Assessing Bicyclist and Pedestrian Exposure to Ultrafine Particles: Passive Shielding with Noise Barriers

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ABSTRACT

From a human health standpoint, a major concern regarding vehicular exhaust is associated exposure to ultrafine particles (UFP), particulate matter with aerodynamic diameter less than 0.1 µm. Concentration of these particles in the urban environment is highest near roadways. Bicyclists and pedestrians traveling in near-road areas with high concentrations of UFP often have high respiration rates that make them particularly susceptible to uptake of these dangerous pollutants. In some roadway environments, physical noise barriers border high-volume roads to reduce noise pollution. Non-motorized facilities may be located within the right-of-way enclosed by these barriers or on the opposite side of the barrier from the roadway. The work presented here assesses the effects of roadside noise barriers on ultrafine particulate exposure in bicycle and pedestrian facilities sited alongside major freeways. Using a unique examination of measured traffic and air quality characteristics in Portland, Oregon, noise barriers were found to reduce roadside UFP levels by at least 12% and as much as 84% along an adjacent bicycle/pedestrian pathway. UFP levels on the "exposed" road side of the noise barriers were highly variable and moderately related to wind conditions but not to traffic conditions. On the "shielded" side of the barriers, the concentration peaks seen on the roadway side were damped, resulting in more stable and lower exposure levels for shared path users behind the noise barriers. Despite varying conditions of wind speed and direction and traffic speed and flow, noise barriers consistently mitigated bicyclist and pedestrian UFP exposure on a near-road pathway.

INTRODUCTION

A growing body of research suggests that negative health outcomes including cardiovascular and respiratory disease, cancer, and increased mortality rates may disproportionately affect populations near high-volume roadways (*1*-*5*). Epidemiological studies have consistently demonstrated relationships between these adverse health outcomes and exposure to traffic-related air pollutants, including ultrafine particles (UFP, particulate matter with aerodynamic diameter < 0.1 µm) (*2*,*5*).

Bicyclists and pedestrians, or "active" transportation users, are often subjected to high concentrations of UFP due to the placement of non-motorized facilities alongside motor vehicle traffic (*6*). In urban locations where space is at a premium, bicycle and pedestrian pathways are often located alongside freeways where uninterrupted right-of-way is available. Higher respiration rates due to physical activity by active roadway users exacerbate the health risks of their exposure to vehicular exhaust (*7*-*9*), and bringing these users within close proximity of high-volume roadways creates a potentially dangerous situation in which bicyclists and pedestrians are exposed to and uptake high concentrations of ultrafine particles.

In some roadway environments, physical noise barriers border high-volume roads to reduce noise pollution for neighboring populations. Although designed for noise abatement, these roadside barriers may play a role in shielding bicyclists and pedestrians from exposure to vehicle-produced ultrafine particles. The objective of this research is to determine if strategic noise barrier and bicycle/pedestrian path designs can mitigate personal exposure to traffic-generated UFP. Detailed traffic and ultrafine particulate measurements near bicycle/pedestrian shared paths alongside two freeways in Portland, Oregon, are used to investigate the impacts of noise barriers on UFP exposure for non-motorized road users.

BACKGROUND

Particulate matter (PM) is generally classified into three categories based on aerodynamic diameter of particles. PM_{10} (coarse particles) and $PM_{2.5}$ (fine particles) are defined as having aerodynamic diameters less than 10 µm and 2.5 µm, respectively. $PM_{0.1}$, more commonly known as UFP, have diameters less than 0.1 µm and are the smallest particulates commonly classified. The health effects associated with PM are diverse in scope, severity, and duration, though it is agreed that UFP are able to penetrate more of the body's natural defenses and potentially cause greater harm than coarser particles (*10*,*11*). People living and working in close proximity to high-volume roadways are more likely to suffer adverse health effects due to exposure to UFP than to PM_{10} or $PM_{2.5}$ (*2*). Furthermore, UFP are non-threshold pollutants, meaning there is no threshold in particle concentration below which human health would not be affected (*2*).

When exposed to UFP, inhalation brings the particles deep into the lungs because of their gas-like behavior, bypassing natural defenses such as cilia or mucous membranes. There, they accumulate over time in the alveolar region of the lungs and pulmonary interstitial spaces, and possibly move into the circulatory system (*10,12*). UFP have between 10^2 and 10^5 times more surface area than larger particulate matter, increasing the potential for UFP to carry foreign toxins into the body (*13*). Chemical composition of vehicle-produced UFP varies greatly depending on vehicle type, combustion processes, and fuel used, though they are primarily composed of soot, which is a by-product of hydrocarbons burning under fuel-rich conditions (*2*).

