Università degli studi di Milano-Bicocca

Data Science Lab on Smart Cities

Final Essay

Air Pollution and Public Health in New York City

Author:
Paola Maria Cavana - 859341 - p.cavana1@campus.unimib.it

July 3, 2024

Abstract

Air pollution in New York City (NYC) is a critical issue that demands attention; residents are exposed to a complex mixture of pollutants including PM2.5, Black Carbon, Ozone (O3), Nitric Oxide (NO) and Nitrogen Dioxide (NO2). This study investigates the spatial distribution of these pollutants across NYC's boroughs and within the Unified Health System areas (UHF42), examining their sources and impacts on public health. Special attention is given to factors such as vehicle emissions which significantly contribute to local air quality degradation. Through data science methodologies, this study offers a thorough analysis of spatial and temporal trends in these pollutants, identifies high-risk areas, and suggests interventions to mitigate associated health risks. The correlation between these pollutants and diseases like asthma is a focal point of the findings. These insights underscore the critical importance of addressing air quality in urban planning and public health policies to enhance the well-being of city residents.

Introduction

1 Air pollution

Air pollution is one of the most urgent challenges we face today. It not only affects climate change, but also poses significant risks to public and individual health, increasing the likelihood of illnesses and fatalities. Air pollution is made up of different chemicals or particles in the air that can harm the health of humans, animals, and plants, and also have the potential to damage buildings. These pollutants can exist in the form of gases, solid particles, and liquid droplets.

Human activities have a profound impact on the environment, contaminating the water we drink, the air we breathe, and the soil where plants grow. The Industrial Revolution brought about significant technological and societal progress but also led to the release of substantial pollutants into the atmosphere. The presence of fine particulate matter (PM2.5) and various gases in the air poses significant threats to human health and the environment. Global environmental pollution has become a significant concern for public health worldwide. It is closely linked with social, economic, legislative, and lifestyle factors. The rapid urbanization and industrialization around the world are worsening this issue, which is closely related to climate change and global warming. These factors have severe consequences for humanity and significant impacts on ecosystems. [1]

In urban areas such as New York City, air pollution comes from a variety of sources, including both human-made and natural sources [2]. Human-made sources, such as emissions from factories, vehicles, planes, and second-hand cigarette smoke, significantly contribute to air pollution levels. In addition, natural sources, such as wildfires, also release pollutants into the atmosphere.

Indoor air pollution is also a significant concern in densely populated cities. Common indoor pollutants include:

- Heating Sources: Burning fuels like kerosene, wood, and coal releases pollutants, making breathing difficult and leaving residues on surfaces.
- Radon Gas: A naturally occurring, cancer-causing gas that accumulates in homes from the ground.
- Construction Materials: Certain materials, such as insulation, can be harmful to health. Poor ventilation can also foster mould growth, particularly in damp, cool areas, spreading spores that can cause health issues when inhaled.

In New York City, where the concentration of vehicles and industrial activities is high, residents are particularly vulnerable to the health impacts of air pollution.

1.1 Ethical and social Implications

Air pollution has significant ethical and social implications, particularly in densely populated urban centers where its effects are most strongly felt. Major contributors, such as vehicular emissions and industrial activities, degrade air quality and expose residents to harmful substances like sulfur dioxide, nitrogen oxides, and particulate matter. These pollutants significantly contribute to respiratory and cardiovascular diseases, exacerbating health disparities among vulnerable populations, including low-income communities and marginalized groups. In cities like New York City, these communities often endure higher pollution levels due to socioeconomic factors, intensifying existing health inequalities.

Addressing these injustices requires robust policies that prioritize environmental justice, ensuring equitable distribution of environmental benefits and burdens. The health consequences of air pollution are severe, resulting in increased hospitalizations, elevated mortality rates, and diminished quality of life, especially impacting children, the elderly, and those with pre-existing health conditions. Tailored public health interventions and improved healthcare access in affected areas are critical to mitigating these effects.

Efforts to reduce air pollution include creating green zones, improving public transportation, and enforcing stricter emission standards for industries and vehicles. These measures are intended to lower pollutant levels and encourage sustainable urban development. However, in many cities, including New York City, inadequate regulations contribute to ongoing environmental degradation and public health risks.

Indoor air pollution from household activities, such as cooking with solid fuels like wood and coal, further compounds health risks, particularly in low-income households globally. Transitioning to cleaner cooking technologies, such as liquefied petroleum gas (LPG) and solar cookers, is essential for reducing indoor air pollution and its associated health impacts. [3]

Empowering communities with knowledge and resources is crucial for promoting sustainable practices and advocating for environmental justice. By engaging residents in decision-making processes and raising awareness about air quality issues, communities can enhance their resilience and collectively pursue cleaner, healthier environments.

In conclusion, addressing the ethical and social implications of air pollution necessitates collaborative efforts across sectors, including policy-making, urban planning, community engagement, and public health initiatives. Cities can improve residents' quality of life and mitigate air pollution's adverse effects by prioritizing equity, environmental justice, and sustainable practices. [4]

1.2 Indicator selection

Air pollution is a complex issue that requires comprehensive indicators to assess its extent and impact on public health and the environment. The selection of appropriate indicators is crucial for understanding the severity of air pollution and guiding effective mitigation strategies. This section outlines key air quality and health indicators that were used to measure the problem and its impacts.

Air quality indicators offer insights into pollutant levels in the atmosphere, reflecting environmental conditions and associated health risks:

- Pollutant Concentrations: Monitoring pollutants such as Black Carbon, PM2.5, NO2, O3, and NO is crucial for identifying pollution sources and assessing their impact on human health. High concentrations of these pollutants indicate poor air quality.
- Air Quality Index (AQI): This standardized metric communicates ambient air quality based on pollutants like PM2.5, PM10, ozone (O3), nitrogen dioxide (NO2), sulfur dioxide (SO2), and carbon monoxide (CO). The AQI categorizes air quality levels (e.g., good, moderate, unhealthy), aiding public awareness and policy-making by integrating multiple pollutants into a single value. [5]

Health indicators quantify the direct impacts of air pollution on human health:

- Hospitalization Rates: The number of hospital admissions due to respiratory and cardiovascular conditions attributed to air pollution. High hospitalization rates indicate the acute health effects of exposure to pollutants.
- Death Rates: Death rates associated with air pollution-related diseases, including lung cancer, stroke, heart disease, and respiratory illnesses. Elevated mortality rates reflect the long-term health consequences of prolonged exposure to polluted air.
- Ashtma Emergency Department Visits: Air pollutants can trigger asthma attacks, prompting individuals to seek urgent medical care. These visits highlight the immediate respiratory risks posed by polluted air, especially for those with asthma and other respiratory conditions.

Each indicator serves a specific purpose in assessing air pollution and its impacts on human health and the environment. The AQI offers a comprehensive air quality assessment integrating various pollutants, crucial for public awareness and policy decisions. The concentration of pollutants helps in identifying sources of pollution and assessing compliance with air quality standards, guiding regulatory actions to reduce emissions. And, finally health Indicators quantify the health impacts of air pollution, informing healthcare planning, public health interventions, and policy-making aimed at protecting vulnerable populations and improving overall air quality.

These indicators collectively form a framework to understand the intricate dynamics between air pollution, human health, and environmental sustainability. By monitoring and analyzing these metrics, policymakers can develop effective strategies to mitigate air pollution and safeguard public health.

2 Dataset selection

For this study, datasets on air pollutants and their health impacts were sourced from NYC.GOV, The Official Website of the City of New York [6]. These datasets were collected for both boroughs and UHF42 regions, emphasizing key pollutants such as black carbon, NO2, NO, O3, and PM2.5. These data are crucial for assessing environmental quality across diverse geographic areas within New York City.

The selected datasets offer a comprehensive range of measurements essential for our analysis:

- Black Carbon: Includes data on Mean Absorbance Units, providing insights into the light-absorbing properties.
- PM2.5: Provides measurements in Mean mcg/m^3, crucial for assessing fine particulate matter concentrations known to pose significant health risks.
- NO and NO2: Quantified in parts per billion (ppb), these nitrogen oxides are indicators of combustion-related pollution sources.
- O3: Also measured in ppb, ozone levels are critical for understanding ground-level concentrations and their potential health impacts.

Air pollution poses a significant environmental threat to New York City residents, particularly through two common pollutants: fine particulate matter (PM2.5) and ozone (O3). These pollutants exacerbate respiratory illnesses, cardiovascular conditions, and contribute to premature deaths, with heightened susceptibility among older adults, children, and individuals with existing heart and lung diseases.

PM2.5, or fine particulate matter, derives primarily from sources such as vehicle emissions and the combustion of fossil fuels. These tiny particles can deeply penetrate the lungs, posing health risks. Chronic exposure to PM2.5 is associated with a range of respiratory issues, including aggravated asthma, reduced lung function, and increased susceptibility to respiratory infections. Furthermore, PM2.5 exposure has been linked to cardiovascular diseases such as heart attacks and strokes, as well as premature mortality among exposed populations.

While, Ozone (O3), knows as smog, forms when pollutants from vehicle emissions, industrial processes, and other sources react in the presence of sunlight. Ozone irritates the respiratory system and inflames lung tissues upon inhalation. This irritation can exacerbate asthma symptoms, leading to increased asthma attacks and other respiratory conditions. Long-term exposure to elevated ozone levels has been associated with chronic respiratory diseases and can worsen existing respiratory ailments, particularly among vulnerable individuals such as children, the elderly, and those with pre-existing respiratory conditions.

