Hyperlocal Ambient Air Pollution Mapping: Washington D.C. Pilot Study

Nov 13, 2023

Version 1.2

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1 Introduction

Aclima is a mission-driven Public Benefit Corporation that deploys active roving fleets of vehicles instrumented with Aclima's proprietary vehicle-mounted mobile sensors and leading-edge sensing technologies, to measure and analyze concentrations of air pollutants and greenhouse gases over broad geographic areas and with hyperlocal, block-by-block resolution.

Aclima conducted hyperlocal mobile air quality measurements from June 15 to June 28, 2023 across three neighborhoods specified by Washington DC's Department of Energy and Environment (DOEE): Mayfair, Brentwood/Ivy City, and Buzzard Point (five census tracts total). Measurements included CO_2, $PM_{2.5}$, NO_2, CO, O_3, Black Carbon, methane, and TVOCs.

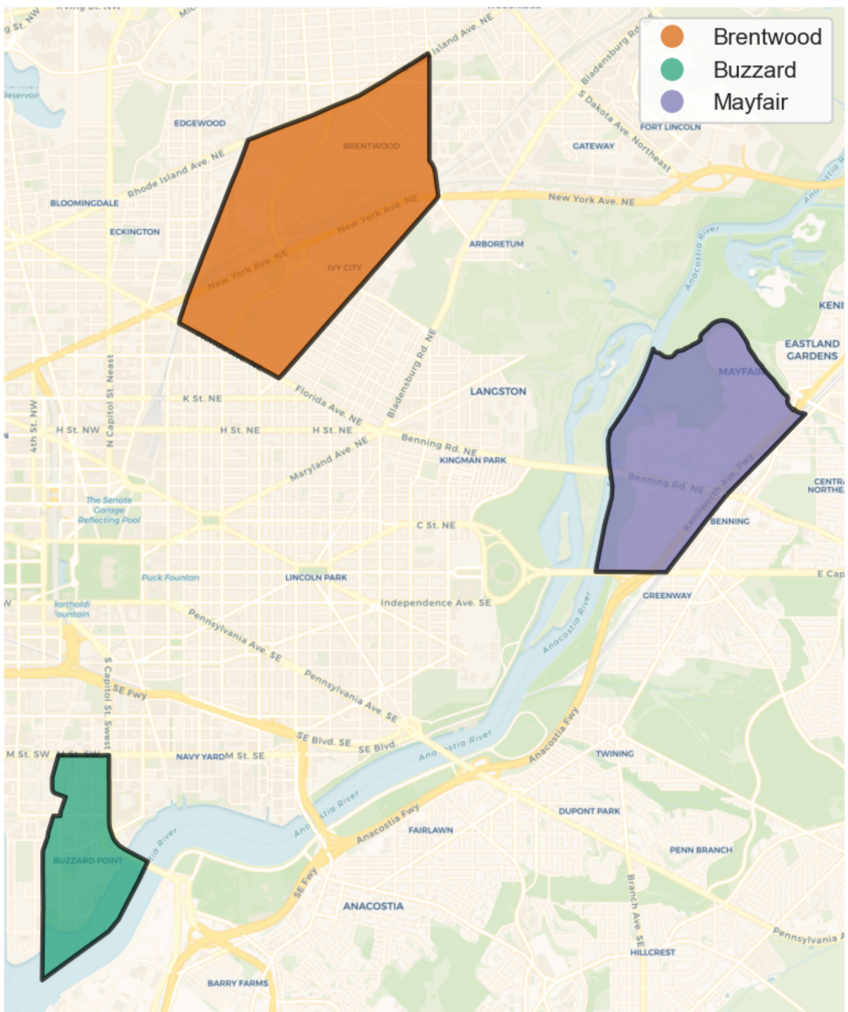

Figure 1. Locations of the three neighborhoods in the DC area where Aclima conducted hyperlocal monitoring.

The goal of this pilot is to provide the DC DOEE and community members actionable analysis about local air pollution, and to support regulators in their mission to understand emissions hotspots of air pollution, target interventions, engage communities, benchmark progress, and optimize investments in local interventions for maximum impact.

Aclima uses its specialized mobile mapping and analysis to generate maps that show typical pollution concentrations with high spatial resolution ("Hyperlocal Maps") across a specific region, city, or community. These maps highlight typical concentrations over a defined measurement period, in this case two weeks for the DC Pilot, illustrating high and low pollution concentrations at the street level. The maps are only one of many data products that can be generated from mobile mapping, but represent a foundational data product that fills a critical gap in understanding the spatial distribution of pollution. Aclima uses verified 1-Hz data to produce concentration estimates aggregated at ~100 m road segment lengths, allowing persistent pollution to be observed block by block in the three neighborhoods.

This report includes the following:

- Pollution maps, including median concentrations for $PM_{2.5}$, O_3, NO_2, CO, CO_2, and black carbon, aggregated to 100m length road segments, and binned into quintiles. These visualizations will allow users to identify areas with the highest air pollution and detect patterns among the different pollutants.
- Diesel Source maps that highlight locations of road segments where direct emissions from diesel exhaust (NOx, black carbon, and/or $PM_{2.5}$) are routinely observed, using Aclima's Diesel Indicator product. Users can leverage these maps to identify potential sources of diesel emissions and plan source-targeted interventions.
- Air Toxics maps that highlight locations where repeated local enhancements of total volatile organic compounds (TVOCs) were observed. These maps can help in the identification of local TVOC hotspots.
- Potential air pollution areas of concern for each neighborhood.
- Comparisons of measured concentrations in each of the neighborhoods relative to the nearest regulatory monitor, demonstrating any hyperlocal spatial heterogeneity in each of the pollutants.

Quarterly or annual driving projects allow for longer-term analyses such as seasonality, day-of-week, and annual averages on a hyperlocal spatial scale. For a two week pilot study, Aclima's analysis includes hourly time resolution for each of the three neighborhoods in the pilot to provide insight into diurnal patterns of different air pollutants, helping to identify sources that might be active at specific times of day (e.g. traffic during rush hour).

This high spatial resolution of Aclima's resulting data products supports identification of emissions sources as well as information on neighborhood-level variability in air pollution concentrations to support disparity analysis.

2 Methodology

Aclima's mobile air pollution monitoring fleets provide a flexible method to measure concentrations of a broad range of air pollutants and greenhouse gases over large, user-defined geographic areas and at higher spatial resolution than traditional monitoring techniques can provide. Aclima's fleet deploys on all public and accessible roadways within a user-defined area. The hyperlocal measurements produced by mobile monitoring can identify localized pollution sources as well as spatial gradients of pollutants across and between neighborhoods. Aclima's sensing system measures ambient air pollution and greenhouse gases at 1-Hz time resolution. Our mapping methodology is designed to drive each road multiple times, balancing sampling across different days of the week and times of day.

The mobile mapping method is not a reference method designed to support the National Ambient Air Quality Standards (NAAQS), which leverage a network of stationary regulatory monitors. Thus, data products from the mobile method do not support assessment of compliance with NAAQS. We assess the single pass mean segment data for conditions that, due to their sampling conditions or timing, are likely to result in biased estimates for typical ambient concentrations. The mobile mapping method is designed to complement NAAQS stationary networks by providing uniquely hyperlocal data.

2.1 One-second concentration measurements, geolocation, and aggregation into road segments

As Aclima's cars drive along publicly accessible roads, sensors within the Aclima Mobile Node (AMN) sample at a 1-second (1 Hz) frequency. These measurements are associated in the Aclima database with a specific 1-s Global Positioning System (GPS) time and location. The raw GPS position information can at times be some meters from the road the car was driving due to the fundamental uncertainty in the GPS measurement as well as external factors, such as tall buildings, interfering with the ability of the GPS system to achieve a solid location fix. The position of the raw GPS data is corrected to align with the route driven by the car, often termed snapping to the road, reducing location uncertainty.

All 1-second measurements are assigned to a ~100m road segment (Figure 2) based on the corrected location (latitude and longitude) of the data point. Each individual drive over a road segment of ~100m in length is defined as a pass. Aclima calculates a mean (average) for all 1-Hz measurements taken for each pass of a specific segment (single pass mean) that is assigned at the centroid of the segment. The number of 1-s measurements for each road segment varies based on the length of the segment, the speed limit of the street, and traffic conditions during the drive pass. Using ~100-m road segments allows multiple data points to be included in the calculation of the single pass mean, improving the estimate of the mean pollution level at that location. The use of the single mean for a road segment serves to give equal weight to all segments along a drive regardless of how many 1-second data points were collected in each segment. The result is time-resolved data at the segment level rather than 1-second.

The mean of the 1-second data points will be influenced by outliers, resulting in a collection of single-pass means that accommodate a greater degree of variability due to sampling than a collection of medians. Therefore, the resultant uncertainty estimates will be more conservative than if a single median had been selected.