UFP can reach extremely high number concentrations, but because of their small size represent an almost insignificant portion of total PM mass. As such, UFP are generally reported in number concentrations rather than mass. High concentrations of UFP are not measured by mass-based PM standards such as those of the national ambient air quality standards (*14*). In a clean environment, ambient UFP concentration levels are usually on the order of a few hundred particles/cm^3, while ambient urban environment concentrations range from a few thousand to about twenty thousand particles/cm^3 (*2*).

Elevated concentrations of UFP near roads in excess of ambient urban concentrations indicate a direct relationship to vehicle emissions (*15*). Gasoline and diesel engines emit particles primarily in the UFP size range (*16*). Studies profiling UFP near roadways have found concentrations up to 25 times higher than background levels near freeways in California (*17,18*), and UFP number concentrations near roadways can reach or exceed 10^5 particles/cm^3 (*2*). Particle number concentrations decrease with distance due to dispersion and coagulation into larger particles outside of the UFP size range. They have been shown to return to background levels around 300m downwind from a roadway (*17*), though this dispersion distance varies with the presence of physical obstacles.

Physical barriers alongside roadways such as dense vegetation, buildings, and other structures, due to their height and impenetrability, impact localized airflow, creating complex dispersion patterns for airborne pollutants (*16,19,20*). One such type of barrier, prominent and common in urban areas, is the noise barrier. Noise barriers along high-volume roadways are constructed exclusively for the abatement of vehicle-generated noise (*21*). Barrier height varies depending on sound level mitigation requirements, as do the distances between the roadway, barrier, and adjacent property lines. By blocking line of sight between an individual and the road, sound levels are decreased by 5 dB (*21*). Each additional meter of barrier height decreases the sound level by 1.5 dB, with the objective to reduce freeway sound levels by 10 dB for households immediately behind the noise barrier (*22*).

Noise barriers may play a role in mitigating UFP exposure for those traveling on bicycle/pedestrian pathways adjacent to the barrier, though this premise has not yet been confirmed. Past studies have recognized a dispersion effect by noise barriers (*16,19,23,24,25*), suggesting the formation of a recirculation cavity behind the wall, where a pathway may be located, when winds blow perpendicular from the freeway. In such situations, the literature estimates pollution concentrations between 0% and 80% of roadside values for distances between 3 and 12 wall heights downwind (*26,27*). Baldauf *et al.* found that the presence of a noise barrier generally reduced particle number concentrations for distances 20-300 meters beyond the barrier at a location in Raleigh, North Carolina (*24*). Ning *et al.* recognized that a recirculation cavity formed in the close vicinity (15 m) downwind of the barrier (*25*). At this point, particle number concentrations were 45-50% of comparable measurements made without the presence of a noise barrier. The UFP dispersal and shielding effects of noise barriers for locations immediately adjacent to the wall have not been measured, and no published research is available concerning UFP exposure for users of multi-use pathways near noise barriers.

Greater understanding of the relationships between noise barriers, traffic characteristics, and bicyclist and pedestrian exposure to UFP is needed to design transportation infrastructure that facilitates lower exposure for active transportation users and protects public health. For example, siting a bicycle/pedestrian path on the road-side or the outside of a noise barrier could substantially impact the exposure of active travelers to traffic-related pollution. This study evaluates continuous traffic data (speed, volume) and wind data (speed, direction) with measured UFP concentrations to demonstrate the impacts of noise barriers on exposure levels for bicyclists and pedestrians near the roadway and to estimate the influence of traffic and wind conditions on these noise barrier effects.

