Analysis of NO2 Concentrations Around Warehouse Facilities in the Chicago Region: Report

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Prepared for Lake Michigan Air Directors Consortium (LADCO)

1. Introduction

1.1. Background

Air pollution poses significant environmental and health risks. NO2, a key air pollutant, contributes to respiratory problems and environmental degradation. Monitoring NO2 concentrations and understanding their dispersion patterns, especially around high-traffic areas like warehouse facilities, is crucial for effective air quality management.

Emissions of nitrogen oxides (NOx, including NO and NO2) from heavy-duty diesel vehicles (HDDV) are particularly important as they are concentrated at warehouses and intermodal facilities (Dickens et al., 2024). The Chicago area, being the largest rail hub in the U.S., has significant emissions from freight handling at intermodal (rail-to-truck) facilities and warehouses (Dickens et al., 2024). These facilities are generally located in communities facing environmental justice concerns, exacerbating health risks in already vulnerable populations. These emissions are important yet under-represented in the Chicago area's emissions inventories (Dickens et al., 2024). Recognizing the importance of addressing these emissions, the Lake Michigan Air Directors Consortium (LADCO) has identified freight handling emissions as a critical area of study.

To help constrain NOx emissions from intermodal and warehouse facilities, we analyzed data collected by EPA Region 5’s Geospatial Measurement of Air Pollution (GMAP) vehicle in the summer of 2023. The GMAP drove around several facilities in Chicago while measuring NO2, wind speed and direction, and other parameters (Fuoco & Haile, 2023). This project aimed to plot these NO2 concentrations and wind data around warehouse facilities in the Chicago region, evaluate NO2 concentrations upwind and downwind of each facility, and track high NO2 concentrations to potential source locations.

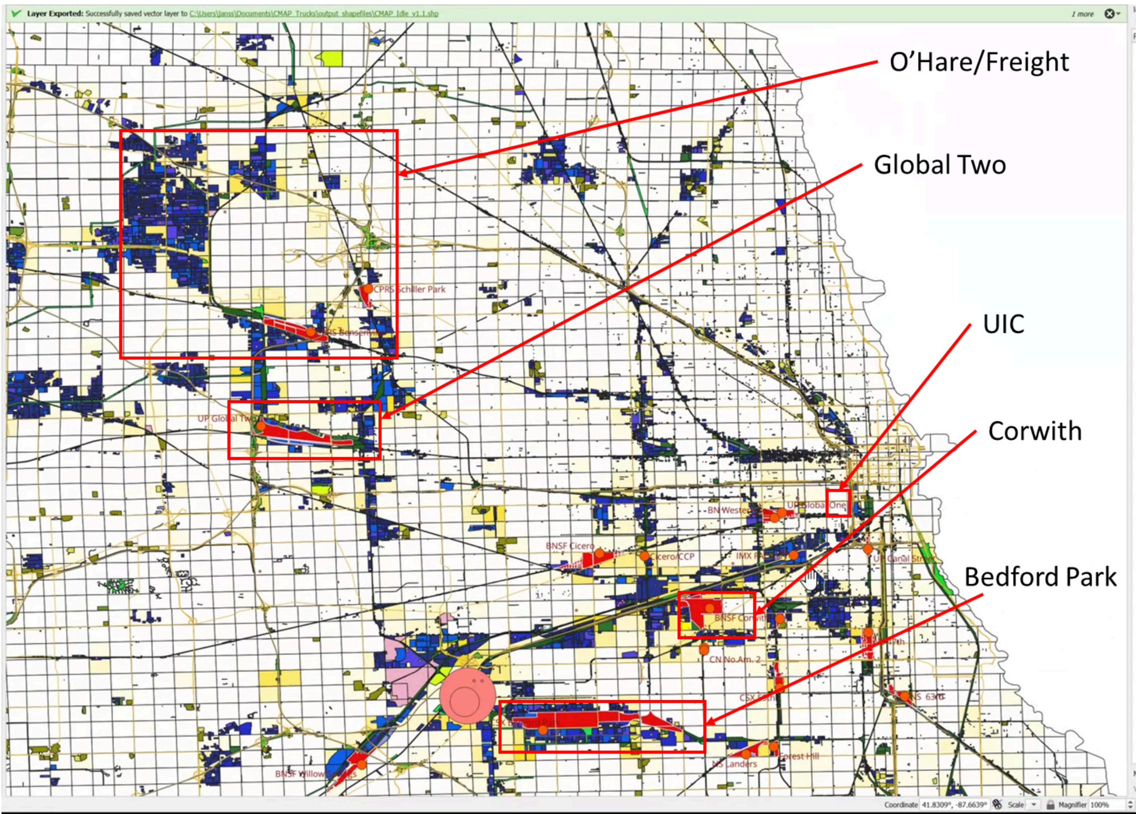

Figure 1: Map of warehouses (blue), intermodal facilities (red), and studied facilities (red boxes) in the Chicago area. Telemetry data suggests areas in yellow have concentrated idling HDDVs (Janssen et. al, 2023).

2. Methodology

2.1. Data Collection

EPA's GMAP was deployed to measure NO2, ozone, meteorology, and other compounds around several intermodal facilities and warehouse-heavy areas in the Chicago region (Fuoco & Haile, 2023). The vehicle followed an outbound route from downtown Chicago (University of Illinois Chicago, UIC) out to the facilities in the morning and an inbound route in the afternoon, conducting two circuits each day at three core sites (UIC, Corwith, and Bedford Park) and a third circuit at either Global Two or O'Hare's warehousing areas (Fuoco & Haile, 2023). UIC was not included in the analysis of this study as it is not an intermodal facility but was included in the measurement study as an urban background site with collocated monitoring.. The facilities are outlined in red in Figure 1, with areas of concentrated idling shown in yellow and warehouses depicted in blue (Dickens et al., 2024).

The GMAP vehicle collected measurements on Tuesday, August 1; Wednesday, August 2; Tuesday, August 8; and Saturday, August 12, 2023, coinciding with flights from the G-V and DC-8 aircraft from the AGES+ campaign (Dickens et al., 2024). The AGES+ initiative is a comprehensive air quality-focused research campaign involving coordinated aircraft-based and ground-based observational activities across the U.S. and Canada to study atmospheric emissions, air quality dynamics, and the impacts of pollution on urban environments (Chemical Sciences Laboratory, n.d.).

The data collected underwent a rigorous quality assurance (QA) process within the U.S. EPA, which included quality control (QC) checks in the field, verification and flagging by data analysts, and validation by an independent Quality Assurance Officer (Fuoco & Haile, 2023). All the data will be available in the NASA AGES+ archive (https://www-air.larc.nasa.gov/missions/staqs/).

2.2. Data Cleaning and Preparation

To facilitate efficient data handling, filtering, and transformation processes, the R packages dplyr and lubridate were used. The initial visualizations revealed that the 1-second wind data were too erratic to discern clear patterns. To address this, one-minute average wind data centered on the top of each minute (0-second mark) were calculated, smoothing out the wind directions and making them more consistent and interpretable. For each minute, the median values of latitude and longitude were selected from the 60-second data centered on the 0-second mark. This method ensures that the representative geographic coordinates for each NO2 observation and wind data are geographically centered on the median location, providing consistency in the data representation. The dataset was divided into AM and PM circuits based on specific time thresholds for each date, ensuring that the data were appropriately segmented for analysis. The AM circuit included the complete outbound route, comprehensive of the circuit at Global Two or O'Hare.

2.3. Defining Facility Boundaries

Data were filtered to focus on specific facilities, dates, and times of day (AM/PM). For each facility and corresponding date, filtered data were plotted with grid lines and a buffer to reveal detailed markings. Additionally, O'Hare was separated into three segments—West, Central, and East—to examine different key features within the facility.

