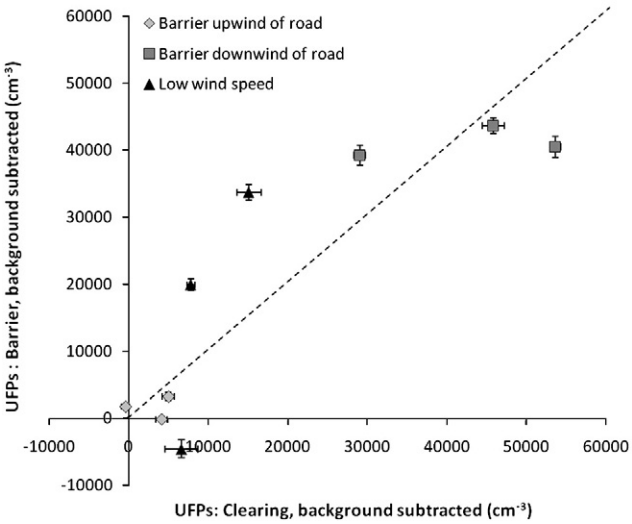

Fig. 6. Comparison of traffic-related ultrafine particle concentrations (<100 nm) measured in a clearing and behind a stand of deciduous trees with leaves at 20 m from a major roadway in Mebane during the early fall (pre-leaf fall). The error bars indicate the standard error of the mean value — if bars are not visible, then the standard error is smaller than the marker size.

and barrier were generally similar for cases observed, with 6 out of the 8 sampling sessions having nearly identical concentrations measured in both environments. The reduced amount of leaves would allow more free transport of traffic emission to the behind-barrier environment.

Evaluating the sessions sampled with leaf-on or evergreen barriers, it appears the vegetation effectiveness on reducing near-road concentrations is much more variable relative to the solid barrier observed in Raleigh. At both sites, the vegetative barrier is only a few trees wide; therefore, gaps due to irregular tree spacing and branch coverage may allow traffic-related pollution to pass through or around the vegetation, and act to trap pollution behind the vegetation under certain wind conditions. The vegetation may also reduce air flow, leading to increased pollutant concentrations due to the more stagnant conditions within and behind the trees. Under situations where the vegetation barrier may be more continuous, either naturally or through landscaping, and have a wider buffer, more consistent reductions similar to the Raleigh case may be expected.

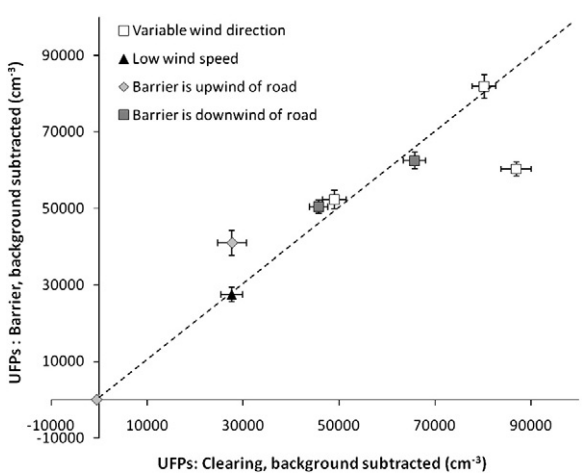

Fig. 7. Comparison of traffic-related ultrafine particle concentrations (<100 nm) measured in a clearing and behind a stand of deciduous trees without leaves at 20 m from a major roadway in Mebane in the winter, after leaf fall. The error bars indicate the standard error of the mean value — if bars are not visible, then the standard error is smaller than the marker size.

3.4. On-road concentrations and barrier effect

Concentrations of $PM_{2.5}$, PM_{10}, BC, and UFPs are reported (Table 4) for the major road and a nearby background area sampled at each location (Fig. 1). While both PM and BC values rely on a number of assumptions – PM relies on assumed particle shape and density, BC relies upon an estimate of mass absorption efficiency – these calculations are done consistently for each location and the relative levels may be informative. In order to allow between-species comparison, Table 4 represents only the sampling sessions where the Aerodynamic Particle Sizer provided useable data (half of the Raleigh campaign and the later campaigns in Chapel Hill and Mebane). In making the site to site comparison, it is important to note that the average wind speed for the sessions sampled at the three sites were similar — ranging from 1.25 to 1.5 m s^{-1}.