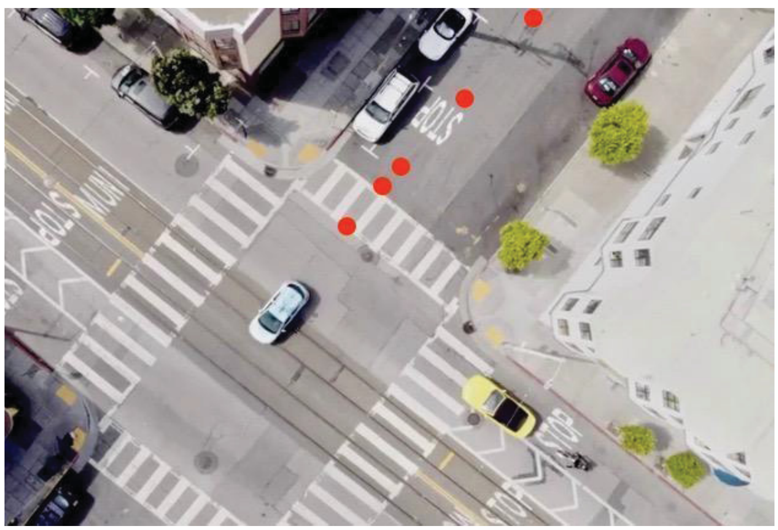

Figure 2. Illustration of 1-Hz data points as red dots aligned to the route of the car.

2.2 Enhancement Event Detection Methodology

As the mobile platform moves through an emissions plume, a temporary increase in concentration may be observed over time, which we call an enhancement event. We define these enhancement events as localized elevation in concentration of a given pollutant within the plume that is measurably distinguishable from the ambient background. These individual enhancement events represent the detection of an emission event for a particular pollutant in the immediate vicinity of the source. The enhancement events benefit from simultaneous measurement of multiple pollutants, which allow for additional specificity in identifying the source of the emissions and our multipass sampling approach, which support identification of the consistency over time with which a specific location is impacted by a particular emissions source.

TVOC Screen Methodology

TVOC enhancement events are calculated using data from our TVOC sensor, which is sensitive to a broad suite of VOC compounds. The enhancements are categorized into three different classes:

- Combustion: A TVOC peak that is measured at the same time as any peaks of Carbon Monoxide (CO), Carbon Dioxide (CO2), or Nitric Oxide (NO) measurements;
- Evaporation: A TVOC peak that happens in the absence of peaks in any of the other pollutants Aclima measures;
- Mixed: A TVOC peak that happens in the absence of a CO, CO2, or NO peak (see "Combustion"), but with the presence of other pollutants Aclima measures (example: Nitrogen Dioxide).

To indicate the consistency over time at a given location where enhancements are observed, we have calculated a "number of distinct days" metric to highlight areas that have seen an enhancement on more than one day. The distinct days metric applied to the sum of peaks of all classes observed within a hexagonal cell approximately 140 m long and wide. The higher the number of distinct days, the higher the likelihood of finding a persistent source of TVOCs in the vicinity of this location.

Diesel Source Indicator

The diesel source indicator seeks to identify areas that are impacted by diesel combustion emissions in the immediate vicinity of the mobile platform as it is sampling. The diesel indication requires both black carbon and NO concentrations that are enhanced above a baseline-adjusted time series, and aggregated to our predefined ~100 m segments. The baseline adjustment uses an algorithm that subtracts features in the baseline that are varying on time scales of minutes to hours and retains the features that vary on the order of seconds. Minimum enhancement thresholds in this baseline adjusted time series are based on the measurements being significantly higher than the sensor limit of detection. Both black carbon and NO have to meet minimum enhancement thresholds simultaneously for the segment to be identified as experiencing emissions from a local diesel source.

3 Results

3.1 Hyperlocal mobile monitoring data allows for identification of air quality differences between blocks in a neighborhood

This section contains pollutant maps of the three neighborhoods in DC included in the two-week pilot. Each pollutant is mapped separately, with segment median concentrations color-coded by quintile. Separate close-up maps of each neighborhood are provided in the appendix of this report.

There are also maps highlighting TVOC hot spots (Figure 9), diesel-influenced segments (Figures 10-11), and diesel-influenced measurements for each neighborhood by road type (Figure 12).

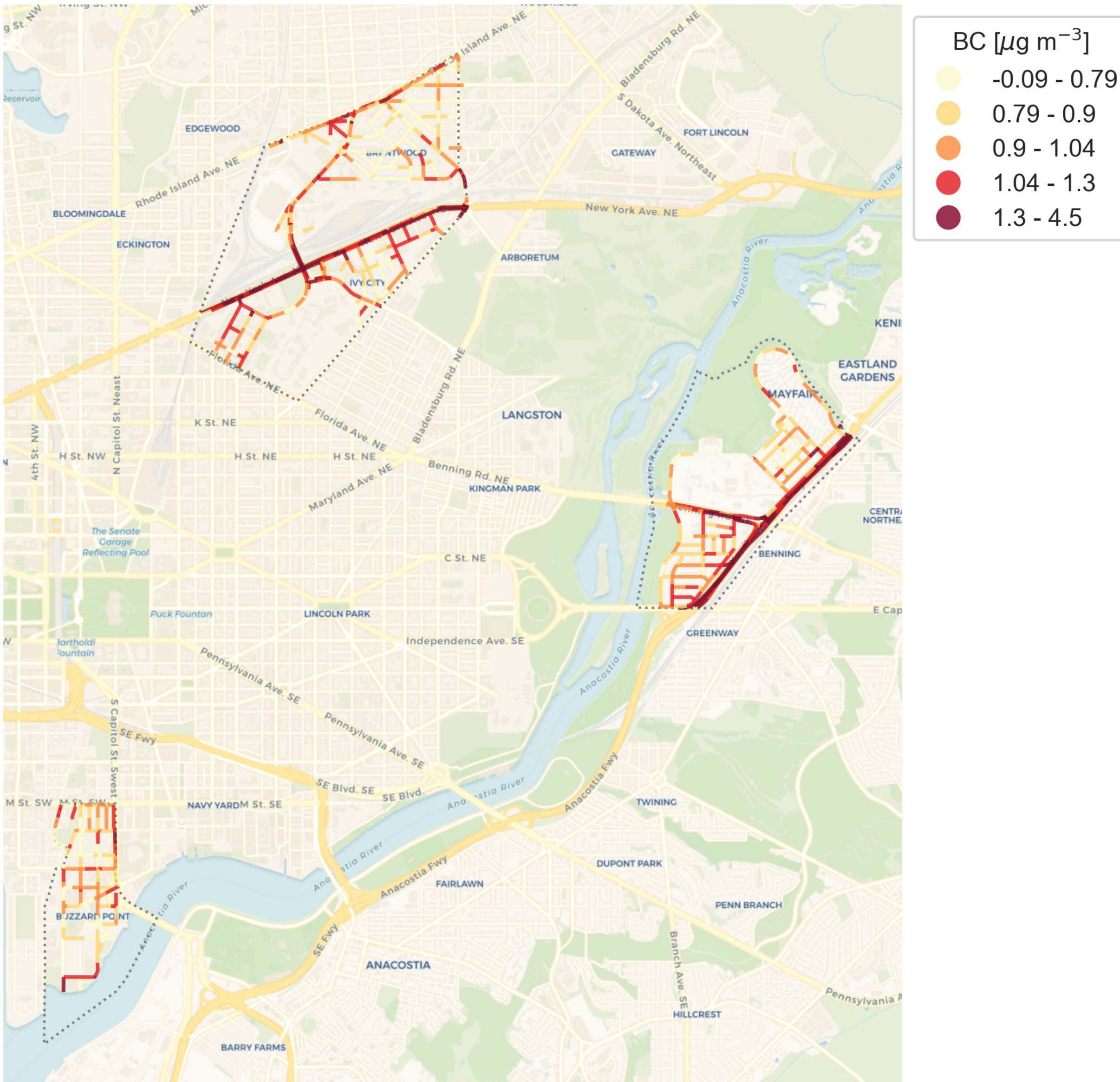

Figure 3. Segment medians of Black Carbon in the three neighborhoods.