The health-related datasets from NYC.GOV provide detailed insights into the impacts of PM2.5 and ozone on residents' health, focusing on:

- Emergency Department Visits:
  - Ozone: Estimating annual asthma-related emergency department visits attributed to ozone exposure, providing insights into acute respiratory impacts on adults and children.
  - PM2.5: Quantifying asthma-related emergency department visits due to fine particulate pollution, reflecting the health burdens associated with PM2.5 exposure.
- Hospitalizations
  - Ozone: Data on hospitalizations due to ozone exposure focus on asthma cases, illustrating the severe respiratory outcomes linked to air pollution.
  - PM2.5:
    * Cardiovascular Hospitalizations (age 40+): Estimating annual hospitalizations for cardiovascular conditions associated with PM2.5 exposure among adults aged 40 and older.
    * Respiratory Hospitalizations (age 20+): Providing insights into hospitalizations related to respiratory illnesses due to PM2.5 exposure across different age groups.
- Deaths:
  - Ozone: Data estimating annual deaths from cardiac and respiratory causes attributed to ozone exposure underscore the significant mortality risks associated with this pollutant.
  - PM2.5: Estimations of deaths attributable to PM2.5 provide crucial information on the long-term health impacts of fine particulate matter pollution, particularly among adults aged 30 and older.

These datasets utilize robust methodologies to assess the health impacts of air pollutants, integrating air quality monitoring data with local health indicators. They are essential for understanding the complex relationship between air quality and public health in urban environments like New York City.

In addition to the datasets sourced from NYC.GOV, which emphasize pollutants such as black carbon, NO2, NO, O3, and PM2.5 across boroughs and UHF42 regions, the study incorporates data from other sources to enhance the breadth of analysis:

- Historical Air Quality Data: Historical daily data on PM2.5 and O3 from AQICN.org, The World Air Quality Index project, spans from 2014 to the present, enabling forecasting of future pollutant levels and analysis of long-term trends. [7]

- Vehicle Miles Traveled: Utilizing datasets from NYC OpenData, updated as of April 10, 2024, provides crucial insights into transportation-related emissions and their impact on local air quality. This dataset, maintained by the Department of Health and Mental Hygiene (DOHMH), details vehicle miles traveled in NYC. [8]

Together, these varied datasets form a robust groundwork for evaluating air quality trends, predicting future patterns, and comprehending the socio-environmental elements affecting public health outcomes in New York City. By integrating these datasets, our study aims to inform evidence-based strategies for improving urban air quality and safeguarding the health of city residents.

3 Spatio-Temporal Analysis

3.1 Spatial Analysis

For spatial analysis, two distinct geographical mappings were utilized: the borough map and the UHF42 map. Here's a brief explanation of each:

- Borough Map: New York City is divided into five boroughs: Manhattan, Brooklyn, Queens, the Bronx, and Staten Island. Each borough serves as a fundamental unit for administrative and geographical delineation within the city.

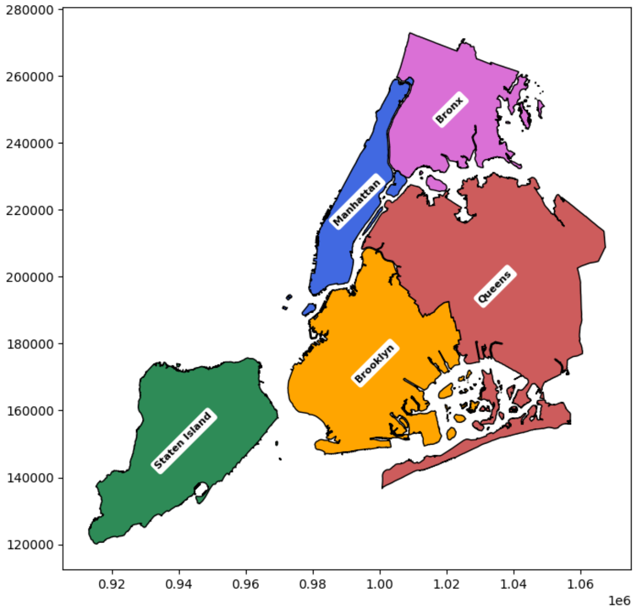

Figure 1: NYC Borough map.

- UHF42 Map: The UHF42 (United Hospital Fund) neighborhoods provide a finer granularity within the boroughs. These 42 neighborhoods are designed for health data analysis and are used to assess health-related trends at a more localized level across the city.

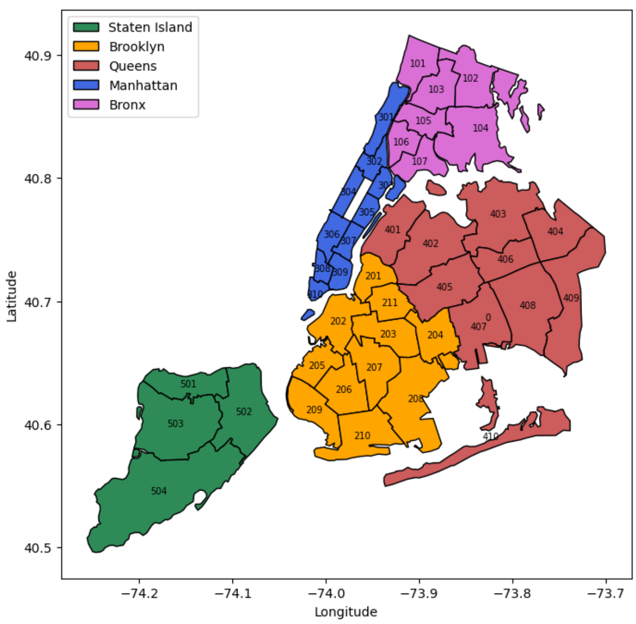

Figure 2: NYC UHF42 map.

For each pollutant studied, a spatial analysis was conducted to examine concentration levels first at the borough level and then within each UHF42 neighborhood. This dual approach allowed capture of both city-wide trends and localized variations in pollutant levels. By leveraging these geographical frameworks, the aim was to uncover spatial patterns and hotspots of pollution across New York City. This analysis is crucial for understanding how environmental factors vary across different scales within urban settings, thereby informing targeted interventions and policy decisions.

To illustrate these findings, Figure 3 presents the concentration levels across New York City boroughs.

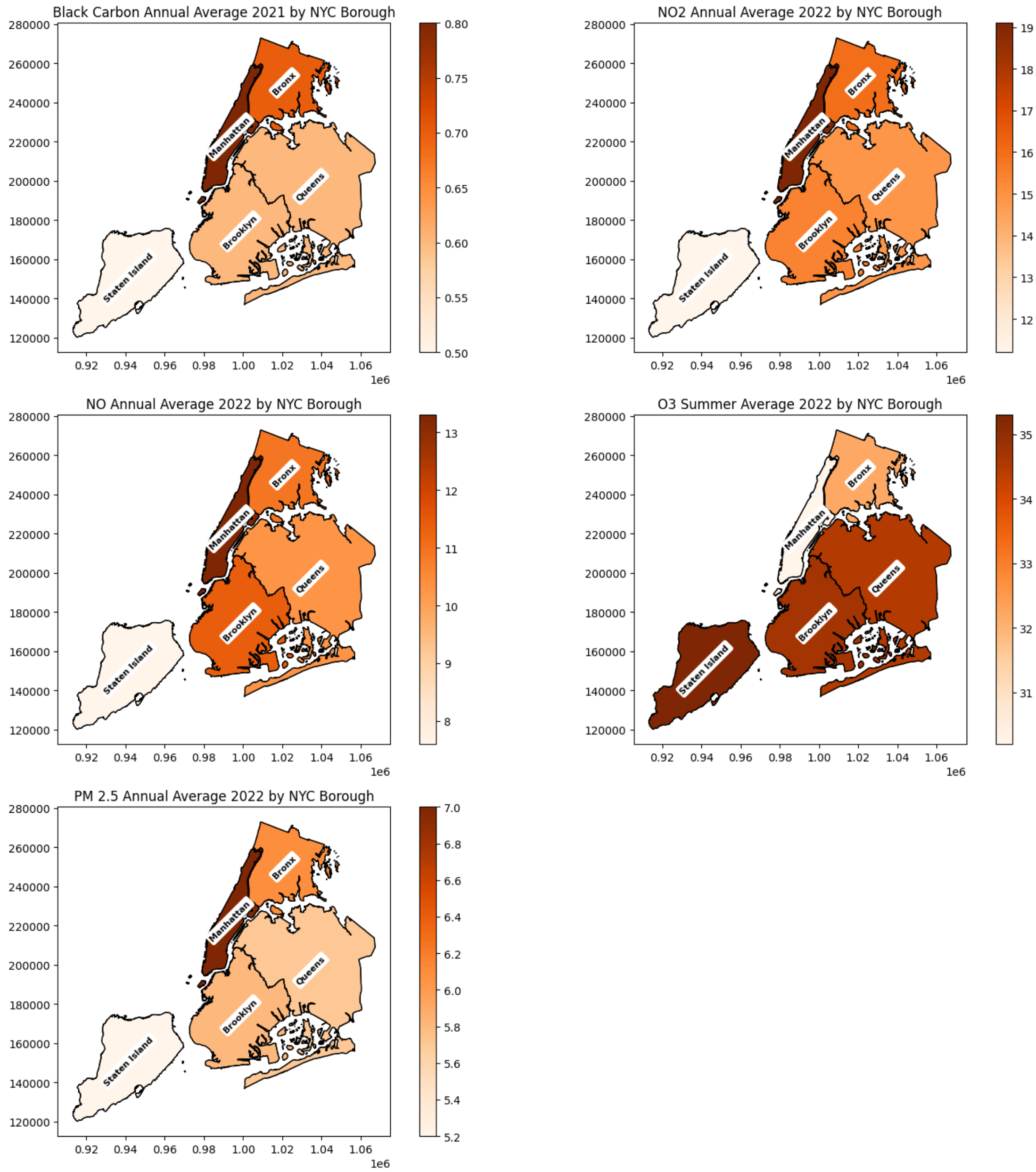

Figure 3: Concentration levels of air pollutants in New York City boroughs in 2021 and 2022, based on data from NYC.gov's health data portal. Pollutants include Black Carbon (2021), NO2 (2022), NO (2022), O3 (2022), and PM 2.5 (2022).