2.4. Wind Comparison Analysis

Accurately measuring wind speed and direction from a moving vehicle can be challenging. To evaluate the accuracy of the wind data collected by the GMAP truck, additional validation was performed by comparing it with 1-minute wind data from the Midway Airport, collected by the

National Weather Service (NWS) and archived by the Iowa Environmental Mesonet (https://mesonet.agron.iastate.edu/request/asos/1min.phtml). This validation focused on the Bedford Park facility due to its close proximity to the Midway Airport. The comparison was conducted over three days (August 2, 8, and 12), as data for August 1 at Midway was unavailable.

The ggplot2 package was used to visualize the distribution of wind direction differences between the GMAP and NWS data. This involved creating histograms and density plots for each of the three days to compare the wind direction measurements from both sources. The wind direction differences were calculated using custom functions to convert degrees to a scale of -180 to 180 degrees, ensuring that differences were measured within the shortest rotational path. This approach prevents discontinuities, such as a change from 359 degrees to 1 degree being recorded as a 2-degree difference rather than a 358-degree difference, providing a more accurate representation of wind direction variability.

2.5. Visualization of NO2 Concentrations with Wind Data

To visualize the data around the studied facilities, detailed maps were created to show the spatial distribution of NO2 concentrations along with wind direction and speed. To plot the data on satellite maps, images of the facilities were retrieved from Google Maps using the ggmap package. Different zoom levels were specified for each facility to provide an optimal view: 13 for Bedford Park and Global Two, 14 for Corwith, and varying levels for the different segments of O'Hare, specifically 13 for West, 13 for East, 13 for Central, and 12 for the overall Hare segment.

NO2 concentrations were visualized using both size and color to convey different concentration levels effectively. The colorRamps package was used to create a color gradient, representing NO2 concentrations up to 80 ppb, with a gradient from low to high values. This cutoff was determined by analyzing the distributions of NO2 concentrations across the facilities (Figure 2) and establishing a consistent threshold for identifying outlier points. Points above this cutoff were set to be gray. The scale_color_gradientn function in ggplot2 was used to implement this gradient, ensuring clear differentiation between concentration levels. Simultaneously, the size of the points varied according to NO2 concentration levels, with three distinct sizes at 30, 60, and 90 ppb. These cutoffs were also determined from the distributions in Figure 2. This dual encoding of data (size and color) visually emphasized the wide gradient of NO2 concentrations and outliers.

Wind direction and speed were represented with arrows to show the direction and intensity of the wind. The length of the arrows was adjusted based on wind speed, and their orientation indicated the wind direction. This was achieved by calculating the end points of the arrows based on wind speed and direction and using the geom_segment function in ggplot2.

2.6. Upwind versus Downwind Analysis

To understand the impact of wind direction on NO_2 dispersion, data points were classified as North, South, East, or West relative to each facility. Specific latitude and longitude boundaries were defined for each facility, including Bedford Park, Corwith, Global Two, and segments of O'Hare (West and East). Central O'Hare was not included in this analysis due to the facility's geometry, which did not allow for clear distinctions between upwind and downwind areas. This classification helped identify upwind and downwind areas, which is critical for analyzing pollutant dispersion patterns.

The average wind direction for each facility, day, and circuit combination (e.g., August 1, Corwith, AM) was then calculated as the average wind direction using vector averaging techniques. Once the average wind direction was established, data points were classified based on their position relative to this direction. For instance, if the average wind direction was from the north to the south, then points at the south end of the facility would be classified as downwind, while points on the north side of the facility would be classified as upwind. For winds with both southerly/northerly and easterly/westerly components, we averaged points on two sides of the facility (e.g., south and east) into both upwind and downwind averages.

To quantify the differences in NO_2 concentrations, the average NO_2 concentration on the upwind side of the facility was subtracted from the average NO_2 concentration on the downwind side, creating a delta value. This delta value represents the estimated change in NO_2 concentration due to the facility. Additionally, the standard deviations of NO_2 concentrations were calculated for both the upwind and downwind areas to understand the variability of NO_2 concentrations within these regions. These values are shown in Table 1. We also calculated the average upwind and downwind concentrations and differences on all AM and all PM circuits of each facility, as shown in Table 2. The standard deviations for these campaign averages are calculated based on the average values and were not determined using propagation of errors.

3. Results and Discussion

3.1. Wind Comparison with Midway Airport

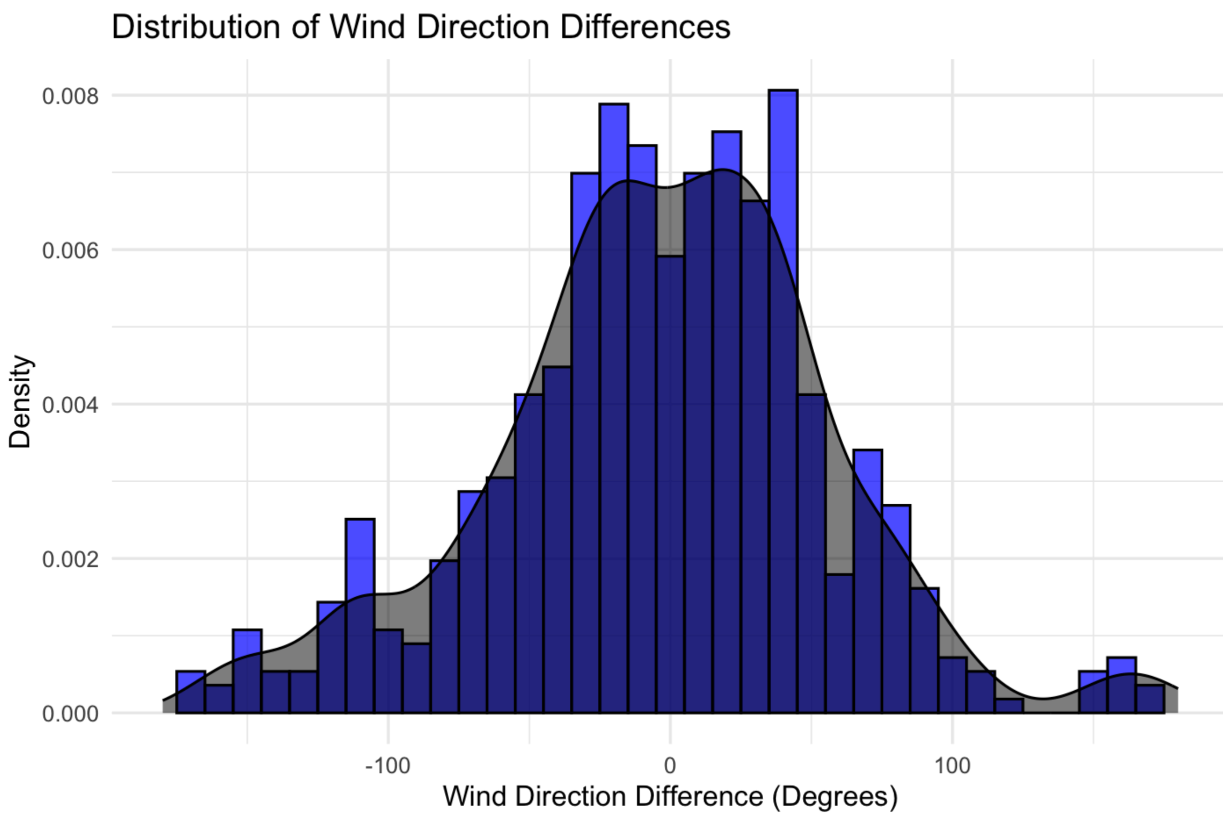

Figure 2: Histogram and density plot show the distribution of wind direction differences between the GMAP truck and Midway Airport data for Bedford Park on August 2, 8, and 12.