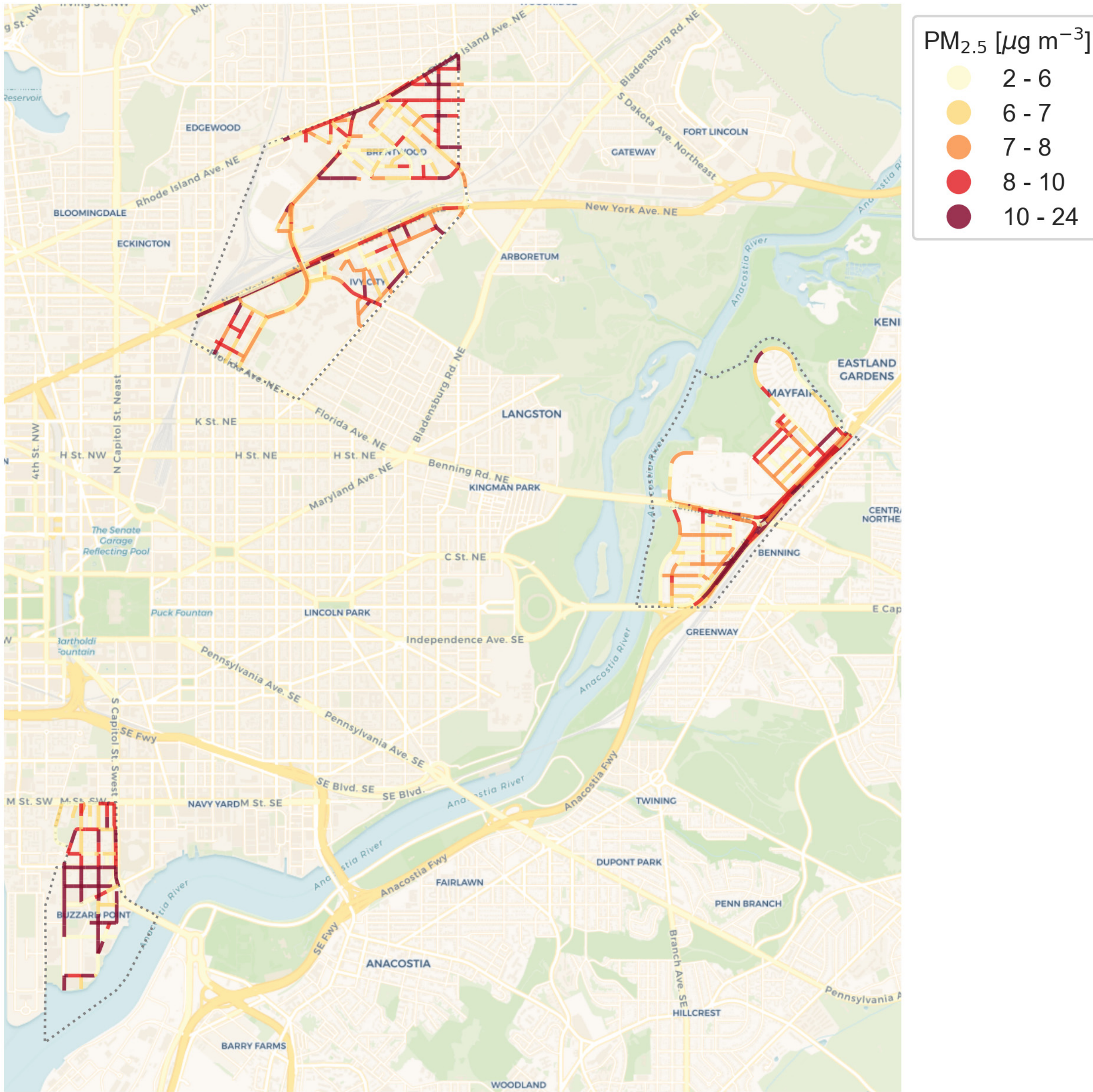

Figure 4. Segment medians of $PM_{2.5}$ in the three neighborhoods.

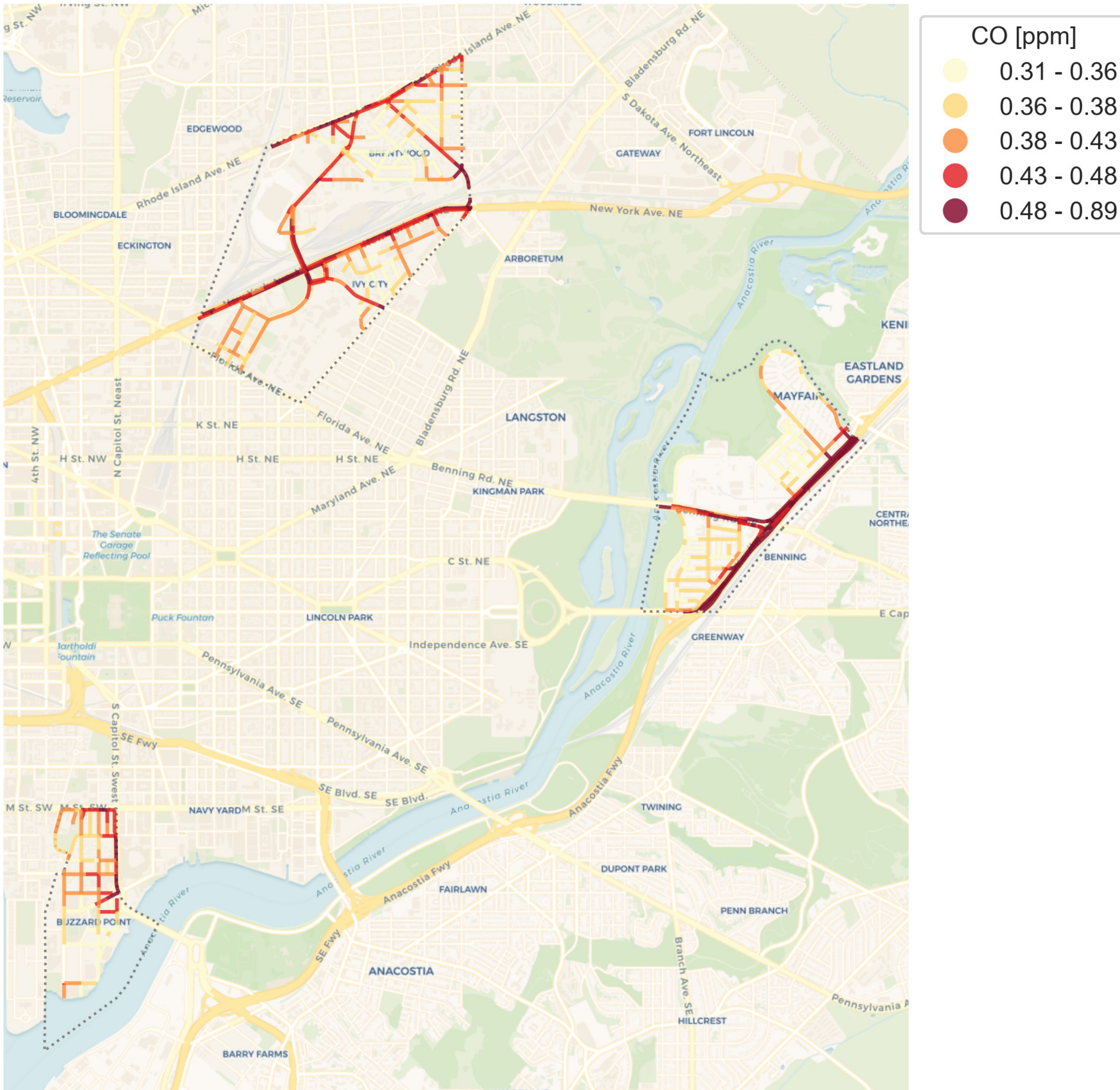

Figure 5. Segment medians of CO in the three neighborhoods.

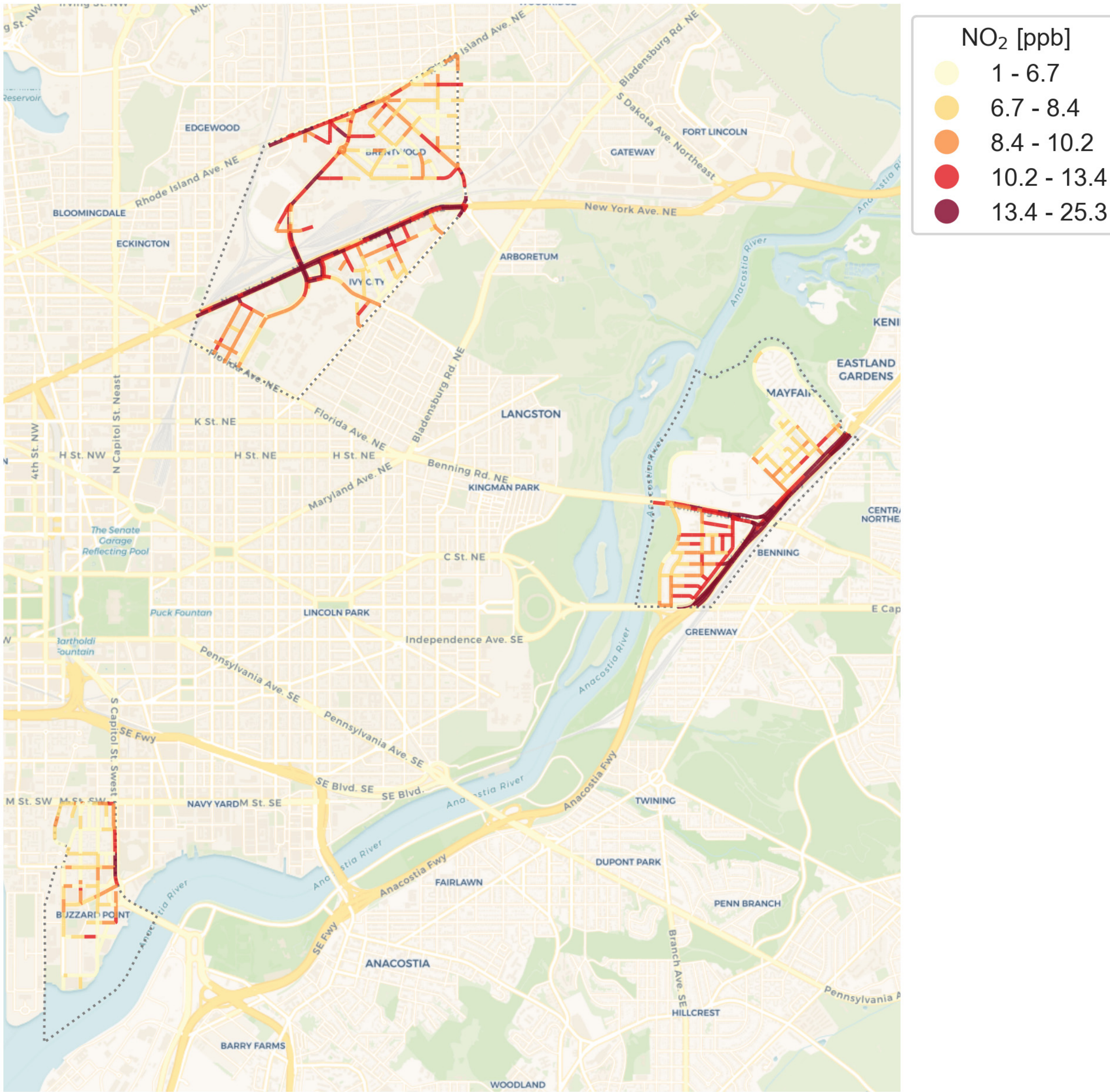

Figure 6. Segment medians of NO_2 in the three neighborhoods.