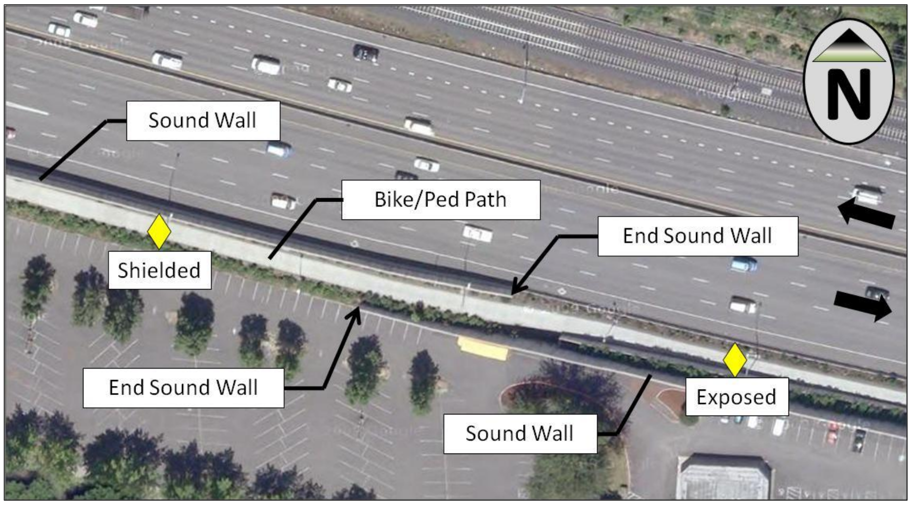
EXPERIMENTAL DESIGN

Description of Sampling Sites

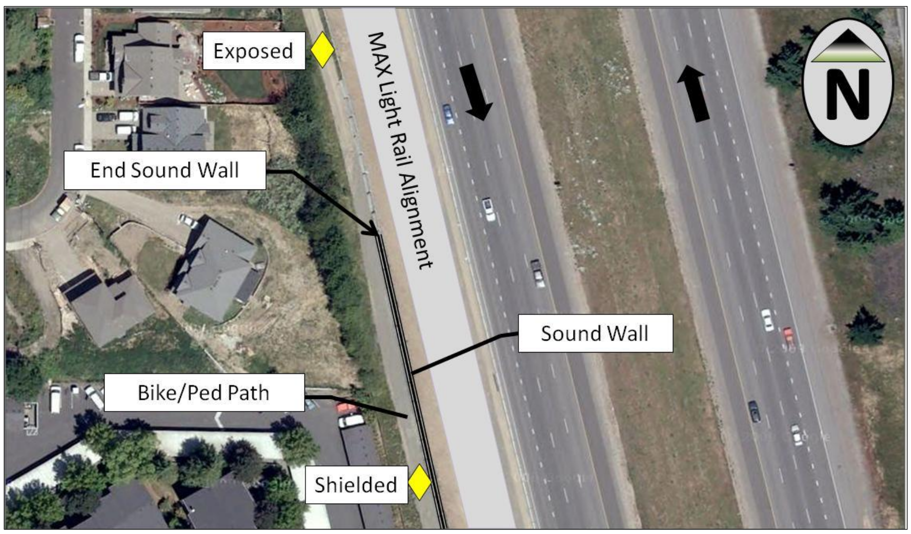
UFP levels were measured near two freeways in Portland, Oregon. Study sites were chosen based on proximity of noise barriers to traffic, absence of other significant UFP sources in the surrounding area, presence of bicycle/pedestrian facilities, geography surrounding the site, and orientation of the roadway to prevailing wind conditions. To facilitate comparison between the two locations, noise barriers located at both sites share similar geometry; both are roughly 15 ft high and one foot thick, though dimensions vary somewhat with local geography.

Site 1: **US-26**, Figure 1a: a 9-lane (5 eastbound, 4 westbound) freeway west of the city center. At the monitoring site, two noise barriers overlap for roughly 95 ft, and the bicycle/pedestrian path passes through the overlap section. The study site directly abuts eastbound vehicle lanes. There is no median; travel directions are separated by Jersey barriers. Land on the south side of the barriers is flat and largely paved, with a parking lot and sparse vegetation. The speed limit is 55 mph. The road grade is negligible. Morning peak-period flows toward the city center are eastbound (near side), while PM peak flows are westbound; both peak periods experience recurring congestion in this area.

Site 2: **Interstate 205**, Figure 1b: an 8-lane (4 northbound, 4 southbound) beltway east of the city center. The bicycle/pedestrian path runs along the west side right-of-way, separated from the road by a single noise barrier for a portion of the path's length at the monitoring site. The remaining length of pathway is not separated from the freeway by any physical barrier. Portland's MAX light rail, on a 50-ft-wide alignment, runs between the bicycle/pedestrian pathway and the freeway. Vehicle directions are separated by a 70-ft median, placing northbound traffic on a slight elevation rise compared to southbound traffic. Residential development on the west side of the freeway is set back from the noise barrier and pathway by a row of trees and small vegetation. The speed limit is 55 mph. The road grade is negligible. The site experiences afternoon peak period congestion in the northbound direction.