We compared the differences in 1-minute mean wind direction between GMAP measurements at the Bedford Park facility and nearby Midway Airport to evaluate potential biases caused by the movement of the vehicle. Figure 3 shows that most of the wind direction differences between the GMAP truck and Midway Airport data fall within ±40 degrees. Specifically, the median wind direction difference is 1.48 degrees, with an interquartile range (IQR) of 71.3 degrees. This indicates that the middle 50% of the data falls within the range of approximately -34.17 degrees to 37.13 degrees. This suggests that while there is generally good alignment between the GMAP truck and Midway Airport measurements, there is significant variability in the wind direction differences

The peak around 0 degrees indicates good overall alignment between the GMAP truck and Midway Airport measurements. However, there are instances where the differences are larger, which could be attributed to real differences in local wind patterns influenced by buildings or other structures that systematically alter wind direction.

Additionally, a Shapiro-Wilk normality test was performed on the wind direction difference data to assess its normality. The test results (W = 0.98609, p-value = 3.644e-05) indicate that the wind direction differences are not normally distributed, which may affect certain statistical analyses but is acceptable for the scope of this study.

This comparison suggests that the GMAP wind data is sufficiently accurate for the purposes of this analysis Nonetheless, it would be beneficial to investigate these differences further in future studies to understand and account for any potential systematic biases.

3.2. NO2 Concentrations around Facilities

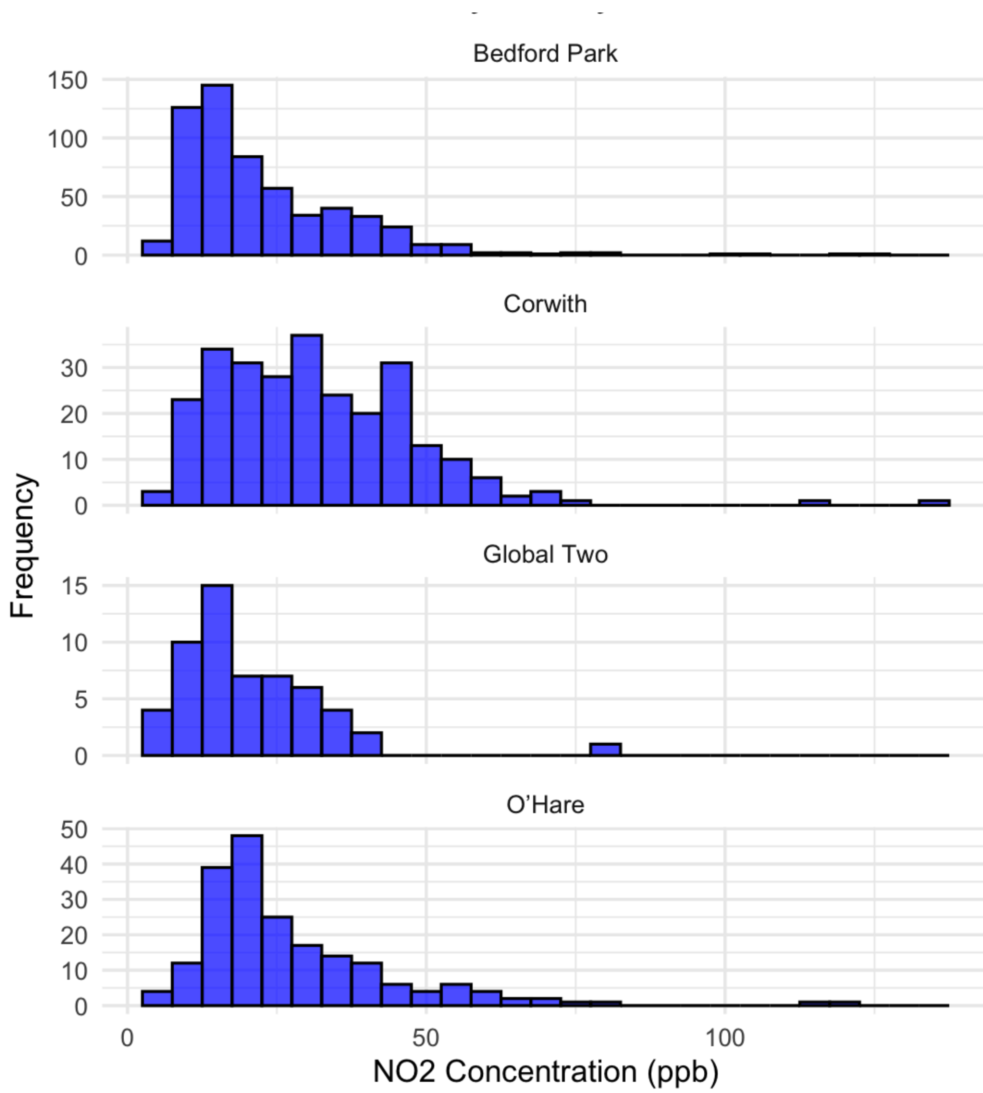

Figure 3: Distribution of NO2 concentrations (ppb) by facility. The histograms illustrate the frequency of NO2 concentration measurements at Bedford Park, Corwith, Global Two, and O'Hare.

The histograms of NO2 concentrations (Figure 3) illustrate distinct patterns across the four facilities:

Bedford Park: The distribution shows a higher frequency of NO2 concentrations below 50 ppb, with a few outliers extending beyond 100 ppb. The mean NO2 concentration is relatively high at 22.94 ppb, indicating consistent emissions, likely from heavy traffic and idling trucks. The standard deviation of 14.98 ppb reflects significant variability, suggesting fluctuating emissions depending on the time of day and traffic intensity.

Corwith: Similar to Bedford Park, Corwith has a wide distribution of NO2 concentrations, with significant variability. The mean NO2 level is the highest among the facilities at 31.44 ppb, reflecting intense activity and emissions at this facility. The standard deviation of 16.70 ppb indicates considerable variability, likely due to fluctuating traffic volumes and idling trucks.

Global Two: This facility has noticeably lower NO2 concentrations compared to Bedford Park and Corwith, with a mean of 20.28 ppb. The lower overall background in this part of the city likely contributes to this observation rather than the direct influence of the facility itself. The standard deviation of 12.19 ppb suggests relatively consistent NO2 levels. However, it is important to note that data for Global Two was limited to only two routes, which constrains the strength of this conclusion.

O'Hare: The distribution at O'Hare shows moderate NO2 levels, with peaks around 20-30 ppb. The mean NO2 concentration is 27.54 ppb, and the standard deviation of 17.01 ppb reflects a high degree of variability. This variation is likely due to the different operational areas like the west, central, and east segments, which have distinct emission patterns.

The lower concentrations at Global Two, and perhaps at O'Hare, might not necessarily reflect a lower overall background in that part of the city rather than the direct influence of the facility itself.

The maps for Bedford Park display low to moderate (blue, less than 40 ppb and often less than 20 ppb) NO2 concentrations around most of the facility, with some hot spots with higher concentrations (Figure 4). Concentrations were generally high on the August 8 AM circuit compared with the other circuits. consistent high NO2 concentrations were consistently high near the middle of the north side of the facility, attributable to a busy intersection with significant traffic. Additionally, the southeast corner, which features extensive truck activity and the H&M International Transportation Intermodal facility, exhibits elevated NO2 levels. It is notable that there is a high school adjacent to this high concentration area, which raises potential environmental justice concerns (shown in Figure 5). Further analysis shows that NO2 concentrations remain relatively high throughout the day, indicating continuous sources of emissions in these areas.

At Corwith, the eastern side of the facility shows greater NO2 concentrations than the west, particularly noticeable on the morning of August 1, suggesting downwind dispersion of pollutants (Figure 6). The eastern side's higher concentrations suggest that prevailing winds might be carrying emissions towards residential areas, which surround the Southern and Eastern sides of the facility, necessitating further investigation into the potential impact on the nearby community. We identified areas where trucks are parked and idling while waiting for containers in the southwest corner of the facility using satellite images. However, NO2 concentrations were not obviously higher in this area. Higher concentrations are also noted consistently near the highway cutting through the upper part of the circuit.

