# MEASURING TEMPORAL AND SPATIAL EXPOSURE OF URBAN CYCLISTS TO AIR POLLUTANTS USING AN INSTRUMENTED BIKE

August 2019

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16. Abstract

Increased use of active transportation can make direct and indirect contributions toward addressing societal transportation issues. However, in the process of cycling for transportation, cyclists are exposed to multiple pollutants that could adversely impact their health. The goal of this study was to better understand the variation in PM2.5 exposure of cyclists depending on the cycling infrastructure along the selected route and the time that they bike. Four routes that represent the wide range of bicycle infrastructure were ridden using an instrumented bike equipped with low-cost PMS5003™ sensors. The resulting PM2.5 exposure maps show that few segments recorded air quality worse than the background concentration. During most of the routes, riders experienced air quality that was better than the air quality documented at the monitoring location. All hot spots with higher PM2.5 exposure were along higher-traffic roadway segments except one. Areas with consistently lower levels of PM2.5 compared to background concentration were all along a multiuse trail. However, cyclist exposure to PM2.5 is impacted more by environmental variables that cause the background concentration to be higher along the entire route than the proximity to vehicles at specific points along any route.

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# Executive Summary

Increased use of active transportation can make direct and indirect contributions toward addressing both the health concerns arising from sedentary lifestyles and other societal transportation issues, including congestion, environmental, and equity problems (World Health Organization, 2002). However, in the process of cycling for transportation, cyclists are exposed to multiple pollutants that could adversely impact their health. Although it has been found that the health benefits of cycling on an individual basis outweigh air pollution and safety impacts, researchers in the Netherlands found that pollutant exposure during a typical trip can be almost double depending on the mode of transport and specific route (Zuurbier et al., 2010).

There are many consequences associated with exposure to high levels of particulate matter. Health effects from significant exposure to fine particulate matter (PM) include respiratory illnesses, cardiovascular disease, and cerebrovascular disease. The U.S. Environmental Protection Agency (U.S. EPA) also attributes particle pollution to other health problems, including reduced lung function, asthma, heart attack, and stroke (EPA Office of Air Quality and Radiation, 2015). The World Health Organization ranks air pollution from particulate matter as the 13th most prominent cause of death worldwide (Anderson et al., 2012). A study from the *Journal of Medical Toxicology* reported that air pollution causes 800,000 premature deaths annually worldwide, with most deaths occurring in Asia, where bicycle use is prevalent (Anderson et al., 2012). Particles with an aerodynamic diameter of 2.5 micrometers or smaller (PM2.5) are particularly harmful to human health (U.S. EPA, 2018). Fine inhalable particles can infiltrate deep into the lungs and enter the bloodstream (U.S. EPA, 2018). As part of the Air Pollution and Health: A European Approach (APHEA) study, daily particulate concentrations and number of deaths were observed for 12 European cities. The analysis revealed that an increase of 50 $\mu g/m^3$ in particulate matter correlated with a 2 percent increase in daily mortality (Katsouyanni et al., 1997).

This research project had two specific objectives: (a) refine the use of an instrumented bicycle for air quality data collection; and (b) map pollutant exposure of cyclists on major cycling routes in Atlanta, Georgia.

Using an instrumented bike with 20 different sensors measuring acceleration, directness of path, roadway slope, pavement condition, object proximity, and air quality, the study team assessed variations in exposure to PM2.5. Low-cost PMS5003™ sensors were calibrated against a GRIMM™ spectrometer and determined to be appropriate for mobile air quality monitoring. Study participants rode the instrumented bicycle on four routes that represent the wide range of bicycle infrastructure available in Atlanta, Georgia. Additional trials were conducted to understand a cyclist's PM2.5 exposure during different times of the day and along different routes. This study resulted in PM2.5 exposure maps that show how a cyclist's exposure differs from the urban background concentration.

The resulting PM2.5 exposure maps show that few segments recorded air quality worse than the background concentration. During most of the routes, riders experienced air quality that was better than the air quality documented at the monitoring location. There were specific segments on which riders were exposed to PM2.5 concentrations that exceeded 10 $\mu g/m^3$, although this exposure was minimal. Lower-traffic sections of roadway and those with bicycle infrastructure that separates the cyclist were not significantly different in the level of PM2.5 exposure, but all hot spots with higher PM2.5 exposure were along higher-traffic roadway segments except one. Areas with consistently lower levels of PM2.5 compared to background concentration were all along a multiuse trail. However, cyclist exposure to PM2.5 is impacted more by environmental variables that cause the background concentration to be higher along the entire route than the proximity to vehicles at specific points along any route. Further work based on the data collection conducted in this study will assess the relationship between PM2.5 and variation in other sensor data.

The use of active transportation modes can have direct and indirect contributions toward addressing a variety of health concerns. Better understanding the exposure of individual cyclists to pollutants can have a profound impact on the health of their commute. The audience for this research is two-fold. First, through dissemination of the data to cyclists, they can make better decisions regarding where and when they travel. The biggest takeaway from this work is that PM2.5 exposure levels are highest in the morning, so cyclists should travel as late as possible to avoid exposure. This temporal variation is much greater than spatial variation tied to roadway infrastructure. However, further work should be undertaken, and this study has resulted in a refined methodology for using an instrumented bicycle for mobile air quality monitoring that can be used in other air quality monitoring work.

The education and workforce development output includes involving students from multiple departments in the project. The team included students from the School of Civil and Environmental Engineering and the College of Computing (Computational Media). In addition to this report and the associated methodology and data collection, the students involved in the study produced two presentations for the CARTEEH Transportation, Air Quality, and Health Symposium.

The data sets from this study include the PM2.5 measurements for multiple runs of each of the routes. These data are available on the CARTEEH website. The data collection procedure can be replicated along other routes as well as in other cities. The code to process the raw data recorded by the sensors into a format accepted by ArcGIS will be made available on Github.

# Acknowledgments

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## Introduction

Increased use of active transportation can make direct and indirect contributions toward addressing both the health concerns arising from sedentary lifestyles and other societal transportation issues, including congestion, environmental, and equity problems (World Health Organization, 2002). However, in the process of cycling for transportation, cyclists are exposed to multiple pollutants that could adversely impact their health. Although it has been found that the health benefits of cycling on an individual basis outweigh air pollution and safety impacts, researchers in the Netherlands found that pollutant exposure during a typical bicycle trip can be almost twice as much as other modes of transport or based on different bicycle routes taken (Zuurbier et al., 2010).

There are many consequences associated with exposure to high levels of particulate matter. Health effects from significant exposure to fine particulate matter (PM) include respiratory illnesses, cardiovascular disease, and cerebrovascular disease. The U.S. Environmental Protection Agency (U.S. EPA) also attributes particle pollution to other health problems, including reduced lung function, asthma, heart attack, and stroke (EPA Office of Air Quality and Radiation, 2015). The World Health Organization ranks air pollution from particulate matter as the 13th most prominent cause of death worldwide (Anderson et al., 2012). A study from the *Journal of Medical Toxicology* reported that air pollution causes 800,000 premature deaths annually worldwide, with most deaths occurring in Asia, where bicycle use is prevalent (Anderson et al., 2012). Particles with an aerodynamic diameter of 2.5 micrometers or smaller (PM2.5) are particularly harmful to human health (U.S. EPA, 2018). Fine inhalable particles can infiltrate deep into the lungs and enter the bloodstream (U.S. EPA, 2018). As part of the Air Pollution and Health: A European Approach (APHEA) study, daily particulate concentrations and number of deaths were observed for 12 European cities. The analysis revealed that an increase of 50 $\mu g/m^3$ in particulate matter correlated with a 2 percent increase in daily mortality (Katsouyanni et al., 1997).

## Research Objectives

The goal of this study was to understand the variation in air quality exposure of cyclists with cycling infrastructure and time of day through PM2.5 mapping from data collected with an instrumented bike. The mapping of pollutant exposure along cyclist routes at different times of day and with varying traffic volumes can allow better planning of cyclist infrastructure and routing of cyclists in trip planners to minimize pollutant exposure. Therefore, the specific objectives of the study were to (a) refine the use of an instrumented bicycle for air quality data collection; and (b) map pollutant exposure of cyclists on major cycling routes in Atlanta, Georgia.

## Literature Review

Three key areas were investigated to understand prior work in the area of air quality exposure of cyclists: (a) adverse health effects from particulate matter exposure, (b) factors that affect air quality and contribute to varying particulate concentrations, and (c) methodologies for measuring human exposure to particulate matter from different modes of transportation. The findings from the literature review suggest it is necessary to control for certain meteorological factors and roadway characteristics. The literature review also found approaches to measuring exposure to particulate matter, which were used as references in developing data analysis parameters and methodologies for this study.

### Adverse Health Effects from Particulate Matter Exposure

There are many consequences associated with exposure to high levels of particulate matter. Health effects from significant exposure to fine particulate matter include respiratory illnesses, cardiovascular disease, and cerebrovascular disease. U.S. EPA also attributes particle pollution to other health problems, including reduced lung function, asthma, heart attack, and stroke (EPA Office of Air Quality and Radiation, 2015).

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Pollutant levels in the air increase as vehicle activity increases (Schweitzer & Zhou, 2010). The attraction of vehicular traffic to a region can be a sign of economic development. However, some researchers have linked urban planning methodologies to poor air quality. Lawrence Frank and Peter Engelke from the University of British Columbia and Georgetown University, respectively, claimed that urban sprawl discourages active modes of transportation, such as walking and cycling (Frank & Engelke, 2005). In contrast, developing more dense urban environments increases congestion and centralizes harmful vehicle emissions (Frank & Engelke, 2005). Dense urban environments and close proximity to high-traffic corridors can negatively impact the health of city residents. A study published by the *American Journal of Respiratory and Critical Care Medicine* examined the patterns between respiratory symptoms in school-aged students and proximity to traffic. Traffic-related pollutant measurements were taken in 10 schools near high-traffic roadways in the San Francisco Bay Area. The chances of bronchitis symptoms and physician-diagnosed asthma were greater in neighborhoods with higher traffic pollutants (Kim et al., 2004).

## Factors That Affect Air Quality

Previous studies included in this literature review indicated that PM concentrations are impacted by meteorological factors including temperature, relative humidity, sun exposure, precipitation, wind speed, and wind direction. Additionally, the literature review suggested that PM concentrations are impacted by roadway characteristics, including traffic volumes, traffic speed, and monitor distance from roadway.

### Meteorological Factors

Meteorology greatly impacts air quality. Air quality can be highly variable over a short timespan due to the effects of weather conditions. There are fewer poor air quality days during winter (Fort Air Partnership, 2018). However, there is the risk that cold temperatures and stagnant air can result in inversions. Inversions trap pollutants in the stagnant air close to the ground and create poor air quality during the winter (Fort Air Partnership, 2015). Inversion layers, or the rapid cooling of air as the atmospheric height increases, trap contaminants among the urban topography (Fort Air Partnership, 2015). The warm upper layer of the atmosphere acts as a lid and prevents the pollutants from dispersing (Waikato Regional Council, 2018).

The effects of inversion layers were examined in a mobile air quality measurement study conducted by the Canadian Regional and Urban Investigation System for Environmental Research in Montreal, Quebec. The objectives of the study were to understand how pollutants vary seasonally and spatially across different neighborhoods in Montreal (Levy et al., 2013). Researchers measured pollutant concentrations of two routes for 34 days and calculated the average concentration of the roadway segment for the year and for each season. It was observed that higher mean concentrations occurred during the winter months due to greater buildup of pollutants from reduced evaporation (Levy et al., 2013). The lower atmosphere is more stable in colder months with less solar radiation (Levy et al., 2013).

Higher humidity, or increased amounts of water vapor in the air, also impacts air quality. Water molecules bind with corrosive gases and form acid solutions (Queensland Government, 2017). The bonds are facilitated by the small size and polar nature of water molecules (Queensland Government, 2017). These acid solutions are extremely harmful to human health and can also cause property damage (Queensland Government, 2017). Relative humidity is generally higher in the summer, and as a result, there are more poor air quality days in the summer (Queensland Government, 2017). Additionally, the presence of sun facilitates chemical reactions between pollutants, resulting in smog (National Oceanic and Atmospheric Administration [NOAA], 2017). Whereas precipitation cleans the air and washes away water-soluble pollutants, days with precipitation and days following heavy precipitation generally have lower pollutant and particulate concentrations (NOAA, 2017).

Wind is one of the most impactful meteorological factors. High-speed winds cause pollutants to disperse far from the original source. Higher winds are generally associated with better air quality because the concentration of particulates is less dense near the source (“Air Pollution: Clean Air in the UK,” 2018). Wind direction also impacts the air quality of a region. Areas downwind from a pollutant source will experience worse air quality because the pollutants are being blown from the source (“Air Pollution: Clean Air in the UK,” 2018). A study published in *Air Quality, Atmosphere & Health* recommends collecting upwind and background air quality measurements due to the effects of wind speed and direction on the dispersion of particulates (Baldauf et al., 2009). It is important to collect background concentrations because wind generated by high-speed vehicles can cause pollutants to travel 50 to 100 m upwind (Baldauf et al., 2009).

Other air quality exposure studies have controlled for temperature, relative humidity, wind speed, and wind direction. Studies using instrumented vehicles have also used global positioning system (GPS) data to record the routes traveled and documented the start and end time of the route.

### Roadway Characteristics

Many studies have been conducted to understand the influence of roadway characteristics, such as traffic volumes, traffic speed, specific location, and distance from the roadway, on a region’s air quality. Studies have shown that pollutant levels in the air increase as vehicle activity increases (Schweitzer & Zhou, 2010). Scientists from the Institute of Environmental Assessment and Water Research found that PM values were greatest in the morning when traffic flow began (Pérez et al., 2010). The PM levels decreased gradually throughout the day due to increased boundary layer and increased wind speeds (Pérez et al., 2010). Other factors, such as nearby construction, increased the PM concentrations at the monitoring site in Barcelona, Spain (Pérez et al., 2010). Additionally, the Canadian Regional and Urban Investigation System for Environmental Research found that neighborhoods that had more identifiable sources of pollutants had higher mean concentrations of all pollutants (Levy et al., 2013). For example, the Anjou neighborhood of Montreal that is close to two major highways and a major interchange had higher pollutant concentrations than the other studied neighborhoods (Levy et al., 2013).

Researchers from Harvard University observed the traffic-related air pollutants in the Mission Hill Neighborhood of Boston, Massachusetts. The results of the study, published in the *American Journal of Public Health*, showed that roadway speed correlated with the type of pollutants emitted (Buonocore et al., 2009). Vehicles traveling at speeds of 15 mph or less emitted ultrafine particulates, whereas vehicles traveling at higher speeds emitted more PM2.5 (Buonocore et al., 2009). The researchers from this study recommended that future work examine patterns between pollutant concentrations and the distance from the monitor to the roadway (Buonocore et al., 2009).

Some researchers have examined the effects of monitor distance from the roadway. Baldauf et al. (2009) published a study in *Air Quality, Atmosphere & Health* that described the factors that affect the collection and interpretation of pollutant concentrations. To ensure continuity in data collection, the article recommended that monitors be placed equal distance from the roadway. Particulate concentrations decrease exponentially when moved farther from the roadway. However, other characteristics, such as roadway curvature, roadway configuration, and meteorology, can also be responsible for these decreases (Baldauf et al., 2009). Researchers can collect the most representative data by having multiple stationary monitoring sites at equal horizontal spacing along the roadway. Another monitor option is to use instrumented vehicles to understand how pollutant concentrations are changing along a corridor (Baldauf et al., 2009).

Baldauf et al. (2013) conducted another study to understand how changing roadway configuration impacts particulate concentrations. This study combined results from fixed-site and mobile air quality monitors. Higher peak concentrations were recorded along at-grade locations. Concentrations at grade were also greatly impacted by vehicle activity. In comparison, concentrations recorded at the top of the cut section were 15 to 25 percent lower than the at-grade concentrations. The authors also recommended that the presence of buildings and other structures be considered when monitoring near-road air quality (Baldauf et al., 2013).

Limited research has been conducted to understand how particulate matter differs with roadway configuration. Very few studies have examined how air quality differs between different types of cycling infrastructure. For example, research has not been conducted to understand if the air quality of a shared lane is different from that of a cycle track. Due to changing distances from vehicular traffic, it is possible that separated cycling facilities could have better air quality.

## Exposure Studies for Different Modes of Transportation

Other studies conducted in Europe used personal monitoring devices or an instrumented bicycle to measure cyclist exposure. There have also been other studies that have compared the PM exposure of different modes of transportation.

Particulate matter exposure is defined as the contact between airborne contaminants and the human body (Watson et al., 1988). Cycling does not emit any pollutants. However, cyclists still risk exposure to particulate matter because cycling facilities are frequently implemented near motorized vehicle infrastructure.