The difference between the on-road levels measured at each site is counterintuitive, as the Mebane site, which has a generally lower traffic volume on I-40/I-85 and less congestion than I-440 in Raleigh, had overall the highest net concentration of all measured PM components after accounting for the background. Average fleet driving speed, determined by the speed recorded by the sampling car, is found to be a stronger indicator of net on-road UFP contribution in comparison to AADT (Fig. 8). These results are similar to those found by Kittelson et al. (2004). However, it should also be noted that the fleet mix is not quantified for this study, thus the relative importance of the fraction of heavy-duty vehicles for on-road UFP levels is not determined.

Model estimates and wind tunnel experiments predict elevated on-road concentrations in the presence of roadside barriers, when the road is upwind of the barrier (Heist et al., 2009; Hagler et al., 2011a). The potential for this occurrence was shown in the earlier Raleigh field study (Baldauf et al., 2008b), with higher CO concentrations measured behind the noise barrier during upwind conditions; however, the existence of higher concentrations on the highway side of the barrier could not be tested during that field campaign. The higher time resolution of the UFP data for this study allowed for a comparison of on-road concentrations in environments with and without roadside barriers present. In order to capture an adequate number of data points, the full length of the on-road sampling route was categorized as barrier-impacted or unobstructed air flow and all sampling sessions were used to calculate the averages in Fig. 8. For all sessions combined, including all wind conditions encountered, the difference in on-road UFP levels with and without barriers is uncertain given the high level of variability in the on-road concentrations. For the solid barrier Raleigh case and the downwind category, which most closely matches past modeling and wind tunnel findings, the on-road concentrations with a barrier were a factor of 1.0 to 2.8 higher than the no-barrier case. The higher range agrees more closely with the previous findings referenced. In order to understand the variability of concentrations observed, further understanding of the transport of emissions in the turbulent on-road environment is needed.

4. Conclusions

Communities throughout the world are grappling with the issue of near-road air pollution – the elevation of air pollution within several hundred meters of a major roadway and the health effects that result from exposures to these concentrations – and are evaluating possible techniques to reduce near-road impacts. In open street environments characteristic of many suburban and urban areas outside of downtown central business districts, a potential mitigation approach for existing or new developments near major roadways is enhancing the dispersion and removal of traffic-related air pollution by means of roadside barriers. If air pollution benefits are determined, air quality value, in addition to noise reduction and esthetic value, may be assigned to these naturally-occurring or manmade barriers and integrated into

Table 4
On-road and background average and standard deviation concentrations at each location.

	Chapel Hill		Mebane		Raleigh	
	Avg wind speed: 1.5 m/s		Avg wind speed: 1.25 m/s		Avg wind speed: 1.27 m/s	
	Major road	Bkgd	Major road	Bkgd	Major road	Bkgd
$PM_{2.5}$ ($\mu g\ m^{-3}$)[a]	6.2 (1.8)[b]	4.7 (0.9)	8.1 (1.8)	4.7 (1.7)	8.7 (2.6)	7.5 (1.9)
PM_{10} ($\mu g\ m^{-3}$)[a]	9.8 (7.1)	6.2 (3.9)	12.1 (5.9)	6.6 (4.5)	11.0 (5.0)	8.9 (3.3)
BC ($\mu g\ m^{-3}$)	2.3 (3.5)	1.1 (2.0)	6.0 (5.1)	0.7 (0.4)	5.0 (3.4)	1.7 (1.5)
UFPs (cm^{-3})	$4.3 \cdot 10^4$ ($4.1 \cdot 10^4$)	$1.1 \cdot 10^4$ ($8.5 \cdot 10^3$)	$1.5 \cdot 10^5$ ($1.0 \cdot 10^5$)	$1.0 \cdot 10^4$ ($9.0 \cdot 10^3$)	$1.1 \cdot 10^5$ ($9.0 \cdot 10^4$)	$2.0 \cdot 10^4$ ($1.1 \cdot 10^4$)