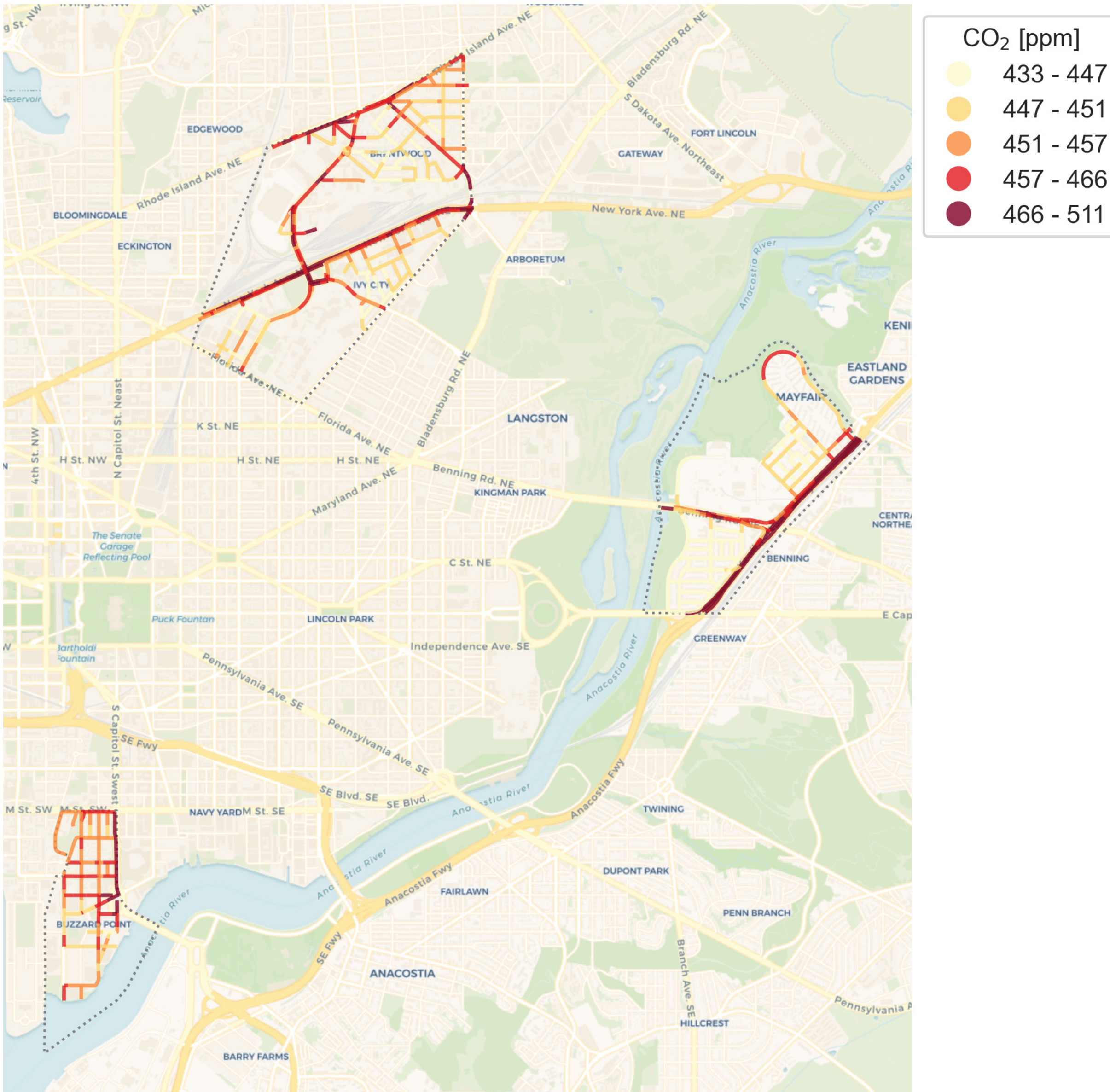

Figure 7. Segment medians of CO_2 in the three neighborhoods.

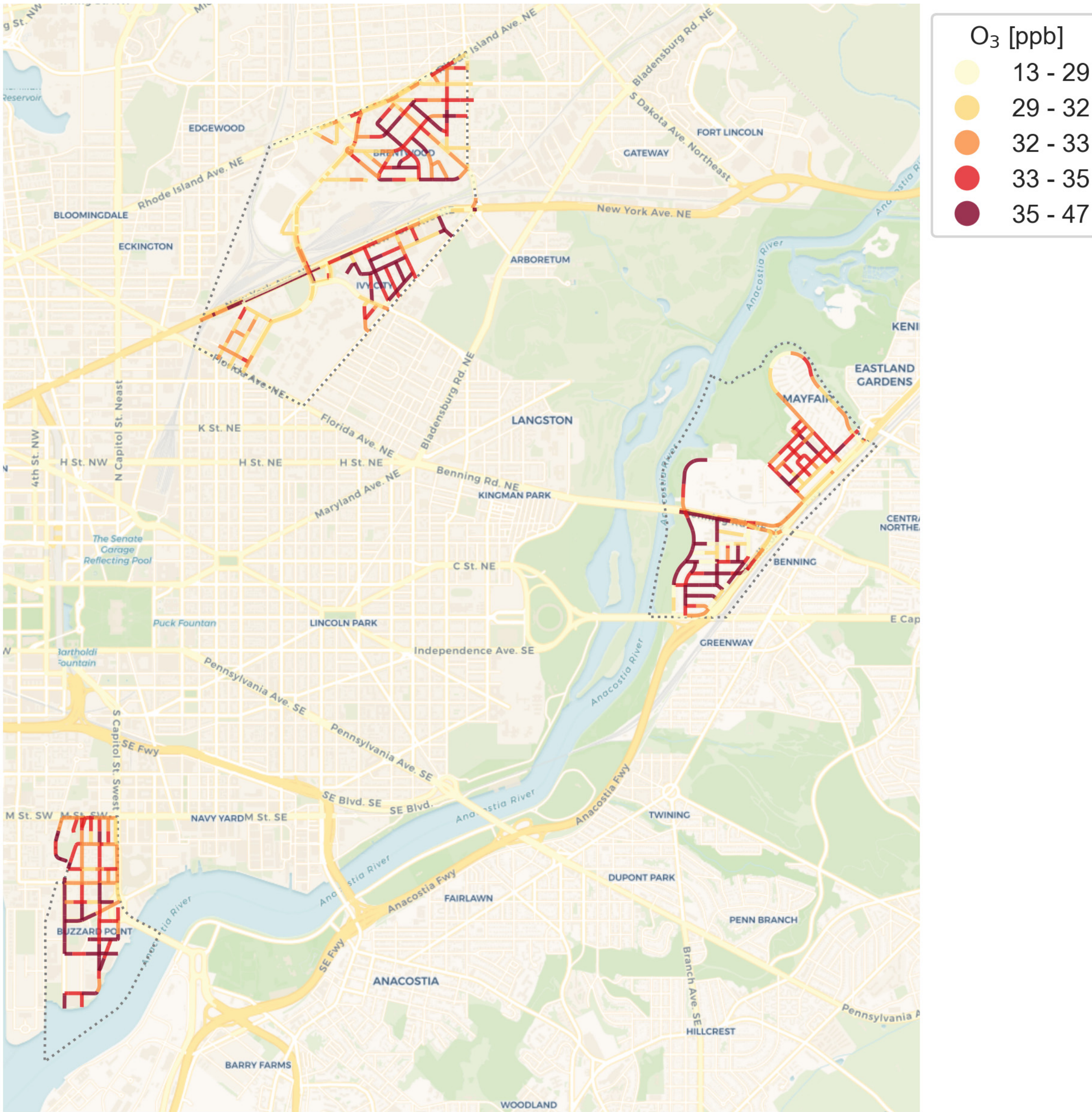

Figure 8. Segment medians of O_3 in the three neighborhoods.

