

Student Cyclists Experience PM_{2.5} Pollution Hotspots around an Urban University Campus

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ABSTRACT

Although cycling has environmental and health benefits, urban cyclists are at risk of exposure to harmful concentrations of fine particulate matter (PM_{2.5}). We used a low-cost particle sensor and MapMyRide to collect geolocated 1-minute PM_{2.5} measurements along four routes surrounding an urban university campus. Measurements were collected from 7:30-9:30 AM during fall 2017 and spring 2018. We found no significant differences in ride-averaged PM_{2.5} concentrations among routes, but all routes experienced higher concentrations when winds blew from the southeast-south-southwest. Hotspots, areas with consistently elevated PM_{2.5} concentrations compared to surrounding areas, were detected along all routes in areas with high traffic density and major signalized intersections. The highest PM_{2.5} concentrations occurred after 8:30, likely due to increased vehicular traffic. Understanding PM_{2.5} variability in urban areas is crucial to allow cyclists to better determine routes to avoid exposure to harmful levels of PM_{2.5}.

Keywords: air pollution, fine particulate matter, hotspots, mobile monitoring, urbanization

INTRODUCTION

As individuals look for ways to decrease their carbon footprint, many are turning to alternative forms of transportation, with cycling at the forefront (Apparicio, et al. 2016). This increase in cycling popularity is especially prevalent near universities in the United States and Canada (MacNaughton, et al. 2014; Pucher et al., 2011). Not only does cycling contribute to reductions in carbon dioxide and particulate matter (PM) emissions but cycling also benefits riders with positive health gains via physical activity (Rojas-Rueda, et al. 2011).

Notwithstanding the benefits of cycle commuting, along streets and sidewalks in urban areas, cyclists may be exposed to potentially hazardous levels of air pollution, especially PM with aerodynamic diameter <2.5 µm, or PM_{2.5} (Apparicio, et al. 2016; Bigazzi, et al. 2016; Gilliland, et al. 2018; Rindy et al. 2019). Exposure to air pollution occurs during various modes of transport, but cyclists have been shown to be one of the most exposed commuter groups ahead of personal vehicle, bus, and light rail commuters (Bigazzi and Figliozzi 2014; Dons, et al. 2012; Ham, et al. 2017; Hankey and Marshall 2015; Int Panis,

et al. 2010). Inhalation of pollutants during biking in urban areas can have negative health effects on cyclists (Apparicio, et al. 2016; Gilliland, et al. 2018; Thai, et al. 2008; Van den Bossche, et al. 2015). Taken together, however, evidence on the advantages and disadvantages of cycle commuting suggests that the positive health effects of systematic biking outweigh the negative ones of exposure (Guariso, et al. 2017).

Although urban cyclists face increased PM_{2.5} exposure, mobile monitoring studies, mostly conducted in European countries (Gilliland, et al. 2018), show that urban environments exhibit high spatial and temporal variability in PM_{2.5} concentrations (Hong and Bae 2012; Targino, et al. 2016). For example, it is not uncommon for cyclists to encounter “hotspots”, locations with consistently higher PM_{2.5} concentrations relative to surrounding areas (Kaufman 2017; Targino, et al., 2016). These PM_{2.5} hotspots often occur near roads, at traffic signals, intersections, bus stations, parking lots, and inclined streets (Apte, et al. 2017; Hong and Bae 2012). Although student commuters represent a fast-growing

population among urban cyclists, few studies have quantified their exposure to PM pollution in and around universities (Gilliland, et al. 2018; Thai, et al. 2008). Better understanding when and where hotspots occur is crucial for cycle commuters, including students, and urban planners as this information can be used to both plan and select routes that minimize exposure to pollution (Bigazzi, et al. 2016; Kaufman 2017).

Therefore, in this study we had three main objectives: 1) use a low-cost particle sensor to quantify spatial and temporal variability in PM_{2.5} concentrations along four routes connecting student residential areas to a university campus; 2) compare ambient PM_{2.5} concentrations obtained from mobile monitoring and a stationary regional monitor; and 3) identify hotspots along cyclist routes.

METHODS

Mobile PM_{2.5} Monitoring

Mobile PM_{2.5} monitoring was conducted by a student cyclist in the City of Denton, Texas, USA. Denton has experienced

an 18% population increase since 2010 and, according to the most recent estimate, the city has a population of 136,268 (U.S. Census Bureau 2017). The University of North Texas (UNT), which has its main campus in Denton, has a population of 38,154 students (All About UNT). Denton is also home to Texas Woman's University, with a student population of 12,835. Thus, students comprise a significant fraction of Denton's population.

Based on Texas Commission of Environmental Quality (TCEQ) PM_{2.5} measurements, Denton is in attainment of the annual PM_{2.5} standard of 12 µg m⁻³. Yet, in Denton, there is only one PM_{2.5} monitoring station. This station is located at the TCEQ Denton Airport South location, approximately 4 km from UNT and ~6.5 km from the urban center where PM_{2.5} levels are expected to be the highest.