Portable air quality monitoring devices have been used to collect PM measurements along popular bicycle routes in Helsinki, Finland; Rotterdam, Netherlands; and Thessaloniki, Greece (Okokon et al., 2017). The Flemish Institute for Technological Research and Ghent University, Department of Information Technology created an instrumented bicycle called the Aeroflex. The bicycle is equipped with a GRIMM™ 1.108 to record PM1, PM2.5, and PM10 measurements (Elen et al., 2012). In addition to many other sensors, there are temperature and relative humidity monitors. The Aeroflex has been used as a mobile air quality monitor in Antwerp, Gent, Brussels, and other cities in Belgium (Elen et al., 2012). An experiment from the Flemish Institute for Technological Research used the Aeroflex for mobile monitoring of ultrafine particles, PM2.5, and black carbon. The study included a fixed route with 20 runs over the course of 10 days (Van Poppel et al., 2013). Researchers documented the date, start and end time of the run, duration of run, temperature, wind direction, and relative humidity. The route was also divided into different zones based on vehicle speed and distance from vehicle traffic. For example, Zone 1 had traffic traveling at 70 km/hr, with approximately 10,000 vehicles per day on the roadway. The zones were also determined by considering the presence of bicycle infrastructure or how close cyclists were to vehicle traffic. Zone 1 had a bike lane separated from the travel lane by a parking lane. Researchers recorded background concentration from a fixed monitor. Because urban air quality is a combination of many local sources, the study subtracted the background concentration from the collected concentrations (Van Poppel et al., 2013).

In addition to experiments using the Aeroflex, Belgium has conducted other studies about exposure to particulate matter in traffic. Dons et al. (2013) used portable aethalometers, GPS devices, and travel diaries to compare the black carbon exposure of more than 1,500 trips in Flanders, Belgium. The resulting data showed that street characteristics and traffic volumes greatly impact an individual's exposure. The researchers found that concentrations on highways (10.7 $\mu g/m^3$) and urban roads (9.6 $\mu g/m^3$) were much larger than those on rural roads (6.1 $\mu g/m^3$). Panis et al. (2010) published a study in *Atmospheric Environment* that compared PM exposure of cyclists and car passengers in three Belgian cities. The cities included Brussels, Louvain-la-Neuve, and Mol. The route was first completed with the participant being driven in a car and then the participant cycling the same route. The study indicated that three factors prevent accurate comparison between the exposure of passengers and bicyclists: (a) breathing frequency is much greater when cycling, (b) the number of particulates that remain in the respiratory tract increase while exercising, and (c) the cycling trip takes longer to complete. The study found that the quantities of particulates inhaled while cycling were 400 to 900 percent higher than while riding in a car.

Many European countries have conducted other cyclist exposure studies. Researchers from the Netherlands are leaders in research pertaining to the health benefits and safety of cyclists. An air quality study in Amsterdam was one of the first publications to monitor the air quality of non-motorized modes of transportation (van Wijnen et al., 1995). The study used personal monitor devices to measure pollutant exposure of cyclists, car drivers, and pedestrians. The monitoring devices measured carbon monoxide, nitrogen dioxide, benzene, toluene, and xylenes. However, a (semi) continuous monitoring vehicle was used to measure particulate matter. There were three routes: two urban routes and one rural route. On all of the routes during all seasons, the readings from the personal monitor devices were higher for car drivers than for cyclists (van Wijnen et al., 1995).

Additionally, the University of Utrecht and the Netherlands Environmental Assessment Agency found that the health benefits of cycling were greater than the risks of cycling compared to driving a private vehicle (De Hartog et al., 2010). The researchers complied results from various studies that compared PM2.5 exposure of cyclists and drivers. The researchers concluded that the PM2.5 exposure of a car driver was only "modestly higher" than that of a cyclist. This study noted that the exposure of some cyclists may be comparable to that of a car driver due to route choice. Cycling trips generally have longer time durations, and cyclists inhale more frequently (De Hartog et al., 2010).

Public health researchers in the Netherlands also collaborated to compare commuters' exposure to particulate matter. In that study, researchers considered fuel type and route choice in addition to mode choice (Zuurbier et al., 2010). The study included exposures of car drivers, bus passengers, and cyclists. Diesel and gasoline cars as well as diesel and electric buses were included. Additionally, a high-traffic and a low-traffic bicycle route were used in the study. Drivers and passengers of diesel vehicles were found to have the highest exposure to particulate matter. When compared with the background concentrations, in-traffic measurements were much higher. Differences between in-traffic exposure and background exposure for cyclists could be explained by the many peaks that occurred while within close proximity to vehicles. The PM2.5 readings were corrected for relative humidity. PM2.5 values from trails with greater than 90 percent relative humidity were omitted from the study (Zuurbier et al., 2010).

A few exposure studies have been conducted in Spain. The Institute of Environmental Assessment and Water Research (Spain) partnered with the National Institute for Public Health and the Environment (Netherlands) to compare air pollution exposure of different modes of transportation across 20 different European cities (Karanasiou et al., 2014). The study compiled findings from many different exposure studies conducted using different instruments, techniques, and methodologies. The study compared four modes of transportation: bicycle, car, bus, and metro. The report concluded that exposure was the greatest for car and the least for bicycle. Due to the many differences between the studies, many variables had to be considered. The variables were divided into four categories: personal factors, mode factors, road traffic factors, and meteorological factors. Some of the most influential characteristics considered included traffic volumes, travel speed, distance between vehicles, and fuel type (Karanasiou et al., 2014).

An exposure study of ultrafine particulates, carbon monoxide, PM2.5, $CO_2$, and black carbon was completed for four modes of transportation in Barcelona, Spain. The modes of transportation included walking, biking, riding a bus, and driving a personal vehicle (De Nazelle et al., 2012). The study included 172 trips completed on two routes. The collected data were divided into five sampling time periods. Three of the sampling periods were traffic peaks (morning, lunch, evening) and two were non-peaks (midmorning, afternoon). The pairwise analysis showed that overall exposure to all pollution was greatest for driving a car and least for walking. This study concluded that exposure is directly related to proximity to exhaust. Researchers controlled for temperature, wind speed, wind direction, and relative humidity. The corresponding background concentration was subtracted from the collected concentrations. All of the bicycle and pedestrian infrastructure was directly adjacent to the vehicle travel lanes. Data were not collected for separated bicycling facilities (De Nazelle et al., 2012).

The Imperial College of London has also produced a few pedestrian exposure studies. Kaur et al. (2005) conducted a pedestrian exposure study along Marylebone Road in central London. Personal air pollution monitors were used to measure exposure of volunteers walking along the roadway in the morning and the afternoon. As expected, the PM2.5 exposure was higher in the morning. It was also found that the recordings from the personal monitors were higher than the recordings from fixed-location monitors. This difference was hypothesized to be from the participants' close proximity to roadway traffic. Another study from the Imperial College of London compared fine particulate matter and carbon monoxide exposure of vehicle drivers, cyclists, and pedestrians (Kaur et al., 2007). Car drivers were found to have the highest exposure to fine particulates and carbon monoxide due to the close proximity to the emission source. The metal exterior of the vehicle did not shield drivers from pollutants. Cyclists and pedestrians had lower exposures. The mobile monitor measurements were compared to measurements from fixed monitor locations. The fixed monitors were found to provide less representative depictions of the air quality in an urban environment because the fixed monitors were located away from vehicle traffic (Kaur et al., 2007).

There have been fewer efforts to understand PM exposure and mode choice in the United States. However, the University of California–Berkeley conducted a scripted exposure study in 2013 (Jarjour et al., 2013). Fifteen participants were recruited to cycle on two predetermined routes. The first route was a bicycle boulevard with very limited interaction with vehicle traffic. The second route was a high-traffic roadway. A condensation particle counter was placed in the rear basket of the bicycle. It was found that exposure to particulate matter, carbon monoxide, and black carbon was greater for all 15 participants on the second route. The study recommended that cities implement separated bicycle facilities to reduce vehicle-related air pollution exposure (Jarjour et al., 2013).

Other efforts in the United States include a study from the University of Wisconsin–Madison to quantify the benefits from reducing car usage in the Midwestern United States (Grabow et al., 2011). The study assumed that 50 percent of short trips were converted to bicycle trips. Using the Community Multiscale Air Quality model, the EPA Benefits Mapping Analysis

Program, and the World Health Organization Health Economic Assessment Tool, Grabow et al. (2011) estimated that the annual average PM2.5 concentration would decrease by 0.1 µg/m$^3$ and the annual health benefits for the region would exceed $4.94 billion. Researchers from the School of Public and International Affairs at Virginia Tech and the Department of Civil, Environmental, and Geo-Engineering at the University of Minnesota have collaborated on multiple studies exploring the relationship between active transportation and PM exposure using a bicycle monitoring platform. The measurements showed that black carbon concentrations decreased by approximately 20 percent by moving one block from a major roadway (Hankey et al., 2015). Another study used facility-demand models and land use regression models to estimate block-level exposure during rush hour in Minneapolis, Minnesota. The modeling results identified 20 percent of local roads where shifting bicyclists to low-traffic roads would reduce exposure by 15 percent (Hankey et al., 2016).

These studies showing the air pollution exposure reduction by moving away from traffic also bring up a question at a segment level of whether air pollution exposure of cyclists would be influenced by the type of infrastructure available (i.e., shared-road versus separated cycle track). Though some studies have experimented with the use of stationary air quality sensors to test the difference in ultrafine particle concentrations for a conventional bike lane and a parking-protected cycle track, there is still a need for a study using mobile air quality measurement to understand variations along a route.

# Methodology

## Instrumentation

An instrumented bicycle (shown in Figure 1) was used to monitor the PM2.5 exposure of cyclists. The instrumented bike components were designed to be attached to participants' bikes and need minimal intervention from the research team once started. Participants' own bikes were used in the study since it was important that the components have minimal impact on participants' experience biking while collecting time-dependent spatial data and PM concentrations. Two components were included in the setup: the first was a handlebar-mounted component that contained the primary compute functions along with sensors for location, altitude, and ambient environmental conditions; the second component was attached to the rear via a seat-post-mounted rack housing proximity and air quality sensors along with power. Across the two components, the sensor platform integrated 20 different sensors that enabled measuring acceleration, directness of path, roadway slope, pavement condition, object proximity, environmental conditions, and air quality.

**Figure 1. Instrumented bicycle with sensors identified.**

To determine which type of air quality sensor to use, the research team tested three sensors: the Nova PM Sensor, the GRIMM™, and the Purple Air. The Nova PM Sensor is a low-cost sensor with a 10-second response time. Initially, the Nova PM Sensor was used, but more precise data were needed for this analysis. The GRIMM™ is a research-grade PM sensor with 97 percent reproducibility and with a wider particulate detection range and faster response time than can be achieved with a low-cost sensor. The Purple Air is a hobbyist sensor that houses two Plantower PMS5003™ sensors and accompanying atmospheric sensors. The Purple Air collects data at 1-second intervals and aggregates the data over 80-second intervals. The Purple Air was expected to provide more accurate data than the Nova PM Sensor.

The Purple Air is connected to a Raspberry Pi to collect all of its readings. The Purple Air only sends readings every 80 seconds, and it is not possible to reduce the time interval. Such a low time density made the Purple Air unsuitable for this project because cyclists can travel farther in 80 seconds than would allow for detailed air quality mapping. The sensors housed in the Purple Air, the Plantower PMS5003™ sensors, collect data every 1 second, so the Plantower PMS5003™ sensors were tested.

It was determined that the PMS5003™ sensors allowed customizability and were easier to work with than the Purple Air. With two PMS5003™ sensors, the sensors could be placed on different parts of the bike or on separate bikes to compare data gathered at the same time. The PMS5003™ sensors were connected to Arduino Unos, which were connected to Raspberry Pis. The PMS5003™ sensors were determined to be adequate for use to collect air quality on the instrumented bicycle.

## Sensor Calibration

To calibrate the air quality sensors used in the instrumented bicycle, the PMS5003™ sensors were compared to the GRIMM™ 1.109 aerosol spectrometer. Thirty-eight runs were conducted with both the GRIMM™ and PMS5003™ sensors attached to the bicycle. The PM2.5 measurements had an average difference of 0.086 $\mu g/m^3$ (SD = 7.384 $\mu g/m^3$). The PM2.5 measurements had a lesser average difference when compared to the PM1 and PM10 measurements. The PM1 measurements had an average difference of 16.932 $\mu g/m^3$ (SD = 48.320$\mu g/m^3$). The PM10 measurements had a lower average difference at 4.983 $\mu g/m^3$ (SD = 4.460$\mu g/m^3$). Overall, it was found that the GRIMM™ and PMS5003™ sensors agreed for PM2.5 for most distances on the test runs, with some short distances of large variation, as shown in Figure 2.

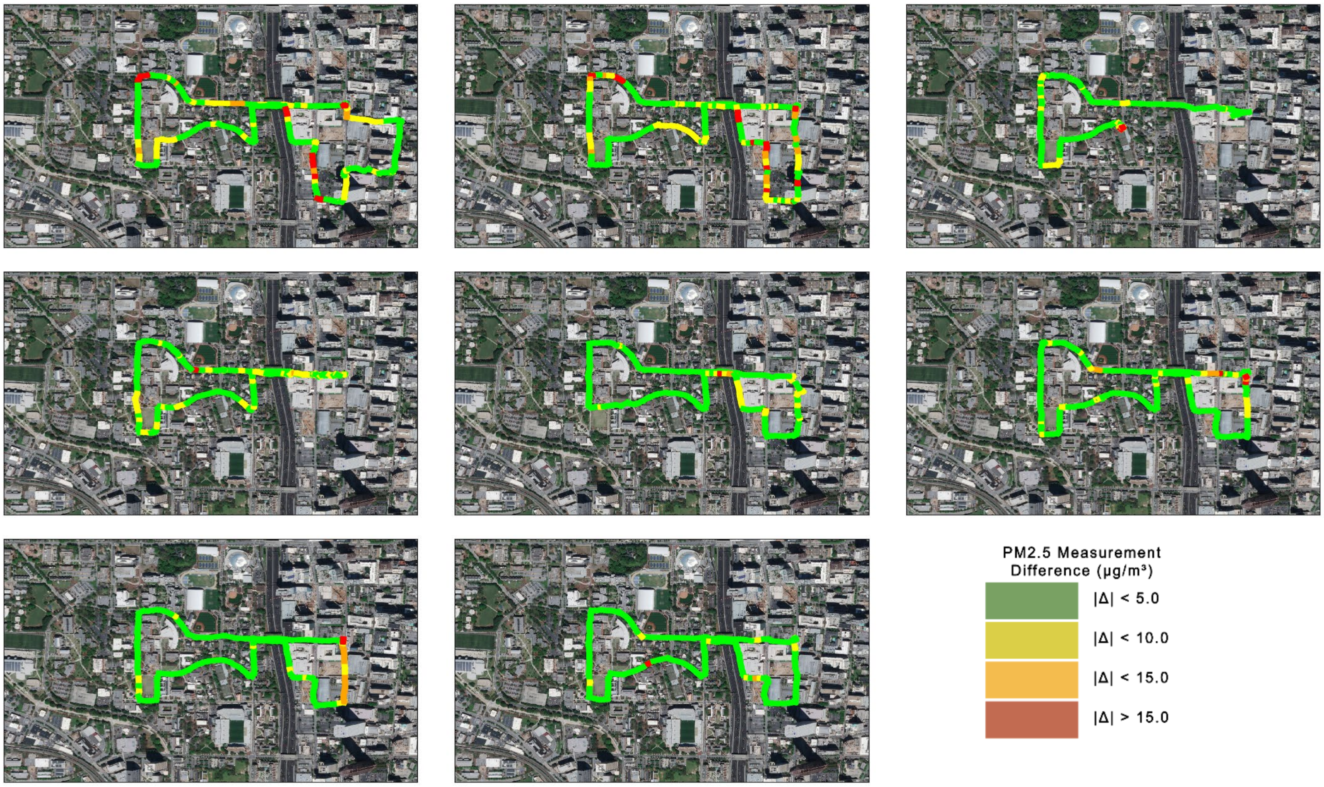

**Figure 2. Differences between GRIMM™ and PMS5003™ sensor readings.**

When reviewing the data, the research team found that the distances with large variation were associated with spikes in the GRIMM™ readings. The GRIMM™ would read a brief increase in particulate matter that was not detected by the PMS5003™. It is likely that the spikes in PM readings from the GRIMM™ were caused by sources of pollution that passed so quickly that the PMS5003™ sensors were unable to detect the particulate matter. It was hypothesized that the sharp increases in particulate matter were caused by passing heavy-duty vehicles, such as buses.

Because the emissions from gasoline and diesel buses are known sources of particulate matter that may impact the comfort level of a cyclist, it was important that the sensors responded to passing buses. The GRIMM™ and PMS5003™ sensors were left at a bus stop for an hour to collect data to test this hypothesis. The particulate concentrations were recorded over time intervals ranging from 6 seconds to 30 seconds. During the test, nine buses and three campus trolleys stopped at the bus stop. One transit vehicle arrived approximately every 5 minutes.

For the 6-second interval, the average difference between readings was 3.841 μg/m$^3$ (SD = 2.122 μg/m$^3$) for the PM 2.5 readings. From this, the research team concluded that the PMS5003™ sensors were not sensitive enough to record particulate matter from passing buses. To remedy the issue in the trial runs, a camera was attached to the instrumented bicycle so that instances when buses passed the cyclist on the roadway could be noted retroactively.

Sensor calibration also included determining an appropriate time interval to record PM concentrations. Data were recorded over several days and averaged over time intervals from 6 seconds to 90 seconds. The research team found that as the time interval increased, the average difference between the GRIMM™ and the PMS5003™ readings did not vary significantly. However, the standard deviation of the difference decreased as the time interval increased, as shown in Figure 3. Thirty seconds was chosen as the optimal time interval to use for testing to achieve a minimum standard deviation of the difference while considering the fact that precision decreases as the interval increases.

