Impact of Bicycle Lane Characteristics on Exposure of Bicyclists to Traffic-Related Particulate Matter

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Bicycling as a mode of transportation is increasingly seen as a healthy alternative to motorized transportation modes. However, in congested urban areas, the health benefits of bicycling can be diminished by the negative health effects associated with inhalation of particulate matter. Particles of small size (ultrafine particles <0.1 μm) are the most harmful, even during short-duration exposure. Because vehicular exhaust is the major source of ultrafine particles, the impact of traffic levels and bicycle lane characteristics on exposure of bicyclists was studied. Ultrafine particle exposure concentrations were compared in two settings: (*a*) a traditional bicycle lane adjacent to the vehicular traffic lanes and (*b*) a cycle track design with a parking lane separating bicyclists from vehicular traffic lanes. Traffic measurements were made alongside air quality measurements. The cycle track design mitigated ultrafine particle exposure concentrations for cyclists. Results showed statistically significant differences in terms of exposure levels for the two bike facilities, as well as correlations between traffic levels and exposure level differences. Results also suggested that ultrafine particle levels and spatial distribution were sensitive to proximity to signalized intersections. Findings of this research indicated that, in high traffic areas, bicycle facility design had the potential to lower air pollution exposure levels of bicyclists.

Bicycling as a mode of transportation is increasingly attractive because of livability initiatives geared toward reducing traffic congestion and air pollution, attempts to increase physical exercise levels, and greenhouse gas concerns. As a result, there has been a growing interest to increase municipal investments in bicycle infrastructure. Because of accessibility needs of commuters and cost constraints, most cycling facilities are located within the existing right-of-way of urban roadways. Cyclists in these facilities face many adverse effects brought on by their proximity to automobile traffic, including vulnerability to conflicts with motor vehicles and air quality concerns from tailpipe emissions.

Vehicular exhaust is the source of a multitude of air contaminants, including particulate matter (PM). Particulate matter of concern ranges in size from the largest, PM_{10} (diameter <10 μm) and $PM_{2.5}$ (diameter <2.5 μm), to microscopic ultrafine particles (UFPs). UFPs have diameters smaller than 0.1 μm. The majority of UFPs present in an urban environment are the result of traffic emissions (*1–3*).

Particle number concentrations, which are dominated by UFPs, have been shown to be significantly higher next to a road (*4, 5*). Elevated levels of UFPs are of concern to bicycle commuters because of the associated health effects and increased respiration and absorption compared with other road users (*6–9*). For a given mass concentration (microns per cubic meter), UFPs have 10^2 to 10^3 times higher surface area than fine particles with diameters in the 0.1- to 0.5-μm range and approximately 10^5 times more than coarse particles (2.5 to 10 μm) (*10*). This higher surface area can increase the potential for UFPs to carry toxins into the human body. The small size allows for the deepest deposition of particles into the alveolar region of the lungs, pulmonary interstitial spaces, and possible passage into the circulatory system; it has been shown that these particles accumulate over time in organ tissues (*11*). The deep deposition of these small particles in high numbers can provoke inflammation, which is linked to increased or exacerbated asthma, and oxidative stress, which is involved in cardiovascular and pulmonary disease. The presence of a high number of particles in the alveolus has been shown to be more critical to adverse effects and more indicative of potential health impacts than is total particle mass concentrations (*12–14*). The human pulmonary and cardiovascular systems are vulnerable to UFPs. Investigation of ultrafine exposure for different types of vehicle and bicycle infrastructure is needed to understand how to lower exposures for commuters and protect public health.

Personal exposure studies have shown significantly increased UFP exposure concentrations associated with increased proximity to traffic and volume of traffic (*15–19*). Traditionally, bicycle lanes have been placed adjacent to motor vehicle lanes. Recent designs in the United States have exchanged the locations of parallel parking and bicycle lanes to create a cycle track in which the cyclist is separated by a barrier (the parked cars) from the traffic stream. The barrier formed by the parked cars has the potential to create a perceptibly safer environment, reducing vehicle–bicycle collisions and attracting new riders who may otherwise feel unsafe biking next to moving vehicles. However, the full safety impact of cycle tracks, especially at intersections (*20*), has not yet been empirically determined because they are a relatively new facility type (particularly in the United States). Although the potential to reduce bicycle–vehicle conflicts has been the primary cited benefit of creating a cycle track, this study seeks only to determine whether cycle tracks also can serve to lower UFP exposure concentrations. Results from the

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(a) (b)

FIGURE 1 Cross-sectional configuration of Southwest Broadway, Portland, Oregon: (*a*) before cycle track and (*b*) with cycle track implementation.

simultaneous assessment of traffic parameters and UFP exposure concentrations for a conventional bicycle lane and a cycle track are presented here.

METHODS

Measurements for this study were conducted on Southwest Broadway, a multilane, one-way southbound street in the downtown Portland, Oregon, core near the Portland State University campus. The road is used by bicyclists, cars, trucks, and buses. Traffic composition and volumes vary at this location throughout the day. Note that there is only one four-leg intersection on this cycle track; all others are three-leg because SW Broadway is adjacent to campus.