Figure 9 is a map of TVOC hotspots that highlight locations where repeated local enhancements of total volatile organic compounds were observed. Brentwood/Ivy City contained the most TVOC hot spots, including both combustion-related TVOCs and evaporative TVOCs from non-combustion sources.

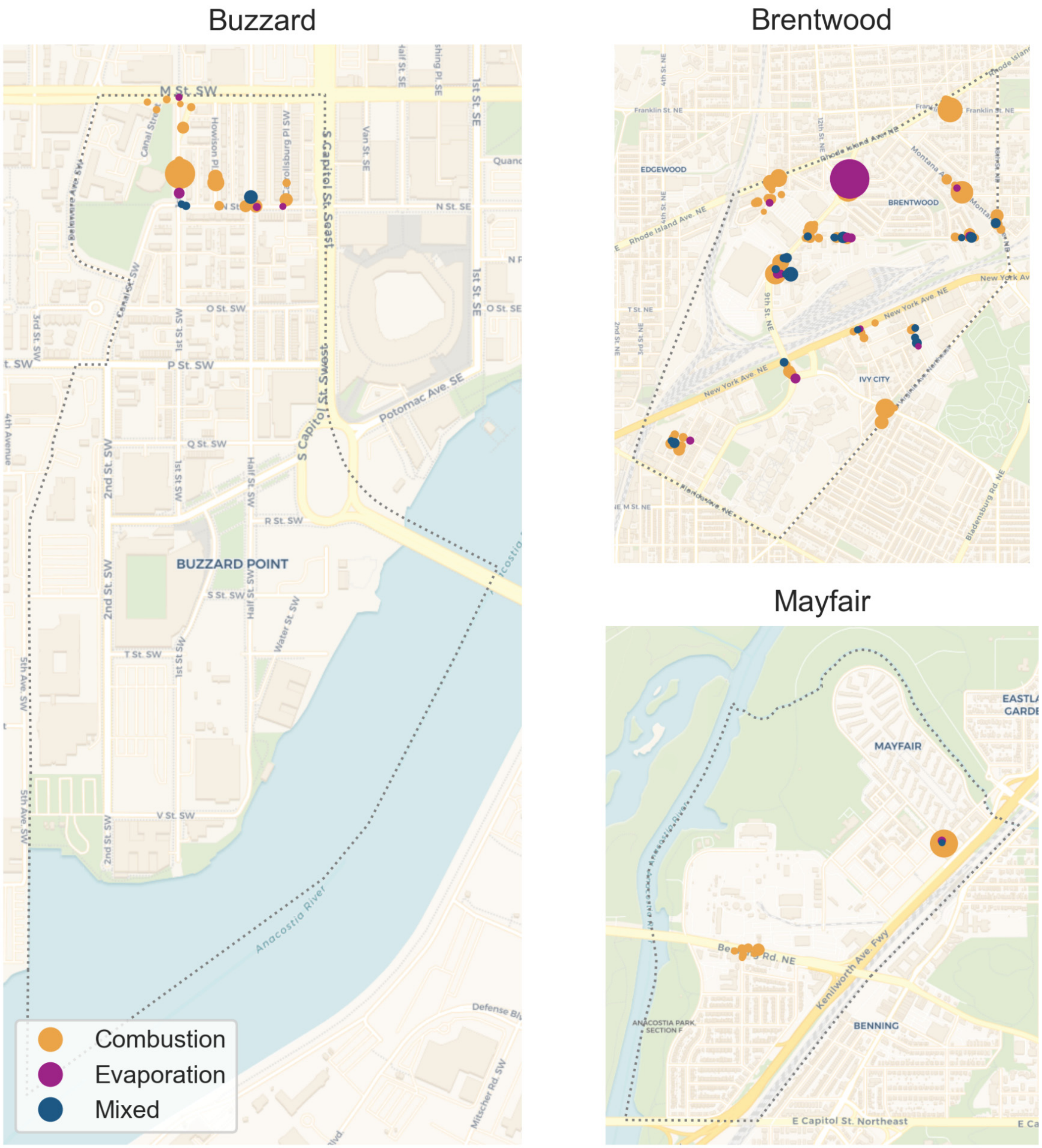

Figure 9. TVOC hot spots detected at least six of the measurement days, including combustion-related TVOCs (orange), evaporative TVOCs (purple), and a mixed combination of the two (blue). The size of the markers indicates the strength of the TVOC peak i.e., the height of the peak observed in the time series.

The diesel indicator uses concurrent black carbon and NO enhancements to identify influences of diesel combustion emissions. This indicator is designed to be selective – both BC and NO enhancements have to be concurrent and both have to be higher than certain thresholds.

Figures 10 and 11 below show locations where the diesel indicator was observed. Figure 10 includes all segments, while Figure 11 excludes highways, showing only surface street segments. Visualizing the diesel indicator on surface streets helps identify areas where diesel combustion emissions are occurring in close proximity to residences, pedestrians, and other locations where individuals can be exposed. For example, Figure 11 demonstrates that surface streets immediately south of New York Ave in Ivy City (Brentwood) are impacted by diesel emissions. These maps are the outcome of two weeks of measurements. It is likely that repeated measurements in this and other similar residential neighborhoods over a longer term would help identify local, persistent diesel emission impacts throughout Washington D.C.

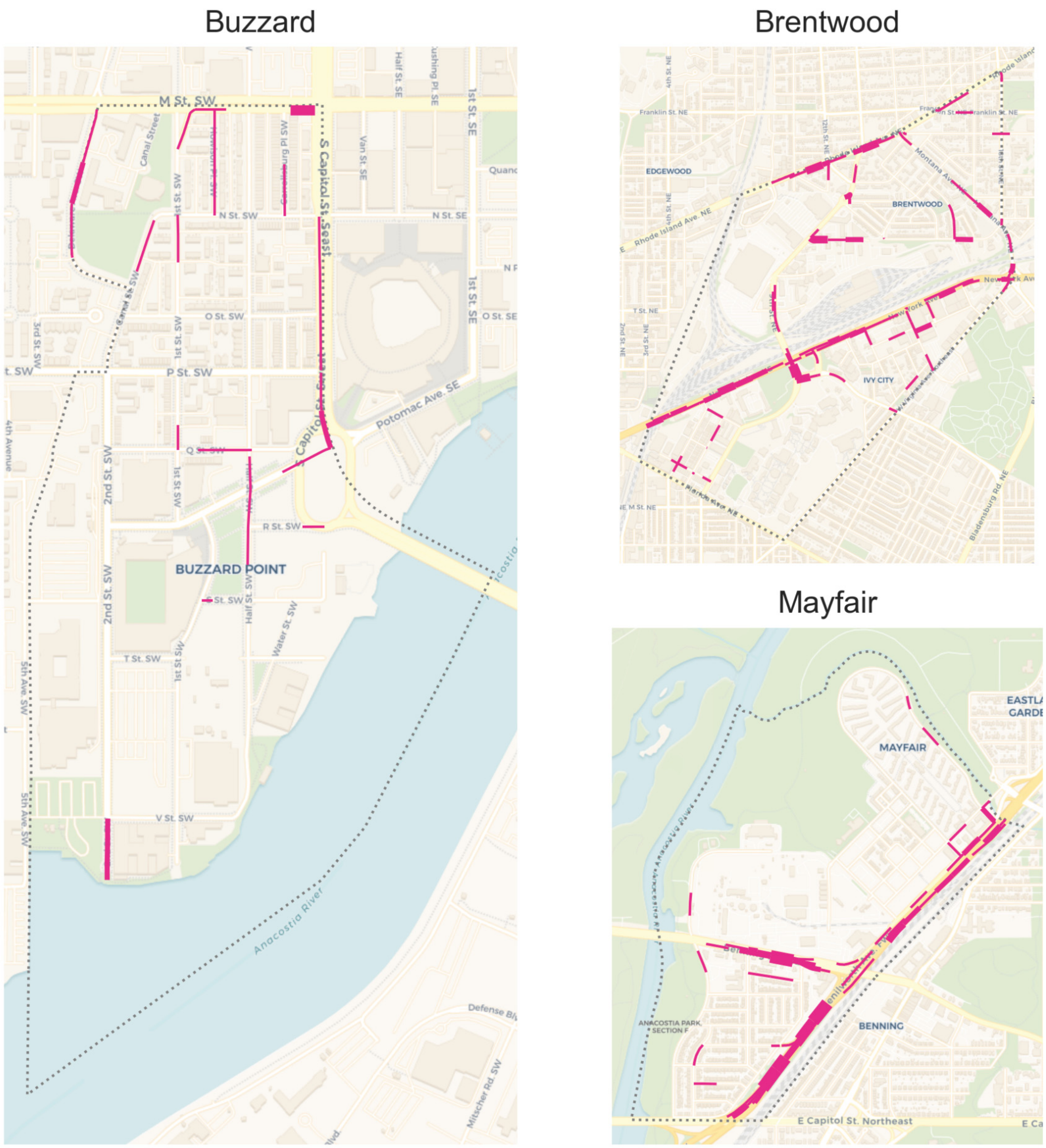

Figure 10. Diesel-influenced road segments **including** highways, where thickness of the pink bars increases with number of diesel observations per segment.