(a)



(b)

FIGURE 1 UFP measurement locations along US-26 (a) and I-205 (b). Diamonds indicate sampling positions. (Images from www.maps.google.com)

Sampling and Instrumentation

Field sampling was conducted at the US-26 site on March 24, April 22, and May 13, 2010, and at the I-205 site on May 27, 2010. Both roadways were sampled during weekdays from approximately 7:00 AM until late morning (between 11:00 AM and noon), with the exception of the March 24 data collection, which was sampled during the afternoon. Temperatures ranged from 62°F (April 22) to 74°F (May 13). Humidity ranged from 59% (April 22) to 71% (May 27). May 27 was cloudy with 0.09 inches of precipitation for the day, while the other sampling days had clear skies.

UFP concentrations were measured using two TSI P-Trak Ultrafine Particle Counters (TSI Model 8525) capable of counting particles ranging from 0.02 µm to 1 µm in diameter and measuring concentrations between zero and $5x10^5$ particles/cm^3. The two P-Traks were factory calibrated within a year prior to data collection. A side-by-side run of the P-Traks in the laboratory for three and a half hours ensured instrument correlation (r^2= 0.996). During data collection, the P-Traks were interrupted every six hours to resaturate the isopropyl alcohol wick, but otherwise ran continuously at 1-second resolutions during each sampling period. The devices were mounted with intake points approximately at breathing level, roughly 5.5 feet, along the side of the bicycle/pedestrian paths in the locations shown in Figure 1 as "Exposed" or "Shielded". One P-Trak, marked "exposed" in Figure 1, was placed either in front of the noise barrier at the US-26 site (Figure 1a) or in a location where no noise barrier is present at the I-205 site (Figure 1b) to gather unshielded concentration levels. Another P-Trak, marked "shielded," was placed 15 feet behind the noise barrier (Figures 1a and 1b) to gather concentration levels influenced by the noise barrier's presence.

Wind speed and direction were measured using up to three RM Young Wind Monitors (Young Model SE), placed at fixed intervals along the bicycle/pedestrian path and adjacent to the P-Traks. The wind speed sensor has an accuracy of ±0.3 m/s or 1% of the reading, whichever is greater. The wind direction sensor has an accuracy of ±2°.

Continuous vehicle counts were obtained from the Portland Oregon Regional Transportation Archive Listing (PORTAL – at www.portal2.its.pdx.edu), an archive of transportation data including freeway loop detector data from the Portland-Vancouver metropolitan region. Dual-loop detectors collecting volume, speed, and lane occupancy at 20-second aggregations are located throughout the freeway system in the region. For this study, the closest loop detector stations to the monitoring site were used for data collection. Loop detector data were gathered for the vehicle travel directions closest to the monitoring site: eastbound and southbound traffic for the US-26 and I-205 sites, respectively. At the US-26 site, the loop detector station is located 1,400 ft upstream of the monitoring site. The loop detector at the I-205 site is approximately 4,750 ft upstream. The loop detectors are located immediately upstream of freeway on-ramps, so both sites have a lane merge intervening between particulate/wind measurements and traffic measurements.

RESULTS

Table 1 shows mean concentration levels and range of exposure concentrations for each date at both the US-26 and I-205 monitoring sites. Using a p-value significance level of 0.05, one-sided paired t-tests were used to evaluate whether exposed concentrations were greater than shielded concentrations. UFP concentration levels were consistently and significantly lower at shielded locations than at exposed locations on all days and at all monitoring sites. The average mean concentration for an exposed P-Trak was 31,700 particles/cm^3. The average mean concentration for a shielded P-Trak was 23,997 particles/cm^3.

TABLE 1 UFP Concentration Comparisons in particles/cm^3 (pt/cc) at 1-second Intervals for US-26 and I-205 Monitoring Locations

	P-Trak Location	Mean Conc. (pt/cc)	St. Dev. (pt/cc)	Median (pt/cc)	1-sec Conc. Range (pt/cc)	Mean Diff. (pt/cc)	Percent Diff.	t-value	p-value
US-26		**March 24**							
	Exposed	31,142	32,178	20,600	4,290 – 388,000	26,236	84%	94.9	< 0.001
	Shielded	4,905	2,345	4,330	2,910 – 50,700				
		April 22							
	Exposed	35,518	26,920	26,100	4,310 – 271,000	4,153	12%	21.1	< 0.001
	Shielded	31,258	25,050	21,000	4,970 – 278,000				
		May 13							
	Exposed	29,270	27,794	21,000	4,210 – 450,000	10,183	35%	54.3	< 0.001
	Shielded	20,126	15,272	16,200	3,690 – 316,000				
		May 27							
I-205	**Exposed**	30,870	25,612	22,200	5,210 – 194,000	10,265	33%	57.0	< 0.001
	Shielded	20,607	18,166	12,900	5,270 – 142,000				

UFP concentrations at exposed locations were consistently greater than shielded locations, though there was a wide range in the mean differences and percent differences (12%-84%).