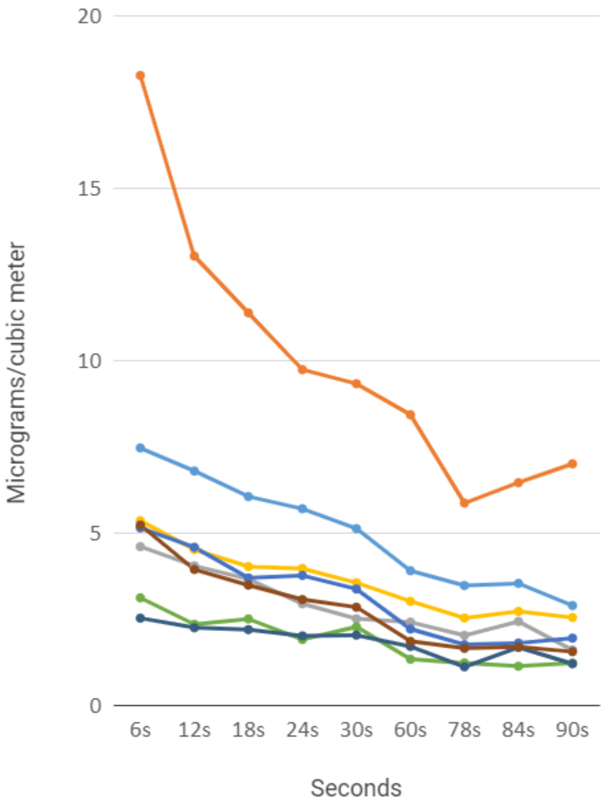

**Figure 3. Effects of time interval on standard deviation of difference between GRIMM™ and PMS5003™ readings.**

Another step in calibration was to test whether attaching the sensors to different types of bicycles impacted the PM readings. Differences in bicycles can be generalized as a difference in vibration experienced by the sensor. Trials were conducted with a bike with fully inflated tires and one with deflated tires with only enough air to protect the bicycle. Four trials were conducted on the Georgia Institute of Technology campus, where vehicles are prohibited. The analysis was completed for the 6-second interval readings. Results showed that the difference between the air quality readings from the GRIMM™ and the PMS5003™ sensors was not statistically significant. The measurements with inflated tires had average differences of 1.8 μg/m$^3$ (SD = 1.3 μg/m$^3$) and 2.1 μg/m$^3$ (SD = 1.5 μg/m$^3$). The measurements with deflated tires had average differences of 1.3 μg/m$^3$ (SD = 1.2 μg/m$^3$) and 1.5 μg/m$^3$ (SD = 1.5 μg/m$^3$). The Wilcox Rank Sum test was performed with each inflated run compared to each deflated run. The resulting p-value for the tests ranged from 0.1245 to 0.205, meaning the null hypothesis that the data belong to the same distribution was rejected. The results of the Wilcox Rank Sum test indicated that vibration does not impact the accuracy of the PMS5003™ sensors.

## Route Selection

The research team developed four different routes that represent the different bicycle infrastructure available in Atlanta, Georgia, and that covered enough of Atlanta so that all participants could ride somewhere convenient to them. The routes are approximately equal in length and take about 30 minutes for cyclists to complete. The routes were also selected to represent the PM2.5 exposure of cyclists throughout the city. To create the routes, maps of where people ride were made using Ride Report data from 2018, Relay Bikeshare data from 2018, and Strava data from 2014. These maps are provided in Figure 4. The most traveled roads are shown in red and have volumes over two standard deviations higher than the average road biked in Atlanta. The Ride Report data best represent commuters. The Relay Bikeshare data include many casual recreational riders, which can be seen by the dark red that covers the Beltline and Piedmont Park. The Strava data include a larger number of sports cyclists, which caused some areas that would not be considered a road that a typical commuter might travel to have a high ridership. Areas with the highest volumes of riders were chosen as areas of focus for designing the routes. By combining the three sources—and weighting the commuter-heavy Ride Report data the most—the cycling hot spots in the city were found.

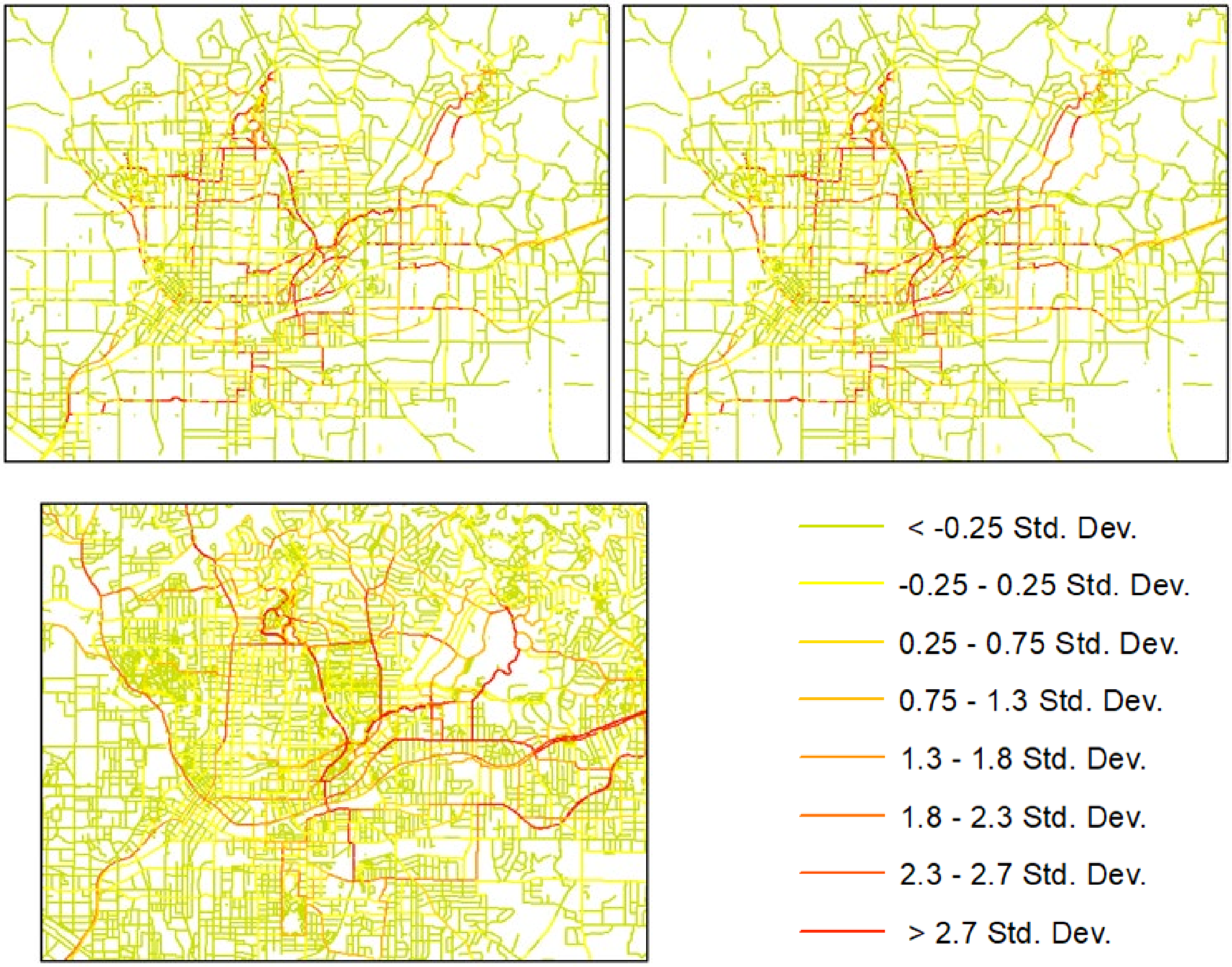

**Figure 4. 2018 Ride Report data (top left), 2018 Relay Bikeshare data (top right), and 2014 Strava data (bottom).**

In conjunction with the bike volume maps, a map of bike infrastructure in Atlanta was also used to develop routes. The routes were designed to have variation in facility and road type. Each route has a segment of low stress (i.e., parks, shared use trail), medium stress, and high stress (i.e., mixed traffic with high car volumes). The routes are located around the city, have a variety of conditions in each, and are located where people regularly ride. The four routes distributed throughout Atlanta are shown in Figure 5. Figure 6, Figure 7, Figure 8, and Figure 9 show the routes with images of the different cycling infrastructure. The routes include paths through green space, protected facilities, and shared roadways with vehicles.

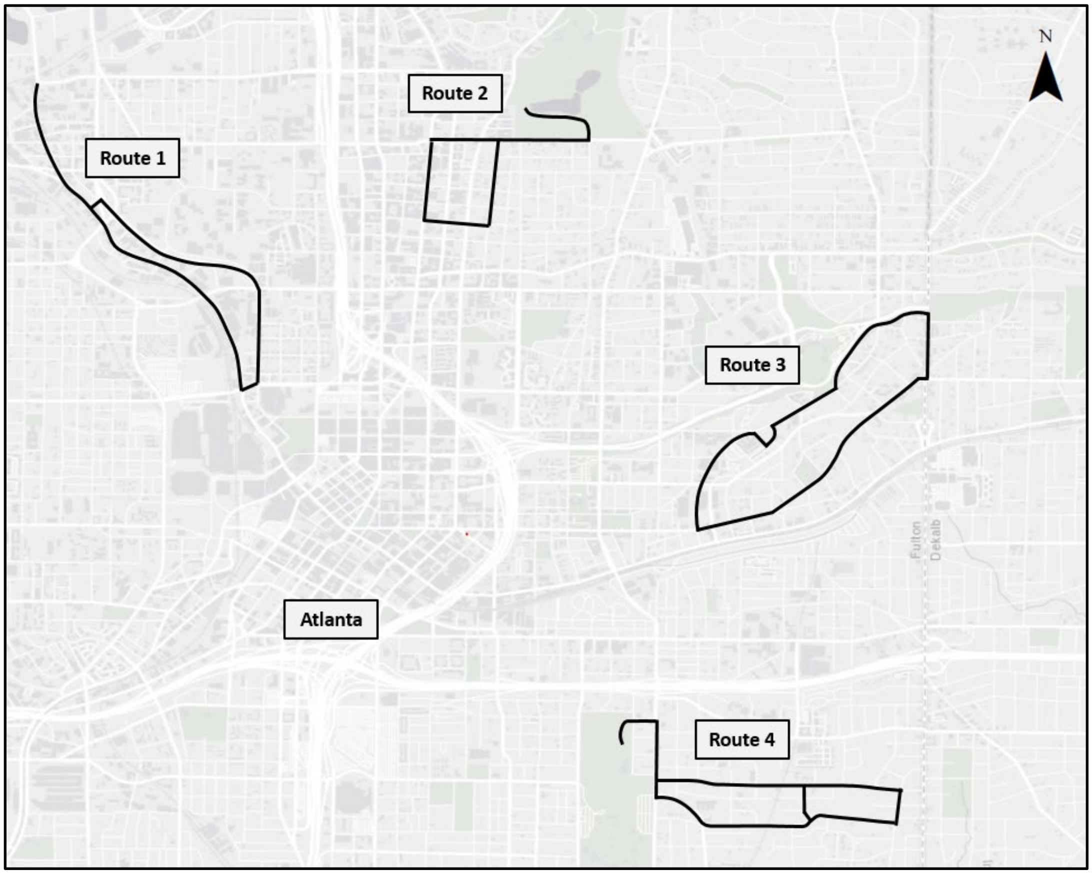

**Figure 5. Selected routes in Atlanta, Georgia.**

Figure 6. Route 1 cycling infrastructure identified.

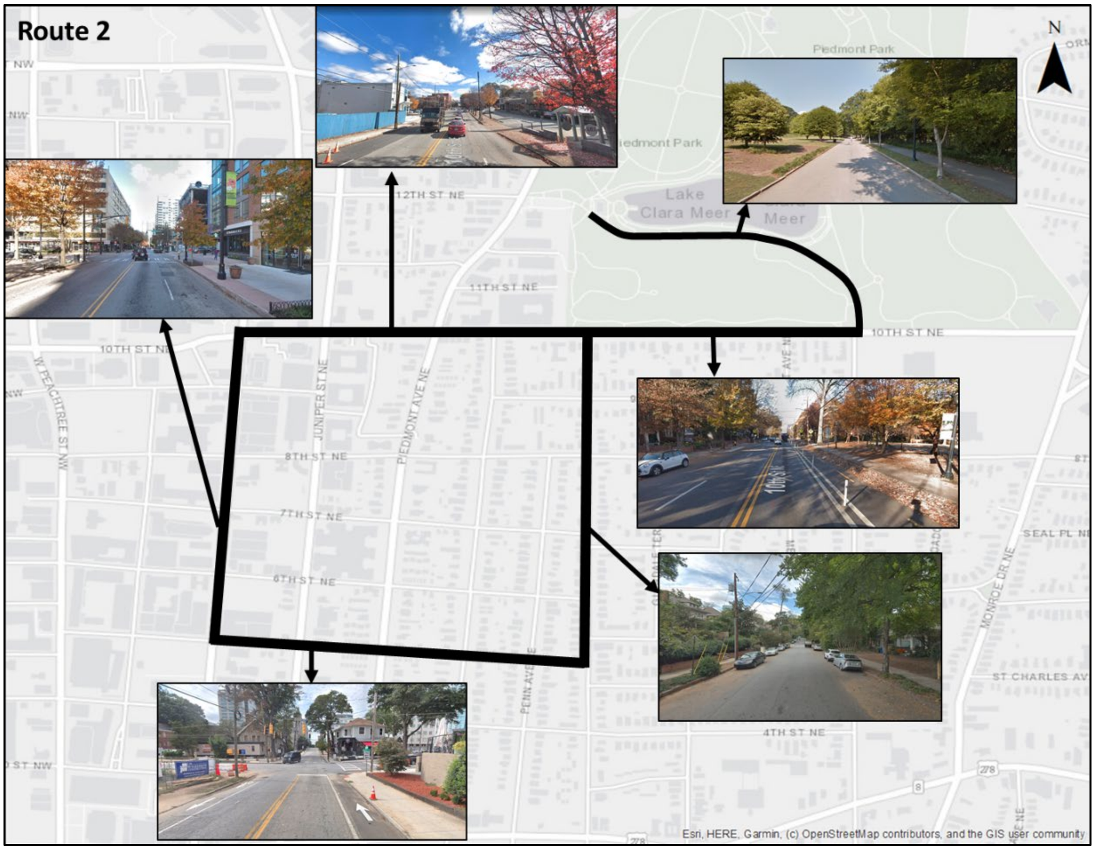

Figure 7. Route 2 cycling infrastructure identified.

Figure 8. Route 3 cycling infrastructure identified.

Figure 9. Route 4 cycling infrastructure identified.

### Data Collection

The study protocol was approved by the Georgia Tech Institutional Review Board. Study participants elected to ride the instrumented bicycle on one of the four predetermined routes. During the data collection period, each of the routes was completed by at least five participants. The rides were completed at different times throughout the day because PM exposure can vary depending on the time of day. In addition to recording PM2.5 concentrations, the instrument recorded the geographic location of the cyclist. This information was used to create maps of the cyclists' PM2.5 exposure.

Further data collection efforts included having a researcher ride one of the routes five different times during the same day and exploring the variability of different commuting routes to Georgia Institute of Technology. Two researchers began their commute in the same neighborhood and rode different routes through Midtown Atlanta to Georgia Institute of Technology. The results of these data collection efforts are shown in the following section.

Because urban air quality is a combination of many local sources, the PM2.5 concentrations were corrected for background concentration. The Ambient Monitoring Program of Georgia Environmental Protection Division's Air Protection Branch maintains a monitoring site on United Avenue that is representative of Atlanta's PM concentration. The monitor provides a PM2.5 reading every hour, and this background concentration was subtracted from the PM2.5 readings from the sensors.

## Results

### PM2.5 Concentration Maps

Multiple runs were completed for each of the four routes. The average difference from the background air quality was computed to summarize the findings from all of the runs during the data collection period. The routes were broken into segments that represent different roadway characteristics.

A few factors were considered to break the routes into segments, including intersection locations, infrastructure types, and inclusion of an appropriate number of data points. Segments were to be long enough to include a representative sample that would mask outliers, but not so long that potential hot spots would be masked. Hot spots were identified by mapping all of the data simultaneously and determining where there were greater differences than the surrounding points. Additionally, major intersections and many minor intersections were identified as their own segments.

Once segments were created, all of the data points from the runs at a given location were selected, and the differences from the background air quality were averaged. Data points were only selected for one segment to avoid skewing the data. Figure 10 shows maps of the average difference from background PM2.5 concentrations for the routes.

The resulting PM2.5 concentration maps show that few segments recorded air quality worse than the background concentration. During most of the routes, riders experienced air quality that was better than the air quality documented at the monitoring location. Riders were exposed to PM2.5 concentrations that exceeded 10 μg/m$^3$ on some specific segments. However, given that the cyclist remained in motion, the time spent along each of the segments was minimal. Cyclists did not receive prolonged exposure to high concentrations along these routes.