Before implementation of a cycle track design, the cross section consisted of three lanes with a traditional bicycle lane located between the right-most travel lane and a row of curb parking (see Figure 1*a*). After cycle track installation, two travel lanes remained, with an offset row of parallel parking providing a buffer to the cycle track, approximately 10 to 11 ft wide (see Figure 1*b*). The arrow in Figure 1*b* points to the cycle track. The curb-to-curb distance was maintained during reconfiguration, requiring only lane restriping, appropriate pavement markings, and new signage.

After implementation of the cycle track, monitoring equipment was set up at a midblock location, north of the intersection with Southwest Harrison Street (Figure 2). Particle number concentrations and traffic measurements were made over 4 days in the span of several months with different combinations of equipment and study durations depending on availability of equipment and personnel. On each study day, two P-Trak UFP counters (TSI Model 8525, TSI Performance Measurement Tools, Shoreview, Minnesota) were placed in a parked car in the parallel parking (buffer) zone on the west side adjacent to the cycle track. P-Trak instruments are commonly used in personal exposure studies of UFP for cyclists and other transportation modes because of portability and technological advances to measure number concentrations (*17*). Number concentrations in ambient air are dominated by UFPs. In comparable studies and personal exposure studies using the P-Trak instrument, particle number concentrations and UFPs are used interchangeably. Before data collection, a run of the P-Trak instruments (recently factory-calibrated) side-by-side in the laboratory for 3.5 h ensured that instruments correlated ($r^2 = .996$).

The parked car was used in a novel method to compare simultaneous measurements of exposure concentrations that would be experienced in a conventional bicycle lane versus a cycle track lane. The sensors were placed on the front seats of the car with the collection tube running out the windows, taped to the side-view mirrors. (Figure 3 shows the setup on the driver's side; the same setup was used on the passengers side.) Measuring exposure on the driver's side of a car parked within this offset parking lane is representative of the exposure concentration in a traditional bicycle lane; exposure measured on the passenger-side represents the cycle track exposure concentration. The driver's side measurements were in the location and proximity to traffic where a bicycle lane would typically be marked and will be referred to as the bicycle lane results. The passenger's side measurements were located a few feet from the cycle track because of the white-striped buffer area. The passenger side measurements are the upward limit for cycle track exposure concentrations because of the passenger-side-view mirror location and width

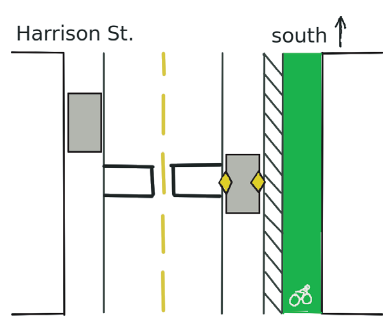


FIGURE 2 Study setup diagram (green lane represents cycle track, gray boxes represent cars, yellow diamonds represent P-Trak instruments, and black lines in traffic lanes represent traffic counters).

(a) (b)

FIGURE 3 Images of collection tube setup on study vehicle: (*a*) driver's side-view mirror and one lane of moving traffic and (*b*) close-up of driver's side-view mirror and collection tube.

of the cycle track. The cycle track UFP concentrations would range lower toward the sidewalk. Exposure concentration is a typical variable used in personal exposure studies to understand potential health impacts of humans in urban transportation microenvironments (*17*). Total or in-traffic exposure is the product of exposure concentration, exposure duration, and breathing rate. All UFP counts were made at 1-s resolution. The P-Trak instrument measures particle number concentrations using condensation with isopropyl alcohol and an optical sensor. Particle number concentrations are obtained for particles in the size range of 0.02 to 1 μm. The particle counts measured by this instrument were dominated by the UFP size range. The maximum concentration level measured by this equipment is 500,000 particles per cubic centimeter.

Four different experimental setups were conducted; each is described according to the study date and time periods in the following paragraphs. The first study design with P-Traks only was implemented on November 24, 2009. Measurements at the first location began at 5:45 a.m. and continued until 10:45 a.m. Particle exposure concentrations were measured in a second parking space from 10:58 a.m. to 1:52 p.m. and in a third parking space from 2:05 to 4:51 p.m. Blocks in the city of Portland tend to be shorter than in most U.S. cities. In all cases, the distance between P-Trak locations along Southwest Broadway did not exceed 50 ft.

Data collection on February 8, 2010, occurred in the same parking space at the midblock location from 5:31 to 10:49 a.m. Traffic data were also collected during this time period using MetroCount 5600 traffic tubes counters (Microcom Pty Ltd., Fremantle, Western Australia, Australia). The traffic counting tubes were placed in the right-most lane next to the vehicle containing the P-Traks and collected individual vehicle records consisting of passage time, vehicle classification (on the basis of length estimates), and speed.

Data collection on June 7, 2010, occurred in the same midblock location as the first parking space on November 24, 2009, and the February 8, 2010, study day. Particle measurements occurred from 6:53 a.m. to 2:20 p.m. In addition, a third P-trak was placed on the edge of the sidewalk closest to the cycle track in the same transect as the car P-traks from 7:54 a.m. to 2:20 p.m. Traffic tubes were placed across both lanes beginning at 5:00 a.m., and traffic data were collected throughout the entire particle measurement period. The heights of the P-trak inlet tubes were maintained at the same elevation across the entire study period.