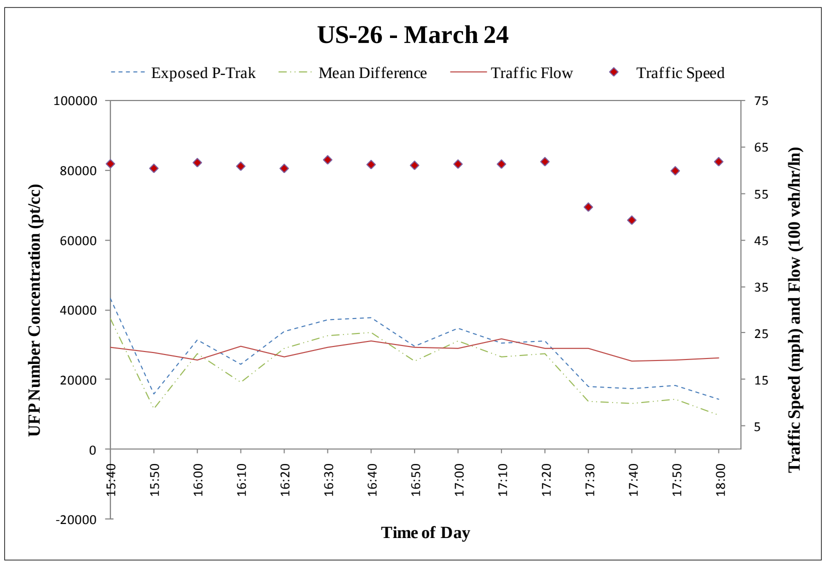
Figures 2 and 3 compare wind and traffic characteristics with UFP concentration levels from both monitoring sites at 10-minute aggregations. The absolute UFP concentrations shown are the values obtained from the "exposed" P-Traks at both sites (see Figure 1 for placement locations). UFP differences are the difference between "exposed" and "shielded" P-Traks at each site.

Figure 2a displays the data collected on March 24 at the US-26 site. March 24 was the only day in which data were collected during PM peak hour traffic rather than AM peak. Wind data were unavailable for comparison. Average shielded UFP concentrations are steadier than the exposed concentrations during the sampling period, with concentrations ranging from 3,745 to 5,747 particles/cm^3. Consequently, the mean difference tracks closely with the average exposed UFP concentrations, which are more volatile. Traffic speeds are constant until congestion at 5:30 PM lowers the average speed to 50 mph, during which time exposed UFP concentrations fall from 31,000 particles/cm^3 to 17,500 particles/cm^3.

Figure 2b displays the data collected on April 22 at the US-26 site. Average exposed UFP number concentrations peak at 9:40 AM with 84,213 particles/cm^3. Wind speed at this time is below 1 m/s and northeasterly, blowing across traffic and roughly normal to the noise barrier's surface. Traffic speeds are steady at approximately 60 mph, and flow is 3,000 veh/hr/ln. At 8:00 AM, average exposed UFP levels are seen to rise slightly as traffic speeds decrease from about 60 mph to 14 mph. The mean difference tracks less closely with exposed concentrations than on March 24, and on four occasions, shielded levels were greater than exposed levels. Traffic speeds are stable during these concentration inversions, but wind conditions are more varied: twice winds are from the north/northwest and twice they are from the south/southeast.

Figure 3a displays the data collected on May 13 at the US-26 site. Traffic speeds range widely from a congestion-induced low of 6 mph at 8:10 AM to a steady 60 mph when conditions clear. Average exposed UFP levels exhibit no apparent relation to traffic speed and in fact reach the morning's lowest level of 11,658 particles/cm^3 when traffic speeds slow to 6 mph, in contrast to the increase seen on April 22. Mean difference levels generally track with average exposed concentrations. Mean difference values for 9:00 AM should be disregarded due to an equipment malfunction which recorded a shielded concentration value of 0 particles/cm^3. Average shielded levels exceed exposed levels once, beginning at 8:10 AM and lasting for roughly 30 minutes. Traffic flow and speeds are at their lowest values during this interval. Wind speeds are below 1 m/s and blowing from the northwest, across traffic and roughly perpendicular to the noise barrier's surface.