Route 1 had three segments with PM2.5 exposure that was 4–8 μg/m$^3$ greater than the background air quality, shown in yellow in Figure 10, and one segment with PM2.5 exposure that was 8–12 μg/m$^3$ greater than the background air quality, shown in orange in Figure 10. The yellow segments were in areas where cyclists were in the roadway with vehicles, and the orange segment was in an area with bike lanes alongside vehicles. Route 2 had five segments with PM2.5 concentrations that were 4–8 μg/m$^3$ greater than the background air quality, all in areas where cyclists were in the roadway with vehicles. Additionally on Route 2, there was an area with PM2.5 concentration that was less than the background air quality, shown in dark green in Figure 10. This segment was along a residential road where cyclists were in the roadway with vehicles. Route 3 had nine segments with PM2.5 concentrations that were 4–8 μg/m$^3$ greater than the background air quality. With the exception of one segment along a mixed-use path (the Atlanta BeltLine™), the yellow segments on Route 3 were in areas where cyclists were in the roadway with vehicles. This one path segment was close to developments that could have high PM2.5, such as restaurants. Four segments on Route 3 had areas with PM2.5 concentrations that were less than background air quality. The dark green segments on the north end of the route were on a multiuse trail through a park, and the dark green segment of the south end of the route was where a bike lane intersected a multiuse trail. Route 4 had similar exposure along the entire route when background air quality was subtracted, regardless of infrastructure.

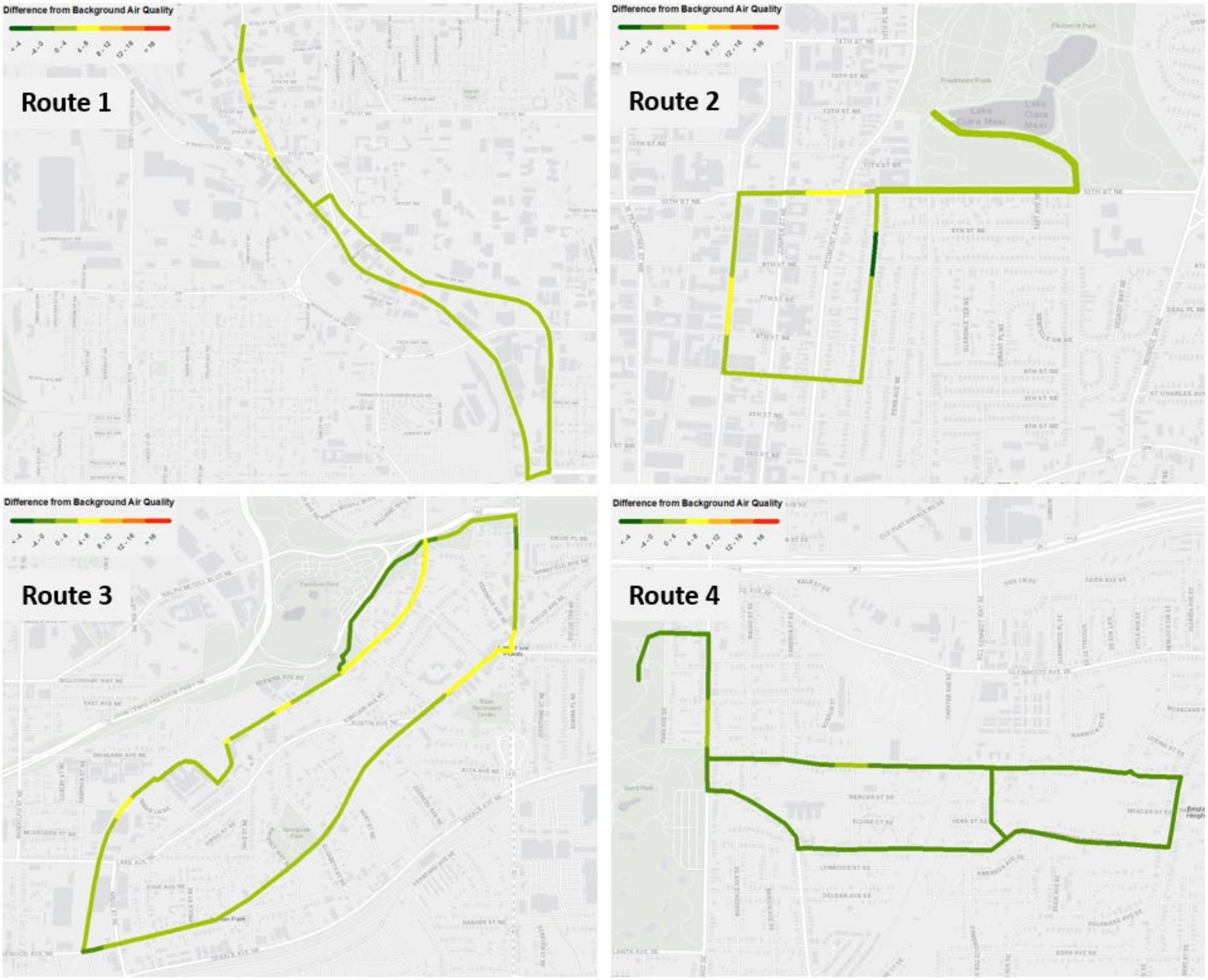

**Figure 10. Difference from background air quality PM2.5 (µg/m$^3$) exposure maps.**

## PM2.5 Exposure Throughout the Day

Particulate matter exposure can vary significantly throughout the day. To examine this variation, a researcher rode one of the predetermined routes (Route 2) five different times throughout the day. Figure 11 shows the PM2.5 exposure maps for these rides, and Figure 12 shows the difference from background air quality PM2.5 exposure maps for these rides. The air quality was best in the morning and afternoon, although hot spots of high PM2.5 concentrations are found throughout the day. The first ride had lower PM2.5 concentrations along the park and the lower-traffic roadways, but higher concentrations along high-traffic roads. The noon and 3 p.m. rides had generally higher PM2.5 along the entire route. The 5 p.m. and 7 p.m. rides had the lowest exposure, with the exception of one area along Peachtree, a major street with a large restaurant density.

**Figure 11. PM2.5 exposure (µg/$m^3$) maps throughout the day.**

**Figure 12. Difference from background air quality PM2.5 (µg/$m^3$) exposure maps throughout the day.**

## PM2.5 Exposure by Route Selection

The implications of different routes can vary from an actual safety, perceived safety, and rider comfort point of view, but the air quality implications can be different as well. The research team wanted to understand the variation in air quality exposure of cyclists depending on the route that they take during their trip. Exploration of these exposure variations began with two researchers commuting to Georgia Institute of Technology from the same neighborhood. The PM2.5 exposure maps are shown in Figure 13.

The researchers commuted on parallel routes on the same morning. They began their commute together and then diverged to different routes. Route 1 avoided high-volume roadways and detoured through a public greenspace and low-volume residential streets. Route 2 included more high-volume roadways equipped with cycling infrastructure. It was expected that the rider on the first route would have lower PM2.5 exposure. However, both riders were exposed to similar concentrations. The average difference from background air quality on the first route was 15.12 µg/m$^3$, and the average difference of the second route was actually lower at 14.56 µg/m$^3$.

The riders documented when they felt as though they experienced poor air quality due to their surroundings. The first rider noted multiple idling trucks and close proximity to a garbage truck for a portion of the commute. However, these reported areas did not have significantly worse air quality than that of the rest of the route. The second rider documented similar experiences. For their entire route, the riders were subject to PM2.5 concentrations that exceeded those recorded at the monitoring site. This finding varied from the initial exposure mapping. Concentrations exceeding the readings at the monitoring site may have been caused by elevated traffic volumes during morning rush hour or increased cyclist interactions with heavy-duty vehicles.

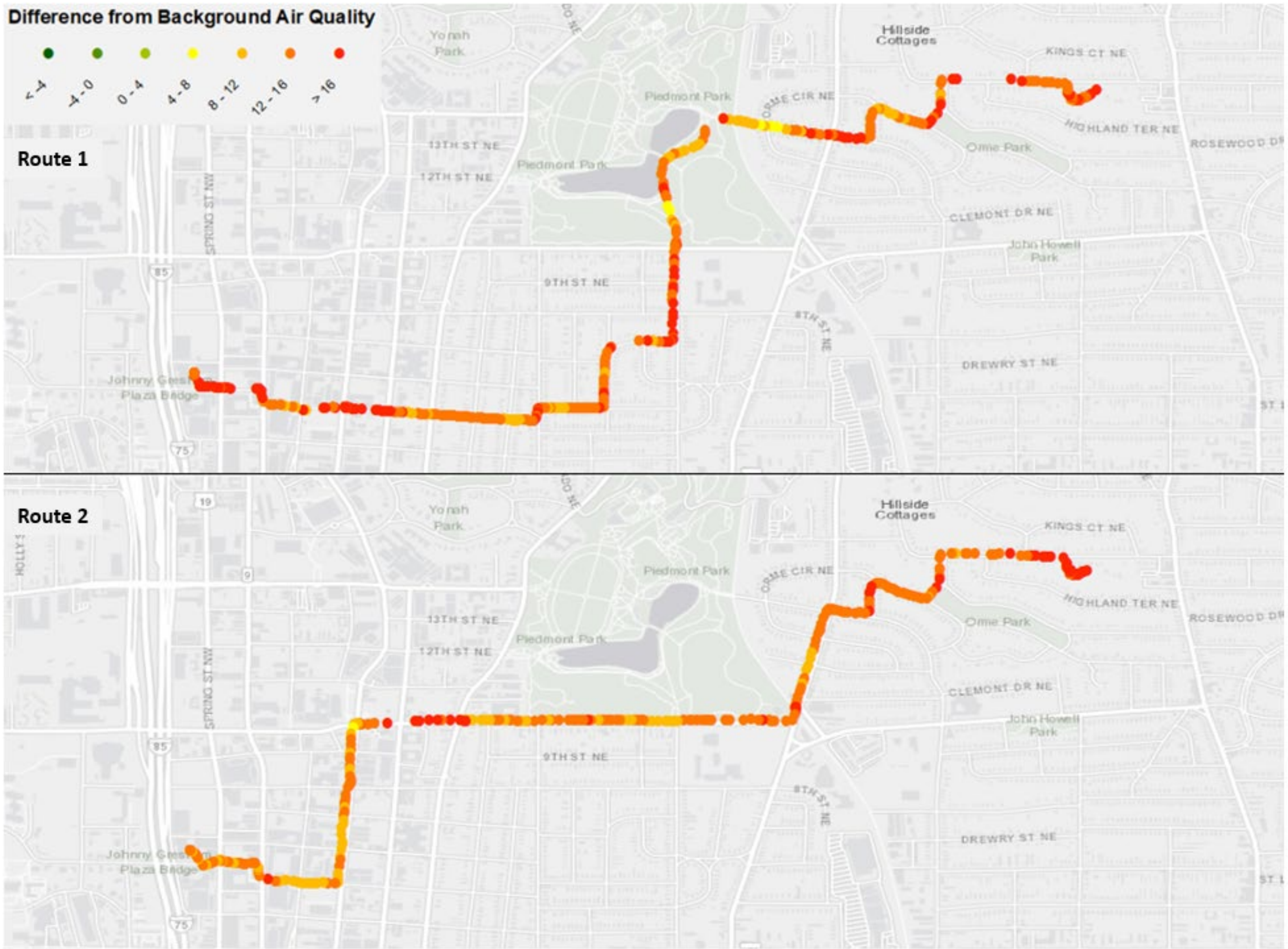

**Figure 13. PM2.5 exposure (µg/m$^3$) maps of routes from the same origin to the same destination.**

## Estimated Total PM2.5 Exposures for Cyclists

As discussed earlier, the PM2.5 concentration field through which the cyclists traveled along their respective routes was highly variable, both within a particular trip and between observations of individual cyclists. For the individual runs, average PM2.5 ranged from 2.2 to 16.6 µg/m$^3$, with an average across all runs of 6.3+/−4.3 µg/m$^3$. These values are, of course, significantly lower than those observed in urban areas throughout much of the world. These average values were not statistically different than the corresponding urban background (i.e., a mean difference of 0.1+/−4.0 µg/m$^3$). While the current sample size is too small to generalize, it suggests that estimates of PM2.5 exposures for the overall cyclist population might be well represented by overall urban mean concentrations. This will require further study.

While actual subject physical characteristics were not recorded due to privacy considerations (available information was limited to sex, age range, and cycling experience), the research team estimated energetic requirements for individual runs assuming a 75-kg mass for males and a 55-kg mass for females using observed speed traces and grades. To characterize the variability in cyclist performance, the researchers observed average speed on selected flat-grade segments for the individual cyclists. These ranged from 5.7 to 15.3 km/hr, with a median value of 12.3 km/hr, indicating that, with one possible exception, the participants were reasonably fit. Estimated average inhalation rates necessary to sustain the observed energy outputs for participants ranged from 26 to 45 l/min while the cyclist was moving. However, both traffic conditions and study requirements for documentation resulted in a significant fraction of "stopped" time (defined in this study as speeds less than 0.15 m/s). Individual stopped fractions ranged from 15.1 percent to 50.5 percent, with an average of 34+/−11 percent. For the stopped times, the average inhalation rate was assumed to be 10 l/min, reflecting light activity.

Thus, for the study routes and conditions, total PM2.5 exposures were estimated to range between 1.8 and 10.5 µg, with an averaged estimated exposure of 4.8+/−3 µg. For comparison, the research team also estimated the difference between the total exposure for the cyclists versus exposure to the urban background for the same time interval. These estimates ranged from 0.4 to 4.2 µg of additional exposure, with an average value of 1.9+/−1.3 µg, or approximately 0.4 µg per kilometer of cycling. These values are significantly less than the variability either within or between runs.

## Conclusions

This experiment was an initial study to assess the feasibility of using an instrumented bicycle to monitor PM2.5 exposure. After initial calibration, the low-cost PMS5003™ sensors were determined to be appropriate for mobile air quality monitoring, although some large spikes in PM2.5 may be missed with such low-cost sensors. Study participants rode the instrumented bicycle on four routes that represent the wide range of bicycle infrastructure available in Atlanta, Georgia. Additional trials were conducted to understand a cyclist's PM2.5 exposure during different times of the day and along different routes. This study resulted in PM2.5 exposure maps that show how a cyclist's exposure differs from the urban background concentration. Hot spot maps were developed to show locations where PM2.5 exposure averaged over multiple runs was higher or lower than background PM2.5 concentrations. All segments where exposure was higher were locations where bikes share the road with high vehicle volumes, except one segment where development is likely causing higher PM2.5. Segments where PM2.5 exposure was lower than background concentrations were all along multiuse trails. These findings are in alignment with previous research that suggested that exposure was higher near high-traffic routes and for motorists due to their proximity to motor vehicles. However, based on multiple runs, including testing one route throughout the day, cyclist exposure to PM2.5 is impacted more by environmental variables that lead the background concentration to be higher along the entire route than by the proximity to vehicles at specific points along any route. Further exploration should include quantification of the specific differences in exposure of different types of cycling infrastructure. Future work should also include efforts to collect more data for routes to common origin-destination pairs and further analysis of how time of day and time of year impact exposure.

Based on the research team's calculations of the total exposure for the cyclists versus exposure to the urban background for the same time interval, values are low enough to show that the health impact of the exercise would far outweigh the small increase in exposure, regardless of the bicycle infrastructure used en route. However, these results are true for Atlanta, Georgia, and locations that enjoy similar levels of particulate matter. This may differ in parts of the world where exposure to particulates is much higher. Therefore, additional further research should seek to replicate these results in other locations. The instrumented bicycle setup used in this study is easily transportable and can be mounted on almost any bicycle to allow for mobile data collection. Documentation of the sensor setup can be found at https://github.com/cledantec/Cycle-Atlanta-SLaB. For additional analysis using the data collected in this study, the data are available on the CARTEEH data-sharing site. Ongoing work by the research team will use the same setup to assess a variety of measures regarding cyclist comfort and exposure.

# Outputs, Outcomes, and Impacts

## Research Outputs, Outcomes, and Impacts

This study produced two presentations for the CARTEEH Transportation, Air Quality, and Health Symposium and a final report documenting the procedures and findings. The outcomes of this study are PM2.5 exposure maps of cyclists in Atlanta, Georgia. The impacts of this study are a refined methodology for using an instrumented bicycle for mobile air quality monitoring and an initial assessment of cyclists' pollutant exposure.

## Technology Transfer Outputs, Outcomes, and Impacts

The data sets from this study include the PM2.5 measurements for multiple runs of each of the routes. The data collection procedure can be replicated along other routes as well as replicated in other cities. This study provides a framework for future cyclist exposure studies. The exposure maps were created using ArcGIS. Additional technology uses included the code to process the raw data recorded by the sensors into a format accepted by ArcGIS.

## Education and Workforce Development Outputs, Outcomes, and Impacts

The education and workforce development output includes involving students from multiple departments in the project, as well as being the subject of an undergraduate summer research program. The ongoing research team included students from the School of Civil and Environmental Engineering and the College of Computing (Computational Media). Students held many responsibilities in this project, including sensor calibration, data collection, data analysis, and data presentation.