For almost all graphs, it is noticeable that Manhattan consistently shows the highest concentration of pollutants among the boroughs. However, there is a notable exception with O3, where the highest concentration is observed in Staten Island, followed by Brooklyn and Queens. This variation can be attributed to different factors, including localized emissions sources and atmospheric conditions.

Moving to a more granular analysis, Figure 4 zooms into the UHF42 neighborhoods.

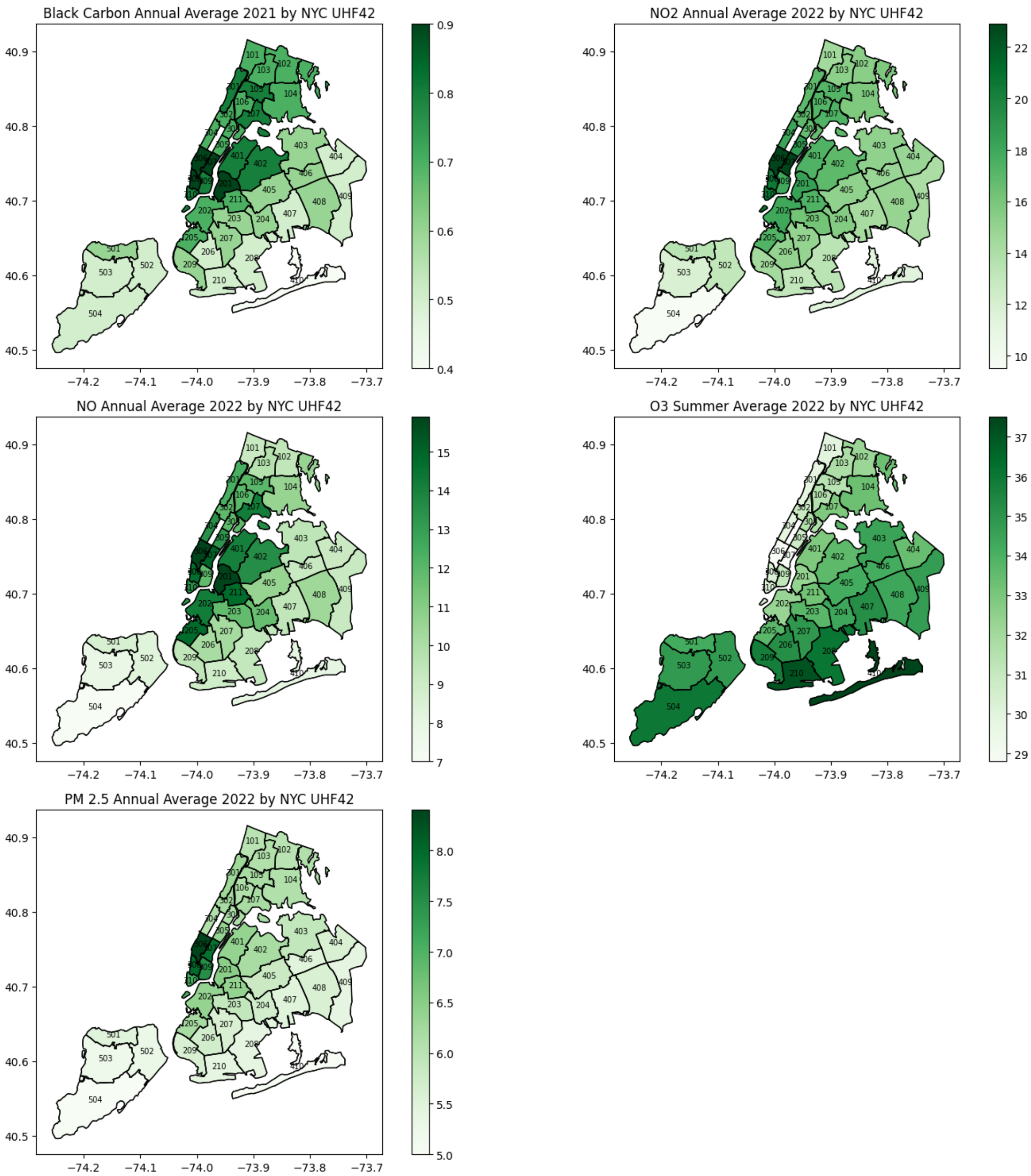

Figure 4: Concentration levels of air pollutants in UHF42 neighborhoods in New York City in 2021 and 2022, based on data from NYC.gov's health data portal. Pollutants include Black Carbon (2021), NO2 (2022), NO (2022), O3 (2022), and PM 2.5 (2022).

For UHF42 neighborhoods, we observe similar pollutants and years as in the borough-level analysis. The neighborhoods predominantly affected by high concentrations of Black Carbon, NO2, NO, and PM 2.5 are 206 (Borough Park), 207 (East Flatbush - Flatbush), and 308 (Canarsie - Flatlands). Additionally, for NO, neighborhoods in Brooklyn such as 201 (Greenpoint), 205 (Sunset Park), and 211 (Williamsburg - Bushwick) also exhibit elevated concentrations. In contrast, high concentrations of O3 are notably found in Queens neighborhoods like 410 (Rockaway) and Brooklyn's 210 (Coney Island - Sheepshead Bay). Staten Island shows consistently elevated levels across its area.

To study these concentrations, ZoLa (New York City's Zoning and Land Use Map) [9] was utilized, providing a straightforward way to research zoning regulations. ZoLa allows users to find zoning information for properties, explore new proposals for neighborhoods, and learn about City Planning initiatives citywide.

It is immediately noticeable that areas in Manhattan with high concentrations of various pollutants are predominantly commercial zones with heavy traffic, a pattern also observed in certain neighborhoods of Brooklyn. In contrast, for O3, concentrations are higher in manufacturing districts and residential areas.

Figure 5 illustrates the zoning and land use characteristics across New York City, highlighting areas where high pollutant concentrations align with commercial and industrial zoning.

These findings suggest a clear correlation between land use, commercial activities, and pollutant concentrations in urban settings. Areas designated for industrial activities and residential living may require specific environmental management strategies to mitigate pollutant levels effectively.

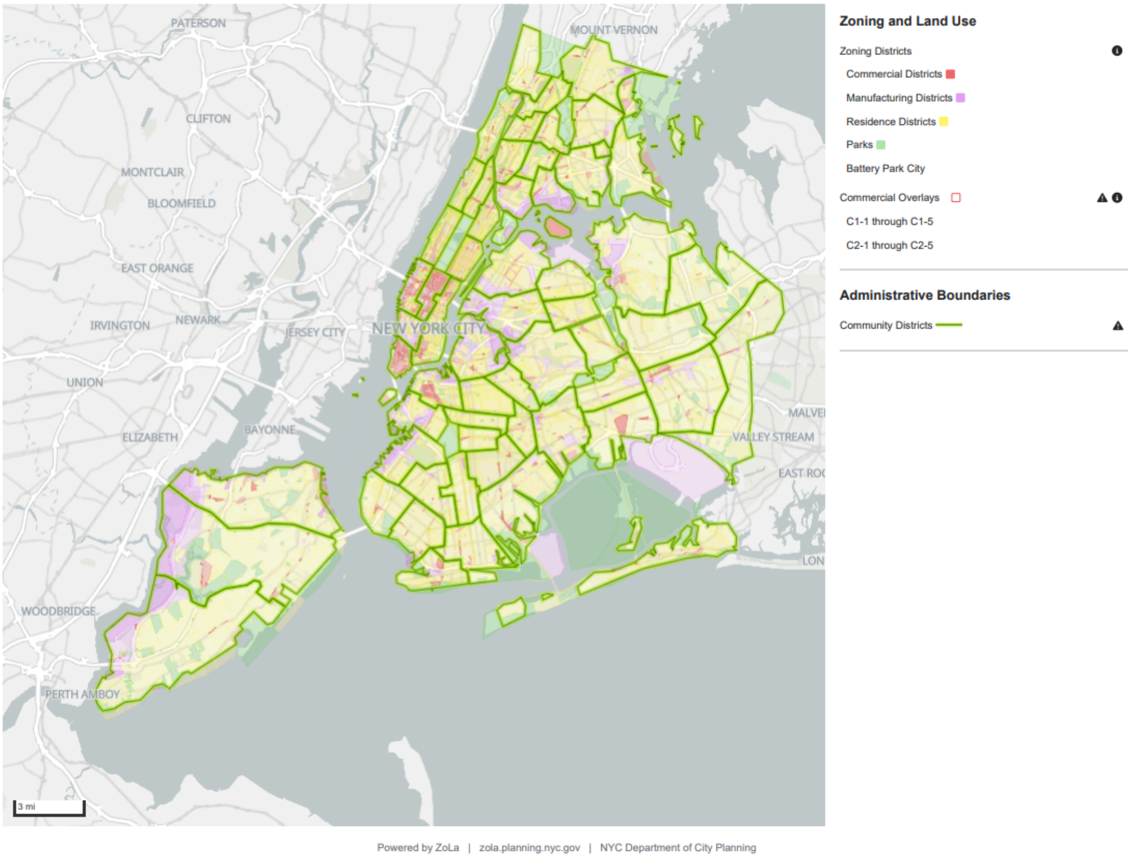

Figure 5: Zoning and land use map of New York City.