In this study, the mobile monitoring campaign centered on UNT campus and surrounding student-housing areas (Fig. 1). The most important student housing areas are located in north, east, south, and westerly directions. In fact, 10,800 student housing beds are located within 1 mile of campus while another 4,100 student beds are within bicycling distance

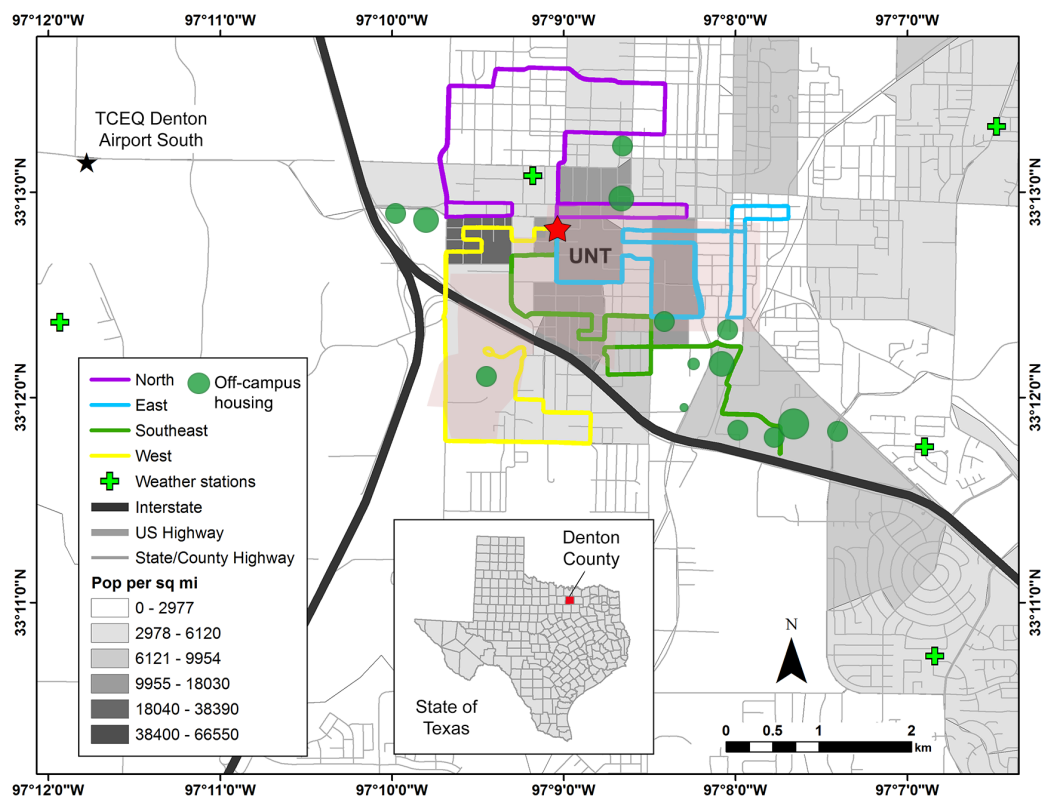


Figure 1. Study area map of the four student cyclist commuter routes near the University of North Texas in the City of Denton, Texas. All routes emanated from the same starting point indicated with a red star. The UNT campus area is shown in light pink shading. The sole Texas Commission on Environmental Quality stationary monitor is represented by the black star.

(UNT Parking and Transportation 2016). When this research was conducted, bike lane infrastructure in and around UNT was limited to just three designated bike lanes, shared lane markings on the main road traversing campus, and contraflow buffered bike lanes on one campus street. Given the very low percentage of students commuting to the university (just 5% of students) and the poor bicycle infrastructure (UNT Parking and Transportation 2016), there are no typical commuter routes to campus.

Therefore, we created four routes that covered all of the major directions that student cyclists travel from surrounding residential areas to UNT campus. The routes we selected also represent the range of conditions that commuters experience while traveling to campus. These include multiple physical barriers to cycling—stop signs, signalized intersections, and heavily trafficked roads. Routes had a distance 13-19 km in length and were named according to the direction from whence they originated: North, East, Southeast, and West.

Mobile monitoring was conducted along the four selected routes from September 2017 to May 2018. During this period, the cyclist carried out 29 rides in the fall and 20 rides in the spring. Prior to each ride, the cyclist was equipped with a Dylos 1700 particle counter and an Apple iPhone with the MapMyRide app. The Dylos was strapped to a pack on the outside of the rider with the inlet exposed to the open environment. The Dylos is a low-cost, portable, battery-powered, true laser particle counter that measures concentration of particles >0.5 (small) and >2.5 (large) μm in $\mu\text{g m}^{-3}$. These are shown as small (>0.5 μm) and large (>2.5 μm) particle readings on the device. For the purpose of this research, only the small particle count was used. Although this is not a conventional cut-off for particle size classification, the >0.5 size class includes all particles from 0.5 to 2.5 μm , most accurately representing PM_{2.5} with respect to the instrument capabilities.

Each ride originated at the same starting location (Fig. 1). All 29 rides in the fall and 13 of 20 rides in the spring began at 7:30 AM. The remaining seven spring rides began at 8:30 AM. These times were chosen to capture PM_{2.5} variability during morning rush hour traffic as students typically commute to school for 8 and 9 AM classes. To collect PM_{2.5} measurements, an “out and back” method was used, whereby the cyclist cycled half of the route and then returned to the starting point on UNT campus following the same path in the reverse direction. Rather than riding a looped route, this method was used to collect PM_{2.5} measurements along the same route at two different times during morning rush hour, similar to the forward and reverse method used by Hankey and Marshall (2015). To capture student commuter class schedules (i.e. Monday/Wednesday/Friday vs. Tuesday/Thursday), each route was completed at least once on each day of the week as well as on weekends. Each route was completed seven to eight times in fall 2017 ($n=29$, September 13–November 5) and five times in spring 2018 ($n=20$, February 9–May 1) for 49 total rides. Sampling was not conducted

during rainy weather. Otherwise, samples were taken in a range of weather conditions.