The final day of data collection occurred on July 13, 2010, from 7:25 a.m. to 9:42 p.m. Particle measurements were made on the driver and passenger sides of the study vehicle in the midblock location. In this setup, traffic data were collected with traffic tube counters across both travel lanes.

RESULTS

Exposure Concentrations

Table 1 contains median and mean concentration values and ranges of exposure concentrations for the driver's side (traditional bicycle lane) and passenger's side (cycle track lane) positions for all study days.

One-sided paired *t*-tests were used to evaluate whether the driver-side exposure concentrations were greater than the passenger-side exposure concentrations. *T*-test results and percentage differences are shown in Table 1. With a significance level of $p = .05$, exposure concentrations were significantly greater on the driver-side representing the typical bicycle lane compared with the passenger-side representing the cycle track facility for all study days.

Although the bicycle lane exposure concentrations were always significantly greater than the cycle track exposure levels, there was a wide range in the mean of the differences and percentage differences (8% to 38%; see Table 1). The greatest difference (38%) between the bicycle lane and cycle track occurred for the second parking space from 10:58 a.m. to 1:52 p.m. on November 24, 2009. The next greatest difference (35%) occurred on the same day in the third space from 2:05 a.m. to 4:51 p.m. The time periods with greatest percentage differences between the two bicycle facility designs overlap with time periods of high traffic volumes for SW Broadway. The smallest difference (8%) occurred on February 8, 2010, from 5:31 to 10:49 a.m. The low volume of traffic in the first hour and a half of this study period would lead to less total UFP emissions and hence the smallest difference for the bicycle lane and cycle track measurements.

TABLE 1 Mean Concentrations, Ranges, Percentage Differences, and *t*-Test Results for Concentration Comparisons of Bicycle Lane and Cycle Track Exposure

		Bicycle Lane			Cycle Track						
Date	Time	Median (part./cm³)	Mean Conc. (part./cm³)	Range (part./cm³)	Median (part./cm³)	Mean Conc. (part./cm³)	Range (part./cm³)	Mean Diff. (part./cm³)	*t*-Value	*p*-Value	Diff. (%)
Nov. 24, 2009	5:45–10:45 a.m.	31,400	43,788	14,500–500,000	30,500	37,498	15,000–365,000	6,125	19.6	<.01	15
Nov. 24, 2009	10:58 a.m.–1:52 p.m.	28,200	56,845	4,510–500,000	26,000	35,802	13,600–500,000	21,043	28.8	<.01	38
Nov. 24, 2009	2:05–4:51 p.m.	25,400	37,476	9,980–500,000	20,600	24,618	2,230–312,000	12,589	29.2	<.01	35
Feb. 8, 2010	5:31–10:49 a.m.	30,600	47,601	12,300–500,000	29,500	44,245	3,340–500,000	3,309	10.3	<.01	8
June 7, 2010	6:53 a.m.–2:20 p.m.	14,700	25,271	3,340–500,00	14,200	20,805	5,750–500,000	4,465	20.9	<.01	18
July 13, 2010	7:24 a.m.–9:42 p.m.	8,290	13,839	2,390–500,000	7,660	10,558	5,620–500,000	3,309	10.3	<.01	24

NOTE: part. = particles; conc. = concentration; diff. = difference.

Particle number distributions showed bicycle lane measurements greater than 300,000 to 500,000 particles per cubic centimeter occurred more frequently compared with cycle track measurements. The inability of the equipment to capture peaks greater than 500,000 particles per cubic centimeter may have caused mean differences to be underestimated. These data suggest fewer peak exposure concentrations occur on the cycle track compared with a conventional bicycle lane because the cycle track measurements are the upper limit (because of cross-sectional location).

Not included in Table 1 are the results for the sidewalk measurements on June 7. The sidewalk median exposure concentration was equal to 12,900 particles per cubic centimeter with a mean concentration of 15,535 particles per cubic centimeter and a range from 6,890 to 433,000 particles per cubic centimeter. The bicycle lane concentrations were significantly greater than the sidewalk, with a mean difference equal to 6,805 particles per cubic centimeter, t value = 28.4, $p < .01$. The percentage difference was 38%. The cycle track concentrations were also significantly greater than the sidewalk concentrations, with a mean difference equal to 2,157 particles per cubic centimeter t value = 20.5, $p < .01$. The percentage difference for the cycle track and sidewalk was 25%.

Comparison with Measured Traffic

Traffic data were collected for 5 h and 20 min from 5:31 to 10:49 a.m. on February 8 during particulate matter collections. Traffic volume for the right-most travel lane during this period was 1,086 vehicles or 204 vehicles per hour per lane. Speeds for vehicles in this lane ranged from 6.40 to 54 mph with a time mean value of 30.11 mph (Figure 4). Traffic composition was not analyzed.