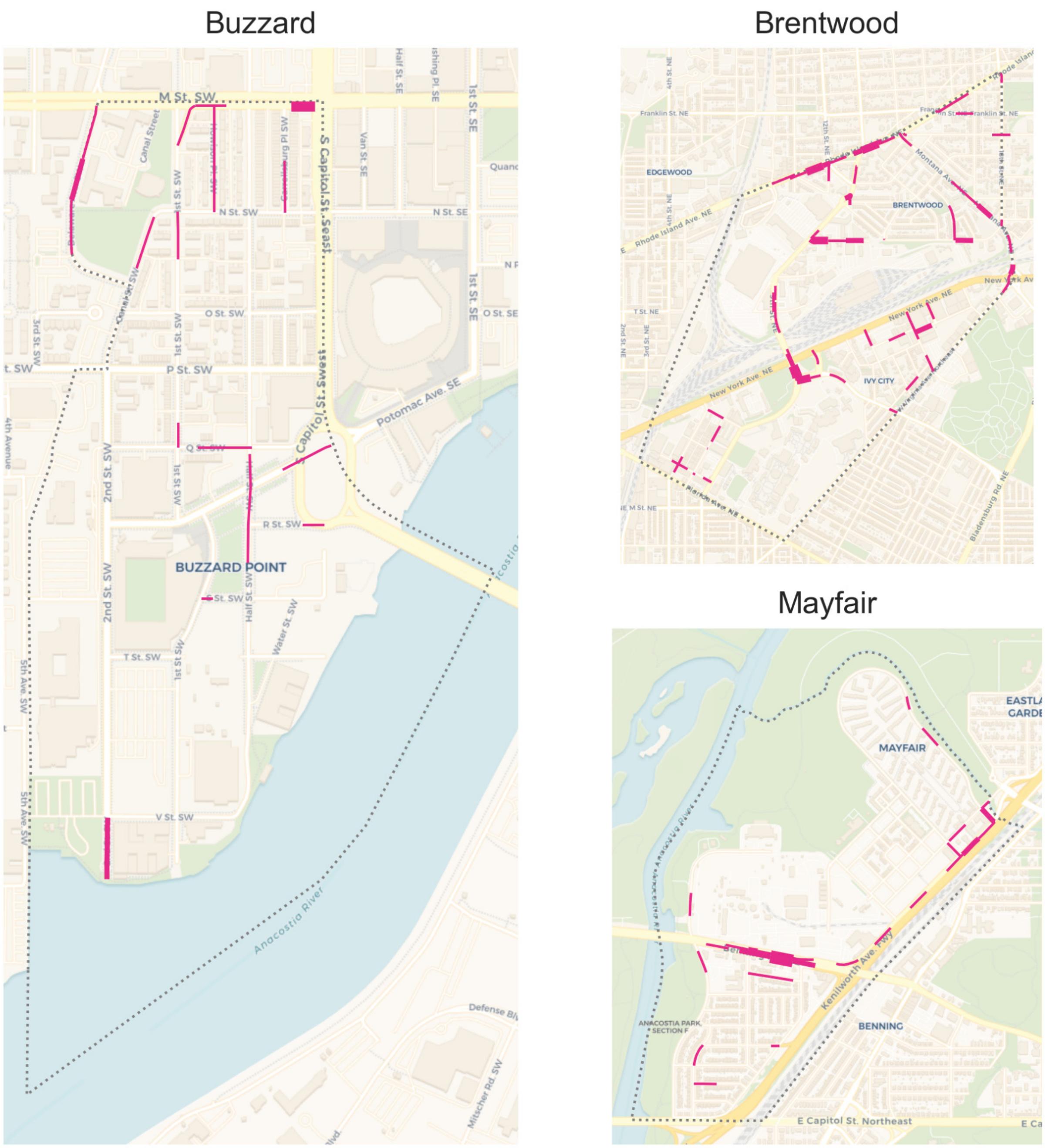

Figure 11. Diesel-influenced road segments **excluding** highways, where thickness of the pink bars increases with number of diesel observations per segment.

Figure 12 shows how many times we observed diesel influence at the road segment level, expressed as a fraction of the total number of times we visited that segment (this percentage can indicate the persistence of diesel emission impacts). These segment-level data are grouped by neighborhood and road type. Mayfair, which has two arterial roadways (Anacostia freeway and Benning Road) has the most persistent diesel emission influence. Buzzard Point, on the other hand, has high diesel emission persistence on its highway segments, but lower on surface streets.

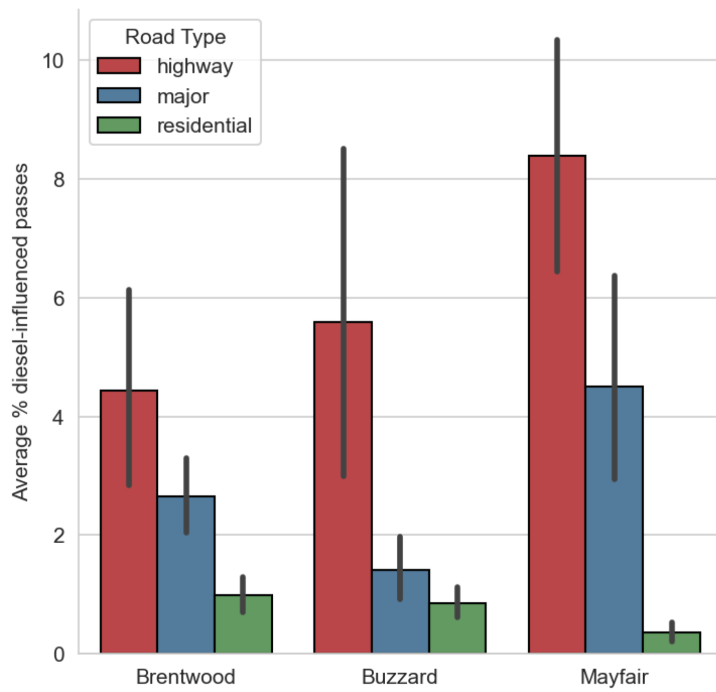

Figure 12. Percent of diesel-influenced drive passes for all segments in each of the three neighborhoods, sorted by the segment road type.

3.2 Diurnal patterns in pollutants

Mobile monitoring provides hyperlocal spatial information on air pollution, but with sufficient samples and driving time, diurnal patterns can also be distinguished in the different neighborhoods. Temporal resolution from a two week pilot study is limited due to sample size, but there are some trends that are still discernible. For example, in Figure 13 below, measurements in Mayfair indicate elevated Black Carbon, CO, CO_2, NO_2, and $PM_{2.5}$ in the early morning hours which likely corresponds to early morning diesel traffic, consistent with the diesel indicator map in Figure 10.

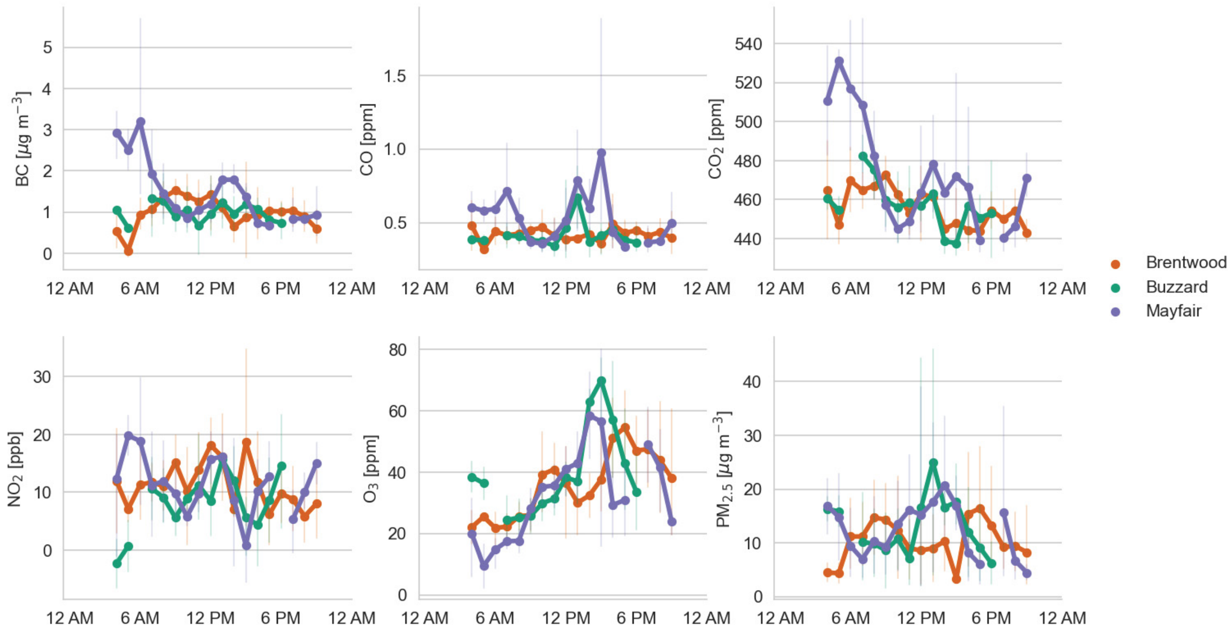

Figure 13. Hourly resolution diurnal plots for Brentwood/Ivy City, Buzzard Point, and Mayfair by pollutant. Vertical bars indicate the 5th and the 95th confidence intervals.