Data Preparation and Analysis

The Dylos 1700 particle counter averages particle counts on a minute basis. Each ride lasted anywhere from 36-52 minutes. The mean PM_{2.5} concentration for each ride was determined from the minute averages calculated by the Dylos. Since the Dylos is a particle counter, all data from the Dylos were converted to PM_{2.5} concentration using the following equation from Steinle et al. (2015):

$$\text{PM}_{2.5} = 4.75 + 2.8 \times 10^{-5} \times [\text{PNC}].$$

To investigate differences in mean PM_{2.5} concentrations among routes, a non-parametric Kruskal-Wallis test was conducted separately for each season (i.e., fall and spring). A Wilcoxon test was used to determine if the individual routes differed between seasons. Non-parametric tests were used because the data were not normally distributed. Data on temperature ($^{\circ}\text{C}$), relative humidity (%), wind speed (kmph), and wind direction were obtained from the weather station closest to each route. Wind directions were grouped into eight categories (N/NNE, NE/ENE, E/ESE, SE/SSE, S/SSW, SW/WSW, W/WNW, NW/NNW) so that each category would have a sample of two or more rides. Depending on the station, data were reported at 5-minute (North and East routes), 15-minute (Southeast route), and 60-minute (West route) intervals. Non-parametric correlations were used to explore relationships between ride-averaged PM_{2.5} concentrations and meteorological data for all routes combined. PM_{2.5} concentrations were compared to PM_{2.5} concentrations from the TCEQ Denton Airport South site (33° 13' 9" N, -97° 11' 47" W) when available to determine the ability of the Dylos to capture PM_{2.5} concentrations on a larger spatial scale. The TCEQ only provides hourly data for PM_{2.5} concentrations; the hourly data for the times during the ride were averaged to determine the TCEQ average for the time ridden. All calculations and statistical analyses were performed using JMPv14. Significance was set at $p < 0.1$.

Hotspot Analysis

The MapMyRide iPhone app collects spatial data points every second as the cyclist moves and then creates a line showing the path traveled. These data were used to match PM_{2.5} concentration data from the Dylos to time and location along the routes. Using the 1-minute data provided by the Dylos, a hotspot analysis was performed using the *Optimized Hotspot Analysis* tool in ArcGIS 10.4.1. This tool is used to identify statistically significant spatial clusters of high values (i.e., hotspots) by determining the significance of each measurement from the Dylos within the context of neighboring measurements. To be a hotspot, a location must have a high PM_{2.5} concentration compared to all other measurements and

a statistically significant z-score (Mitchell 2005). Due to variability in $PM_{2.5}$ concentrations, hotspots were determined for each individual ride, with hotspots identified as locations with a z-score significant at the 90% confidence level. The hotspots were then grouped by route (i.e., all rides per route combined) and visually inspected for similarities. Areas that were classified as having significantly higher $PM_{2.5}$ concentrations on >50% of the rides (four of seven rides in the fall, and three of five in the spring) were classified as hotspots in this study.

RESULTS AND DISCUSSION

Route and Seasonal Differences in $PM_{2.5}$ Concentrations

Mean $PM_{2.5}$ concentrations along the four commuter routes ranged from 9–10.8 $\mu\text{g m}^{-3}$ during fall 2017 and from 9.4–13.9 $\mu\text{g m}^{-3}$ during spring 2018. Significant differences among routes were not detected in either fall or spring. Significant differences between seasons were also not detected for any of the four routes sampled. However, spring $PM_{2.5}$ concentrations were elevated compared to fall for three of the four routes. Mean spring $PM_{2.5}$ concentrations were 28.7%, 29.6% and 5.7% higher compared to fall along the Southeast, East, and West routes, respectively. The North route was the only route to experience a lower (7.5%) concentration in spring compared to fall. The lower mean $PM_{2.5}$ concentrations measured in fall are consistent with a previous study that found that large urban areas in Texas have the lowest $PM_{2.5}$ concentrations during this season (Barrett and Sheesley 2014).

Because there were no differences in mean ride-averaged $PM_{2.5}$ concentrations among routes or between seasons, we pooled $PM_{2.5}$ concentration data for all rides and routes. Closer examination of these $PM_{2.5}$ data revealed higher ride-to-ride variability in $PM_{2.5}$ concentrations measured between 7:30–8:30 AM during spring compared to fall (Fig. 2). During fall, mean ride-averaged $PM_{2.5}$ ranged 2.5-fold, from 6–16.1 $\mu\text{g m}^{-3}$ ride, whereas in spring there was a 5-fold difference among rides (5.4–27.6 $\mu\text{g m}^{-3}$).

Higher springtime variability in $PM_{2.5}$ concentrations could be due to several factors, including higher and more variable wind speeds as well as increased temperatures (Parkhurst, et al. 1999). Increased production of secondary $PM_{2.5}$ in the spring, as a result of increased biogenic precursor emissions, could also lead to higher $PM_{2.5}$ concentrations (Parkhurst, et al. 1999). Finally, dust intrusions from West Texas during the spring peak dust season, may also contribute fine PM to sites in central and eastern Texas (Ponette-González, et al. 2018).