Traffic increased throughout the morning peak period (with a maximum near 8:30 a.m.), then remained relatively constant throughout the remaining time (Figure 5*a*). The steeper increase in traffic flow up until 8:15 a.m., followed by stabilization of the mean and greater variability in traffic flow, may be caused by the intersection reaching capacity or a change in intersection signalization timing as the morning progressed. UFP number concentrations from the driver's side P-Trak averaged at 5 min intervals also show an increase up to a peak in a Loess smoothing curve around approximately 8:15 a.m. (Figure 5*b*). Exposure concentration differences between the bicycle lane and cycle track showed a peak around 8:40 to 8:45 a.m. (Figure 5*c*).

Traffic data obtained on June 7 were invalid because of a data collection error. Traffic data for July 13 were collected for approximately 14 h, including the morning and evening periods. The total traffic count from 7:25 a.m. to 9:42 p.m. across both lanes was 8,232 vehicles or 294 vehicles per hour per lane.

Traffic increased relatively linearly from 10:15 a.m. until a peak around 4:15 p.m., as shown by a Loess smoothing curve in Figure 6*a*. Traffic declined through the rest of the evening until the tubes were disconnected. UFP concentrations from the driver's side averaged over a 5-min interval show an increase up to a point around noon (Figure 6*b*). Figure 6*b* shows the variability or range of the UFP exposure concentrations around the Loess curve to be greater during the early and middle parts of the day compared with the end of the day when traffic volumes were decreasing. Exposure concentration differences also show a peak at noon (Figure 6*c*).

On July 13, the time mean speed of vehicles in the right-most motor vehicle travel lane (adjacent to research vehicle) was 28.34 mph, with a range from 1.20 to 53 mph. The left-most travel lane (furthest from the cycle track and study vehicle) had a time mean speed of 25.83 mph with a range from 5.70 to 56.50 mph. Both lanes together averaged 27.62 mph, with a range from 11 to 44.80 mph.

The averaged speeds over 5-min intervals of vehicles in both lanes did not fluctuate much through the day with the Loess smoothing curve not deviating far from the range of 25 to 32 mph (Figure 7). The decreasing trend in speed in the morning from 7:30 to 11:00 a.m. seen on February 8 was also seen on July 13 (Figures 4 and 7). This trend continued on July 13 until the median speed dipped to approximately 25 mph from 1:30 to 2:30 p.m. Speed began to increase linearly at approximately 5:00 p.m. on July 13. Traffic counts peaked around 4:15 p.m., so the time periods with fewer cars on the road followed the slight increase in car speeds. Analysis of the individual traffic variables to UFP levels using regression and functional optimization techniques did not result in a statistically significant relationship. The results of this analysis suggest that the interaction of traffic speed and traffic counts alone cannot functionally account for