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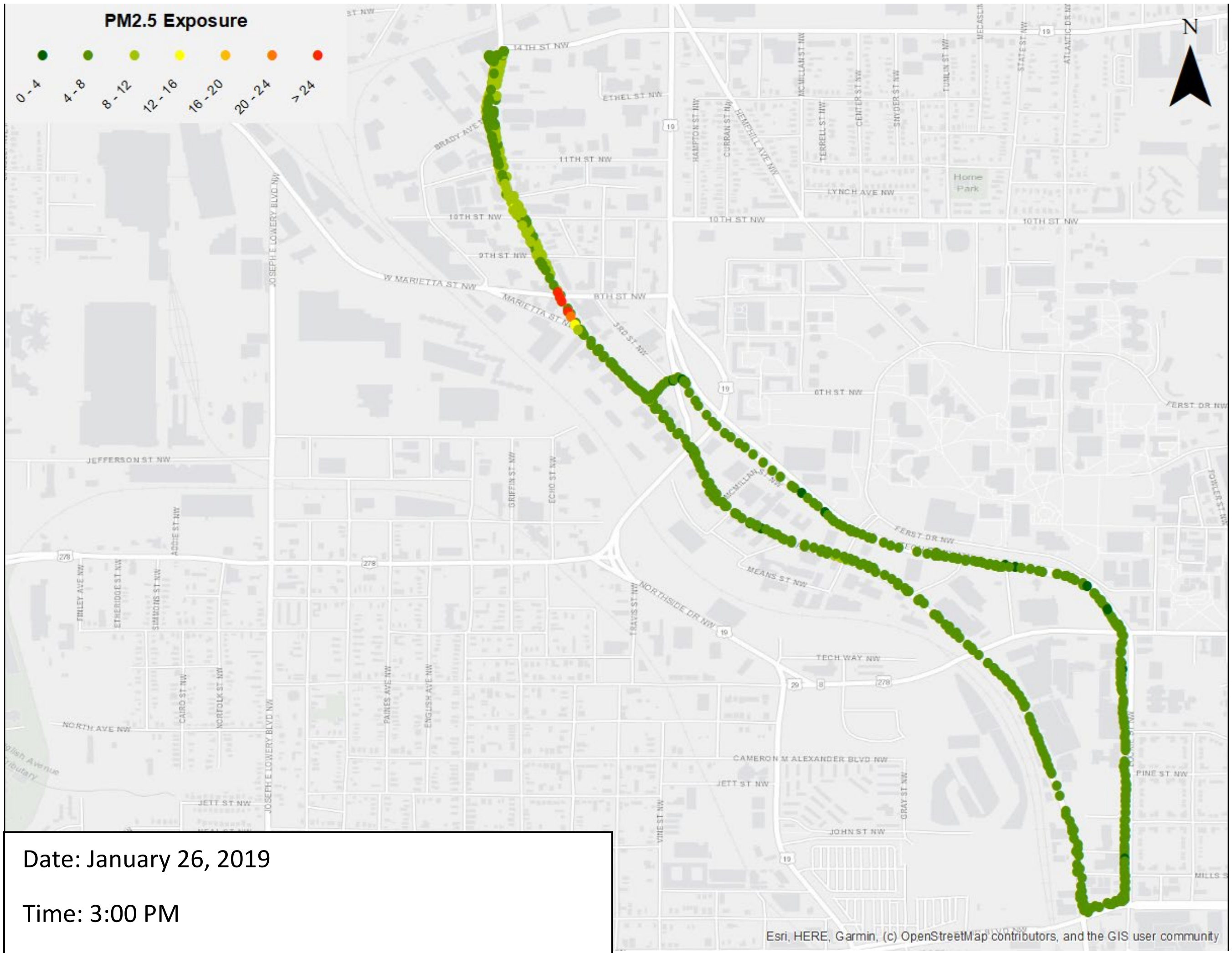
# Appendix: PM2.5 Exposure Maps

## Route 1

Date: December 5, 2018

Time: 10:00 AM

Background Air Quality Concentration: 7.7 μg/m$^3$



Date: January 26, 2019

Time: 3:00 PM

Background Air Quality Concentration: 3.9 µg/m$^3$

Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Date: January 31, 2019

Time: 2:30 PM

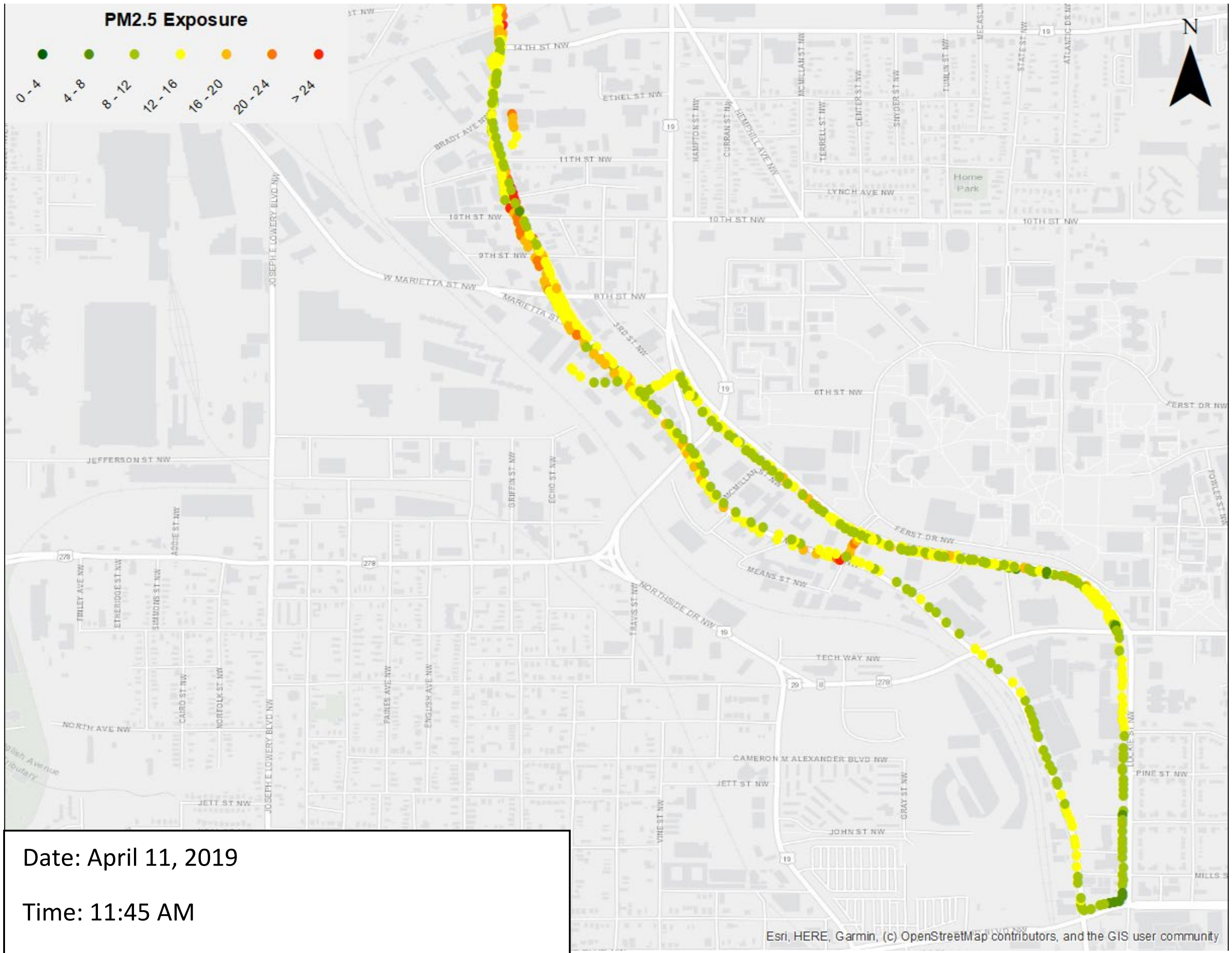
Background Air Quality Concentration: 4.1 µg/m$^3$

Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Date: February 24, 2019

Time: 10:15 AM

Background Air Quality Concentration: 6.6 µg/m$^3$



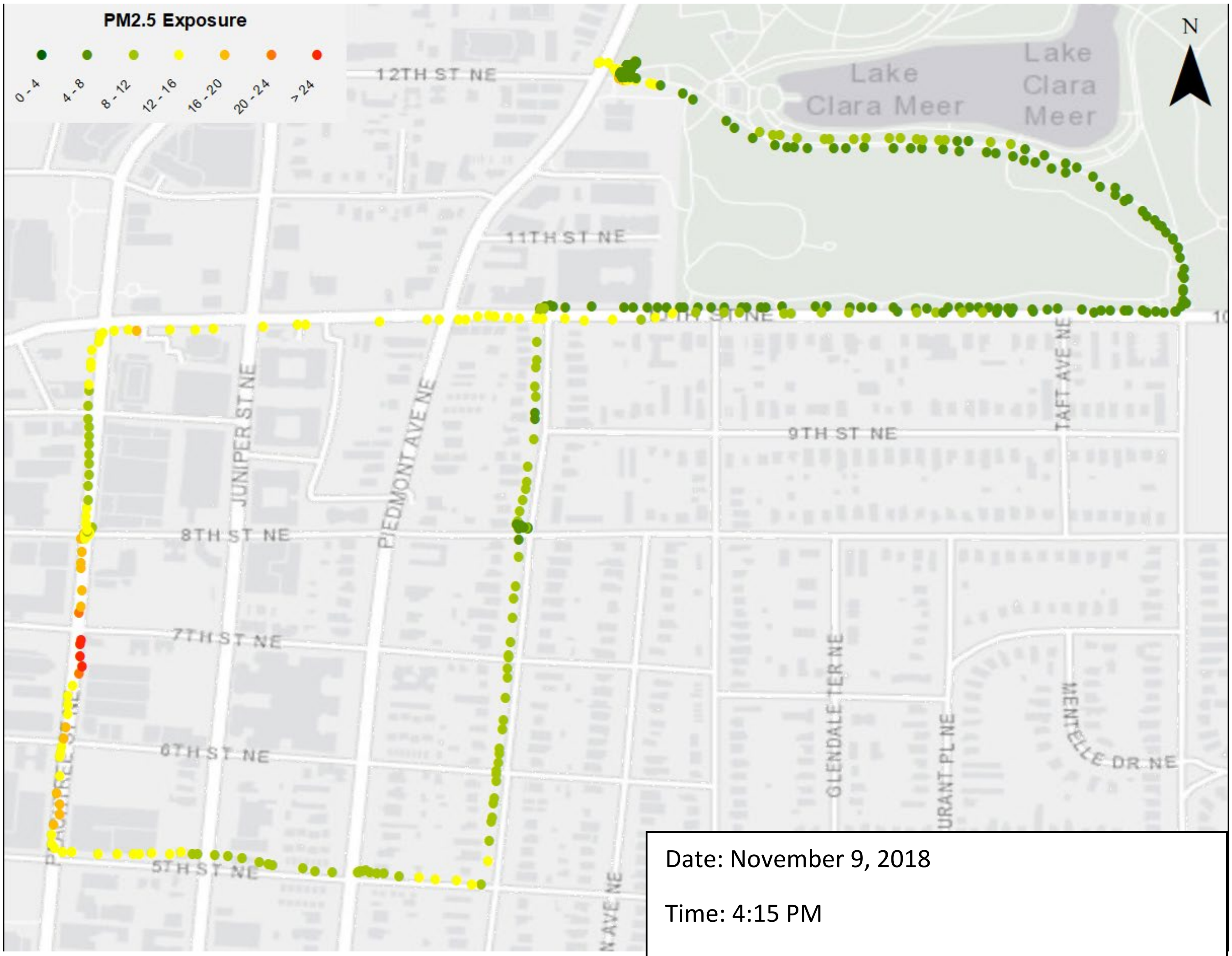
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Date: April 11, 2019

Time: 11:45 AM

Background Air Quality Concentration: 6.6 μg/m3

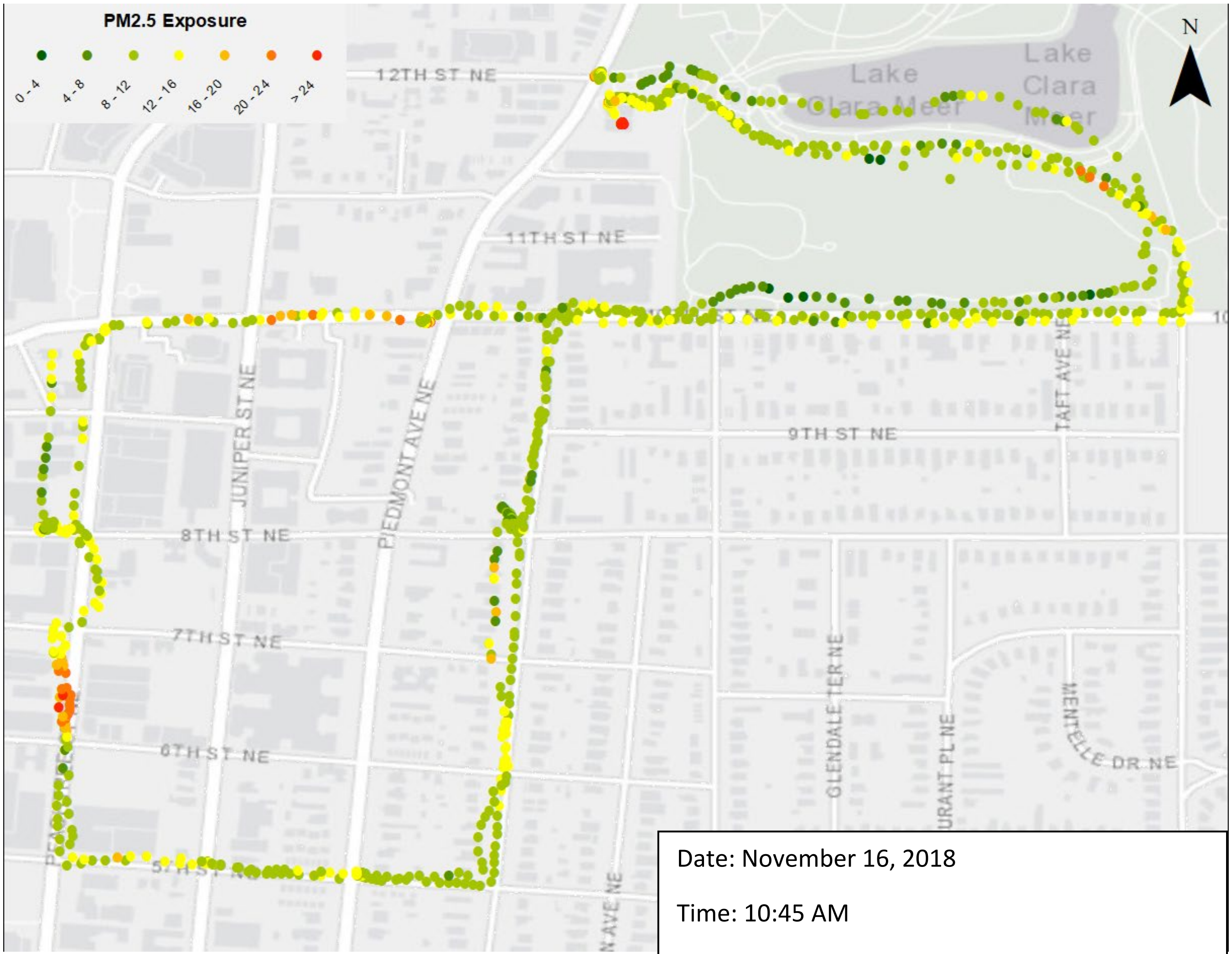
## Route 2



Date: November 9, 2018

Time: 4:15 PM

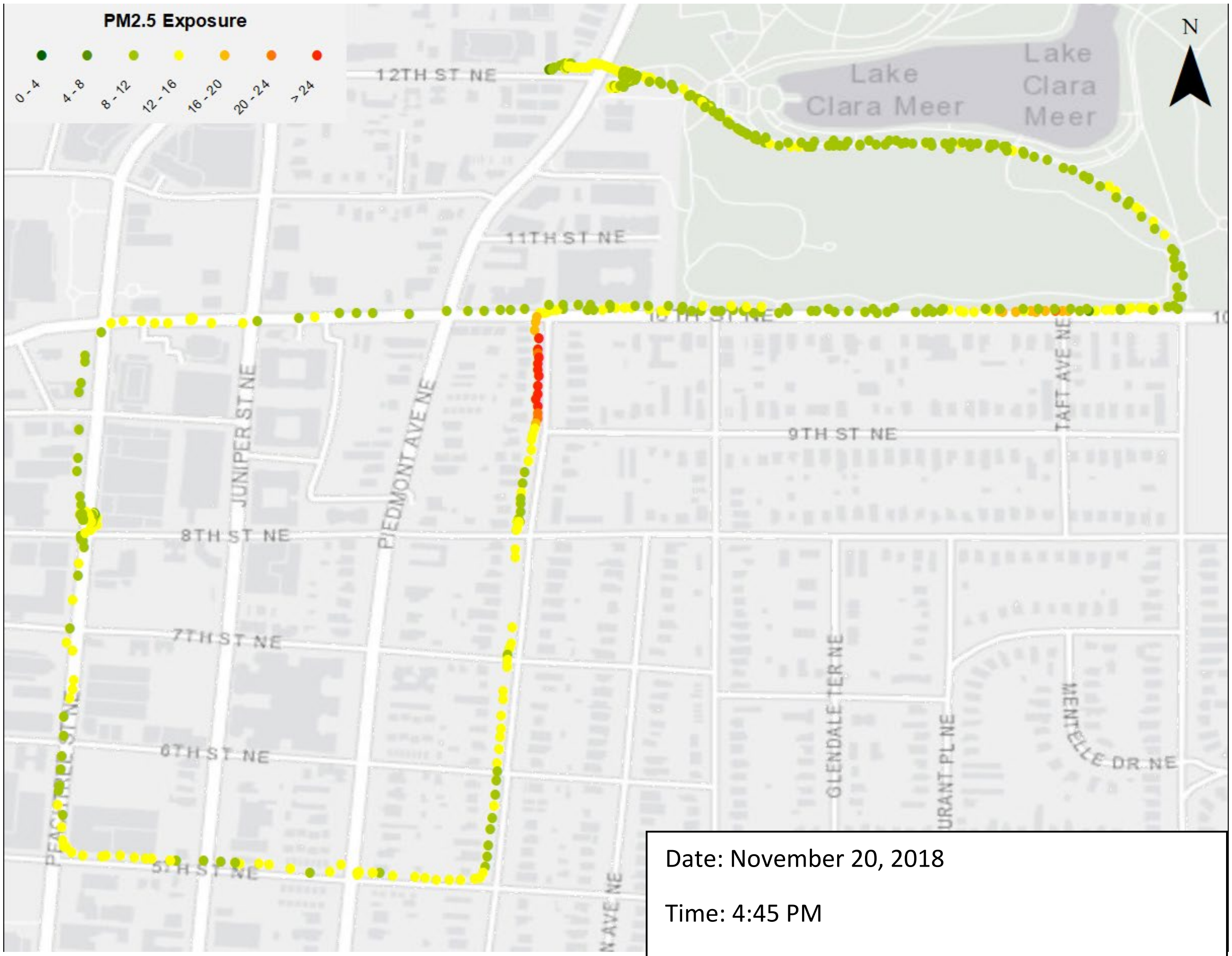
Background Air Quality Concentration: 6.3 µg/$m^3$