[a] PM values are estimated from size-resolved particle counts.
[b] Standard deviation is calculated as the average of the standard deviations calculated for each individual session.

urban planning decision-making. The ability to assess multiple societal consequences of infrastructure management decisions, in terms of economics or health effects, would contribute to full-cost accounting within a systems framework, the approach currently advocated by the U.S. Environmental Protection Agency (Fiksel et al., unpublished).

This research study measured concentrations of ultrafine particles in roadway areas which had either a structural solid noise barrier or a porous thin tree stand present. Concentrations were mapped in on-road, near-road, and background areas using a mobile sampling platform and sessions were repeated under a variety of meteorological conditions. The study determined that a solid 6 m structural barrier consistently lowered near-road concentrations (10 m from road) by approximately half for multiple wind conditions and when traffic-related excess air pollution is evident. The results for the vegetative barrier sites are variable, with cases where the behind-barrier levels are higher or lower than levels observed in a nearby clearing. The inconclusive finding as to the benefits of near-road vegetation in reducing UFP levels is likely related to several conditions of this study. First, the focus on thin, non-continuous vegetation stands – a common feature for developments proximate to roadways – increased the chance of transport of emissions through the variable barrier. The tree stands had only moderate LAI values (~3) and the tree spacing allowed for irregular gaps in the barrier structure. Another challenge of the study is that the local wind trends were frequently low speed and variable in direction, limiting the ability to assess true downwind conditions over a 2–3 h mobile sampling period, although the conditions are still important from a population exposure perspective. Given the consistent finding that solid barriers reduce near-road air pollution relative to unobstructed air flow, at least in the very close vicinity of the roadway, it is possible that a lower porosity vegetation buffer may likewise improve near-road air pollution. Additional research is warranted to further evaluate the potential effects of roadside vegetation on near-road air quality.

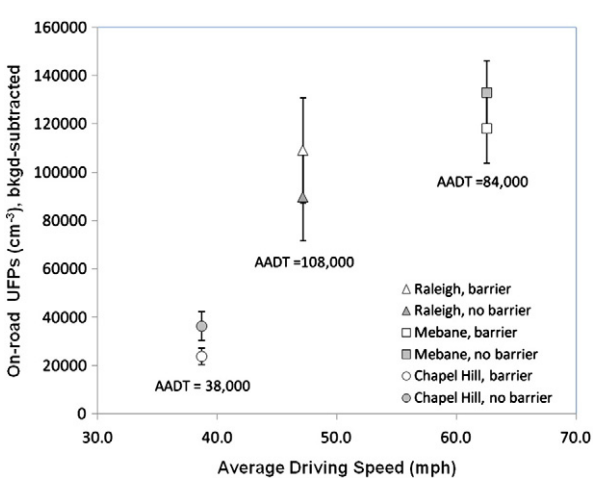

Fig. 8. Ultrafine particle concentrations measured on the major roadways at each site compared with driving speed. For each sampling session, the background concentrations are subtracted from the on-road measurements. The error bars indicate the standard error of the mean value, with N set as the number of sampling sessions (10 for Raleigh, 16 for Chapel Hill, 18 for Mebane) per location.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.scitotenv.2011.12.002.