3.3 Potential air quality areas of concern in the three regions

Examples of potential air quality areas of concern are included in the following sections for each of the three regions measured during this two week pilot. This is not an exhaustive list of all areas of concern that could be identified from this pilot study, but an example of analyses that can identify air pollution hotspots and potential sources.

3.3.1 Brentwood/Ivy City

Two pollution hotspots of concern in the Brentwood/Ivy City neighborhoods are included below, including a non-combustion-related TVOC hotspot near a gas station and elevated CO_2, $PM_{2.5}$, NO_2, CO, black carbon, and diesel impact along New York Avenue NE in Ivy City.

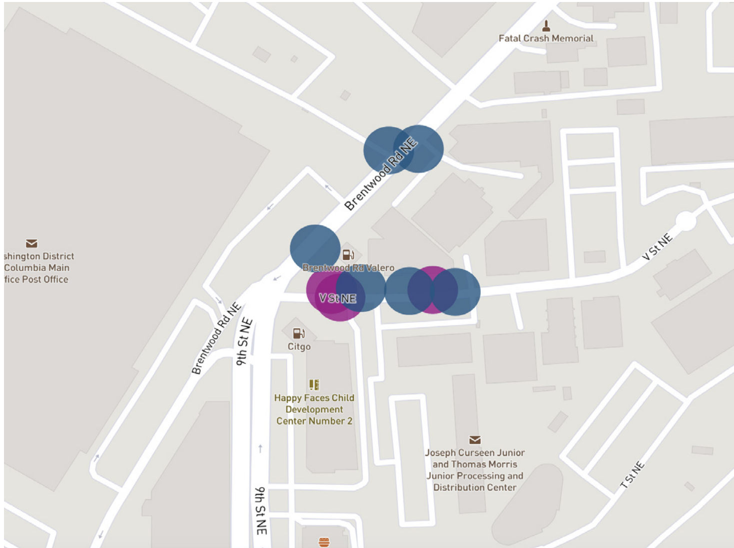

Figure 14. Map of Evaporative (purple) and mixed-source (blue) TVOC peaks detected across 5 unique days around a gas station in Brentwood.

The section of New York Avenue NE runs alongside a large railyard, and is consistently in the top quintile of CO_2, $PM_{2.5}$, NO_2, CO, and black carbon (Figure 15). Due to proximity to the railyard, pollutants measured here are likely from both road traffic and rail operations.

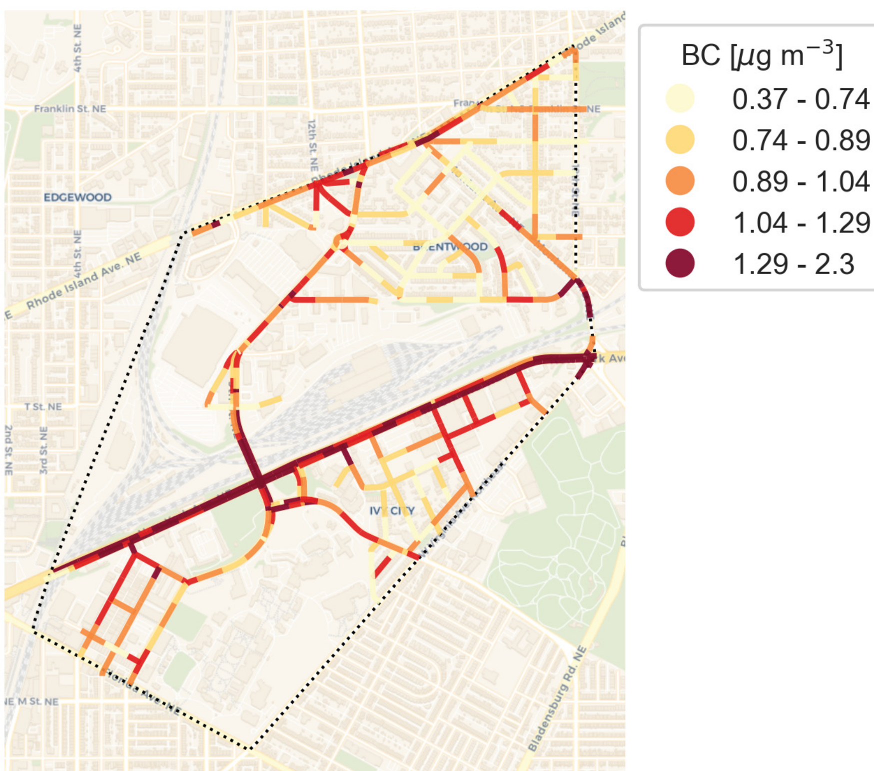

Figure 15. Segment medians for BC in the Brentwood/Ivy City neighborhoods.

3.3.2 Buzzard Point

Concentrations of $PM_{2.5}$ in Buzzard Point were consistently in the upper quintile of the concentrations measured during the two-week pilot. One method for source investigation is through comparison of co-emitted pollutants. In Buzzard Point, some of the segments with high concentrations of $PM_{2.5}$ contain low concentrations of combustion byproducts such as CO, indicating a non-combustion source of the particulate matter.

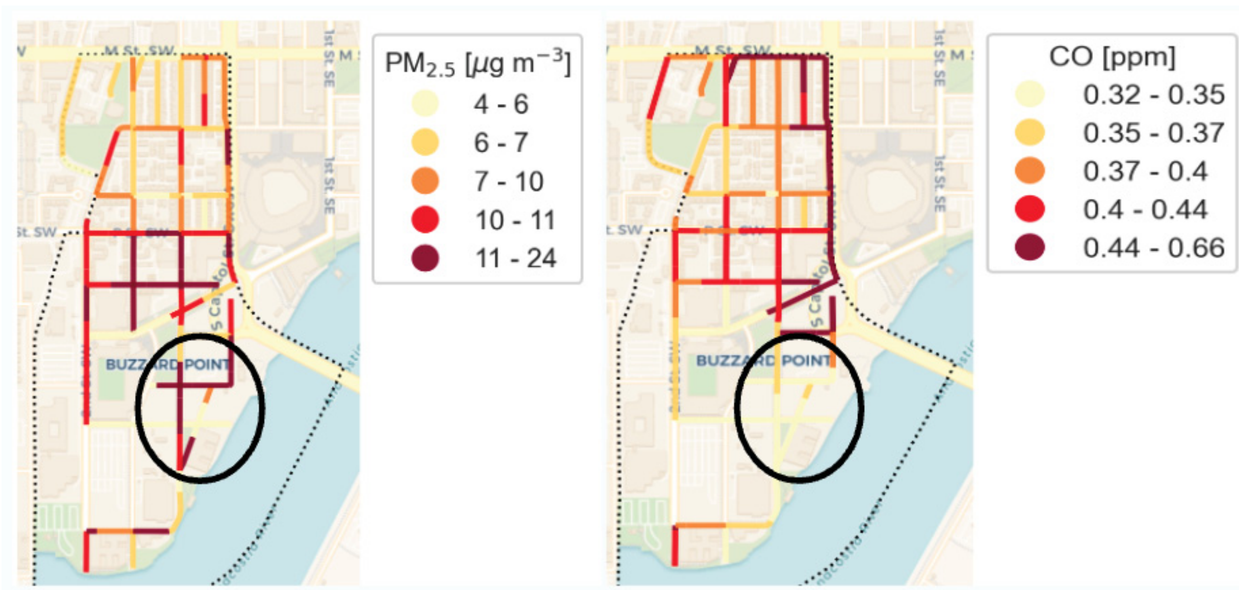

Figure 16. Segment medians for $PM_{2.5}$ (left) and CO (right) in Buzzard Point, with black circles highlighting segments with high $PM_{2.5}$ and low CO.

Clusters of persistent, non-combustion-related TVOCs were also detected near King-Greenleaf Recreation Center (Figure 17). The source or sources of these clusters is not immediately apparent.

Figure 17. Map of Evaporative (purple) and mixed-source (blue) TVOC peaks detected across 5 unique days near King-Greenleaf Recreation Center.

3.3.3 Mayfair

Mayfair and the surrounding residential neighborhoods are impacted by proximity to the Anacostia Freeway and Benning Road. There is a strong spatial gradient in $PM_{2.5}$, BC, CO, and NO_2 that is highest on and near the two major roads, and decreases in concentration with increasing distance from the roads.