One of the corners of the Global Two facility, located approximately in the top middle of the polygon, includes the intersection of prominent roads and railway lines (Figure 7). This area is characterized by the convergence of key transportation routes, serving as access points for trucks entering the facility. Despite this being the primary entrance for trucks, there is not a high amount of emissions seen there. The facility has implemented measures to limit idling, which may contribute to the generally lower NO2 levels observed, as reflected in the histogram, although these low NO2 levels also must reflect a lower overall background in this area (Figure 2). Although data are limited due to fewer laps conducted around this facility, the available data may be consistent with effective emission control measures on wait times, which, in turn, reduce idling (Chicago Global 2, 2023). There is also a notable NO2 hotspot in the bottom right corner on August 1, indicating that high local NOx emissions from some sources can still contribute to the overall NO2 levels.

The O'Hare maps reveal distinct NO2 concentration patterns on August 8, the only day data were collected. The west segment shows high NO2 levels near warehouses on the Western and Southern sides. The central segment, one of the few places in the U.S. where intermodal activity transitions directly from plane to truck, also displays significant NO2 levels, especially on the eastern side, which is downwind of this intermodal activity. In the east segment, large yards and freight warehouses seem to be the primary contributors to elevated NO2 levels. The overall map integrates data from all three segments, providing a comprehensive view of NO2 distribution across the entire facility.

Bedford Park

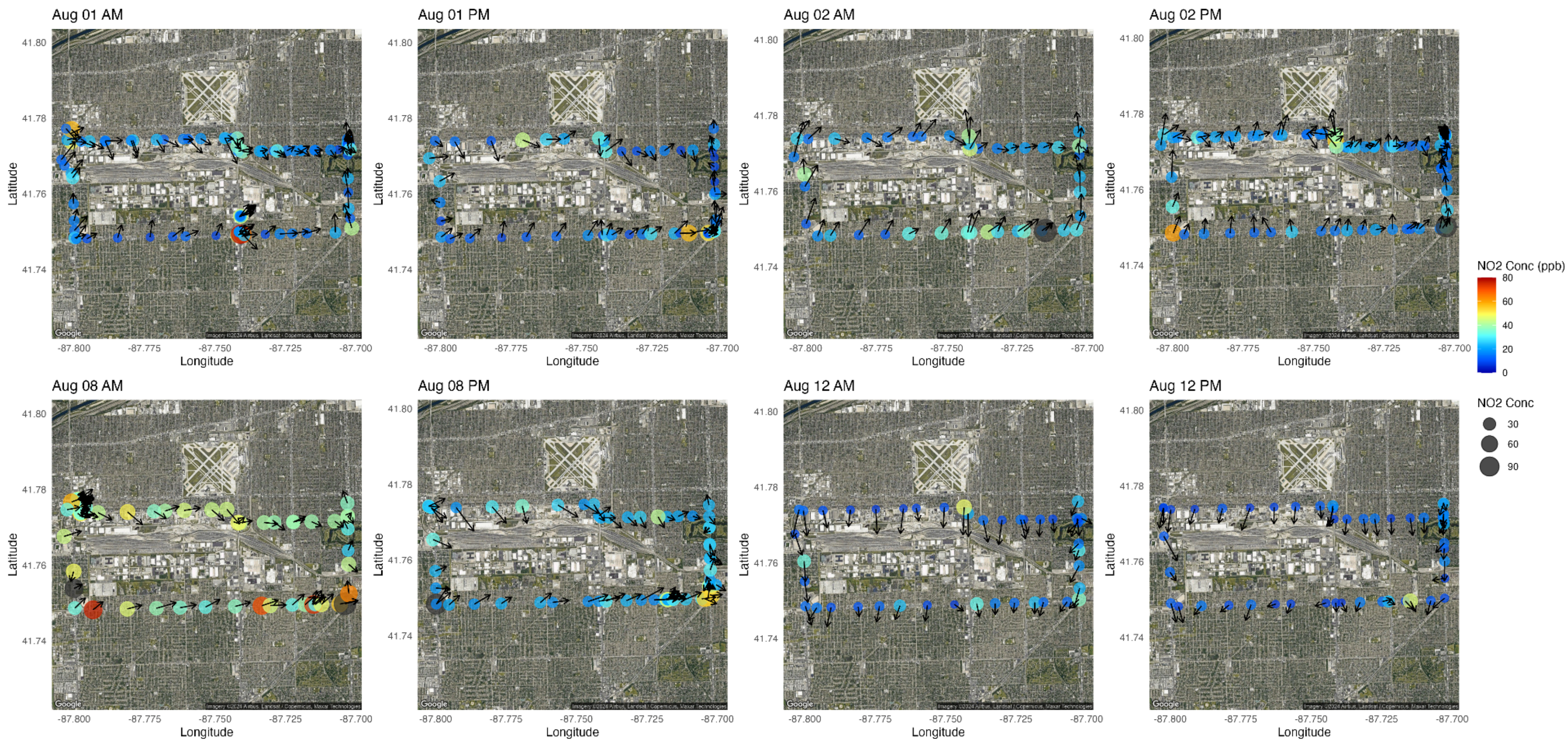

Figure 4: Aug 01 AM and PM, Aug 02 AM and PM, Aug 08 AM and PM, Aug 12 AM and PM: NO2 concentrations with wind data across different times of the day and dates.

Figure 5: Satellite view (Google Maps) of Bedford Park highlighting St. Rita of Cascia High School (yellow box) in the southeast corner, adjacent to the H&M International Transportation Intermodal facility. The red lines indicate the boundary of the Bedford Park study area.