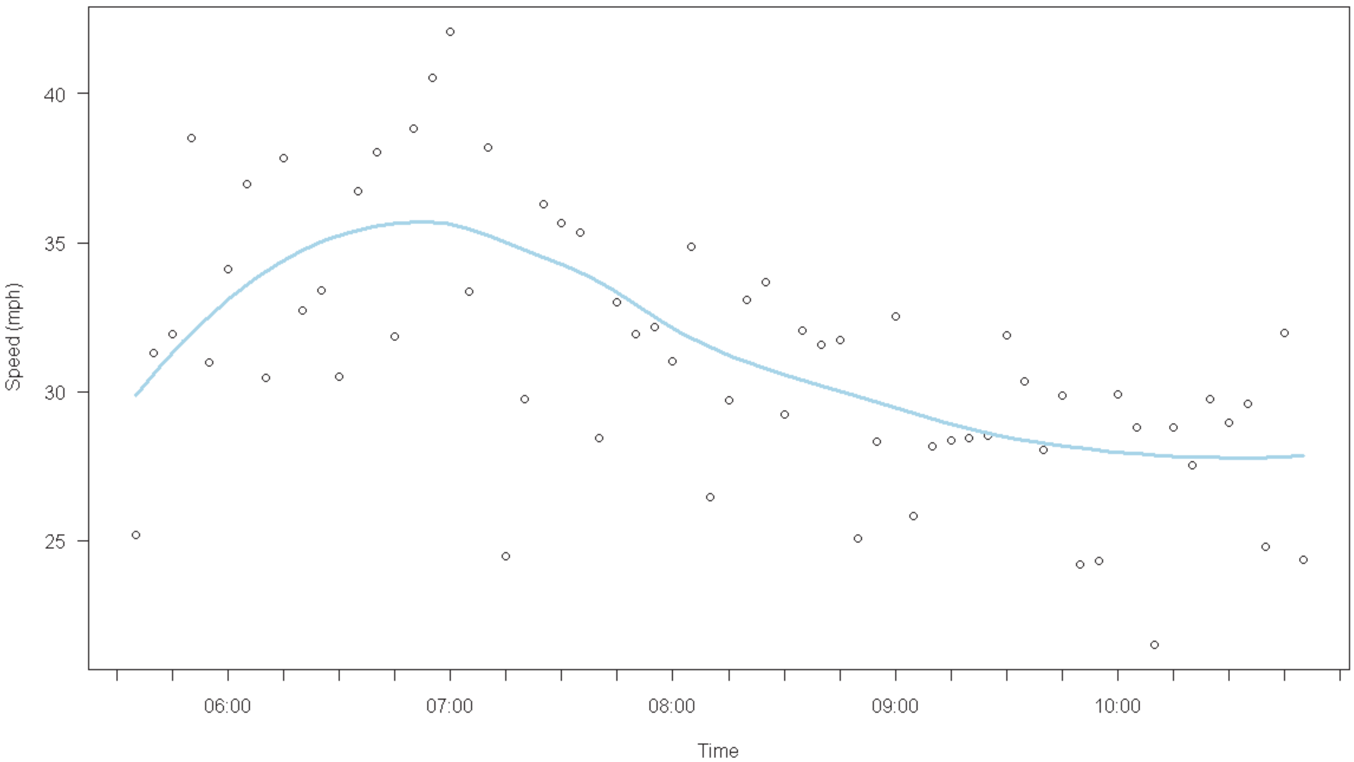


FIGURE 4 Speed on February 8, 2010, averaged over 5-min intervals with Loess smoothing curve.

the data measured in this study. Traffic composition and wind measurements are also likely needed to understand the functional relationship between traffic and UFP levels at this study site and are to be investigated in further studies.

DISCUSSION OF RESULTS

UFP exposure concentrations were significantly greater on the driver's side than the passenger's side for all study days. The 1-s sampling interval captures very quick changes and short-term peak exposures, explaining the wide range of particle number concentrations for the bicycle lane and cycle track positions. The cycle track has the potential to lower ultrafine exposure concentrations compared with a traditional bicycle lane.

The differences in the UFP levels for the typical bicycle lane and cycle track are most likely caused by the increased horizontal distance from the traffic stream and the airflow over the parked vehicle. Over this distance, UFPs coagulate (*21*) and grow to larger, potentially less harmful particles. It is unlikely that the parked cars act as a physical barrier for the UFPs to which particles collide with the car surfaces and adhere to them.

UFPs behave as a gas, and this explanation would relate more appropriately to larger particles with greater mass. However, future studies will test dry deposition of UFPs for the possibility of additional explanation. The possibility of a traffic–pollution shadow on the passenger-side of the car where the cycle track collection tube intake was located will be evaluated in future work using a computational fluid dynamic model to generate wind fields.

The continued significant decline in exposure concentrations from bicycle lane to cycle track to sidewalk also shows a strong likelihood of horizontal distance being the mechanism for the exposure level differences. An assessment of pedestrian exposure to air pollutants along a major road in central London, United Kingdom, found UFP number counts to be significantly higher when walking along the curb-side edge of the sidewalk compared with the building side (*22*). The width of the sidewalk is comparable to the width of the parking lane and buffer zone placed between the cycling lane and motor vehicles in the cycle track design.

The placement of the study vehicle from 10:58 a.m. to 1:52 p.m. on November 24 was different than the midblock location just north of SW Harrison used on all other study days. For this time period, the vehicle was at the front parking spot closest to the traffic light at the intersection north of SW Harrison. This time period showed the greatest mean and percentage difference for the bicycle lane and cycle track concentrations. Future studies should further investigate the effect of proximity to signalized intersections and signal queuing on UFP concentrations. Placing study vehicles in differing proximities to intersections, along with enhanced traffic monitoring, may lead to a better understanding of geometric and traffic effects on UFP exposures.

Traffic data from February 8 and July 13 indicate a traffic pattern on Southwest Broadway of increasing traffic beginning at 5:30 a.m., elevated traffic flows past the morning peak period into the afternoon (10:45 a.m. to 4:00 p.m.), and a decline in traffic flows beginning at 5:00 p.m. (Figure 5*a* and 6*a*). The greatest exposure concentration differences of 38% and 35% (Table 1) for the two bicycle facilities occurred during 10:45 a.m. to 1:52 p.m. and 2:05 to 4:51 p.m., within the time period of elevated traffic flows. The highest exposure concentration differences from Figure 5*c* and Figure 6*c* occur around 8:45 a.m. and noon, also within the elevated traffic flow pattern. Figure 6*c* shows decreased exposure concentration differences