Date: November 16, 2018

Time: 10:45 AM

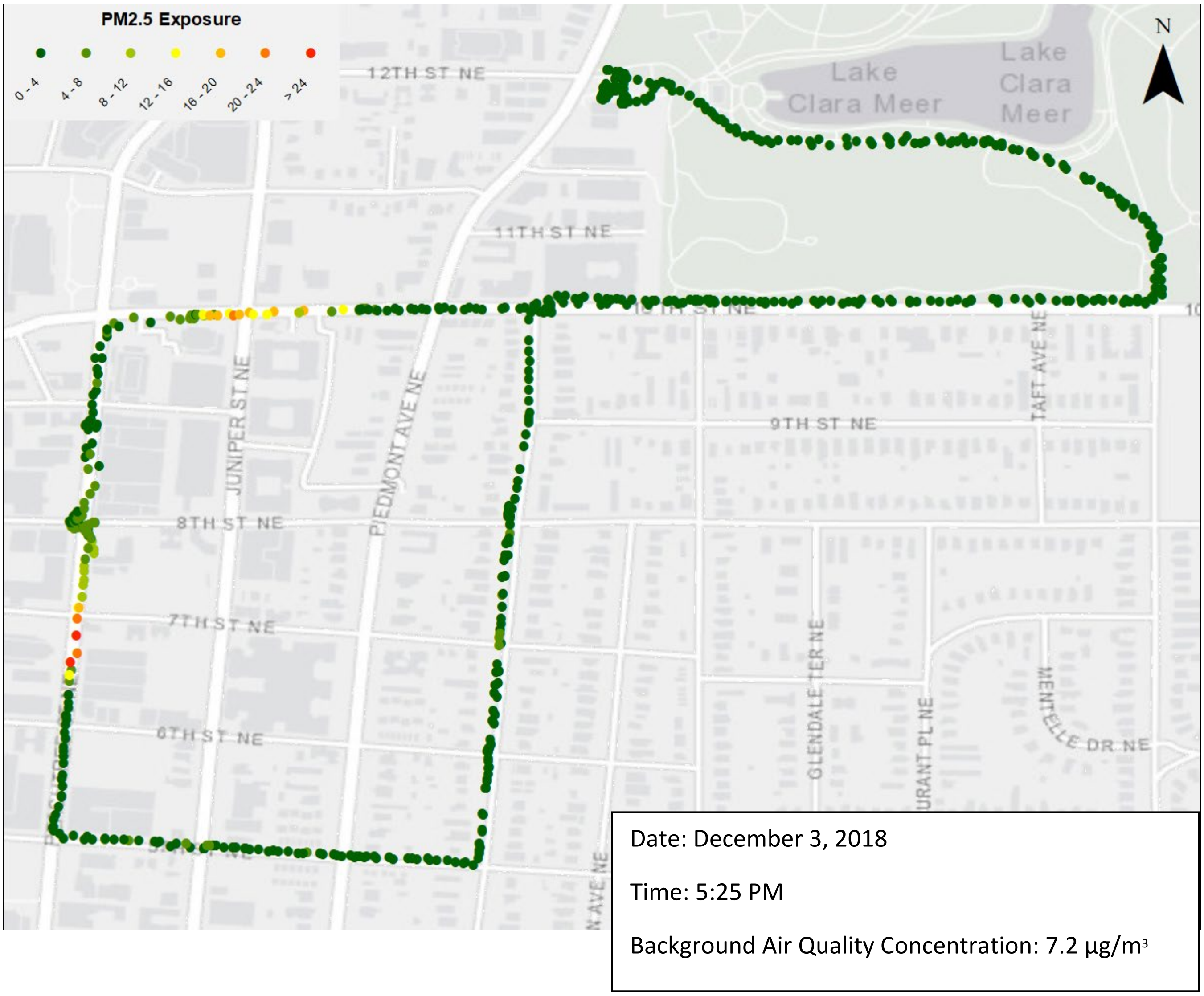
Background Air Quality Concentration: 6.2 µg/m$^3$



Date: November 20, 2018

Time: 4:45 PM

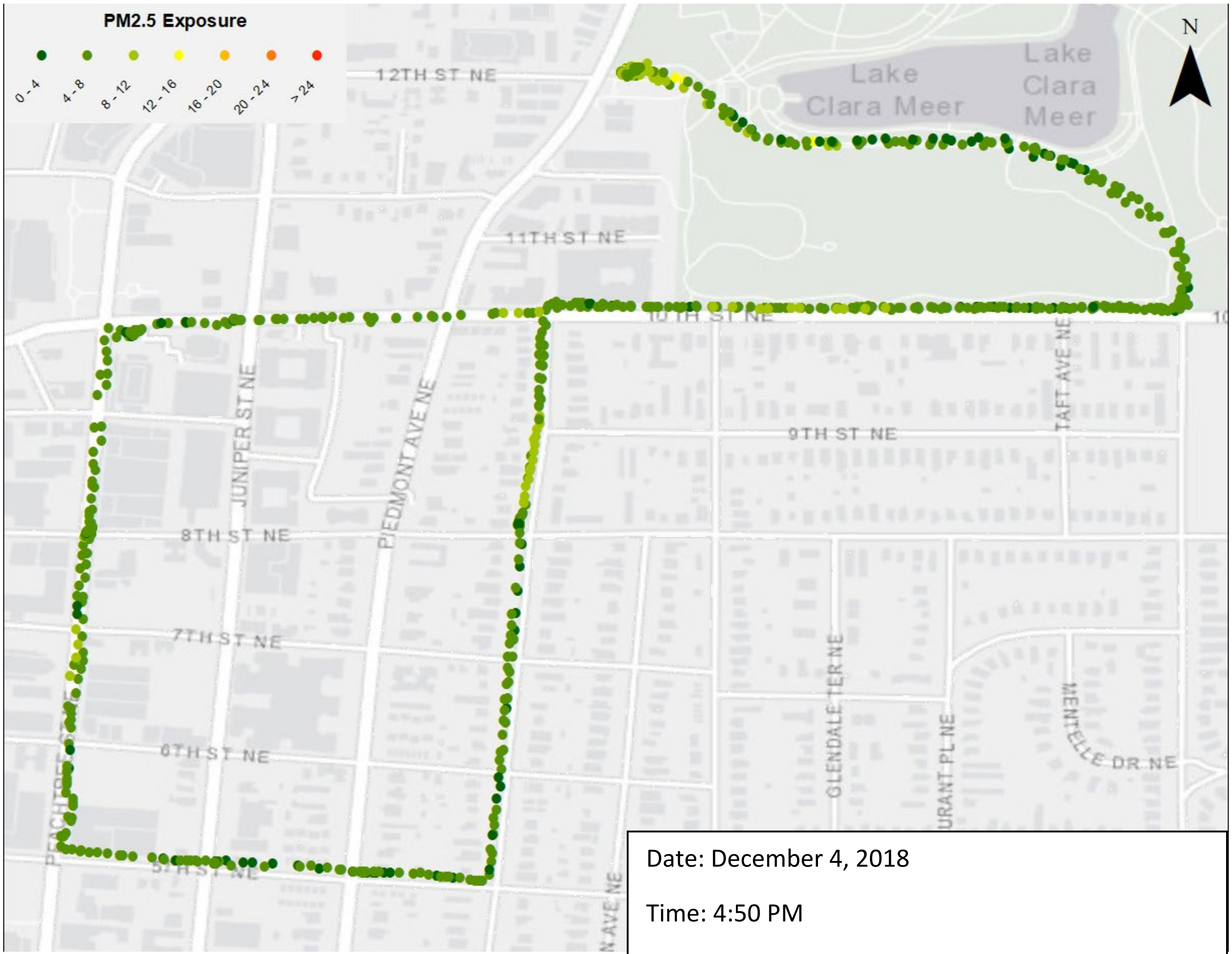
Background Air Quality Concentration: $9.3\ \mu g/m^3$



Date: December 3, 2018

Time: 5:25 PM

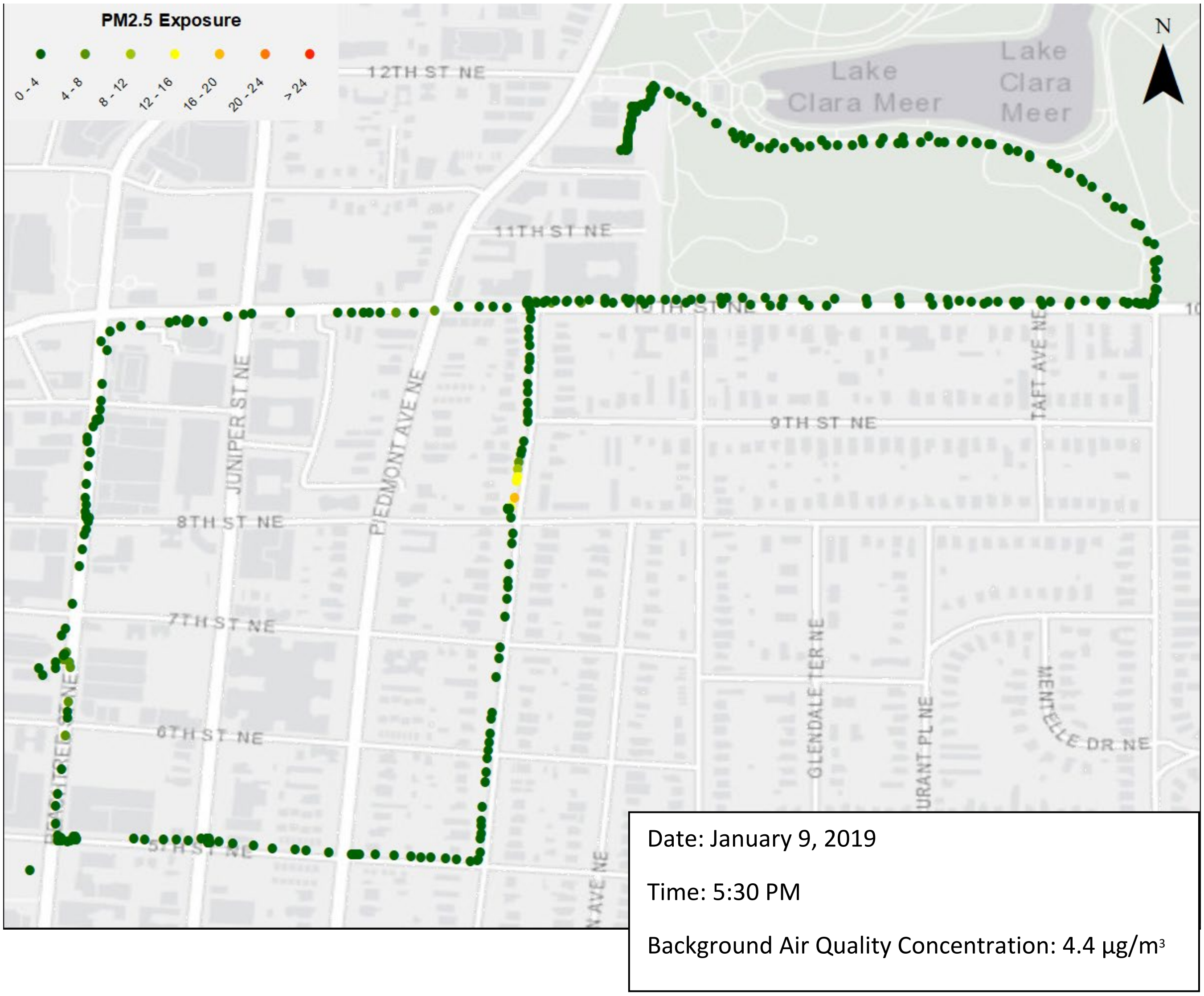
Background Air Quality Concentration: 7.2 µg/$m^3$



Date: December 4, 2018

Time: 4:50 PM

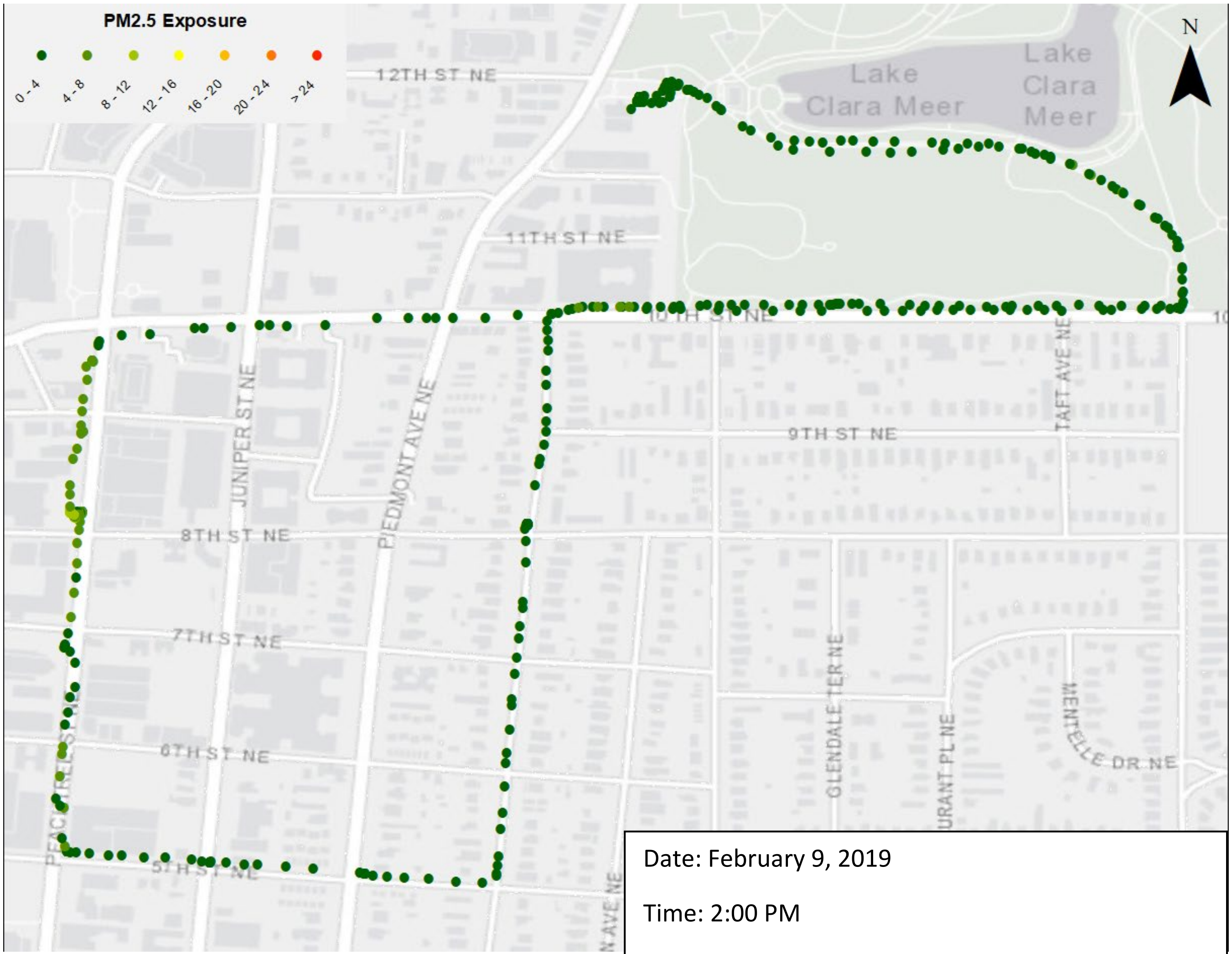
Background Air Quality Concentration: 6.7 µg/m$^3$