Corwith

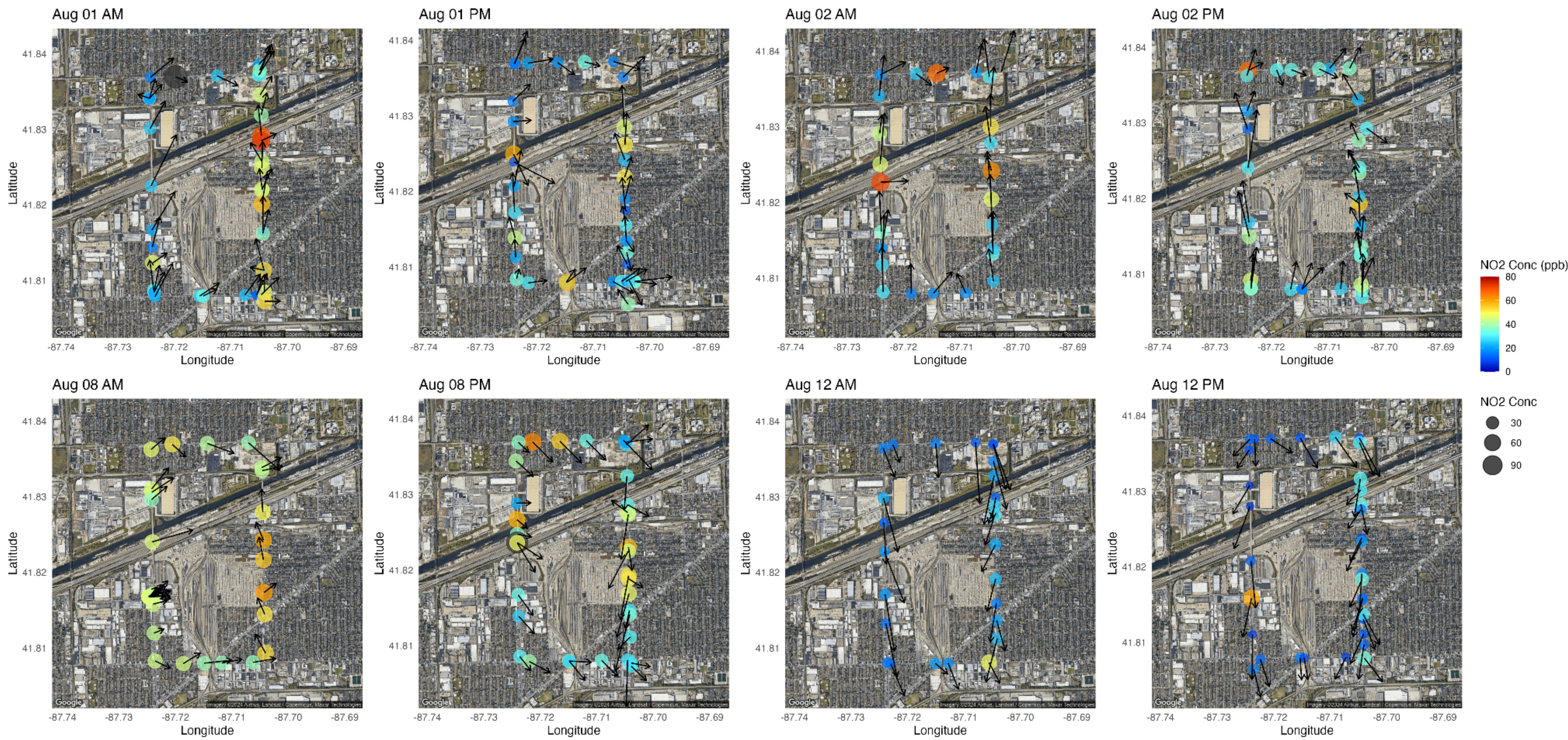

Figure 6: Aug 01 AM and PM, Aug 02 AM and PM, Aug 08 AM and PM, Aug 12 AM and PM: NO2 concentrations with wind data across different times of the day and dates.

Global Two

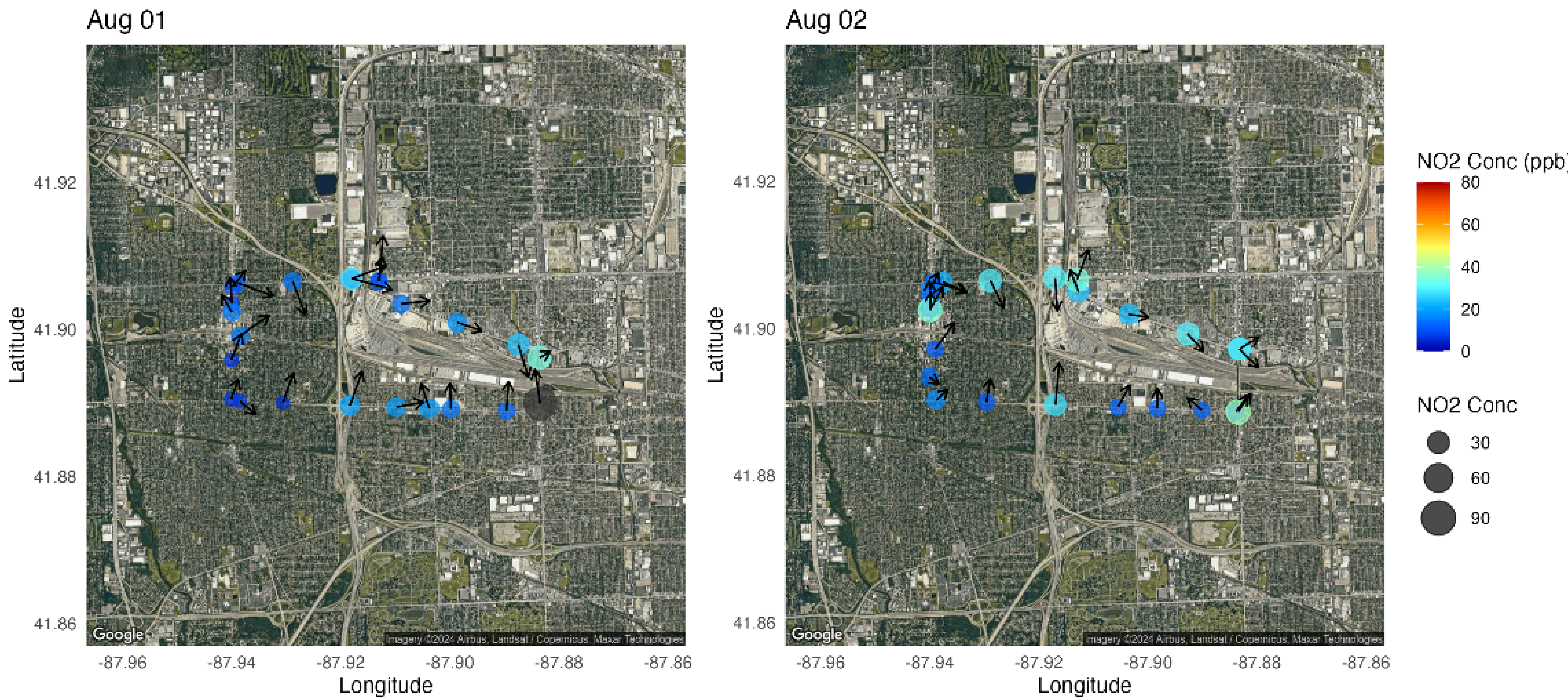

Figure 7: Aug 01 AM and Aug 02 AM: NO2 concentrations with wind data across different dates.