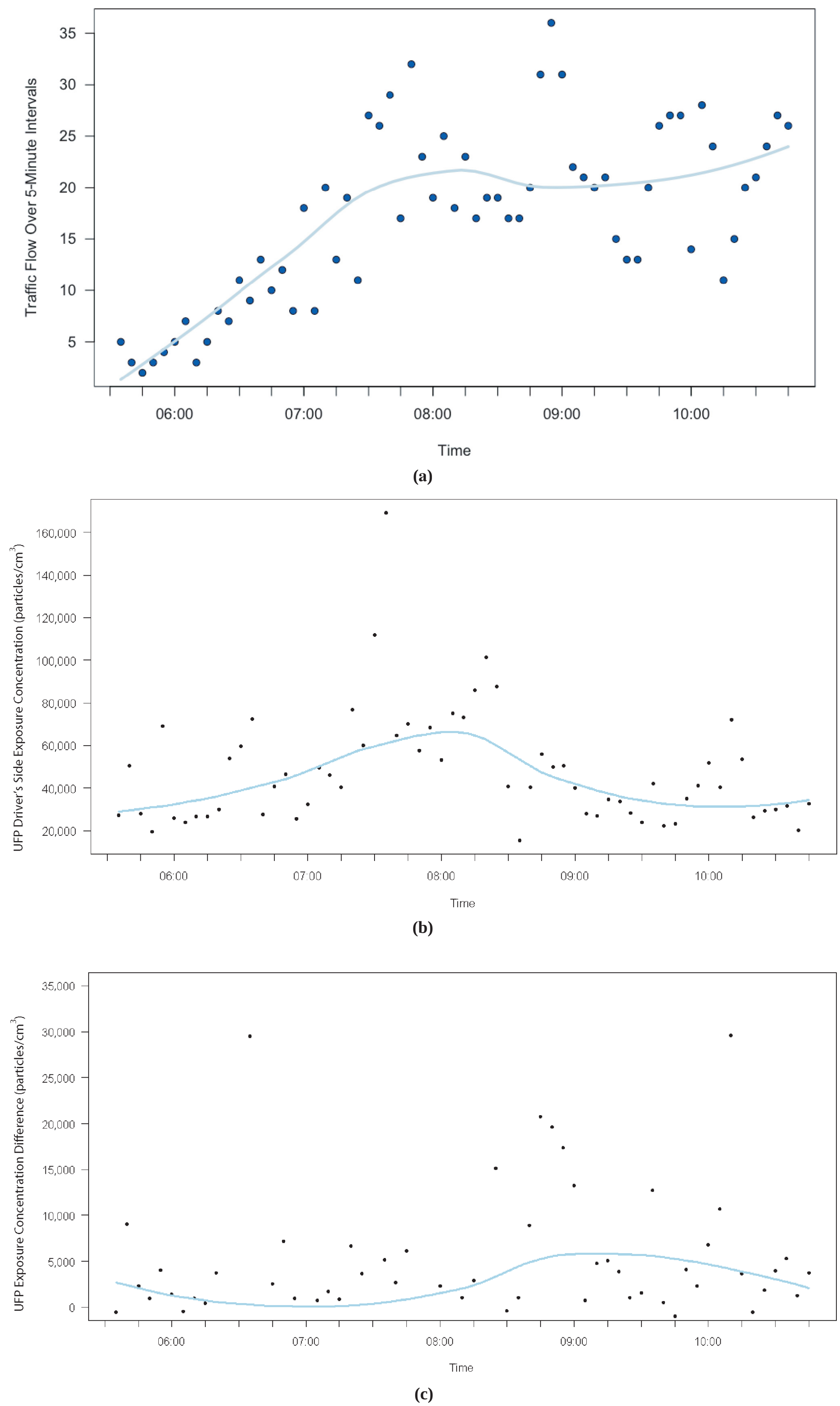
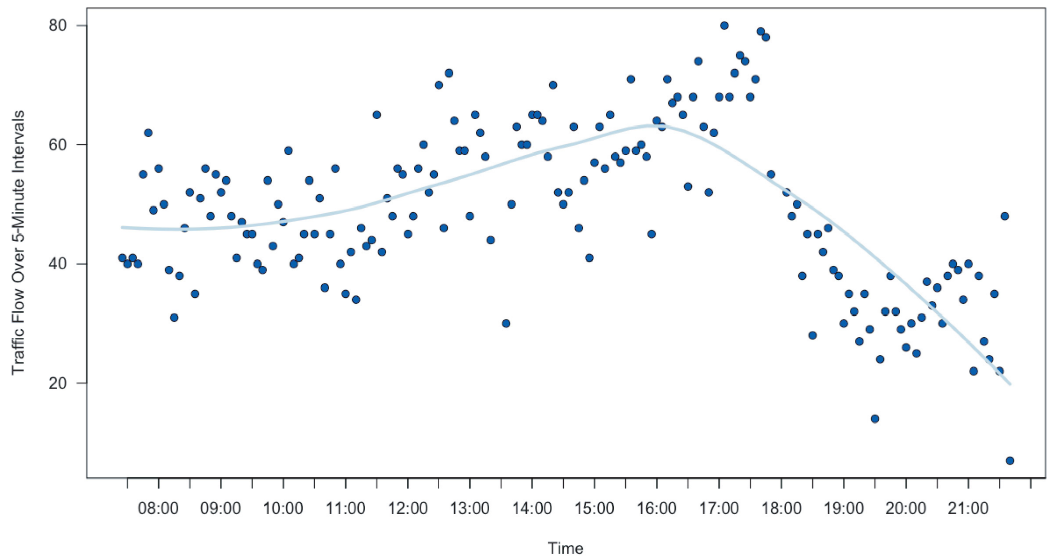
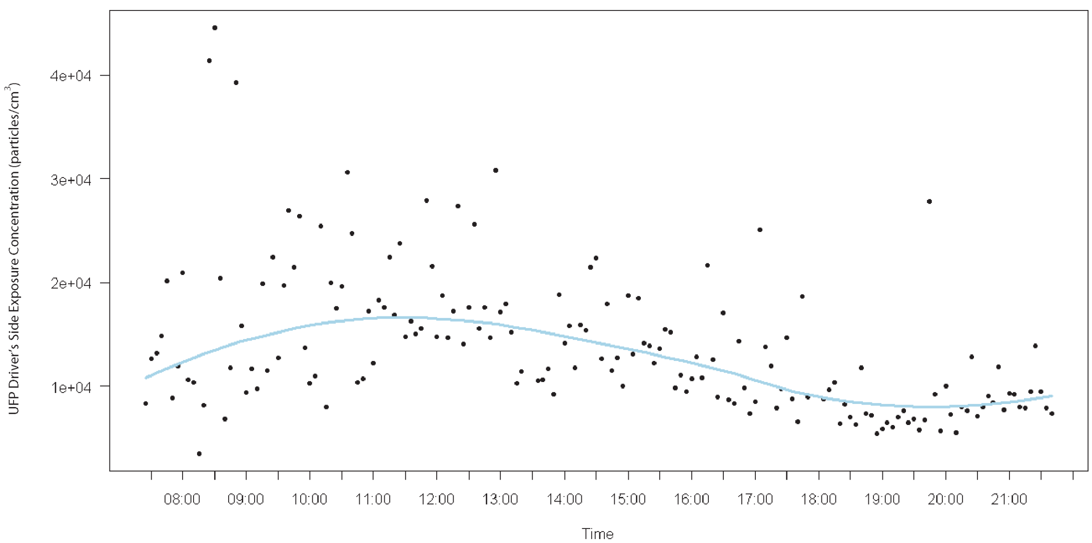