Dylos vs. TCEQ Stationary Measurements

Data from the TCEQ site were available for the fall 2017 rides only. Measurements from the TCEQ monitor provided similar average concentrations to those obtained from the mobile monitoring campaign for the City of Denton as a whole (Table 1). For the fall, the mean TCEQ monitor $PM_{2.5}$ concentration was 9.6 $\mu\text{g m}^{-3}$ and the average of the four routes in Denton was 9.8 $\mu\text{g m}^{-3}$. Even so, the fall data showed that mean $PM_{2.5}$ concentrations collected with the Dylos along the West and East routes were higher than the TCEQ averages on

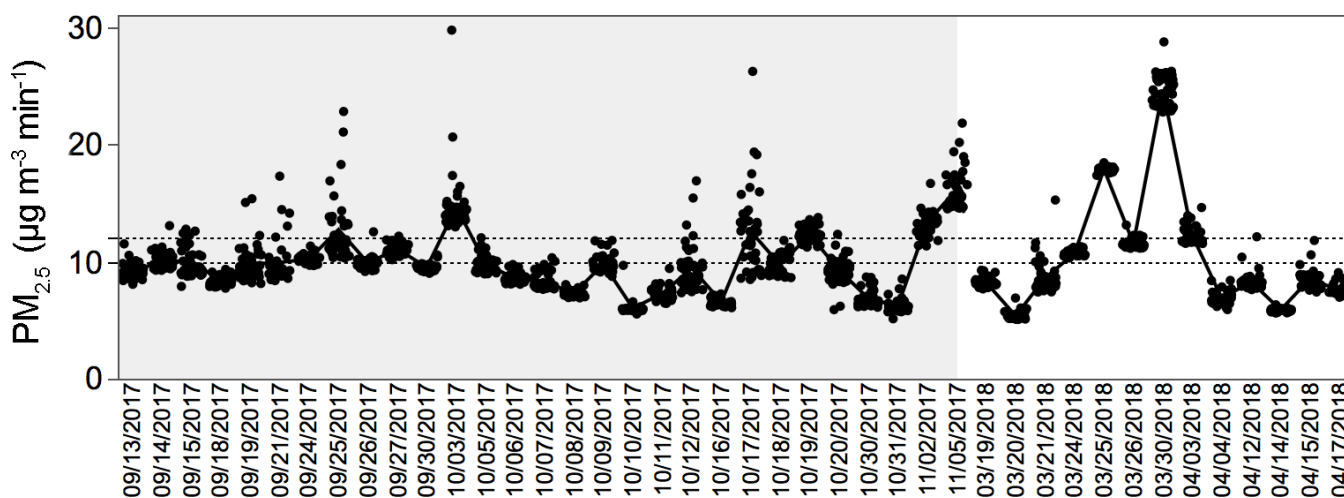


Figure 2. Concentrations of $PM_{2.5}$ ($\mu\text{g m}^{-3} \text{ min}^{-1}$) measured along four student commuter cyclist routes near the University of North Texas in the City of Denton, Texas. All samples were collected from 7:30–8:30 AM from September 2017 to May 2018 ($n=42$ days total). Grey shading indicates fall. Note line break between fall and spring seasons. The dashed lines represent the World Health Organization recommended annual $PM_{2.5}$ limit (10 $\mu\text{g m}^{-3}$) and the Texas Commission on Environmental Quality Organization recommended annual $PM_{2.5}$ limit (12 $\mu\text{g m}^{-3}$).

Table 1. Mean PM_{2.5} concentrations measured along four student commuter cyclist routes near the University of North Texas in the City of Denton, Texas, from September 2017 to May 2018, and at the TCEQ location. N.D. indicates no data available for this time.

Route	Fall 2017			Spring 2018		
	PM _{2.5} ± s.d. ($\mu\text{g m}^{-3}$)	TCEQ PM _{2.5}	No. Rides	PM _{2.5} ± s.d. ($\mu\text{g m}^{-3}$)	TCEQ PM _{2.5}	No. Rides
North	10.2 ± 2.56	11.69	7	9.44 ± 3.6	n.d.	5
East	9.03 ± 1.37	8.75	7	11.7 ± 7.22	n.d.	5
Southeast	10.8 ± 2.5	11.19	7	13.9 ± 7.86	n.d.	5
West	9.01 ± 3.01	6.6	7	9.52 ± 4.91	n.d.	5
Average	9.8	9.6		11.0		

those measurement days, with the West route 26.7% higher and the East route 3.1% higher than the TCEQ station. The North and East averages, however, were both lower than the reported TCEQ averages, by 14.6% and 3.6%, respectively.

The TCEQ Denton Airport South monitor is located well outside of Denton's urban core, therefore we expected that there would be differences between the Dylos mobile measurements and the TCEQ-reported PM_{2.5} concentrations. For example, each of the routes had maximum one-minute PM_{2.5} concentrations ranging from 16.9 to 29.7 $\mu\text{g m}^{-3}$. These maximum values provide a snapshot of the variability in PM_{2.5} concentrations in the urban core that is not detected by stationary monitors outside of the city. Differences in PM_{2.5} measurements between mobile monitoring and fixed stations have also been found in previous studies. For example, in London, Ontario, Canada, cyclist exposure on bicycle routes was found to be 2–4-fold higher than ambient measurements of PM_{2.5} (Gilliland, et al. 2018). These studies highlight the

need for fine-scale measurements of PM_{2.5} exposure within urban areas. Mobile monitoring technologies present new opportunities to better understand and characterize urban air quality versus traditional stationary monitoring systems (Krecl, et al. 2014; Van den Bossche, et al. 2015).