3.2 Temporal Analysis

For each pollutant considered in the evaluation of air quality in New York City, trends were plotted from 2009 to the most recent available data, which is 2021 for Black Carbon and 2022 for the other pollutants. For O3, the analysis uses summer averages. It's important to note that O3 is evaluated in the summer because its formation is influenced by higher temperatures and increased sunlight, leading to higher concentrations during this season. [10]

The following images illustrate these trends:

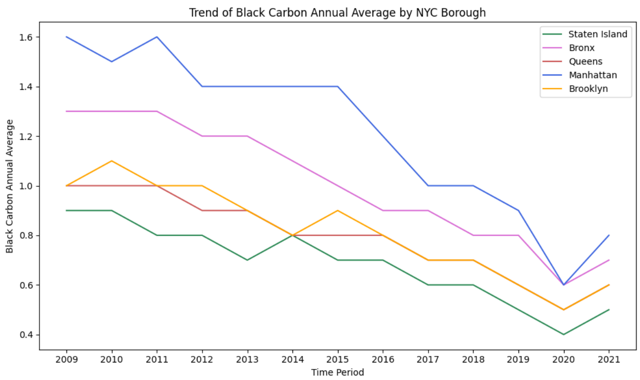

Figure 6: Trend of Black Carbon levels in New York City from 2009 to 2021.

Figure 6 illustrates the trend of Black Carbon, showing a decline until 2020, followed by a slight increase. The significantly low levels in 2020 can be attributed to the impact of COVID-19, which led to a reduction in traffic and industrial activities.

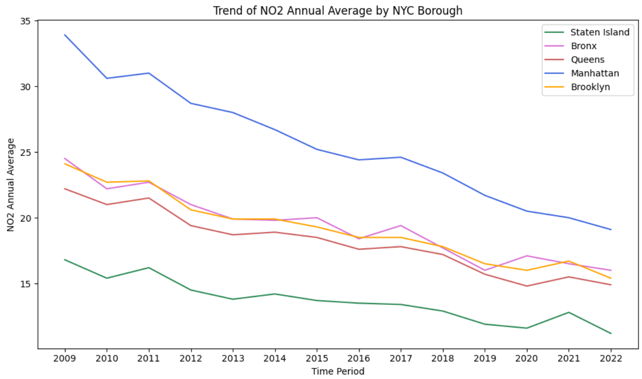

Figure 7: Trend of NO2 levels in New York City from 2009 to 2022.

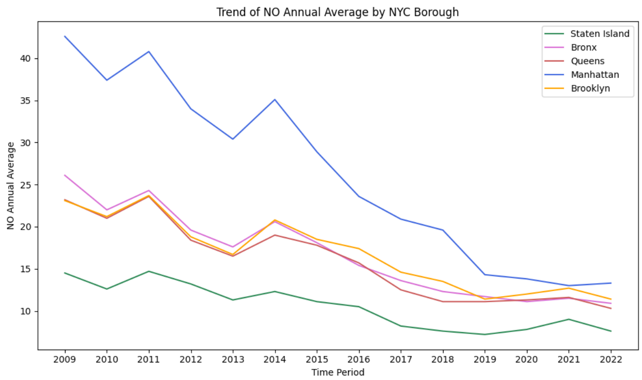

Figure 8: Trend of NO levels in New York City from 2009 to 2022.

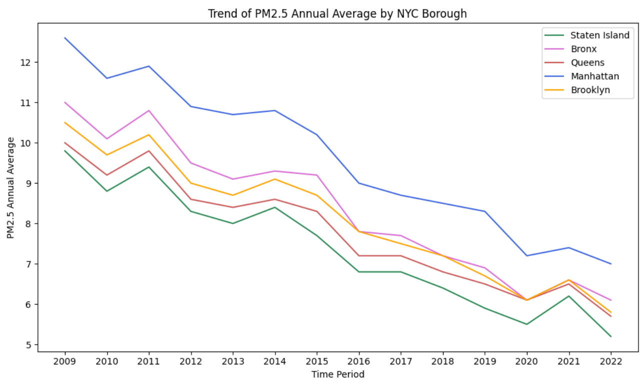

Figure 9: Trend of PM2.5 levels in New York City from 2009 to 2022.

NO, NO2, and PM2.5, as well as Black Carbon, show a decline until 2020, with a slight increase thereafter.

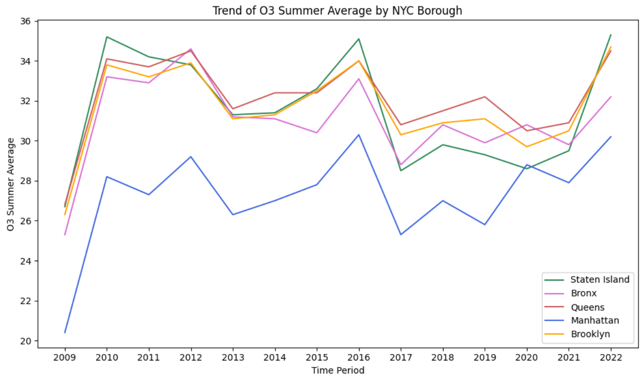

Figure 10: Trend of O3 levels (summer average) in New York City from 2009 to 2022.

Figure 7 shows the trend of O3. It started at a low point in 2009, spiked sharply in 2010, and then maintained consistent values with some annual peaks.

Manhattan consistently shows higher levels of NO, NO2, Black Carbon, and PM2.5 compared to other boroughs. However, for O3, Manhattan has lower levels, with the other boroughs having similar concentrations.

To visualize the distributions of pollutant concentrations, boxplots for each pollutant are included:

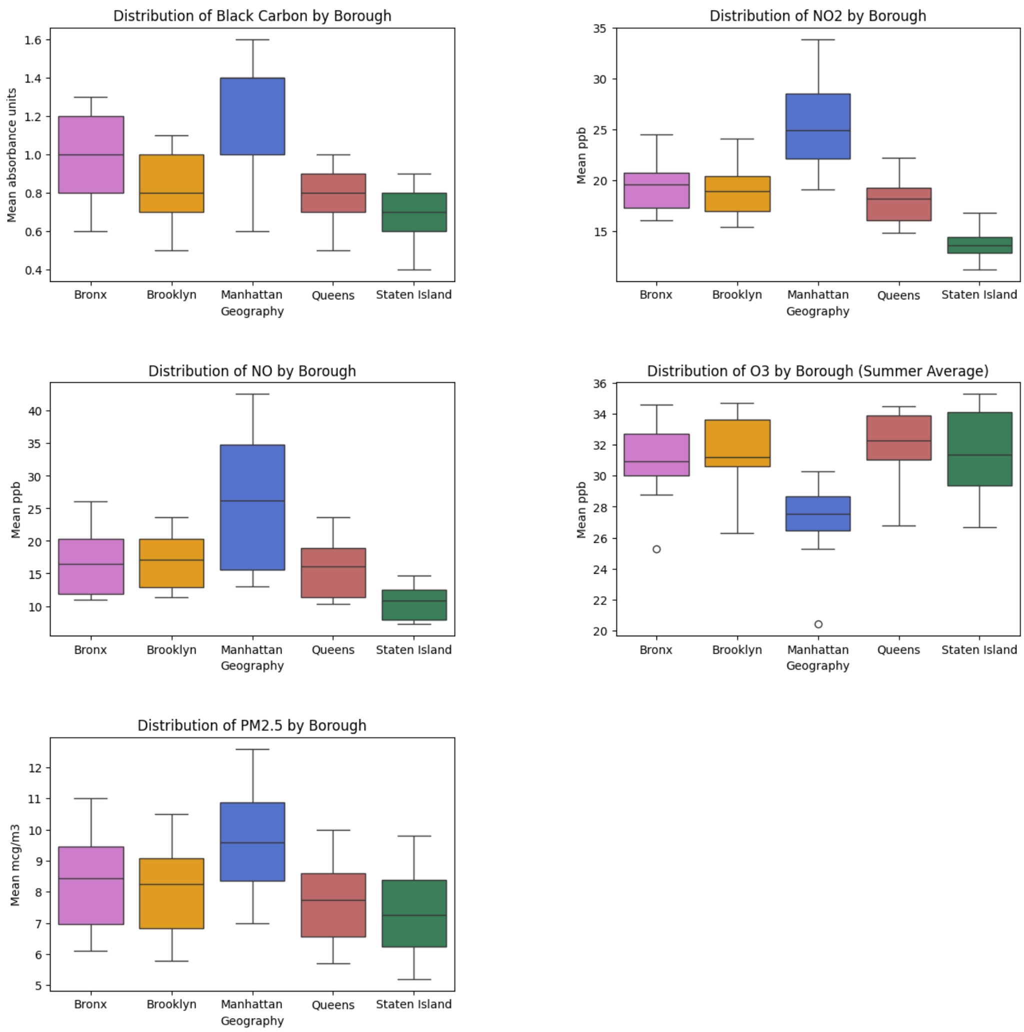

Figure 11: Distribution of each pollutant.