FIGURE 5 Data for February 8, 2010, averaged over 5-min intervals with Loess smoothing curve: (*a*) traffic flow, (*b*) UFP concentrations from driver's side, and (*c*) UFP concentration differences between bicycle lane and cycle track sides.



(a)



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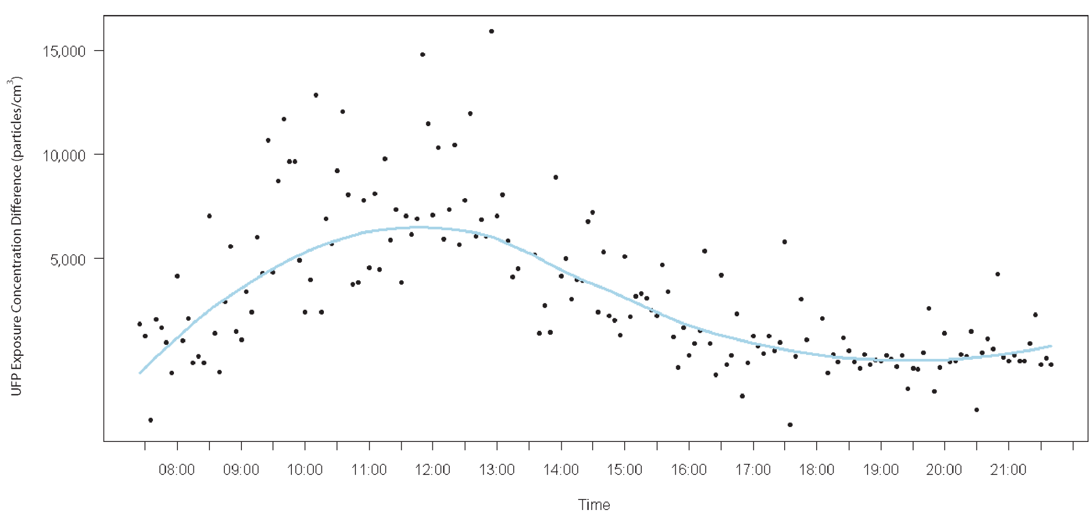

(c)

FIGURE 6 Data for July 13, 2010, averaged over 5-min intervals with Loess smoothing curve: (*a*) traffic flow, (*b*) UFP concentrations from driver's side, and (*c*) UFP concentration differences between bicycle lane and cycle track sides.