Meteorological Data and PM_{2.5} Concentrations

PM_{2.5} concentrations varied significantly by wind direction ($p < 0.1$, Fig. 3). Compared to all other directions, concentrations were highest when winds originated from the NE/ENE, SE/SSE and were also elevated with S/SSW winds. Concentrations were lowest with NW/NNW winds. Moderate correlations were also detected between PM_{2.5} concentrations, temperature ($p = 0.41$, $p = 0.0044$) and relative humidity ($p = 0.50$, $p = 0.0004$).

That southerly winds affected PM_{2.5} concentration is consistent with land use surrounding UNT and our general study area. Increased PM_{2.5} concentrations occur when SE/SSE and S/SSW winds travel over I-35, transporting vehicular emissions into the study area. The confluence of two branches of I-35, a major highway system stretching across the central United States from Texas to Minnesota, is positioned just west of the UNT campus (Fig. 4). Elevated PM_{2.5} concentrations also occur with NE/ENE winds, likely due to transport of emissions from a local power plant. The weak correlations with temperature and relative humidity could reflect seasonal differences in meteorological conditions, or chemical reactions that affect fine particle formation (Tai et al. 2010).

PM_{2.5} Hotspots

Hotspots were detected on all routes in both seasons (Fig. 4). For the fall, the East route had the most hotspot designations, followed by the West, North, and Southeast routes (Table 2). The East route also had the largest cumulative distance covered by hotspots in the fall with almost a quarter of the route distance covered by hotspots. For the North, Southeast, and West routes, the total number of hotspots and total distance

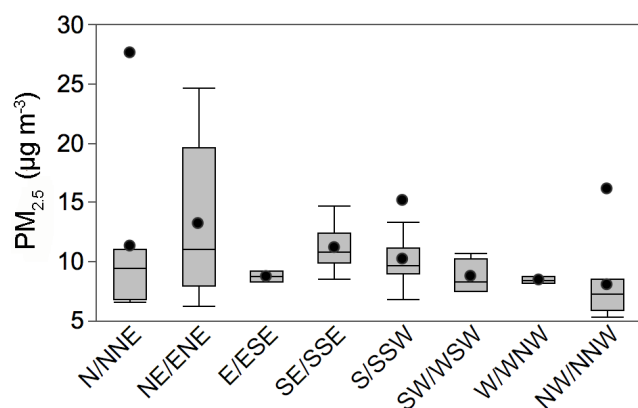


Figure 3. Median and mean (black dot) PM_{2.5} concentrations measured along four student commuter cyclist routes near the University of North Texas in the City of Denton, Texas, from September 2017 to May 2018. Wind directions are displayed along the x-axis.

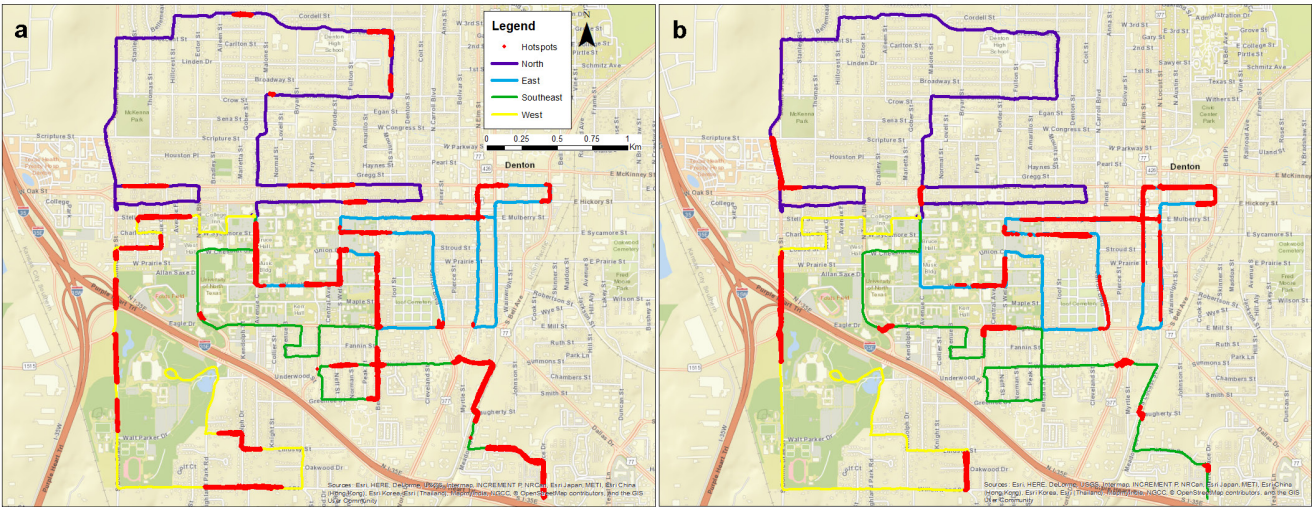


Figure 4. Hotspot map of the four student cyclist commuter routes near the University of North Texas in the City of Denton, Texas, for (a) fall 2017 and (b) spring 2018. Hotspots are shown in red, with the routes shown in yellow (West), green (Southeast), blue (East), and purple (North).