3.3 Seasonality Analysis

For each pollutant, possible seasonal patterns were analyzed. As previously mentioned, O3 concentrations are higher in the summer and have been excluded from this analysis. Figure 12 shows the seasonal patterns for the other pollutants. The following observations were made:

- Black Carbon and PM2.5: Both pollutants show similar concentrations during summer and winter.
- NO2 and NO: Concentrations are higher in the winter.

Here is the corresponding figure illustrating these patterns:

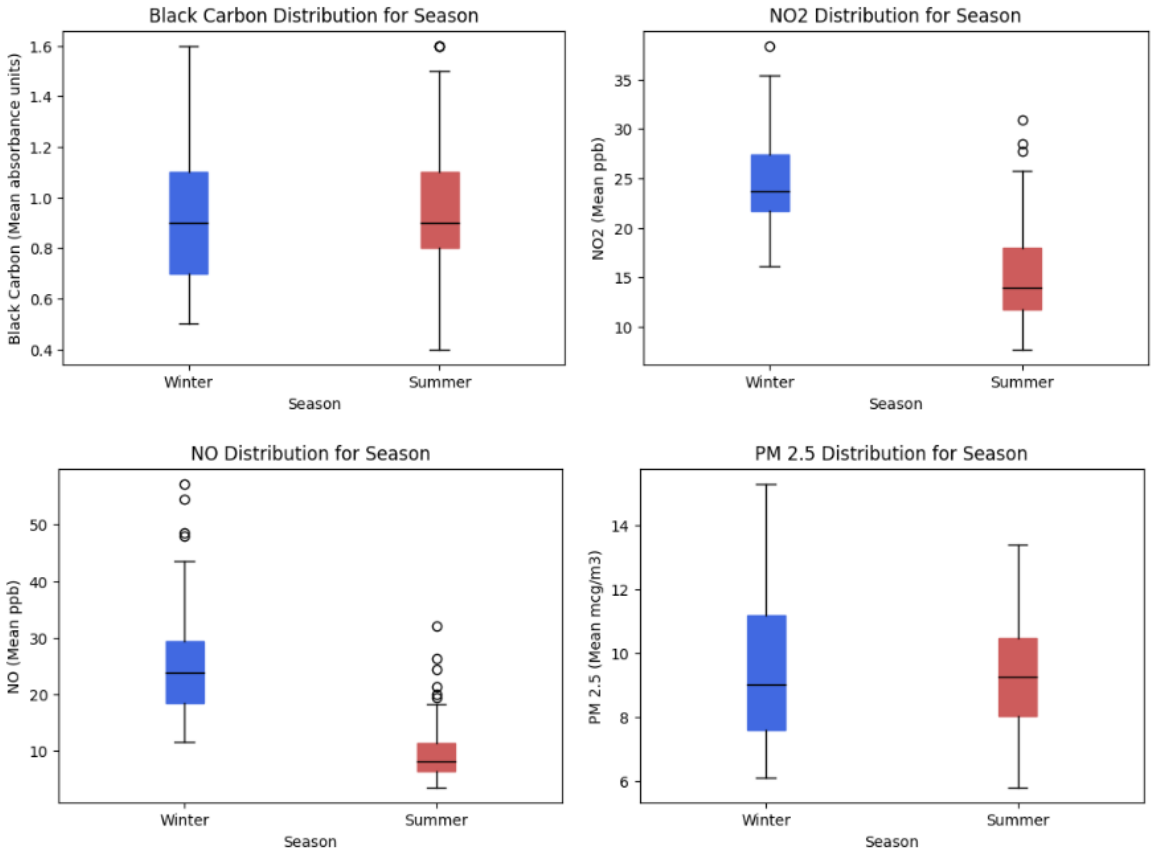

Figure 12: Seasonal patterns of Black Carbon, NO2, NO, and PM2.5.

Analysing seasonal patterns helps in understanding the variations in pollutant levels throughout the year, providing valuable insights into the factors contributing to changes in air quality across different seasons.

3.4 Traffic Analysis

As mentioned earlier, traffic is one of the primary contributors to air pollution in New York City. This project examines the annual vehicle miles traveled data for cars, trucks, and vehicles in general. Data analysis was conducted both at the borough and UHF42 neighborhood levels, yielding the following conclusions:

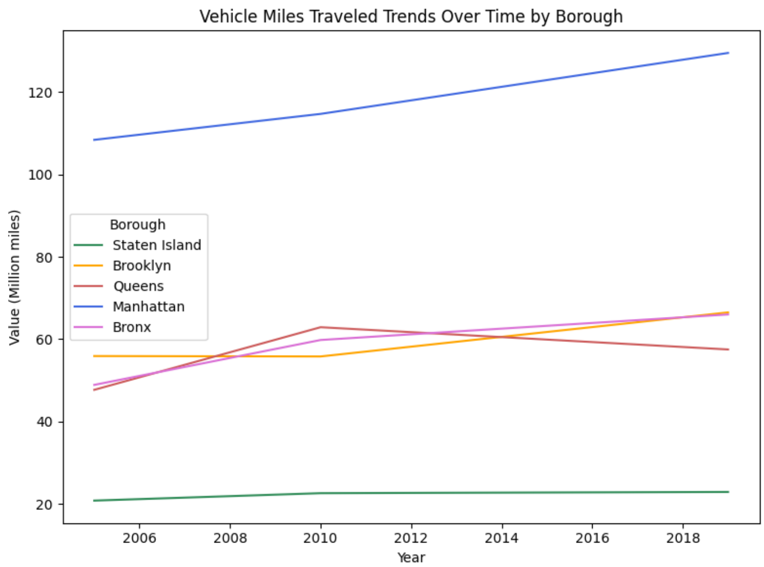

Figure 13: Trend plot for vehicle miles traveled over the years in New York City boroughs

The plot for vehicles in general summarizes both cars and trucks, with Manhattan showing the highest vehicle miles traveled over time, followed closely by Brooklyn, Queens, and the Bronx, and Staten Island having the lowest. The aggregated data highlights these results:

- Manhattan 117.5 million miles per square mile
- Brooklyn 59.4 million miles per square mile
- Bronx 58.2 million miles per square mile
- Queens 56.0 million miles per square mile
- Staten Island 22.1 million miles per square mile

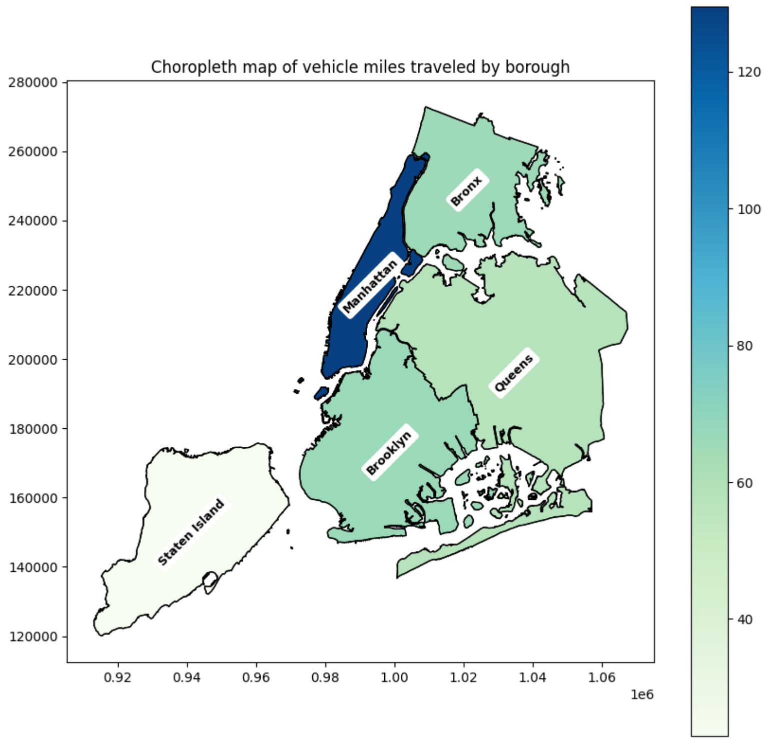

Figure 14: Choropleth map showing vehicle miles traveled in New York City boroughs

For UHF42 neighborhoods, the analysis focuses on the choropleth map illustrating vehicle miles traveled:

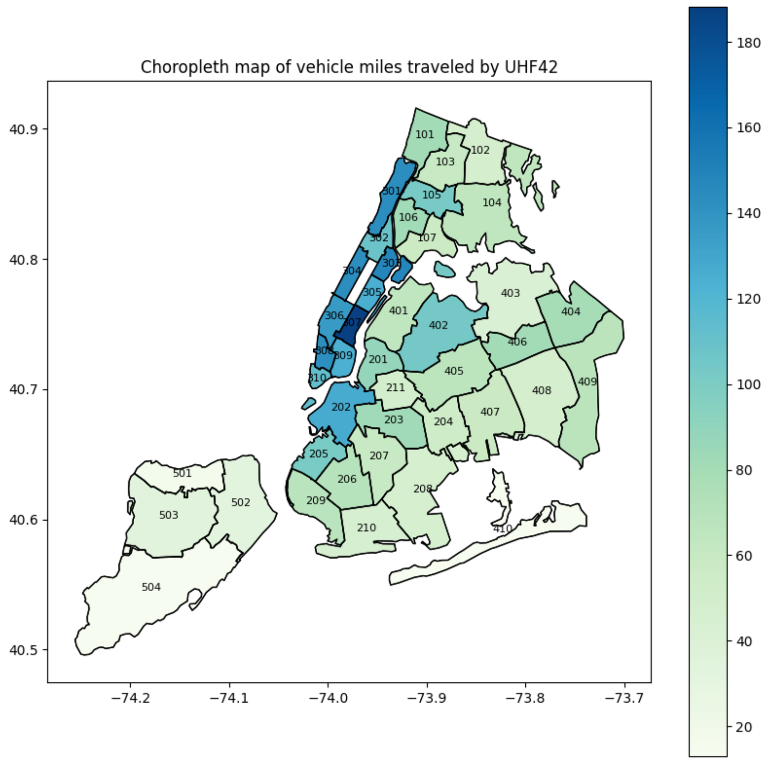

Figure 15: Choropleth map showing vehicle miles traveled in UHF42 neighborhoods

Top-ranking areas include:

- 307: Gramercy Park - Murray Hill (182.4 million miles per square mile)
- 303: East Harlem (134.3 million miles per square mile)
- 308: Greenwich Village - SoHo (133.3 million miles per square mile)
- 305: Upper East Side (126.3 million miles per square mile)
- 304: Upper West Side (124.7 million miles per square mile)
- 306: Chelsea - Clinton (123.0 million miles per square mile)
- 309: Union Square - Lower East Side (120.3 million miles per square mile)
- 301: Washington Heights (115.8 million miles per square mile)
- 202: Downtown - Heights - Slope (104.2 million miles per square mile)
- 402: West Queens (100.1 million miles per square mile)

These findings highlight how areas with high vehicle miles traveled also experience higher levels of pollution, underscoring the significant impact of traffic on urban air quality and public health. This emphasizes the urgency for sustainable transportation policies and infrastructure improvements to alleviate these effects.

4 Health Impact

The health impact analysis in this study focuses on the relationship between air pollution and health outcomes across different boroughs of New York City (NYC). Understanding this relationship is crucial as it highlights the broader social determinants of health, such as poverty and health insurance coverage, which influence the susceptibility of communities to the adverse effects of pollution.

4.1 Poverty and Health Insurance Coverage

To understand the health impact of air quality and pollution, an examination of the poverty rate of different boroughs and the distribution of health insurance among adults was conducted. These factors are significant because they can influence access to healthcare and the ability to manage pollution-related health conditions.

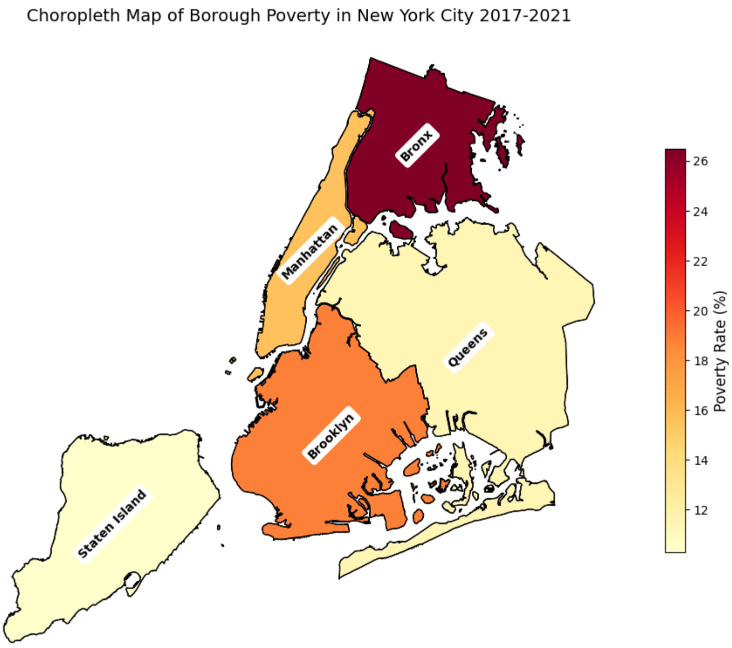

Figure 16: Poverty rate by borough (2017-2021)

Using a choropleth map, the poverty rates across NYC boroughs from 2017 to 2021 were visualized, revealing stark differences in poverty levels:

- Bronx: The highest poverty rate at 26.5
- Brooklyn: The second highest at 18.8
- Manhattan: 15.6
- Queens: 11.4
- Staten Island: The lowest at 10.3

These disparities are critical as higher poverty rates are often associated with poorer health outcomes due to limited access to healthcare, nutritious food, and clean environments.

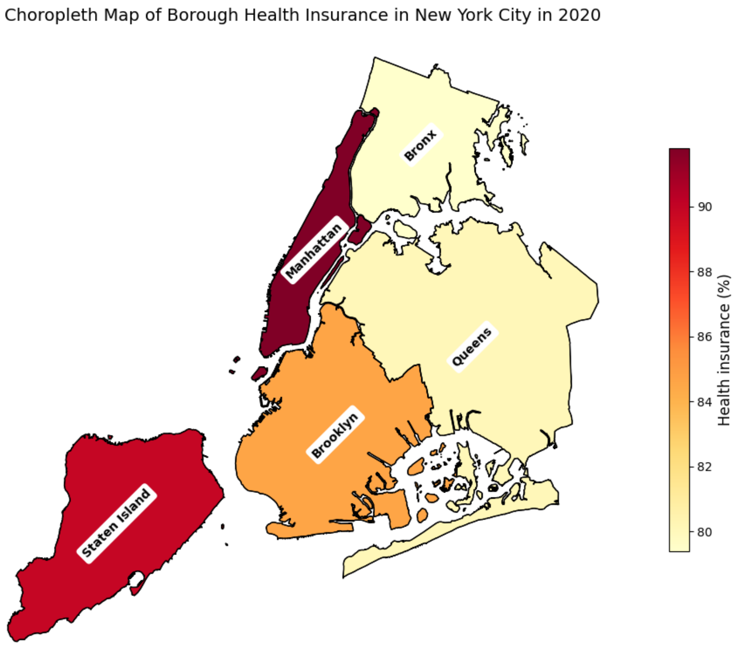

Figure 17: Health Insurance Coverage (2020)

Conversely, the distribution of health insurance coverage among adults in 2020 showed a different pattern. A higher rate of health insurance coverage suggests better access to healthcare services, which can mitigate the health impacts of pollution:

- Bronx: 79.4
- Brooklyn: 84.6
- Manhattan: 91.8
- Queens: 80.1
- Staten Island: 89.9

From this data, Manhattan and Staten Island have the highest health insurance coverage rates, while the Bronx has the lowest, potentially exacerbating the health impacts of pollution in the Bronx.

Now, following these preliminary discussions, we can move on to the health impact analysis, specifically examining asthma emergencies and hospitalizations, as well as deaths related to ozone and PM2.5 pollution in New York City (NYC).

4.2 Asthma Emergency

From 2005 to 2019, significant variations were observed in emergency visits linked to both ozone and PM2.5 across different neighborhoods of New York City. Figure 18 illustrates temporal trends for ozone-related emergency visits by borough, highlighting elevated rates in the Bronx. Notably, neighborhoods such as 105 (Crotona - Tremont), 106 (High Bridge - Morrisania), and 107 (Hunts Point - Mott Haven) exhibit high rates for ozone-related emergencies.

Similarly, Figure 19 depicts PM2.5-related emergency visits, showing comparable trends across NYC boroughs. In the Bronx (Figure 20), the same neighborhoods - 105 (Crotona - Tremont), 106 (High Bridge - Morrisania), and 107 (Hunts Point - Mott Haven) - also report elevated emergency visit rates due to PM2.5 pollution (Figure 21). These findings underscore the significant impact of both pollutants on respiratory health within urban communities. Understanding these localized patterns is essential for implementing targeted interventions to reduce asthma-related emergency visits and enhance respiratory health outcomes in these areas.

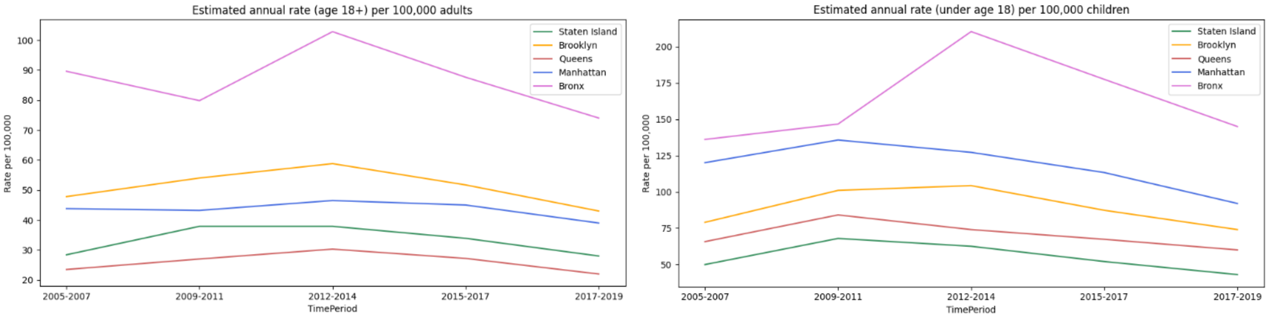

Figure 18: Temporal Trends of Asthma Emergency Rates due to Ozone in NYC Boroughs (2005-2019)

Note: The left plot depicts estimated annual rates per 100,000 adults (age 18+), while the right plot shows rates for children (under age 18).