Figure 3b displays the data collected on May 27 at the I-205 site. The P-Traks were located on the west side of the highway. Due to the orientation of the freeway at this location, a northwesterly wind results in vehicle emissions being blown *away* from the monitoring site, and from approximately 8:00 AM until the end of the time interval shown in Figure 3b, wind blew primarily from the northwest at 1-2 m/s. Average UFP concentrations recorded during this time by the exposed P-Trak ranged from 10,000 to 50,000 particles/cm^3. Early in the morning, however, at 7:10 AM, an easterly wind, perpendicular to the noise barrier's surface, blew at roughly 1 m/s directly across the freeway towards the monitoring site. Average exposed UFP concentration levels rose to 99,127 particles/cm^3 during this time period, a level at least 50,000 particles/cm^3 higher than at any other point during the morning. The mean difference during the 7:10 AM spike is 37,509 particles/cm^3. For the remaining duration of the data collection, the average mean difference is 8,659 particles/cm^3. Average shielded levels were greater than exposed levels once at 7:40 AM. Wind speeds at this time had recently shifted from the southwest to the northwest and traffic flow was decreasing from 3,950 to 2,050 veh/hr/ln.



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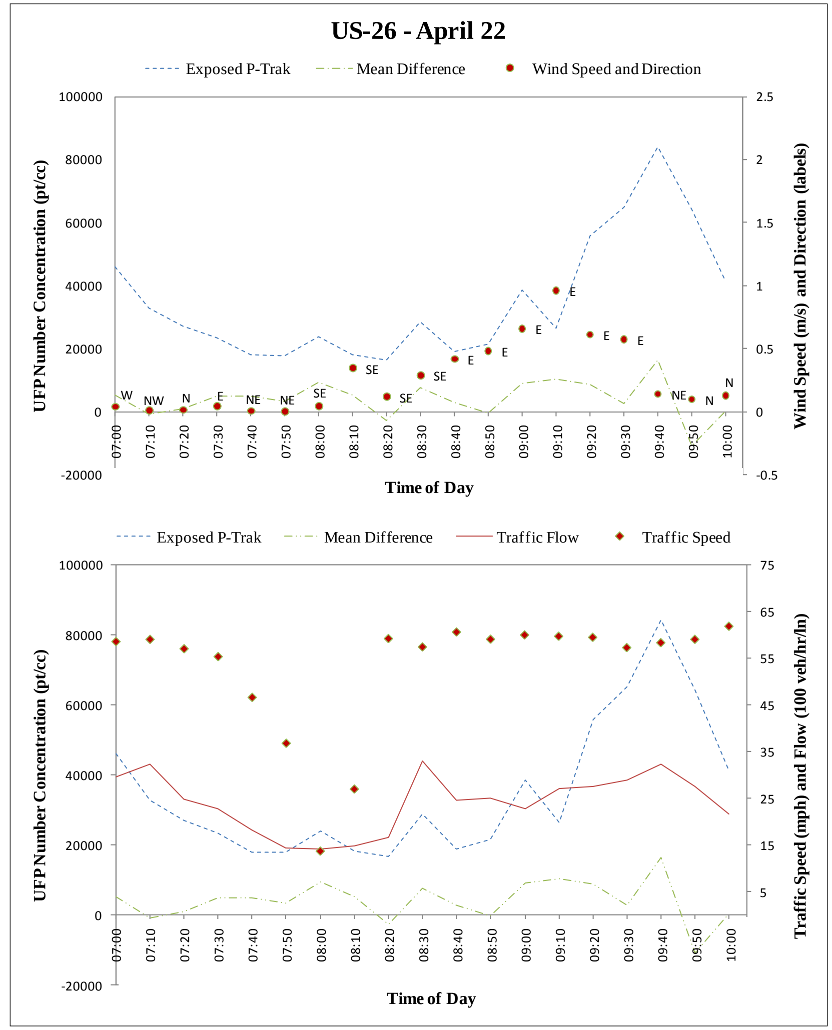

(b)

FIGURE 2 10-minute UFP concentration aggregations in particles/cm^3 (pt/cc) with wind and traffic characteristics on (a) March 24 and (b) April 22
[note that wind data were unavailable for March 24]