Table 2. Route length, hotspot count, cumulative linear hotspot distance, and the proportion of the route covered by hotspots for each of four student cyclist commuter routes sampled near the University of North Texas in the City of Denton, Texas, from September 2017 to May 2018.

Route	Route Length (km)	Hotspot Count		Hotspot Linear Distance (km)		Hotspot (%)	
		Fall	Spring	Fall	Spring	Fall	Spring
North	18.4	7	2	1.52	0.62	8	3
East	13.2	9	11	3.17	4.48	24	34
Southeast	13.6	6	5	2.19	0.73	16	5
West	13.3	8	2	2.57	1.06	19	8
Total	58.5	30	20	9.45	6.81	16	12

covered by hotspots decreased in spring 2018. However, the East route had two more hotspots in the spring than fall, and total distance covered by hotspots increased substantially (Table 2). Despite the large increase in hotspot distance in the spring on the East route, the overall number of hotspots, distance covered by hotspots, and the percentage of routes covered by hotspots decreased from fall 2017 to spring 2018.

As expected, hotspots were found in areas with high traffic density and near major signalized intersections along the four routes. Previous studies have found positive correlations between traffic density and elevated black carbon concentrations, a component of PM_{2.5}, as well as increased concentrations at traffic signals due to increased acceleration at these signals (Targino, et al. 2016). As cyclists travel through urban environments, they encounter these hotspots, increasing their

exposure to PM_{2.5}. To illustrate, on 17 October 2017, the cycle commuter in this study experienced PM_{2.5} concentrations above the Environmental Protection Agency's PM_{2.5} break-point between good and moderate air quality (i.e., 12 µg m⁻³) during 23 of 42 minutes ridden (55%; Fig. 5).

To avoid PM_{2.5} hotspots, cyclists can vary their routes, and the time of their commute. For example, cyclists can reduce their exposure to harmful PM_{2.5} pollution by 33% by using only designated bike paths instead of shared roadways (MacNaughton et al., 2014). Harmful exposure can also be avoided by commuting at times with lower traffic density. For example, student cycle commuters in Denton could plan their commute to end before 8:30, to avoid the sharp increase in PM_{2.5} occurring after this time. Our data show that the four student commuter routes were relatively similar in PM_{2.5}

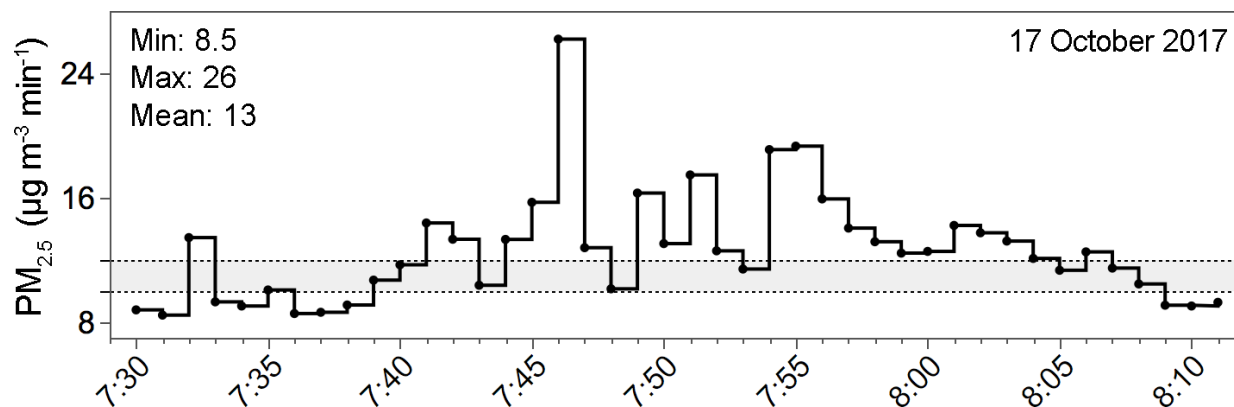


Figure 5. Example run of the mobile measurements of PM_{2.5} at one-minute intervals along the East route on October 12, 2017.