O'Hare

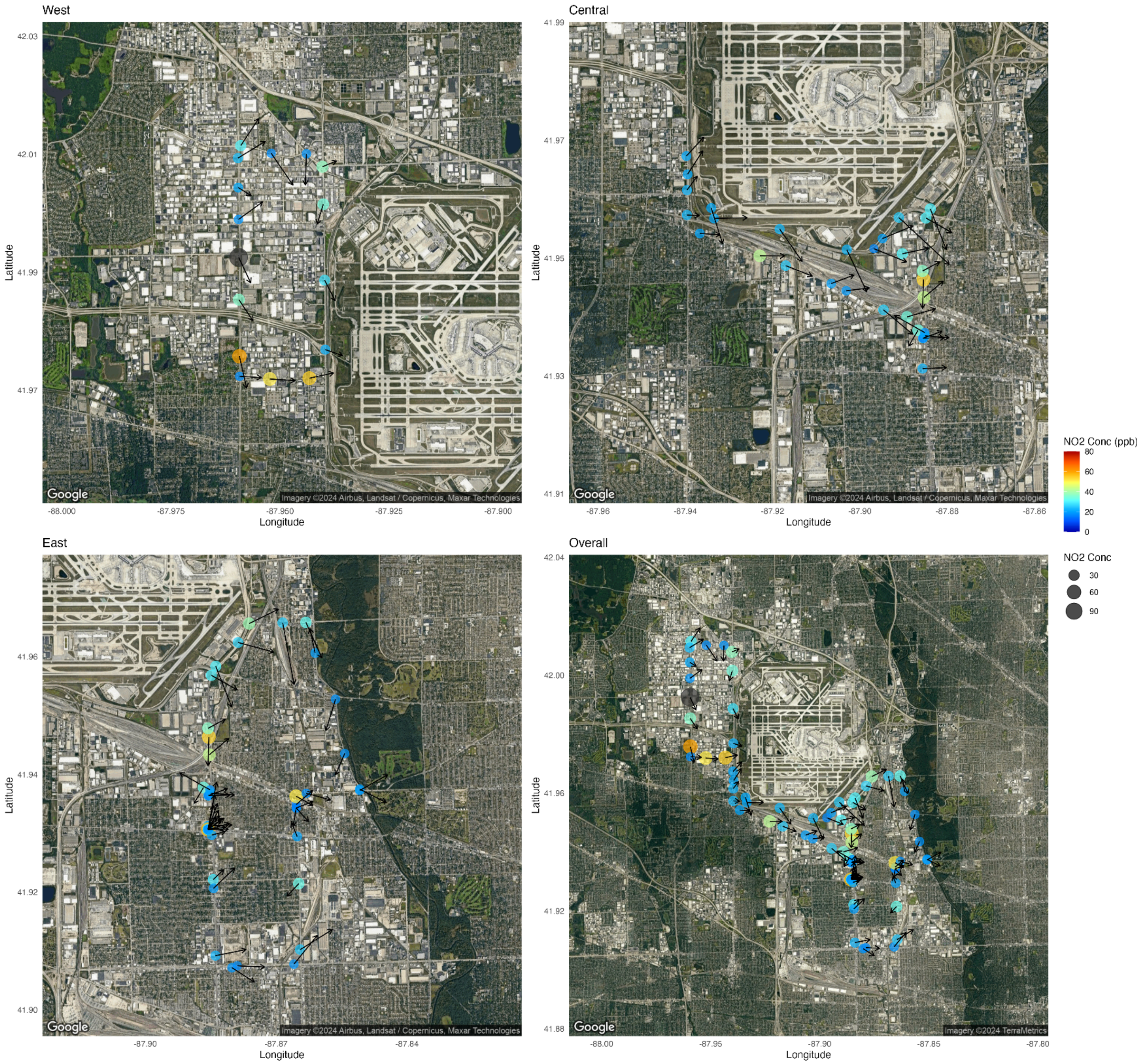

Figure 8: West, Central, East, Overall on Aug 08: NO2 concentrations with wind data showing various segments of the O'Hare facility.

3.3 Upwind and Downwind NO2 Concentrations

To determine the impact of emissions from the facilities on NO2 concentrations in the area, average NO2 concentrations upwind and downwind of each facility were compared. This comparison was done separately for AM and PM circuits to capture potential differences in emission patterns throughout the day. Table 1 summarizes the result for each circuit, and Table 2 provides the average of all AM and PM circuits of each facility.

Table 1. Detailed Upwind and Downwind NO2 Concentrations by Date and Circuit

Facility	Date (August)	Circuit	Upwind (ppb)	Downwind (ppb)	Δ	Std Dev Upwind	Std Dev Downwind
Bedford Park	1	AM	21.51	18.78	-2.73	16.91	10.01
Bedford Park	1	PM	18.08	17.60	-0.48	12.53	8.99
Bedford Park	2	AM	30.33	21.95	-8.38	25.46	9.03
Bedford Park	2	PM	19.12	17.82	-1.30	11.33	11.64
Bedford Park	8	AM	45.42	41.40	-4.02	16.64	11.82
Bedford Park	8	PM	32.10	38.42	6.32	12.44	35.49
Bedford Park	12	AM	13.82	15.36	1.54	9.14	7.15
Bedford Park	12	PM	11.35	13.35	2.00	4.15	9.96
Corwith	1	AM	26.15	42.84	16.68	11.57	27.54
Corwith	1	PM	29.34	25.07	-4.27	13.58	13.00
Corwith	2	AM	31.42	35.09	3.67	16.83	16.51
Corwith	2	PM	29.69	37.13	7.45	9.09	15.19
Corwith	8	AM	42.80	49.46	6.67	2.76	7.58
Corwith	8	PM	42.27	37.37	-4.90	24.40	9.46
Corwith	12	AM	13.28	22.90	9.62	2.52	14.29
Corwith	12	PM	15.75	16.07	0.32	8.37	9.54

Global Two	1	NA	17.68	17.26	-0.42	19.59	7.84
Global Two	2	NA	17.44	26.04	8.60	9.23	5.93
O’Hare West	8	NA	37.65	34.90	-2.75	31.93	14.04
O’Hare East	8	NA	21.68	25.84	4.16	9.91	10.73

Table 2: Summary of Upwind and Downwind NO2 Concentrations by Facility and Circuit

Facility	Circuit	Upwind (ppb)	Downwind (ppb)	Δ	Stand Dev Upwind	Stand Dev Downwind	Stand Dev Δ
Bedford Park	AM	27.52	24.37	-3.15	17.29	9.50	4.19
Bedford Park	PM	20.16	21.30	1.14	10.61	16.52	3.83
Corwith	AM	28.94	36.33	7.39	13.01	20.44	6.28
Corwith	PM	29.76	28.79	-0.97	13.40	11.72	2.57
Global Two	AM	17.56	21.65	4.09	14.41	6.88	4.68
O'Hare West	AM	37.65	34.90	-2.75	31.93	14.04	8.06
O'Hare East	AM	21.68	25.84	4.16	9.91	10.73	3.17

It is important to note that the Standard Deviation (Δ) column was derived from the standard deviation of the averages rather than through error propagation. The analysis of upwind and downwind NO2 concentrations reveals several key insights:

Bedford Park: The differences between upwind and downwind NO2 concentrations vary throughout the day and across different dates. For instance, on August 8th PM, there is a noticeable positive difference, indicating higher downwind concentrations. However, on other dates and times, the differences are less pronounced or even negative. The standard deviation values suggest significant variability in NO2 levels, which might be influenced by localized traffic and idling patterns within the facility.

Corwith: There is a consistent positive difference in NO2 concentrations during the AM circuits, especially on August 1st and 2nd, suggesting higher or less dispersed emissions in the morning. This pattern aligns with expectations that emissions are more concentrated during the morning, either due to rush hour emissions or due to the confining low boundary layer. The PM circuits show less consistent differences, which may be due to reduced truck activity or increased dispersion effects later in the day. The higher standard deviations for downwind measurements in the morning indicate greater variability in NO2 levels, likely due to fluctuating traffic volumes and idling trucks.

Global Two: The facility shows lower overall NO2 concentrations on both upwind and downwind sides, which likely reflects the overall lower NO2 levels in that part of the city. However, there are still notable emissions hotspots, particularly in the southeast corner, suggesting contributions from transient emissions. The AM data shows a slight positive difference in NO2 concentrations, indicating that emissions are higher downwind, but the overall impact is less pronounced than at Corwith but larger than at Bedford Park. The lower standard deviations for downwind measurements suggest more consistent NO2 levels around this facility, at least on the two circuits driven.

O'Hare: The West segment of the O’Hare circuit shows high NO2 levels near warehouses, while the East segment indicates significant emissions from yard and freight warehouses. The central segment, characterized by intermodal activity from plane to train, also shows considerable NO2 levels, especially on the downwind Eastern side. The variability in NO2 levels, as indicated by the standard deviations, reflects the diverse sources of emissions and the complex dispersion patterns influenced by airport operations and nearby traffic.

The data reveal some distinct patterns of NO2 dispersion around each facility, with variations influenced by the time of day, facility operations, and local traffic and a lot of variability of uncertain origin. We appeared to observe a consistent source of NO2 emissions from the Corwith yard in the morning, but signals from other facilities were less clear. Our observations will be affected by the distance from the facility at which the GMAP drove. Kerr et al. (2024) observed that peak NO2 levels often occur 2-3 kilometers downwind from emission sources, as it takes time for NO to convert to NO2 through atmospheric reactions. Given our close range to the facilities, this factor may have impacted our measurements. However, our observations of some very sharp peaks located near large emissions sources (such as Interstate 55 near Corwith) suggest that this may not be a major issue. Future studies could further refine these insights by incorporating more granular spatial and temporal data, as well as examining the influence of meteorological factors on pollutant dispersion. Connection of the ground data with airborne and satellite measurements at the same time would also be insightful.

4. Conclusion

The analysis of NO2 concentrations around various facilities in the Chicago area reveals both larger scale patterns in NO2 concentrations and local hot spots. We identified that at least the Corwith yard consistently added NO2 to downwind air in the mornings. For future studies, a more focused approach involving fewer facilities but with more frequent and comprehensive data collection is recommended. This would provide a richer dataset and allow for a more nuanced understanding of NO2 dispersion patterns. Furthermore, it was observed that NO2 hotspots tended to occur near highways, warehouses adjacent to the measurement routes, and busy intersections. Addressing these specific areas could be beneficial in reducing overall NO2 levels.