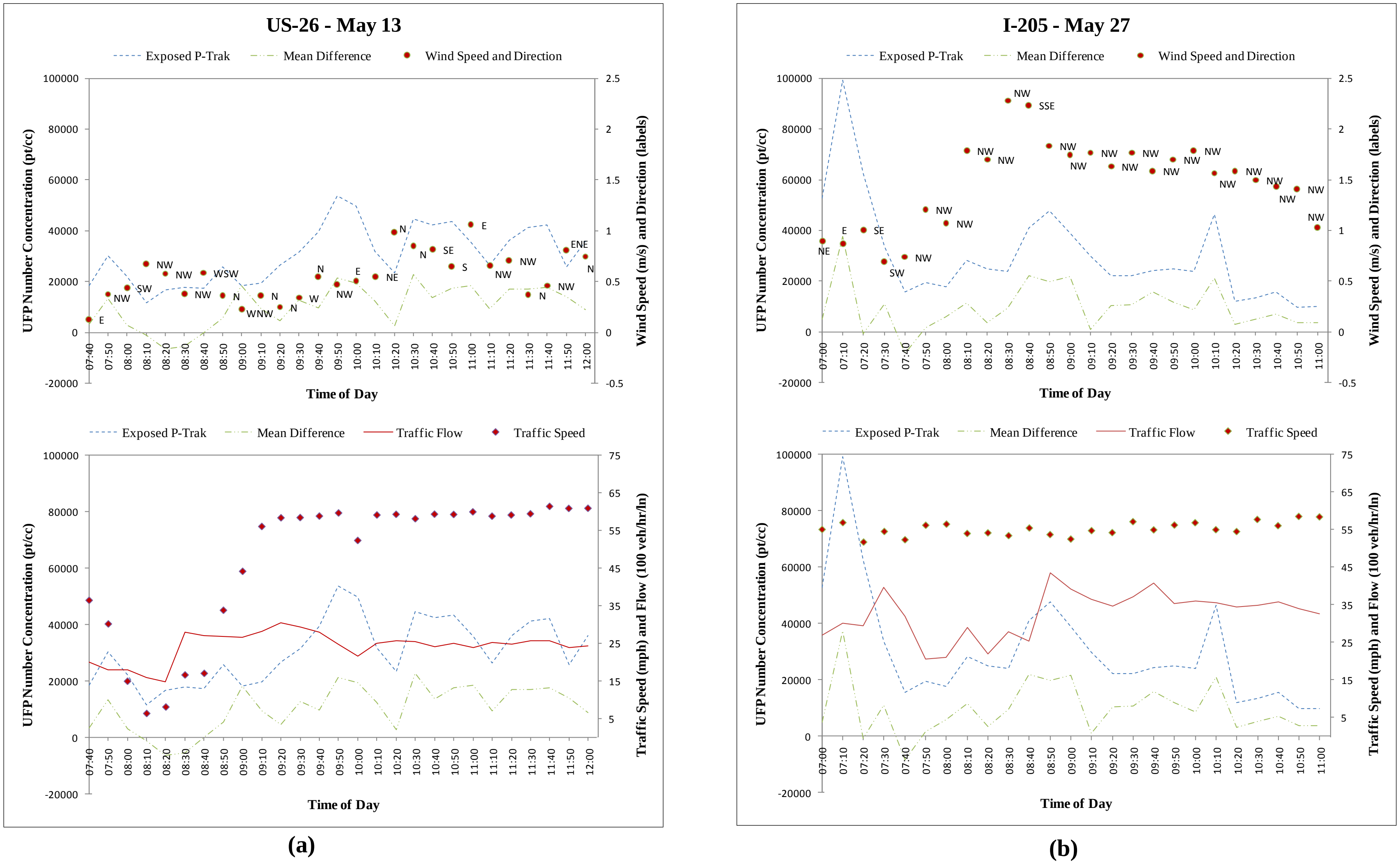

FIGURE 3 10-minute UFP concentration aggregations in particles/cm^3 (pt/cc) with wind and traffic characteristics on (a) May 13 and (b) May 27

DISCUSSION

A statistically significant difference in UFP concentration levels was measured between exposed and shielded P-Traks. Table 1 shows a shielding effect of 12-84% of the exposed concentration levels, meaning users of shielded bicycle/pedestrian pathways are exposed to at least 12% fewer ultrafine particulates than those using other observed facility configurations. When taking into account the increased respiration rate (and subsequent particulate uptake) common among bicyclists and pedestrians, the health implications of a 12% reduction in exposure concentration could be important.