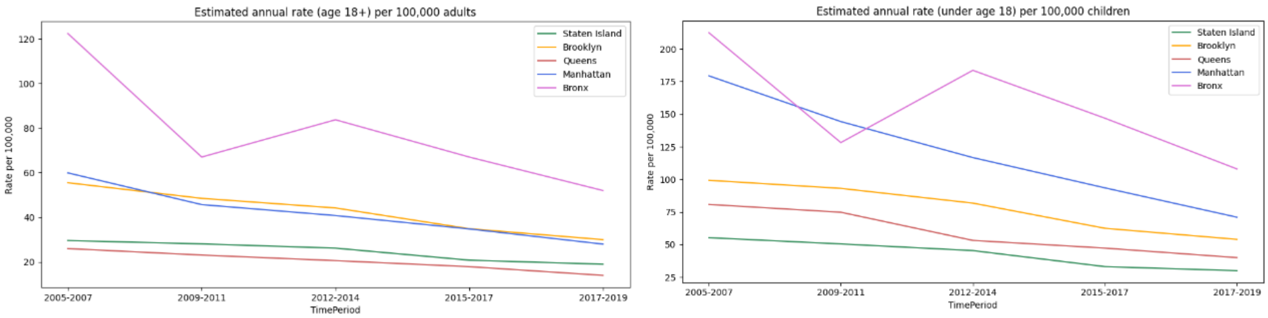

Figure 19: Temporal Trends of Asthma Emergency Rates due to PM2.5 in NYC Boroughs (2005-2019)

Note: The left plot depicts estimated annual rates per 100,000 adults (age 18+), while the right plot shows rates for children (under age 18).

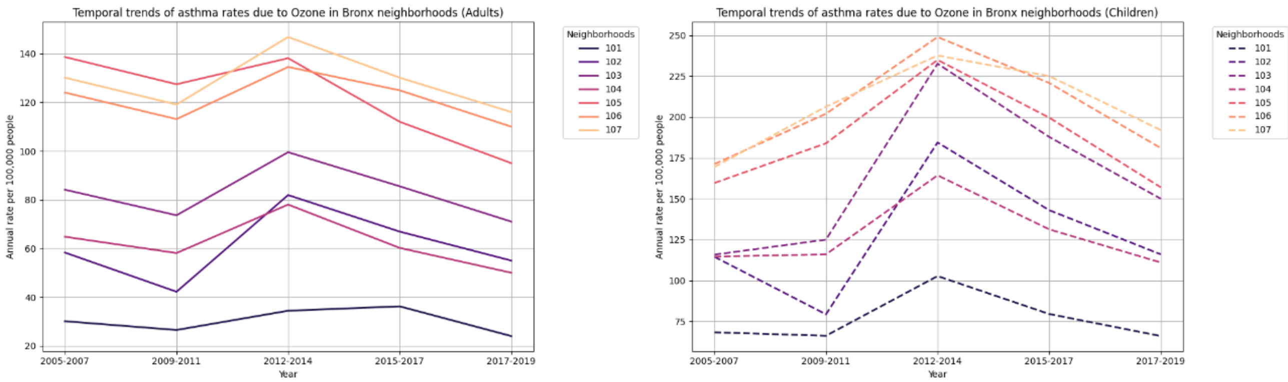

Figure 20: Temporal Trends of Asthma Emergency Rates due to Ozone in Bronx UHF42 (2005-2019)

Note: The left plot depicts estimated annual rates per 100,000 adults (age 18+), while the right plot shows rates for children (under age 18).

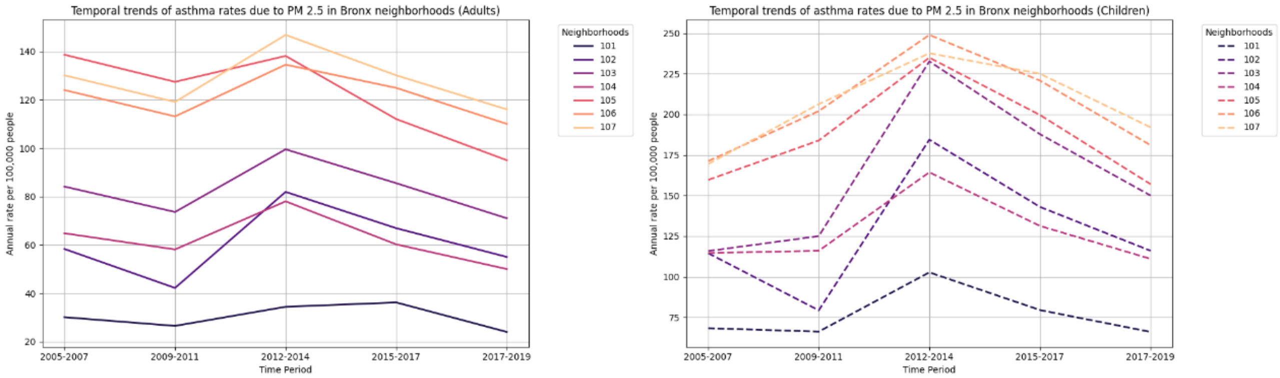

Figure 21: Temporal Trends of Asthma Emergency Rates due to PM2.5 in Bronx UHF42 (2005-2019)

Note: The left plot depicts estimated annual rates per 100,000 adults (age 18+), while the right plot shows rates for children (under age 18).

These findings underscore the significant impact of ozone and PM2.5 pollution on respiratory health across New York City, with pronounced effects observed in Bronx neighborhoods. Addressing these localized health disparities requires targeted interventions aimed at reducing asthma-related emergency visits and improving overall respiratory health outcomes. Moving forward, it will be crucial to further investigate the specific drivers of these high emergency rates and to assess the long-term effectiveness of mitigation strategies. Such efforts are essential for fostering healthier urban environments and mitigating the adverse health effects of air pollution on vulnerable populations.

4.3 Hospitalization

Analyzing hospitalizations due to environmental factors provides critical insights into the public health impacts of air pollution in urban settings like New York City. This section examines asthma and cardiovascular hospitalizations associated with ozone and PM2.5 pollution across NYC boroughs during the period from 2017 to 2019.

To start, the pie charts below illustrate estimated hospitalizations for adults and children between 2017 and 2019:

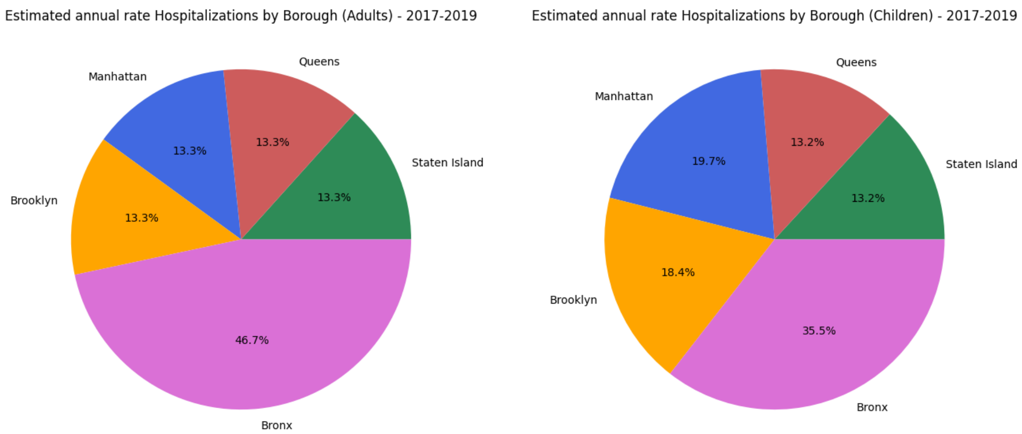

Figure 22: Estimated Asthma Hospitalizations due to O3 by Borough - 2017-2019

Note: The left plot depicts estimated annual rates per 100,000 adults (age 18+), while the right plot shows rates for children (under age 18).

These figures highlight significantly higher hospitalization rates in the Bronx compared to other boroughs, underscoring a substantial impact of ozone pollution on respiratory health in this area.

For cardiovascular hospitalizations linked to PM2.5 among adults aged 40 and above, another interesting pattern emerges. The following pie charts illustrate the estimated number and rate by borough during 2017-2019:

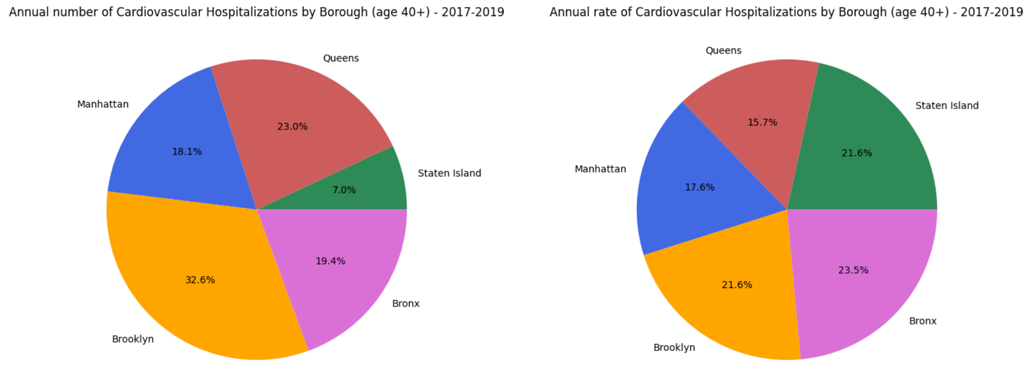

Figure 23: Estimated Cardiovascular Hospitalizations due to PM2.5 by Borough - 2017-2019

Note: The left plot depicts estimated annual number (age 40+), while the right plot shows the estimated annual rates per 100,000 adults (age 40+).