While the current study provides valuable insights into NO2 dispersion patterns, it also highlights the need for more detailed and frequent data collection to better inform emission reduction strategies. Future efforts should focus on these high-impact areas to effectively mitigate NO2 pollution and improve air quality.

5. Acknowledgements

Scott Hamilton, Rachel Kirpes, Marta Fuoco and Kate Haile of EPA Region 5 collected the GMAP data. Robert Francis & Cristina Presmanes (EPA R5) helped process and validate the data. John Cashman, Ehron Stout, & Dave White (Illinois EPA) loaned the NO2 and O3 analyzers and provided excellent support with installation and operation of the analyzers. Dr. Brad Pierce (UW-Madison) and Mark Janssen, Dr. Angie Dickens, and Zac Adelman (LADCO) helped plan and coordinate the field measurements. Dr. Angie Dickens and Mark Janssen from LADCO provided invaluable support throughout the project. Additionally, ChatGPT assisted in the preparation and editing of this report.

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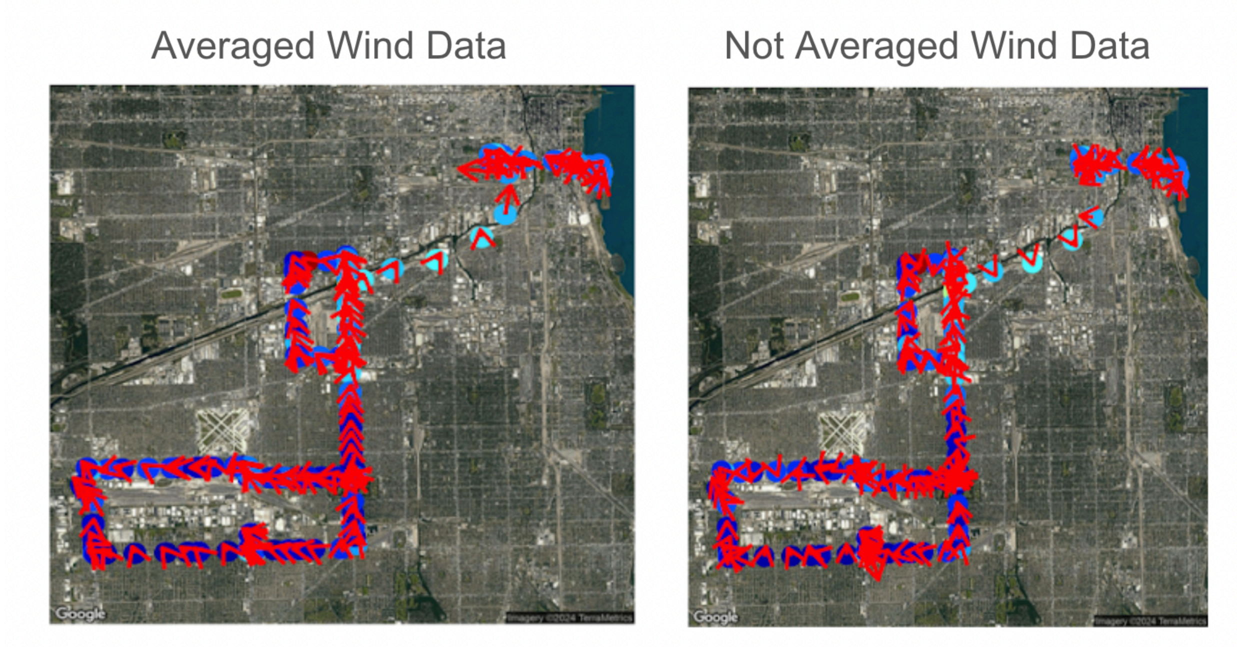
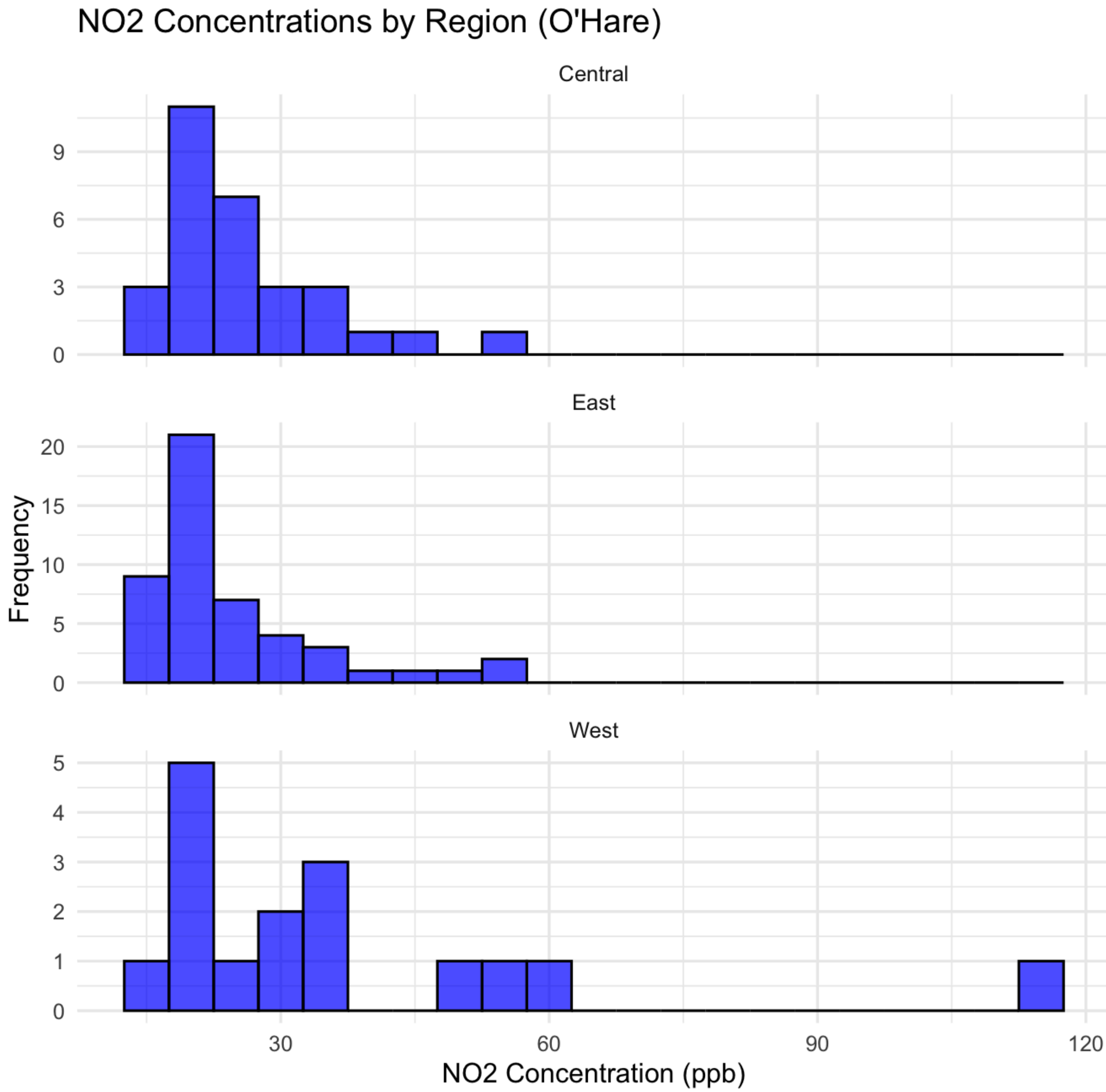
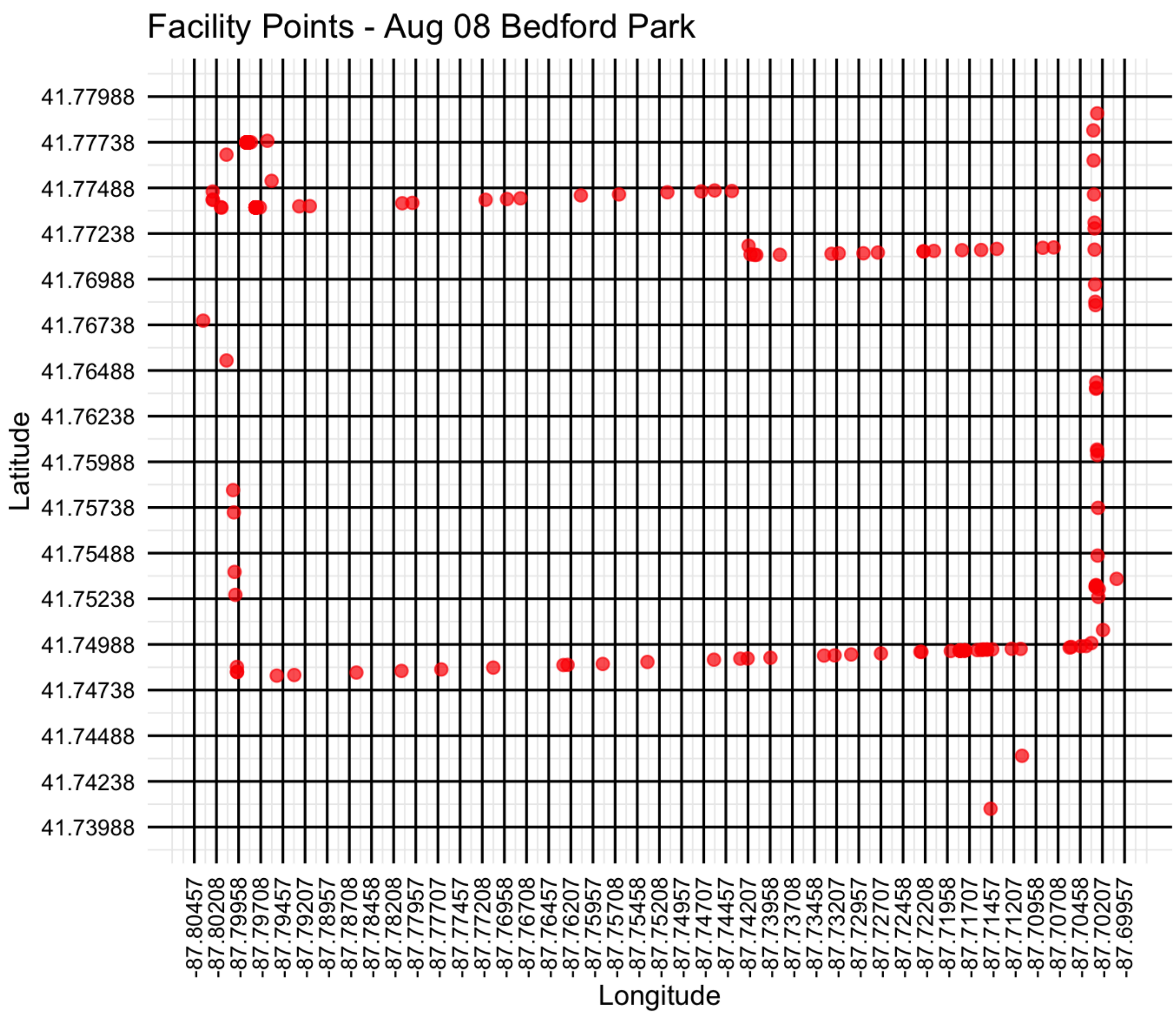