References

Baldauf R, Thoma E, Hays M, Shores R, Kinsey J, Gullett B, et al. Traffic and meteorological impacts on near-road air quality: summary of methods and trends from the Raleigh near-road study. J Air Waste Manage Assoc 2008a;58:865–78.
Baldauf R, Thoma E, Khlystov A, Isakov V, Bowker G, Long T, et al. Impacts of noise barriers on near-road air quality. Atmos Environ 2008b;42:7502–7.
Beckett KP, Freer-Smith PH, Taylor G. Urban woodlands: their role in reducing the effects of particulate pollution. Environ Pollut 1998;99:347–60.
Beckett KP, Freer-Smith PH, Taylor G. Particulate pollution capture by urban trees: effect of species and windspeed. Glob Chang Biol 2000;6:995-1003.
Bowker GE, Baldauf R, Isakov V, Khlystov A, Petersen W. The effects of roadside structures on the transport and dispersion of ultrafine particles from highways. Atmos Environ 2007;41:8128–39.
Buccolieri R, Gromke C, Di Sabatino S, Ruck B. Aerodynamic effects of trees on pollutant concentration in street canyons. Sci Total Environ 2009;407:5247–56.
California Environmental Protection Agency. Air quality and land use handbook: a community health perspective. http://www.arb.ca.gov/ch/handbook.pdf2005.
Fiksel, J., Araujo, R., Bruins, R., Conolly, R., Dix, D., Dodder, R., Fontaine, T., Gatchett, A., Gilliland, A., Leazer, J., Sergeant, A., ten Brink, M., and Yund, C. Framework for integrated research and systems thinking: An integrative, transdiciplinary approach to formulation, investigation, and implementation of sustainable solutions toteh environmental challenges of the 21st century. U.S. Environmental Protection Agency, Office of Research and Development, 20 p., unpublished, 2011.
Finn D, Clawson KL, Carter RG, Rich JD, Eckman RM, Perry SG, et al. Tracer studies to characterize the effects of roadside noise barriers on near-road pollutant dispersion under varying atmospheric stability conditions. Atmos Environ 2010;44:204–14.
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;60:328–36.

Hagler GSW, Tang W, Freeman MJ, Heist DK, Perry SG, Vette AF. Model evaluation of roadside barrier impact on near-road air pollution. Atmos Environ 2011a;45:2522–30.
Hagler GSW, Yelverton TLB, Vedantham R, Hansen ADA, Turner JR. Post-processing method to reduce noise while preserving high time resolution in Aethalometer real-time black carbon data. Aerosols and Air Quality Research 2011b;11:539–46.
Heist DK, Perry SG, Brixey LA. A wind tunnel study of the effect of roadway configurations on the dispersion of traffic-related pollution. Atmos Environ 2009;43:5101–11.
Karner AA, Eisinger DS, Niemeier DA. Near-roadway air quality: synthesizing the findings from real-world data. Environ Sci Technol 2010;44:5334–44.
Kittelson DB, Watts WF, Johnson JP. Nanoparticle emissions on Minnesota highways. Atmos Environ 2004;38:9-19.
Lin M-Y, Khlystov A. Investigation of ultrafine particle deposition to vegetation branches in a wind tunnel. Aerosol Sci Technol 2012;46:465–72.
Lin XJ, Barrington S, Nicell J, Choiniere D, King S. Livestock odour dispersion as affected by natural windbreaks. Water Air Soil Pollut 2007;182:263–73.
Moore EO, Arch D. A prison environment's effect on health-care service demands. J Environ Syst 1981;11:17–34.
Ning Z, Hudda N, Daher N, Kam W, Herner J, Kozawa K, et al. Impact of roadside noise barriers on particle size distributions and pollutants concentrations near freeways. Atmos Environ 2010;44:3118–27.
Nowak DJ, Crane DE, Stevens JC. Air pollution removal by urban trees and shrubs in the United States. Urban Forestry Urban Greening 2006;4:115–23.
Shannon MW, Best D, Binns HJ, Johnson CL, Kim JJ, Mazur LJ, et al. Ambient air pollution: health hazards to children. Pediatrics 2004;114:1699–707.
Sullivan WC, Kuo FE. Do trees strengthen urban communities, reduce domestic violence? Urban and Community Forestry Assistance Program Technology Bulletin; 1996.
Ulrich RS. View through a window may influence recovery from surgery. Science 1984;224:420–1.
Wells NM. At home with nature: effects of “greenness” on children's cognitive functioning. Environ Behav 2000;32:775–95.
Yamartino RJ. A comparison of several single-pass estimators of the standard deviation of wind direction. J Climate Appl Meteorol 1984;23:1362–6.