Large differences between exposed and shielded measurements correspond across multiple sites and days, pointing to a broader mitigating condition rather than a unique site effect. This trend includes exposed P-Traks located both in an area with no noise barrier and in an area where a noise barrier is present. Mean concentration values were within the expected range based on the literature review. Morawska *et al.* (*2*) found ambient urban concentrations to be on the order of a few thousand to as high as twenty thousand particles/cm^3, and Zhu *et al.* (*17,18*) found concentrations around roadways to be up to 25 times higher than urban background concentrations. At the most extreme, then, the literature would expect a peak concentration level of 500,000 particles/cm^3. On May 13 at the US-26 site, the highest 1-second peak concentration of the study was recorded on the exposed side at 450,000 particles/cm^3, very close to the extreme value, but the concurrent shielded side concentration was only 45,100 particles/cm^3. Other days and locations shown in Table 1 exhibit high peak concentrations as well. Notably, no shielded location yielded concentrations above 400,000 particles/cm^3.

Wind Impacts on Noise Barrier "Shielding" Effectiveness

Factors involved in the shielding effectiveness of noise barriers are many, though literature suggests a strong dependence on wind conditions (*19*). The I-205 site proved to be an ideal situation on May 27 for isolating wind effects on noise barrier effectiveness due to the steady traffic speeds (speed ±2 mph). Table 2 shows the 10-minute average UFP concentrations at I-205 on May 27 during the period with easterly wind (7:10–7:20 AM) and an average of the ensuing northwesterly wind periods (7:40–11:00 AM, excluding a south-southeasterly wind from 8:40–8:50 AM). The noise barrier shielded pathway users 38% when winds were normal to its surface and 37% when winds were at an angle, despite the fact that the wind directions were associated with different absolute concentrations. For the other study periods, concentration differences tracked with roadside concentrations over changing wind speed and direction, resulting in consistent shielding effectiveness as measured by percent difference. It appears that noise barriers may shield a consistent percentage of roadway UFP regardless of concentration level. Noise barriers may also shield shared path users equally well regardless of whether wind blows perpendicular or at an angle to the barrier surface.

TABLE 2 Concentration Differences During Varying Wind Directions at I-205

Time Interval	Wind Direction†	Exposed P-Trak	Shielded P-Trak	Mean Diff	% Diff
7:10–7:20 AM	Perpendicular	99,127	61,621	37,506	38%
7:40–11:00* AM	Angled	25,021	15,650	9,371	37%

† – relative to noise barrier

* – excludes 8:40–8:50 AM

Traffic Impacts on Noise Barrier "Shielding" Effectiveness

Traffic speed and flow were found to exhibit little influence over short-term changes in UFP concentration levels despite motor vehicles being the clear source of UFP. Low vehicle speeds sometimes track with low UFP levels, as seen early on May 13 (Figure 3a), and at other times track with spikes in UFP levels, as seen at 8:00 AM on April 22 (Figure 2b). However, these correlations were not consistently observed and therefore conclusions between traffic characteristics and noise barriers' mitigation effects cannot be made at this time. The impacts of traffic speed and flow on near-road UFP levels and associated noise barrier abatement may be isolated in future work.

CONCLUSIONS

Understanding the influence of traffic and the physical environment on UFP concentrations is an essential component in evaluating human exposure to pollution in urban environments. In this paper, we examine the UFP exposure of bicyclists and pedestrians on multi-use paths adjacent to freeway noise barriers. Using concurrent traffic, wind, and ultrafine particulate measurements, UFP levels were found to be higher along shared paths placed in front of noise barriers (on the freeway side) or in locations where no noise barrier is present than those behind noise barriers (on the residential side). The shielding effectiveness of the noise barrier varied by study site and day, but did not appear to relate to traffic or wind conditions. The barrier was also consistently effective at passively shielding the shared path by reducing pathway concentrations relative to highly varying exposed-side concentrations.

Utilizing pre-existing freeway right-of-way for bicycle/pedestrian pathways is a cost-effective way to provide non-motorized transportation facilities and promote the use of active transportation modes, especially in urban environments where space is at a premium. But these facilities can expose bicyclists and pedestrians to UFP levels much higher than urban background levels. This research shows that increased UFP exposure can be partially mitigated by placing the multi-use path on the side of noise barriers away from freeway traffic, though shielded exposure rates still exceed typical urban background levels. While noise barrier placement depends on a variety of factors including safety, cost, and future roadway expansion, air quality concerns may be a new consideration in determining barrier location and the siting of shared path facilities adjacent to existing barriers.

Further research into air flow and pollutant dispersion around noise barriers is needed to show the path and barrier design conditions which are most effective at mitigating UFP exposure. For example, the shielding effectiveness of varying barrier heights and materials is not yet known, nor is the effect of spacing between roadway and wall, and between wall and path. Future research will also investigate more varied traffic congestion conditions and fleet mix to help determine which traffic management strategies can further mitigate road user exposure to UFP.

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