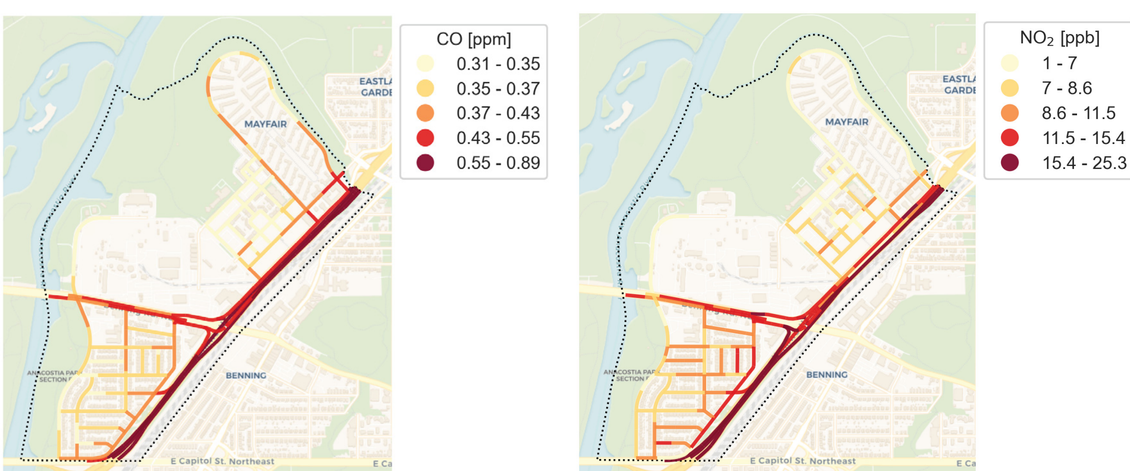

Figure 18. Segment medians for CO (left) and NO_2 (right) in Mayfair

A map of diesel impact in the area suggests significant diesel contribution on both Anacostia Freeway and Benning Road, as well as a number of the nearby side roads.

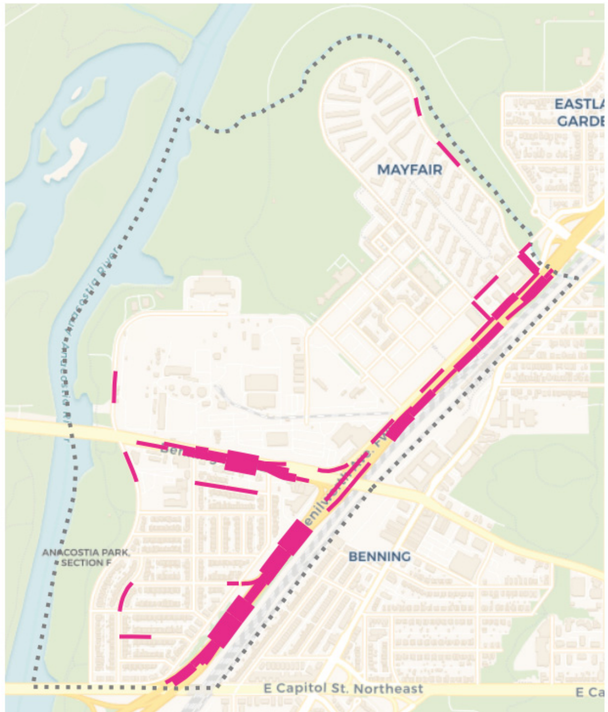

Figure 19. Diesel-influenced road segments in the Mayfair and surrounding neighborhoods, where thickness of the pink bars increases with the number of diesel observations.

3.4 Mobile monitoring captures spatial heterogeneity of neighborhoods near DOEE stationary monitoring sites

DC DOEE regulatory monitors operating during the 2-week pilot provided a temporally matched dataset for comparison with the mobile measurements. Direct comparisons of regulatory site concentrations and mobile data collected within a 250m radius of the site is included in the Appendix. We expect the pollution concentrations to be spatially heterogeneous due to the hyperlocal variability measured by the mobile platform reflecting local sources. The degree of spatial heterogeneity can be illustrated by comparing the distribution of segment medians in each neighborhood with temporally matched data from the nearest stationary regulatory monitors.

The spatial heterogeneity of the three neighborhoods is displayed in Figure 20 as a probability density function of all segment median values from the 2-week pilot for each of the 3 neighborhoods. While stationary monitors capture the temporal variability, the sites do not capture the variability of pollution concentrations within these neighborhoods. For instance, the density plot in Figure 20 shows over 20 ug/m3 spread of $PM_{2.5}$ in three neighborhoods, whereas the four regulatory sites are clustered around a 1 ug/m3 range. The accompanying bar plots show the 10-90th percentile ranges of segment medians grouped by neighborhood and road type and further demonstrate that even the 10-90th percentile ranges of mobile monitoring far exceed the full range of the four regulatory sites. The 1 hour precision for the Aclima Mobile Node (AMN) is also shown in Figure 20 (see Appendix A.1), to put the magnitude of variations captured in the neighborhoods and across road types into context with sensor uncertainty.

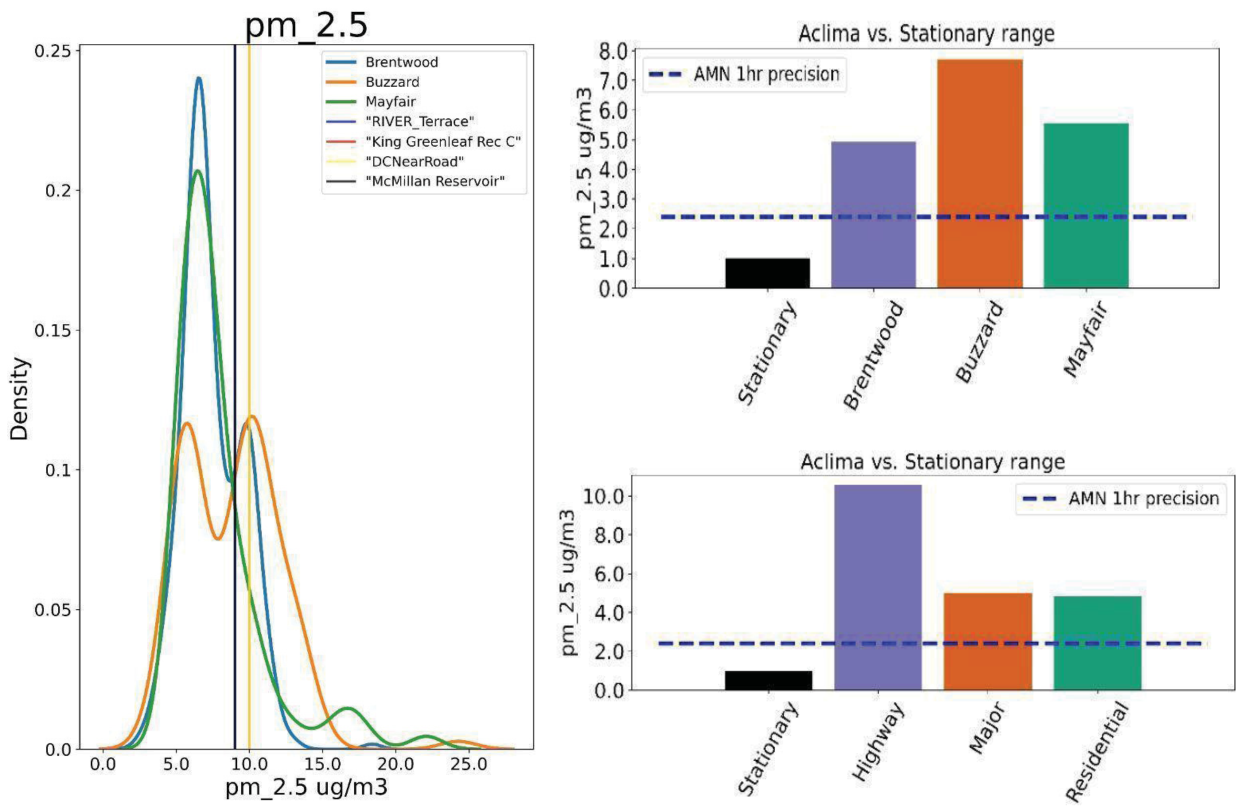

Figure 20. Probability density plot (left) showing the distribution of two-week segment median $PM_{2.5}$ concentrations for all segments in Brentwood/Ivy City (blue), Buzzard Point (Orange), and Mayfair (Green), and the nearest DC DOEE regulatory sites two-week medians (River Terrace, King Greenleaf Rec Center, DC Near Road, and McMilan Reservoir). Note the King Greenleaf Rec Center $PM_{2.5}$ median overlaps with the DC Near Road median, and McMillan Reservoir overlaps with River Terrace.; Accompanying the density plot distribution are the two bar plots that compare the range of the four DC DOEE regulatory sites' medians to 10-90th percentile ranges of the road segment median $PM_{2.5}$ concentrations in the three neighborhoods and three road types. The 1 hr precision metrics from the sensor vs stationary comparison (see Appendix A.1) is overlaid to put the magnitude of variations captured in the neighborhoods and across road types into context with sensor uncertainty.

4 Conclusions

This two-week pilot successfully captured significant spatial variability in each of the measured pollutants, as well as identifying actionable pollution hotspots in each of the three neighborhoods. Additional diurnal, weekly, monthly, and seasonal analyses can be derived from a longer analysis campaign.

Continuous stationary monitoring captures a temporally complete but spatially limited picture of air pollution in a complex urban area. Mobile monitoring provides an important and complementary dataset to regulatory monitoring, capturing the hyperlocal differences in air pollution from block to block, identifying trends and pollution sources, and providing actionable insights to all of the diverse communities in Washington D.C.

An extended, city-wide campaign would make hyperlocal information like this available for all D.C. communities.