Date: January 9, 2019

Time: 5:30 PM

Background Air Quality Concentration: 4.4 µg/$m^3$



Date: February 9, 2019

Time: 2:00 PM

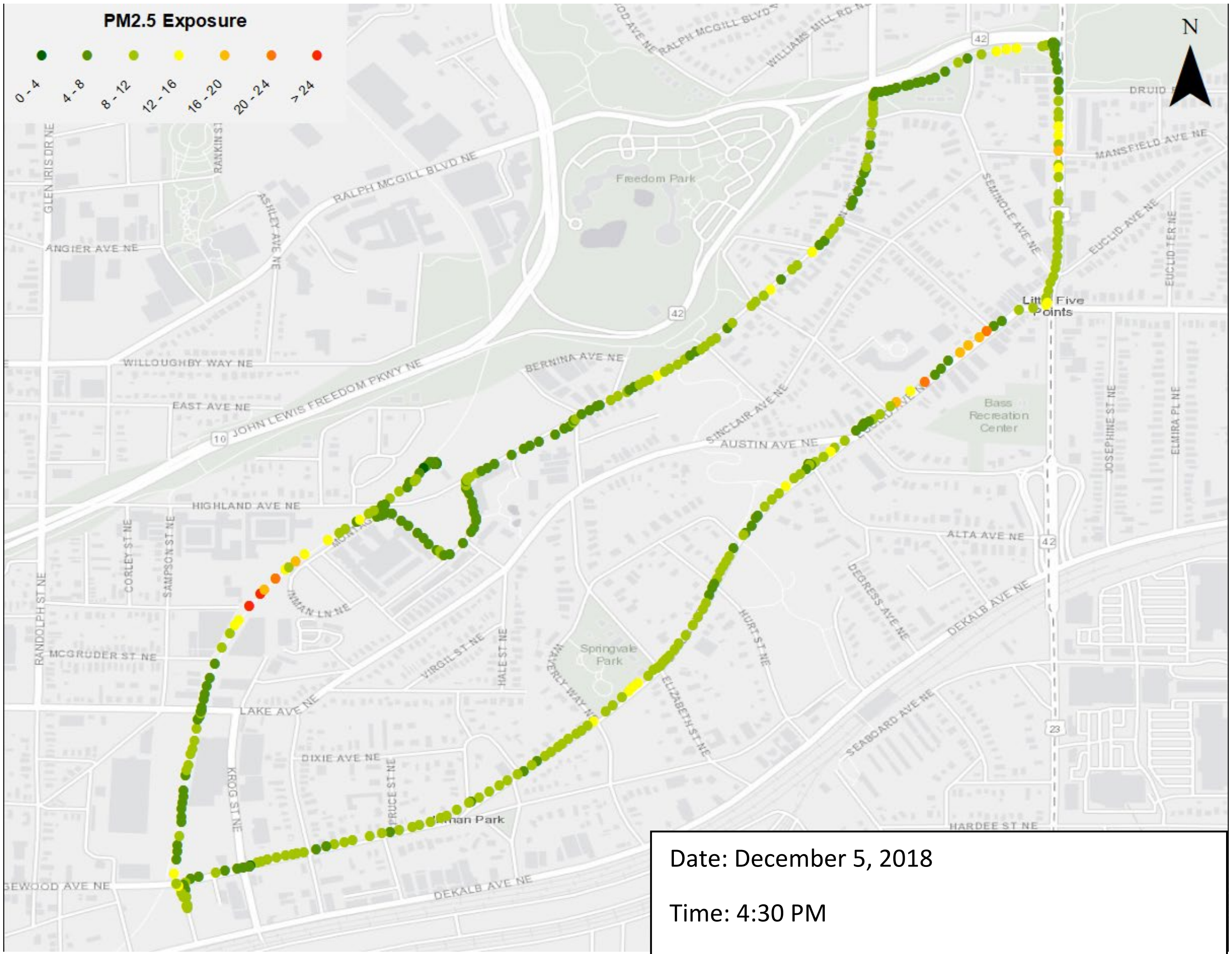
Background Air Quality Concentration: 2.2 µg/$m^3$

## Route 3

Date: December 3, 2018

Time: 3:00 PM

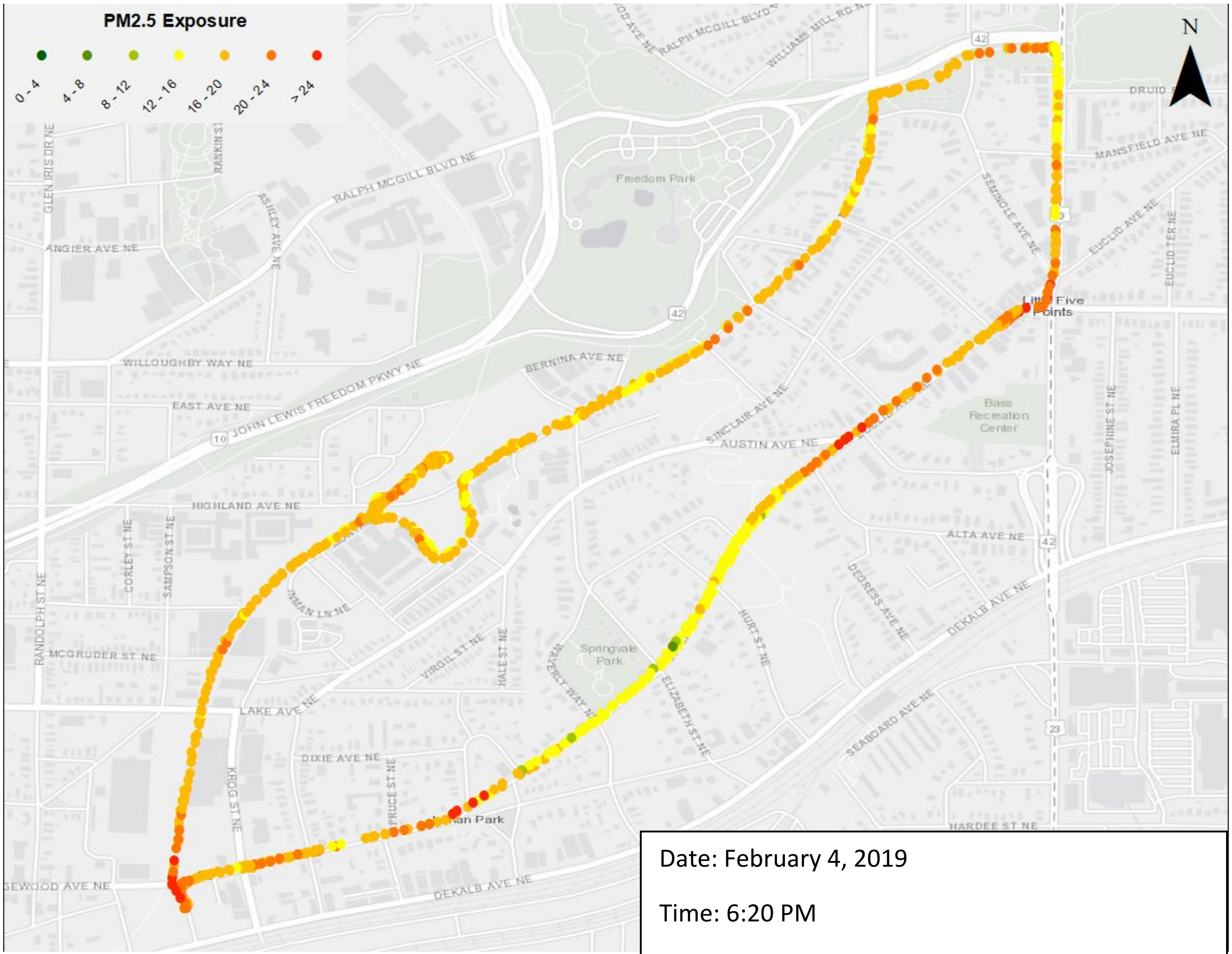
Background Air Quality Concentration: 7.8 µg/m$^3$



Date: December 5, 2018

Time: 4:30 PM

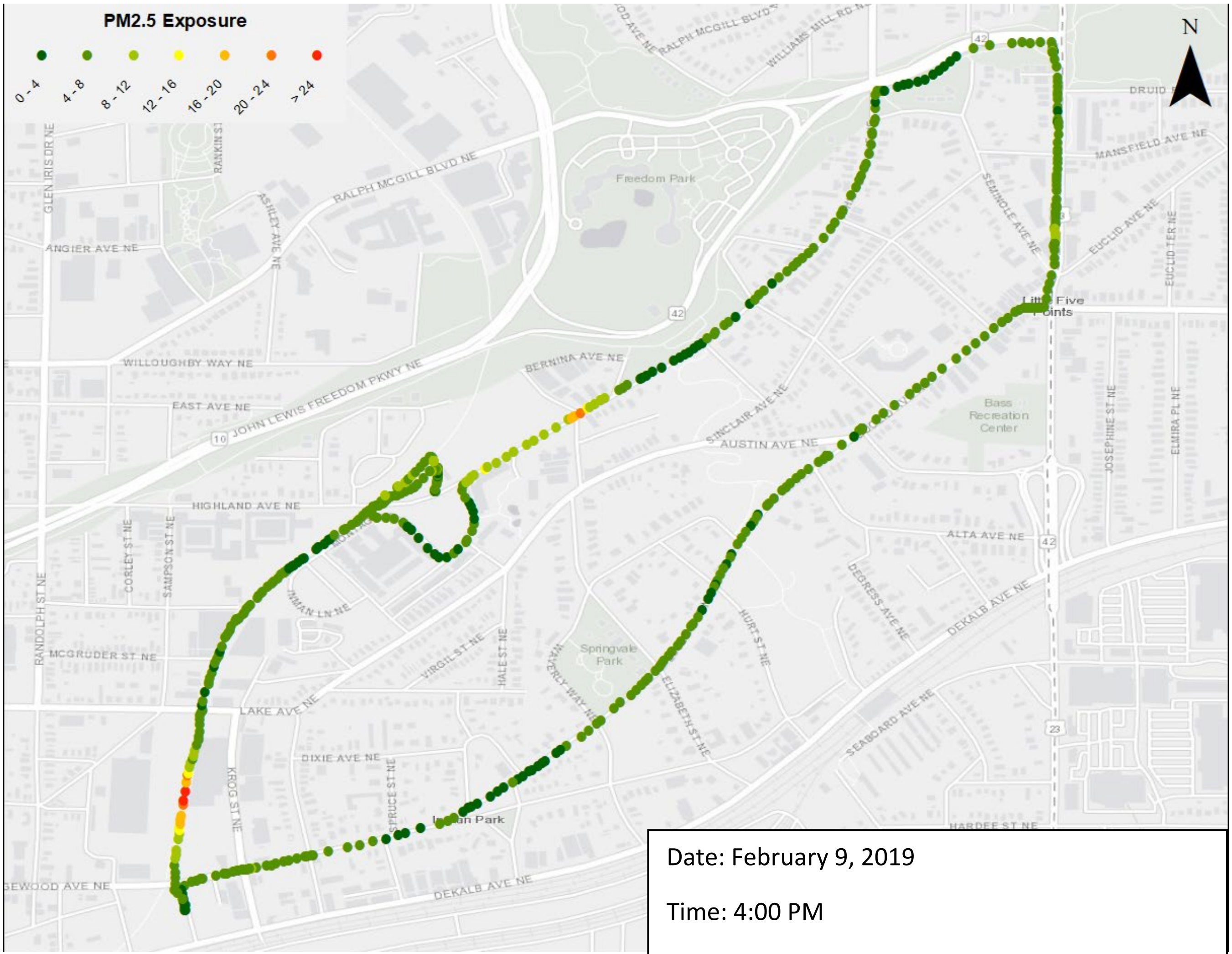
Background Air Quality Concentration: 5.2 µg/m$^3$



Date: February 4, 2019

Time: 6:20 PM

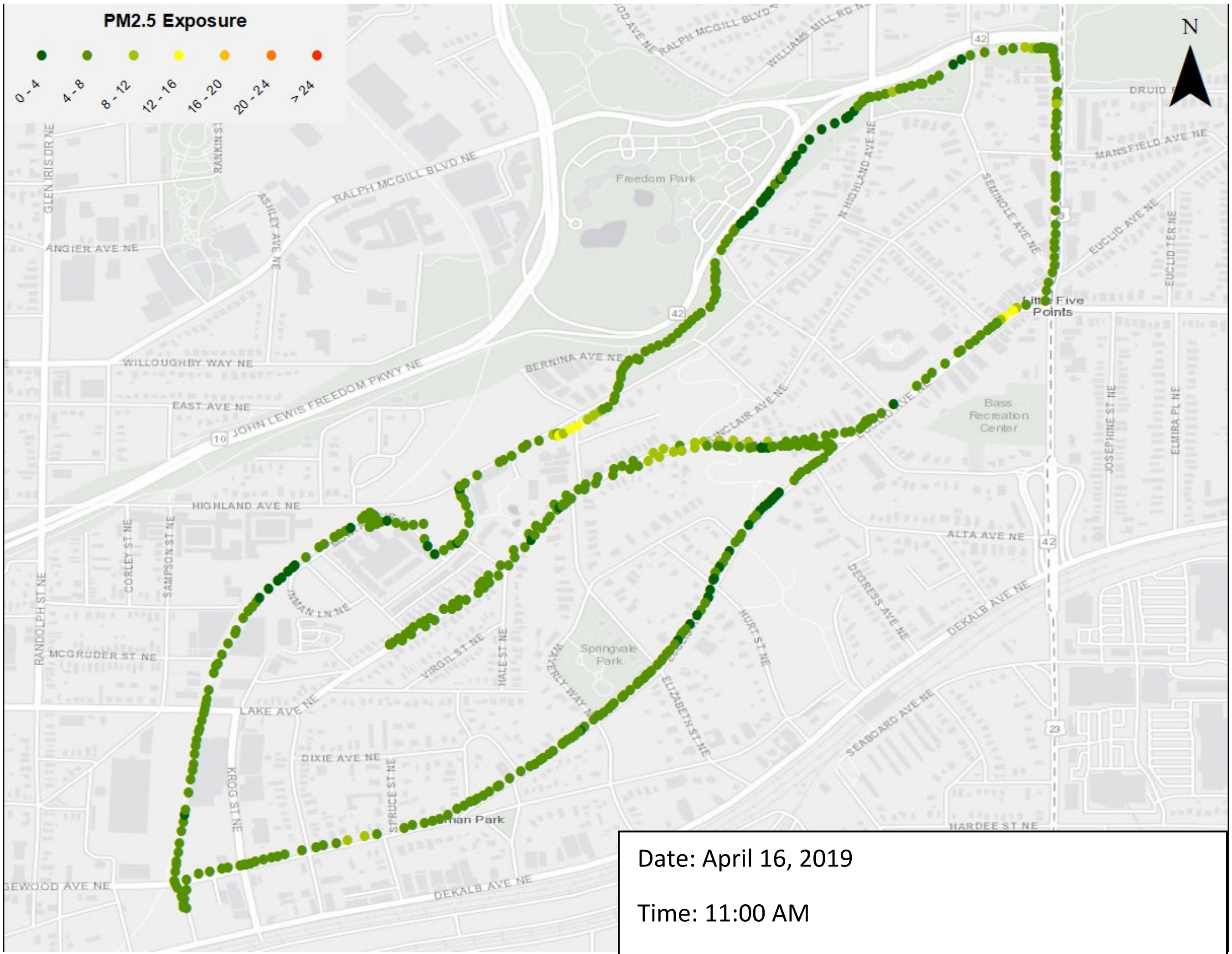
Background Air Quality Concentration: 9.2 μg/m$^3$