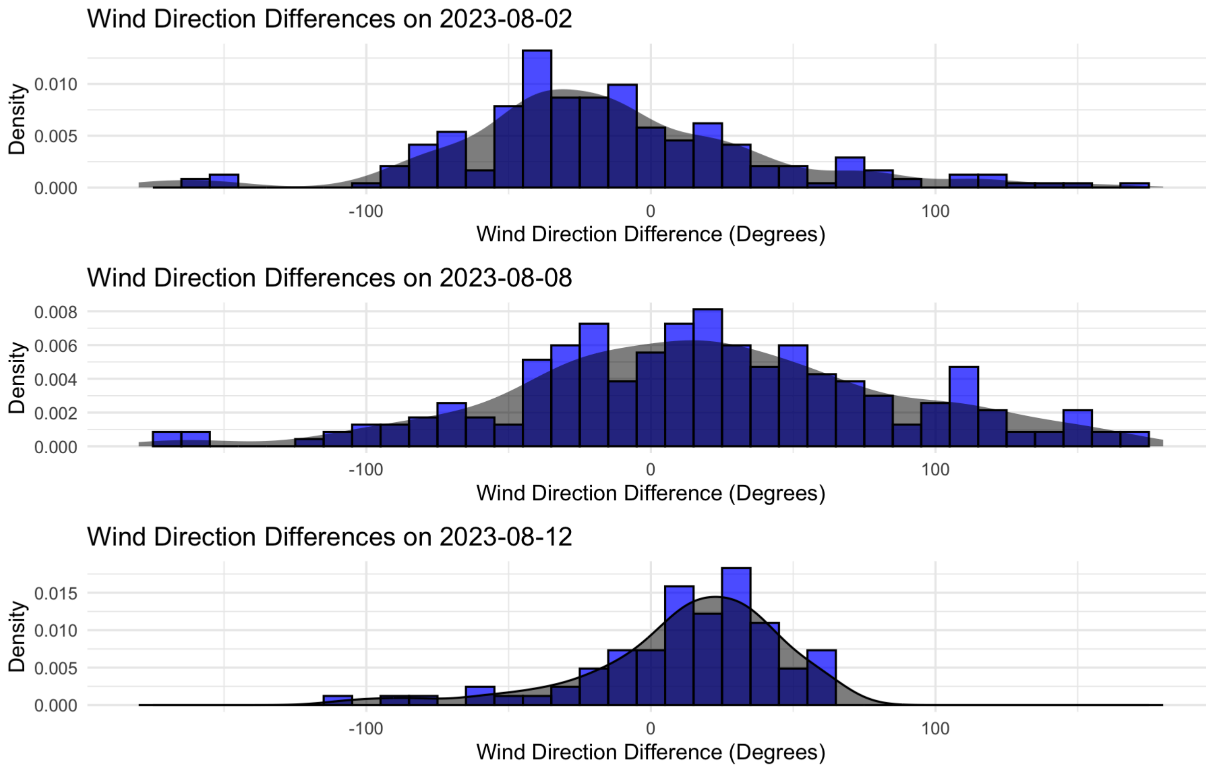
Appendix Figure 1: Comparison of wind data visualization for the GMAP routes around the Chicago area. The left image shows the wind data averaged over one-minute intervals, resulting in smoother and more consistent wind direction patterns. The right image displays the original, non-averaged wind data, which is more erratic and difficult to interpret. The averaging process helps in providing clearer insights into the wind patterns affecting NO2 dispersion.



Appendix Figure 2: Histograms of NO2 concentrations (in ppb) for three regions of the O'Hare facility: Central, East, and West. The x-axis shows the NO2 concentration, while the y-axis indicates the frequency of measurements within each concentration range.



Appendix Figure 3: Displays the grid lines used to determine the boundaries and cardinal sides of the Bedford Park facility. The red points represent the geographic coordinates of the measurement points, plotted against the latitude and longitude grid to ensure accurate spatial analysis of NO2 concentrations and wind data. This method was applied to all facilities across different days to verify that each point was classified correctly and the boundaries were accurate.



Appendix Figure 4: Histograms and density plots of wind direction differences between the GMAP truck and Midway Airport data for three dates: August 2, August 8, and August 12, 2023. The x-axis represents the wind direction difference in degrees, and the y-axis represents the density of these differences.