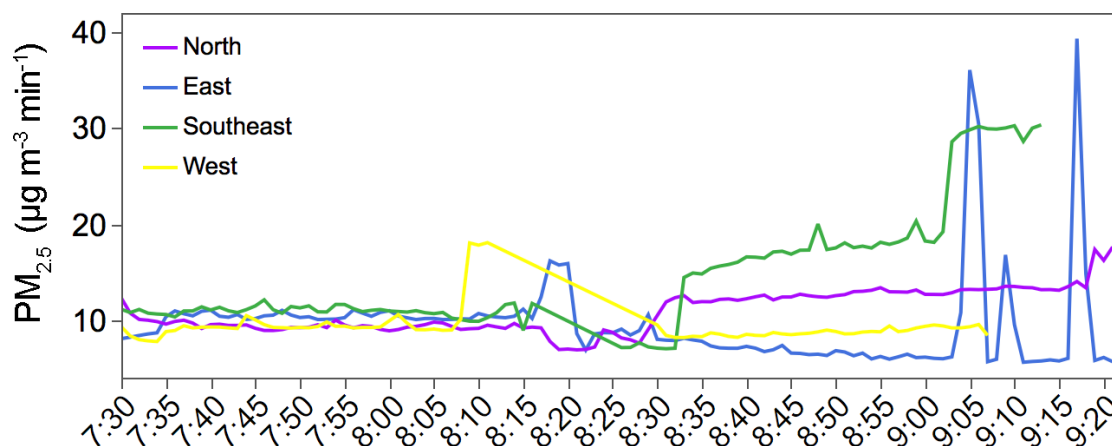


Figure 6. Concentrations of PM_{2.5} ($\mu\text{g m}^{-3} \text{min}^{-1}$) measured along four student commuter cyclist routes near the University of North Texas in the City of Denton, Texas. Samples were collected from 7:30-9:30 AM from September 2017 to May 2018 ($n=49$ days total).

concentrations between the hours of 7:30 and 8:30 AM. However, on seven days when measurements were conducted from 8:30-9:30 AM, there was considerable divergence in concentrations among routes (Fig. 6). The Southeast route increased dramatically shortly after 8:30 AM; afterwards, concentrations rose steadily until there was another jump at 9 AM. Along the North route, concentrations also increased to above $10 \mu\text{g m}^{-3}$ and remained relatively steady until another small rise at 9 AM. The West route showed a peak at 8:05 AM followed by a decrease to concentrations slightly lower than those for 7:30 to 8:30 AM. Finally, the East route similarly showed a peak between 8:15-8:20 followed by a steady decline in concentrations. The East route exhibited three sharp peaks occurring between 9:00 and 9:15. Rush hour traffic, characterized from 06:00 to 10:00, has been shown as a time of significant increase in PM_{2.5} concentrations, especially in urban areas (Chen, et al. 2016).

In 2016, only 5% of UNT students bicycled to campus. Several factors limit bicycle commuting to and around UNT: lack of protected bike lanes, few connections between campus and downtown, high-speed roadways, lack of driver awareness and physical barriers (i.e., intersections, four way stops, sidewalk gaps). However, in a transportation survey, 34% percent of students reported interest in biking (UNT Parking and Transportation). The information collected as part of this study could be incorporated into future transportation plans, which seek to increase student cycling to and from campus.

CONCLUSIONS

Cyclists are one of the most at risk commuter groups to exposure to unhealthy PM_{2.5} concentrations (Ham, et al. 2017). However, through increased awareness and new monitoring

strategies, cyclists can limit their exposure to harmful PM_{2.5} concentrations. This study showed that student cyclists experience PM_{2.5} pollution hotspots around an urban university campus. Stationary PM_{2.5} monitors are able to sufficiently provide background concentrations but are not able to capture the minute-to-minute variability in PM_{2.5} across the urban landscape. Low-cost portable monitors are an emerging technology allowing for greater detail in PM_{2.5} measurements both temporally and spatially. Improved monitoring networks across urban landscapes will allow for a better understanding of PM_{2.5} variability and allow cycle commuters to avoid harmful exposure.