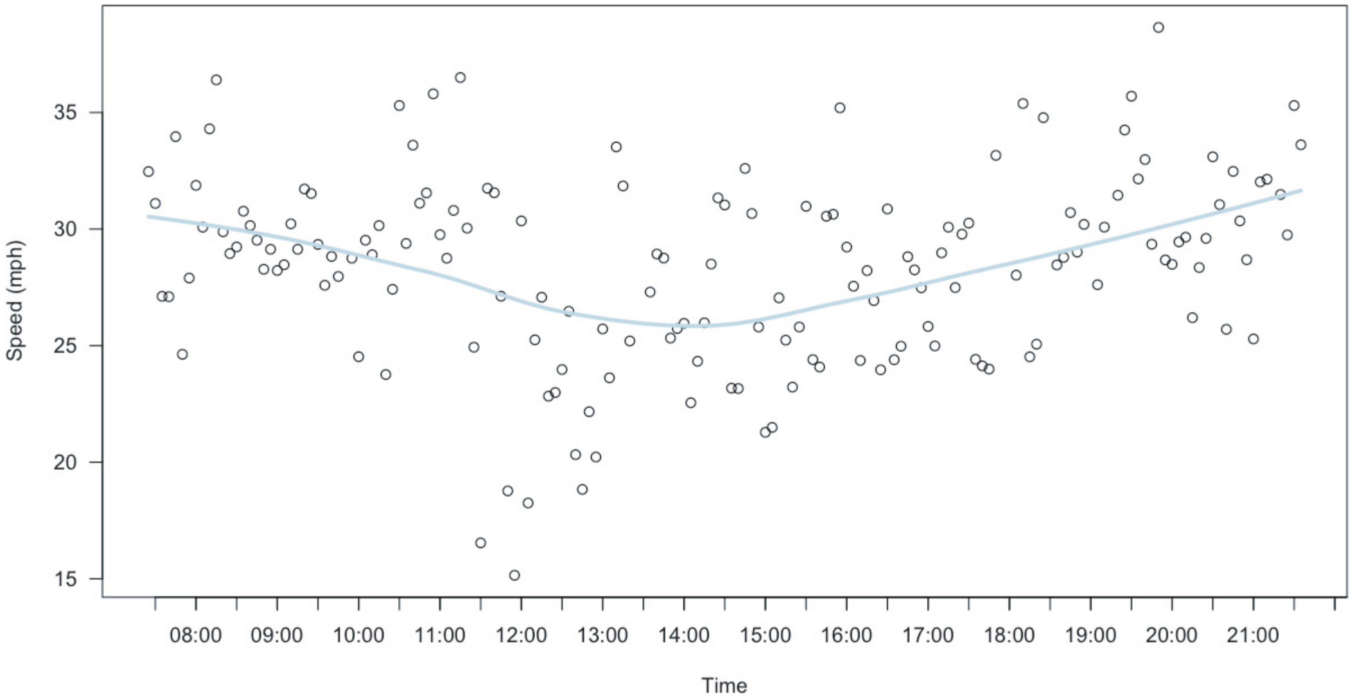

FIGURE 7 Speed on July 13, 2010, averaged over 5-min intervals with Loess smoothing curve.

from 7:00 to 8:00 p.m. during a time period of declining traffic and lowest traffic flows. These results begin to indicate the greatest exposure level differences for the bike facilities occur when traffic was greatest. Future work will continue to collect full-day traffic and air quality measurements to track this relationship of higher exposure concentration differences associated with higher traffic levels.

A count of bicyclists before installation of the cycle track found that bicycle volumes peaked around 9:00 a.m. and again at 5:30 p.m. (approximately 60 bicycles per h). The time spans of elevated motor vehicle traffic and bicyclist traffic overlap on SW Broadway. The results suggest that cycle track facilities have the greatest potential to mitigate UFP exposures for bicyclists on roadways and transportation environments with concurrently high auto use and cyclist activity. The traffic flow peak around 4:00 p.m. on July 13 was not matched by a peak in UFPs, which were declining from a peak around midday (Figure 6*a* and 6*b*). This finding suggests that the data may be missing an important correlate, such as wind parameters. Future work with radar and video to capture traffic composition and the use of three-dimensional ultrasonic anemometers that measures vertical and horizontal wind fluxes will allow for further exploration into such effects.

CONCLUSION

An original method was developed to measure and compare simultaneous ultrafine particulate exposure for cyclists in a traditional bicycle lane and a cycle track. UFP number concentrations were significantly higher in the typical bicycle lane than the cycle track for all study days, and nearly all study periods within those days. The higher frequency of exposure concentrations greater than 300,000 to 500,000 particles per cm^3 in the bicycle lane compared with the cycle track suggest a cyclist may encounter less peak exposure concentrations in the cycle track. In addition, the cycle track measurements in this study are the upper limit because of cross sectional location. Significantly lower ultrafine number concentrations measured on the cycle track are attributable to the increased distance from the motorized traffic provided by the cycle track configuration. Increasing the bicycle facility distance from traffic sources is difficult in cities with set road widths. A cycle track with a parking lane buffer offers a realistic solution for roads in urban areas with parking lanes to potentially lower ultrafine exposures for cyclists.

Traffic measurements showed the exposure concentration differences to be greatest at times of highest traffic volumes, emphasizing the importance of mitigation techniques in areas with simultaneously high volumes of motor vehicle and bicycle commuters. Initial findings showed possible effects of proximity to signalized intersections on increased UFP exposure concentration differences for a bicycle lane and cycle track. These elements need to be studied in further detail along with local wind and more temporal and seasonal measurements of traffic and associated UFP exposure levels.

The findings of this study showed a cycle track roadway design may be more protective for cyclists than a traditional bicycle lane in terms of lowering exposure concentrations of UFPs. This, of course, must be balanced against other considerations such as vehicle–bicycle conflicts at intersections and other design considerations. On the basis of these initial findings, understanding roadway and traffic effects on exposure levels can help guide bicycle facility design and pinpoint locations in which mitigation of exposure levels by placement of facilities such as cycle tracks may be most important.

ACKNOWLEDGMENTS

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