Date: February 9, 2019

Time: 4:00 PM

Background Air Quality Concentration: 4.3 µg/m$^3$

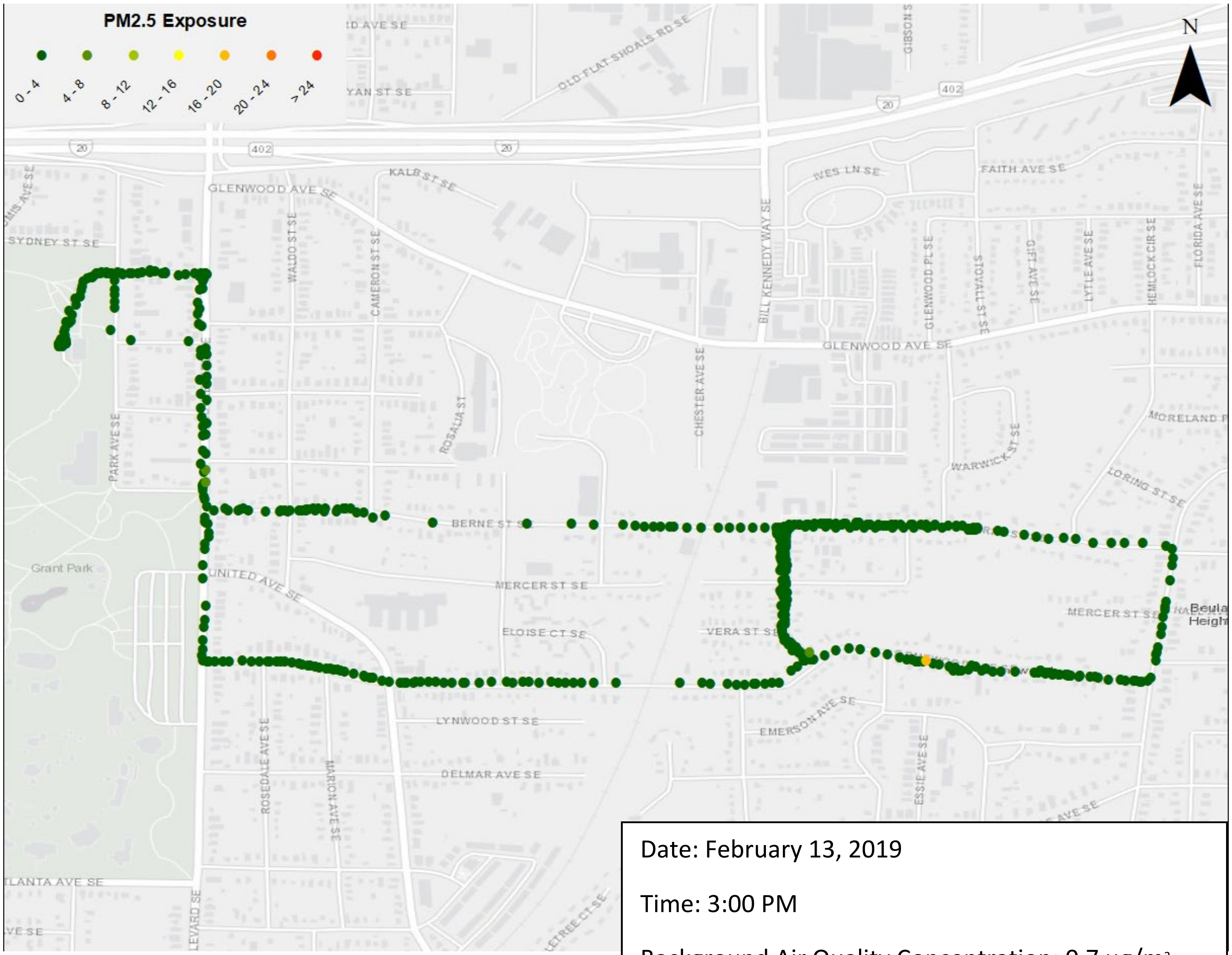


Date: April 16, 2019

Time: 11:00 AM

Background Air Quality Concentration: 5.3 µg/m$^3$

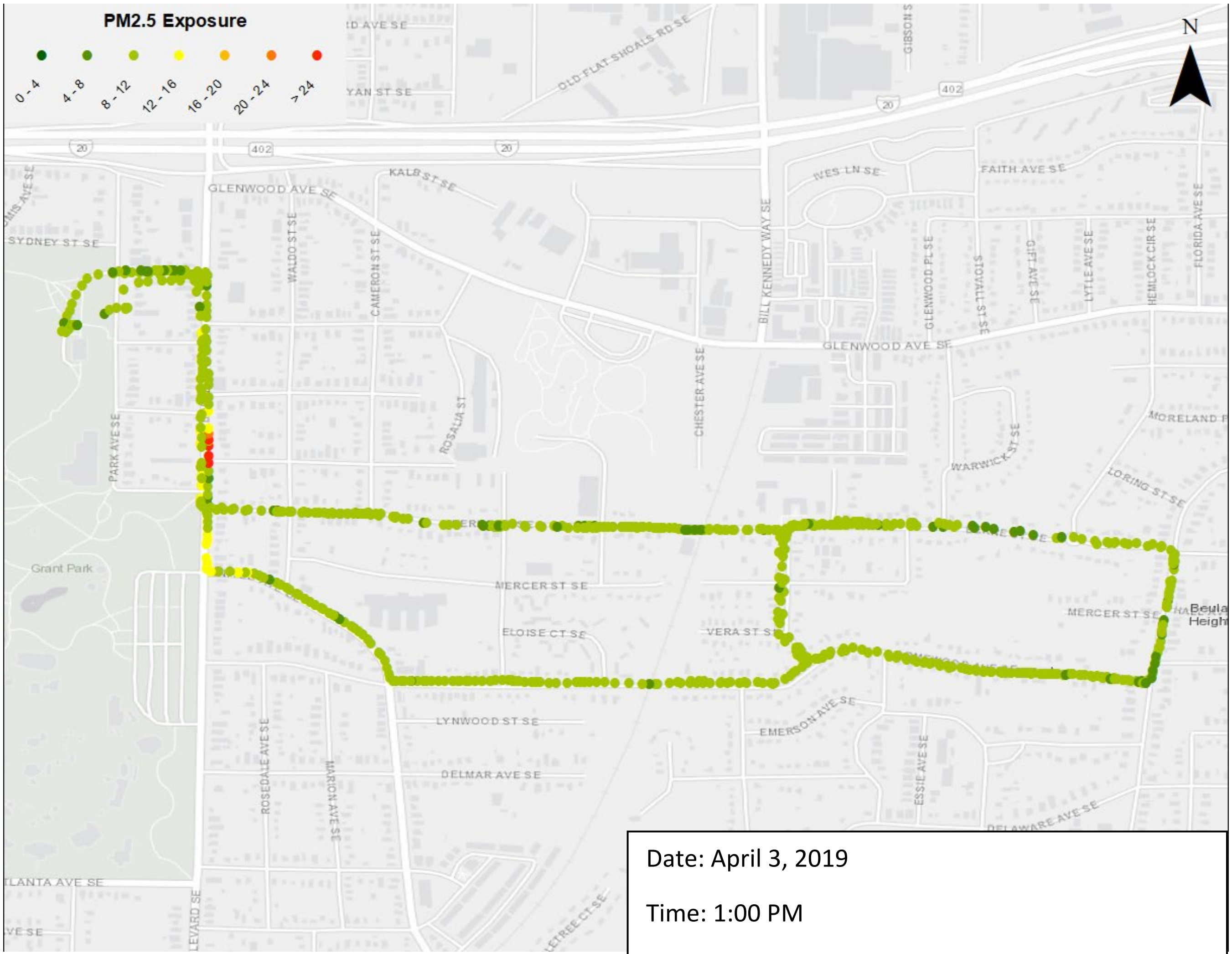
## Route 4



Date: February 13, 2019

Time: 3:00 PM

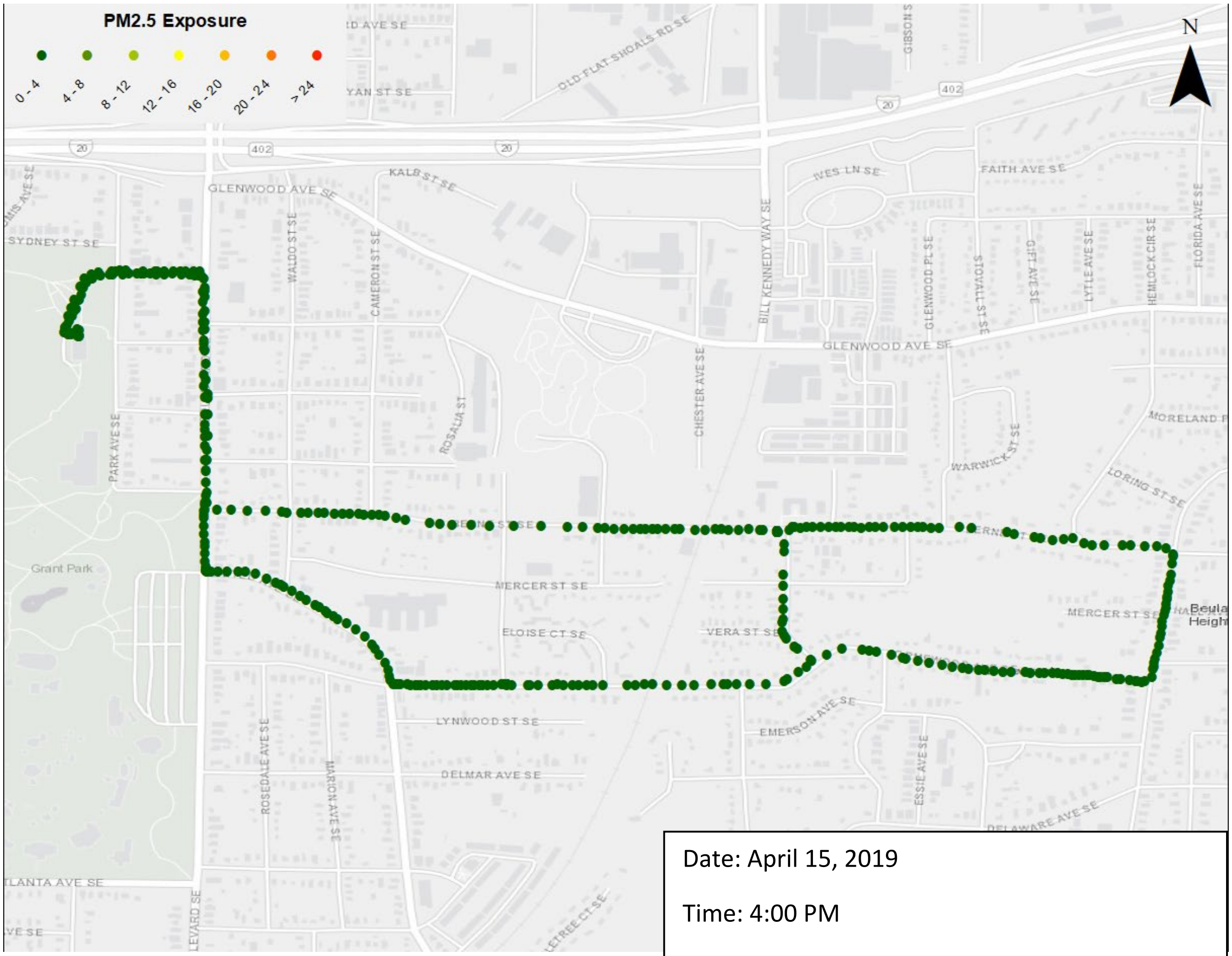
Background Air Quality Concentration: 0.7 µg/m$^3$



Date: April 3, 2019

Time: 1:00 PM

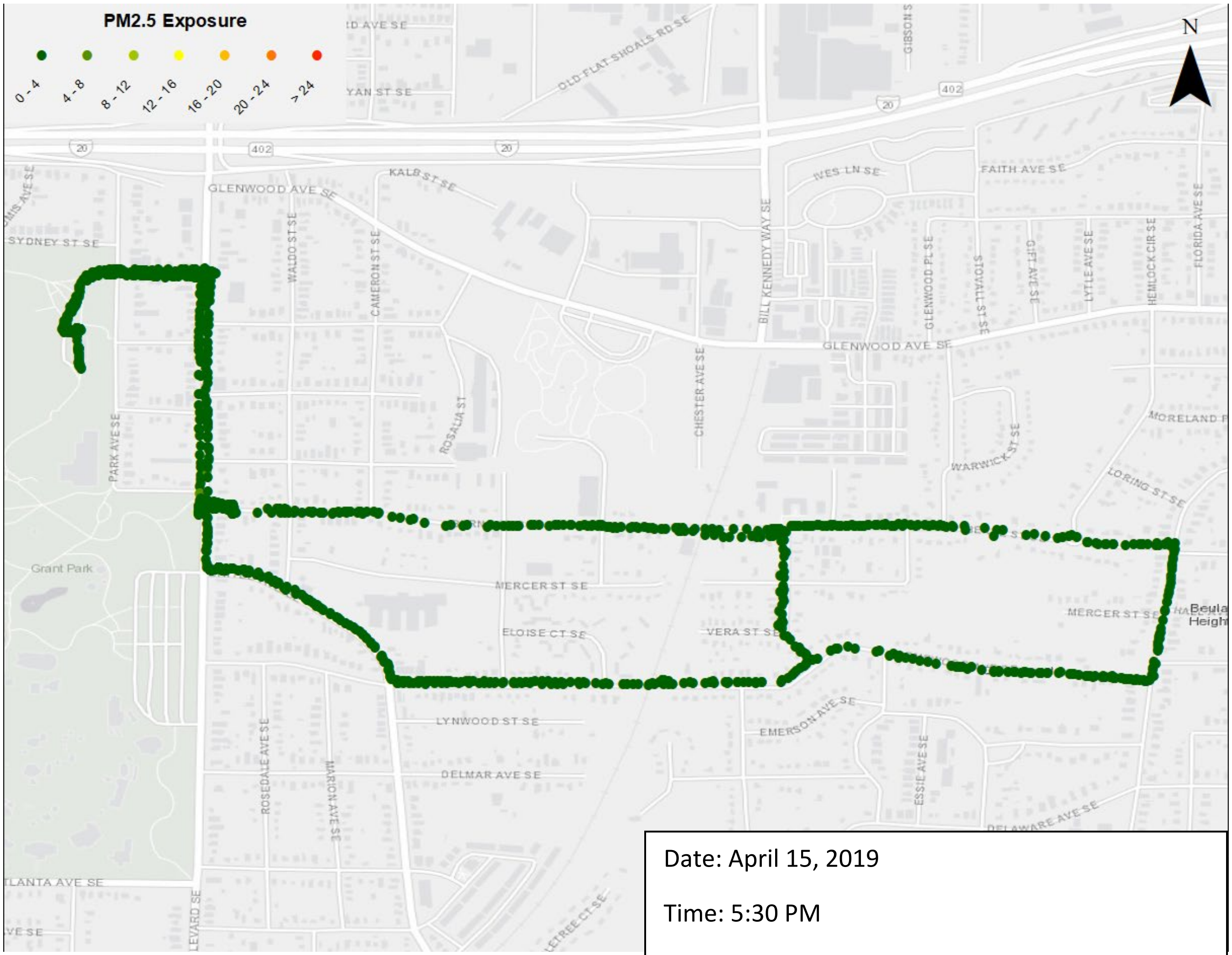
Background Air Quality Concentration: 5.1 µg/m$^3$



Date: April 15, 2019

Time: 4:00 PM

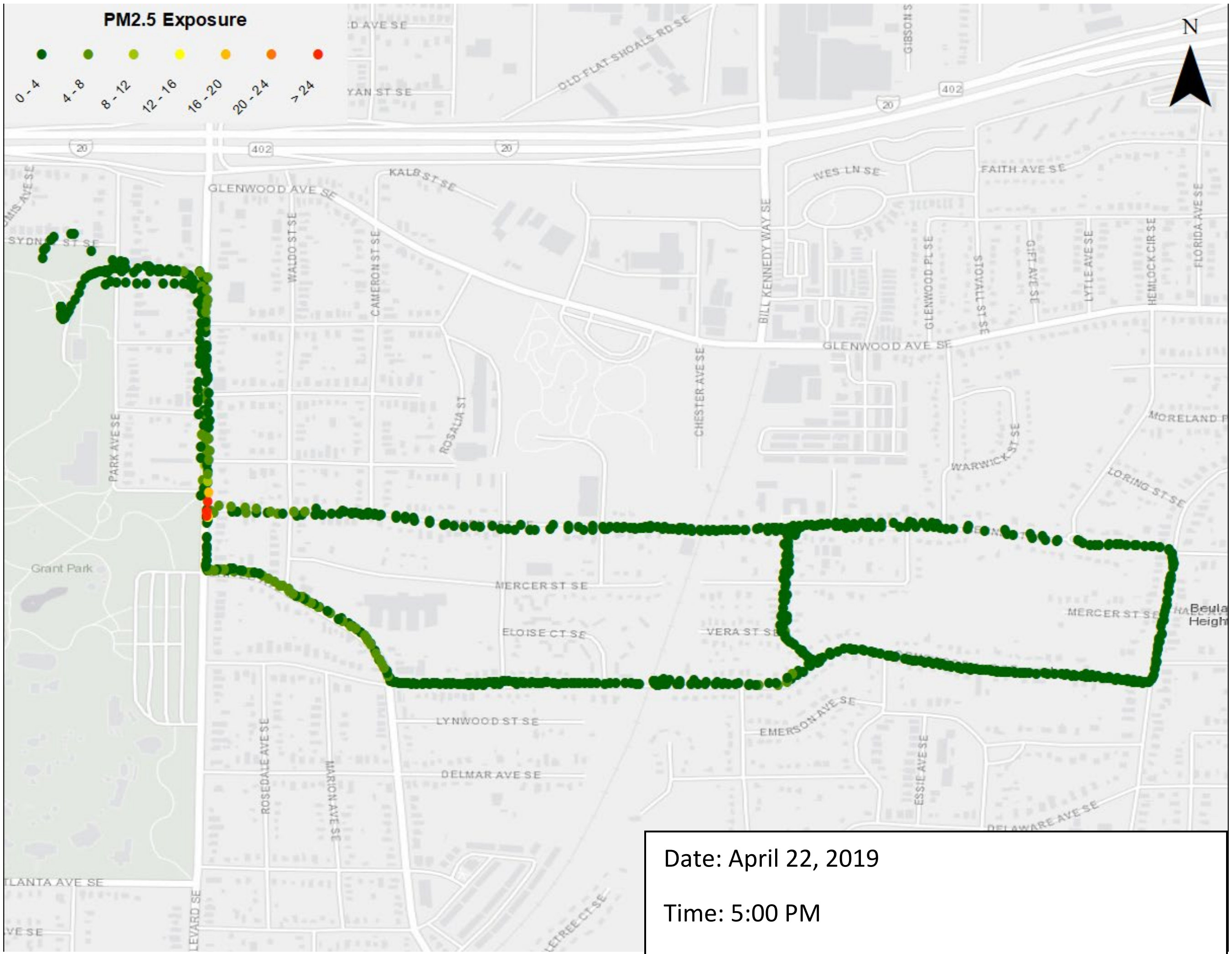
Background Air Quality Concentration: 5.6 µg/m3



Date: April 15, 2019

Time: 5:30 PM

Background Air Quality Concentration: 5.8 µg/$m^3$



Date: April 22, 2019

Time: 5:00 PM

Background Air Quality Concentration: 8.1 µg/m3