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REFERENCES

- Apparicio, P., M. Carrier, J. Gelb, A.M. Séguin, and S. Kingham. 2016. Cyclists' Exposure to Air Pollution and Road Traffic Noise in Central City Neighbourhoods of Montreal. *Journal of Transport Geography* 57: 63-69.
- Apte, J.S., K.P. Messier, S. Gani, M. Brauer, T.W. Kirchstetter, M.M. Lunden, J.D. Marshall, C.J. Portier, R.C.H. Vermeulen, and S.P. Hamburg. 2017. High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data. *Environmental Science and Technology* 51: 6999-7008.
- Barrett, T.E. and R.J. Sheesley. 2014. Urban Impacts on Regional Carbonaceous Aerosols: Case Study in Central Texas. *Journal of Air and Waste Management Association* 64: 917-926.
- Bigazzi, A.Y., J. Broach, and J. Dill. 2016. Bicycle Route Preference and Pollution Inhalation Dose: Comparing Exposure and Distance Trade-Offs. *Journal of Transport and Health* 3: 107-113.
- Bigazzi, A.Y. and M.A. Figliozi. 2014. Review of Urban Bicyclists' Intake and Uptake of Traffic-Related Air Pollution. *Transport Reviews* 34: 221-245.
- Chen, T., J. He, X. Lu, J. She, and Z. Guan. 2016. Spatial and Temporal Variations of PM_{2.5} and its Relation to Meteorological Factors in the Urban Area of Nanjing, China. *International Journal of Environmental Research and Public Health* 13: 921.
- Dons, E., L. Int Panis, M. Van Poppel, J. Theunis, and G. Wets. 2012. Personal Exposure to Black Carbon in Transport Microenvironments. *Atmospheric Environment* 55: 392-398.
- Gilliland, J., M. Maltby, X. Xu, I. Luginaah, and T. Shah. 2018. Influence of the Natural and Built Environment on Personal Exposure to Fine Particulate Matter (PM_{2.5}) in Cyclists Using City Designated Bicycle Routes. *Urban Science* 2: 120.
- Guariso, G. and M. Volta, (eds.) 2017. *Air Quality Integrated Assessment: A European Perspective*. Springer International Publishing. 110 pages.
- Ham, W., A. Vijaya, N. Schulte, and J.D. Herner. 2017. Commuter Exposure to PM_{2.5}, BC, and UFP in Six Common Transport Microenvironments in Sacramento, California. *Atmospheric Environment* 167: 335-345.
- Hankey, S. and J.D. Marshall. 2015. On-Bicycle Exposure to Particulate Air Pollution: Particle Number, Black Carbon, PM_{2.5}, and Particle Size. *Atmospheric Environment* 122: 65-73.
- Hong, E.S. and C.H. Bae. 2012. Exposure of Bicyclists to Air Pollution in Seattle, Washington: Hybrid Analysis Using Personal Monitoring and Land Use Regression. *Transportation Research Record: Journal of the Transportation Research Board* 2270: 59-66.
- Int Panis, L., B. de Geus, G. Vandenbulcke, H. Willems, B. Degraewe, N. Bleux, V. Mishra, I. Thomas, and R. Meeusen. 2010. Exposure to Particulate Matter in Traffic: A Comparison of Cyclists and Car Passengers. *Atmospheric Environment* 44: 2263-2270.
- Kaufman, R. 2017. Novel Air Pollution Study Gauges Individual Cyclists' Risks. *Eos*. 98.
- Krecl, P., C. Johansson, J. Ström, B. Lövenheim, and J.C. Gallet. 2014. A Feasibility Study of Mapping Light-Absorbing Carbon Using a Taxi Fleet as a Mobile Platform. *Tellus B: Chemical and Physical Meteorology* 66: 23533.
- MacNaughton, P., S. Melly, J. Vallarino, G. Adamkiewicz, and J.D. Spengler. 2014. Impact of Bicycle Route Type on Exposure to Traffic-Related Air Pollution. *Science of the Total Environment* 490: 37-43.
- Mitchell, A. 2005. *The ESRI guide to GIS analysis, Volume 2: Spatial Measurements and Statistics*. Environmental Systems Research Institute. 240 pages.
- Parkhurst, W.J., R.L. Tanner, F.P. Weatherford, R.J. Valente, and J.F. Meagher. 1999. Historic PM_{2.5} /PM₁₀ Concentrations in the Southeastern United States—Potential Implications of the Revised Particulate Matter Standard. *Journal of Air and Waste Management Association* 49: 1060-1067.
- Ponette-González, A.G., J.D. Collins, J.E. Manuel, T.A. Byers, G.A. Glass, K.C. Weathers, and T.E. Gill. 2018. Wet Dust Deposition Across Texas During the 2012 Drought: An Overlooked Pathway for Elemental Flux to Ecosystems. *Journal of Geophysical Research: Atmospheres* 123: 8238-8254.
- Pucher, J., R. Buehler, and M. Seinen. 2011. Bicycling Renaissance in North America? An Update and Re-Appraisal of Cycling Trends and Policies. *Transportation Research Part A: Policy and Practice* 45: 451-475.
- Rindy, J.E., A.G. Ponette-González, T.E. Barrett, R. Sheesley, and K.C. Weathers. 2019. Urban Trees are Sinks for Soot: Elemental Carbon Accumulation by Two Widespread Oak

- Species. *Environmental Science and Technology* 53: 10092-10101.
- Rojas-Rueda, D., A. De Nazelle, M. Taino, and M.J. Nieuwenhuijsen. 2011. The Health Risks and Benefits of Cycling in Urban Environments Compared With Car Use: Health Impact Assessment Study. *BMJ* 343.
- Steinle, S., S. Reis, C.E. Sabel, S. Semple, M.M. Twigg, C.F. Braban, S.R. Leeson, M.R. Heal, D. Harrison, C. Lin, and H. Wu. 2015. Personal Exposure Monitoring of PM_{2.5} in Indoor and Outdoor Microenvironments. *Science of the Total Environment* 508: 383-394
- Tai, A.P.K., L.J. Mickley, and D. Jacob. 2010. Correlations between Fine Particulate Matter (PM_{2.5}) and meteorological variables in the United States: Implications for the sensitivity of PM_{2.5} to climate change. *Atmospheric Environment* 44: 3976-3984
- Targino, A.C., M.D. Gibson, P. Krecl, M.V.C. Rodrigues, M.M. dos Santos, and M. de Paula Corrêa. 2016. Hotspots of Black Carbon and PM_{2.5} in an Urban Area and Relationships to Traffic Characteristics. *Environmental Pollution* 218: 475-486.
- Thai, A., I. McKendry, and M. Brauer. 2008. Particulate Matter Exposure along Designated Bicycle Routes in Vancouver, British Columbia. *Science of the Total Environment* 405: 26-35.
- University of North Texas. 2019. We Are Creative Innovation. [<https://allabout.unt.edu/>]. Last accessed 08 April 2019.
- University of North Texas. 2016. Parking and Transportation Final Master Plan.
- U.S. Census Bureau. 2017. Quick Facts. [<https://www.census.gov/quickfacts/fact/table/dentoncitytexas,dentoncountytexas/POP010210>]. Last accessed 23 July 2020.
- Van den Bossche, J., J. Peters, J. Verwaeren, D. Botteldooren, J. Theunis, and B. De Baets. 2015. Mobile Monitoring for Mapping Spatial Variation in Urban Air Quality: Development and Validation of a Methodology Based on an Extensive Dataset. *Atmospheric Environment* 105: 148-161.

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