These images show that Staten Island and Brooklin emerge as a critical areas for cardiovascular hospitalizations related to PM2.5, although the Bronx still maintains a significant rate.

Regarding respiratory hospitalizations linked to PM2.5 among adults aged 20 and above, the following pie charts highlight data by borough during 2017-2019:

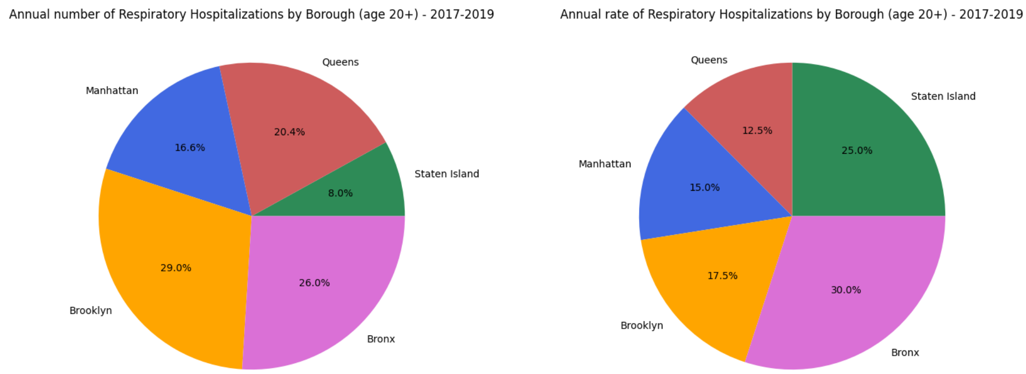

Figure 24: Estimated Cardiovascular Hospitalizations due to PM2.5 by Borough - 2017-2019

Note: The left plot depicts estimated annual number (age 20+), while the right plot shows the estimated annual rates per 100,000 adults (age 20+).

In this analysis, a decrease in hospitalizations is observed in Brooklyn, with an increase in Staten Island, while the Bronx continues to exhibit high rates of respiratory hospitalizations.

These findings confirm the significant impact of air pollution on public health at the local level, underscoring the need for targeted strategies to improve air quality and reduce adverse respiratory health outcomes in urban communities of New York City.

4.4 Deaths

Tragically, the impact of air pollution extends to mortality rates, with ozone and PM2.5 pollutants contributing to premature deaths among NYC residents. Analyzing annual mortality data from 2005 to 2019 highlighted varying rates across boroughs, with certain areas consistently reporting higher mortality rates per 100,000 adults. This section examines the detailed findings for deaths attributed to both ozone and PM2.5 pollution.

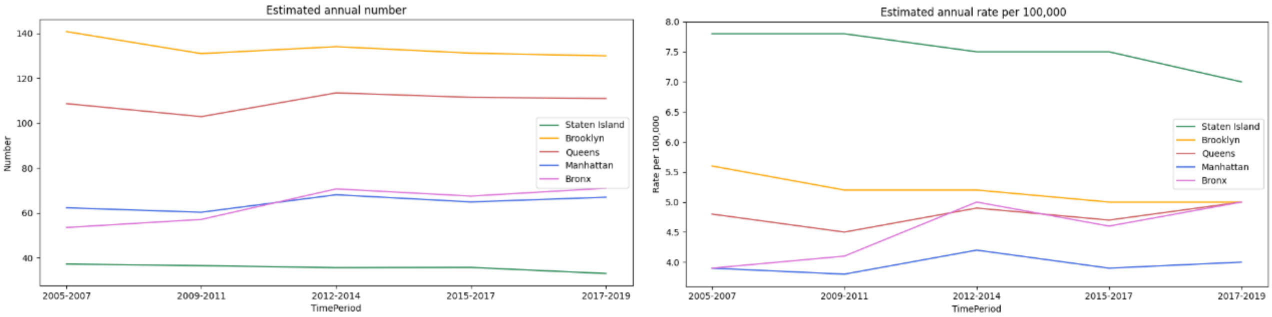

Figure 25: Estimated Deaths due to Ozone by Borough (2005-2019)

Note: The left plot depicts estimated annual number, while the right plot shows the estimated annual rates per 100,000.

As shown in Figure 25, over the period from 2005 to 2019, Staten Island recorded the highest estimated annual rate per 100,000 adults due to ozone, starting at nearly 8 and gradually decreasing to 7. Here are the detailed results:

Table 1: Deaths due to Ozone by Borough - 2017-2019

TimePeriod	Geography	Estimated annual number	Estimated annual rate
2017-2019	Bronx	71.0	5.0
2017-2019	Brooklyn	130.0	5.0
2017-2019	Manhattan	67.0	4.0
2017-2019	Queens	111.0	5.0
2017-2019	Staten Island	33.0	7.0

In Figure 26, the temporal trend for estimated deaths due to PM2.5 is shown.

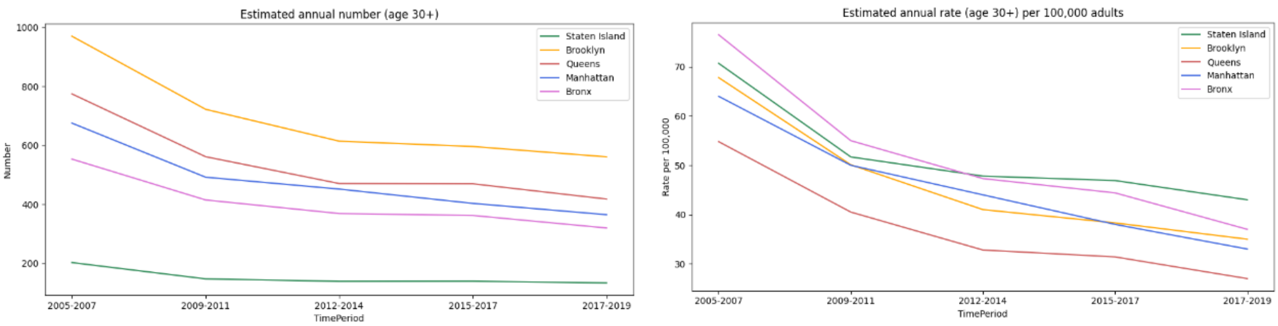

Figure 26: Estimated Deaths due to PM2.5 by Borough (2005-2019)

Note: The left plot depicts estimated annual number (age 30+), while the right plot shows the estimated annual rates (age 30+) per 100,000 adults.

Here are the detailed results:

Table 2: Deaths due to PM2.5 by Borough - 2017-2019

TimePeriod	Geography	Estimated annual number (age 30+)	Estimated annual rate (age 30+)
2017-2019	Bronx	320.0	37.0
2017-2019	Brooklyn	561.0	35.0
2017-2019	Manhattan	365.0	33.0
2017-2019	Queens	418.0	27.0
2017-2019	Staten Island	134.0	43.0

These tables provide insights into mortality rates for the most recent available year data (2017-2019). They highlight Staten Island as consistently reporting higher mortality rates per 100,000 adults compared to other boroughs for both ozone and PM2.5 pollutants.

The comprehensive analysis reveals the complex relationship between air quality, pollution, and public health outcomes in NYC. By examining asthma emergencies, hospitalizations, and mortality rates linked to ozone and PM2.5 pollutants, compelling evidence emerges of the disproportionate burden borne by vulnerable communities, particularly in the Bronx. These findings underscore the imperative for targeted policies and interventions aimed at improving air quality and safeguarding public health across all boroughs of New York City.

5 Time series analysis

This chapter delves into the time series analysis conducted to predict future levels of PM2.5, O3, and the Air Quality Index (AQI), all of which are closely correlated with cardio-respiratory diseases. The analysis utilized daily air quality data from New York City, spanning from 2014 to the present, and included measurements of PM2.5, O3, NO2, and CO. The dataset underwent meticulous cleaning and processing to ensure accuracy and consistency, including date format conversion, sorting, duplicate removal, and handling missing values.

At this stage, and with this dataset, the Air Quality Index (AQI) was calculated. Given the comprehensive availability of PM2.5 data, the AQI was determined using PM2.5 measurements. The AQI calculation follows the standard breakpoints defined by the Environmental Protection Agency (EPA) [11], which translate PM2.5 concentrations into AQI values.

The following table details the breakpoints used to calculate the AQI from PM2.5 concentrations:

Table 3: Breakpoints for Calculating AQI from PM2.5 Concentrations

PM2.5 Concentration ($\mu g/m^3$)	**AQI Value**	**AQI Category**
0.0 - 12.0	0 - 50	Good
12.1 - 35.4	51 - 100	Moderate
35.5 - 55.4	101 - 150	Unhealthy for sensitive groups
55.5 - 150.4	151 - 200	Unhealthy
150.5 - 250.4	201 - 300	Very unhealthy
250.5 - 350.4	301 - 400	Hazardous
350.5 - 500.4	401 - 500	Hazardous

The AQI values were categorized into six levels: 'Good', 'Moderate', 'Unhealthy for sensitive groups', 'Unhealthy', 'Very unhealthy', and 'Hazardous'. This categorization helped in visualizing the distribution and trends of air quality over time. The figure below illustrates the AQI trends from 2014 to the present, showcasing significant fluctuations and peak pollution events, including an alarming peak AQI value of 296.

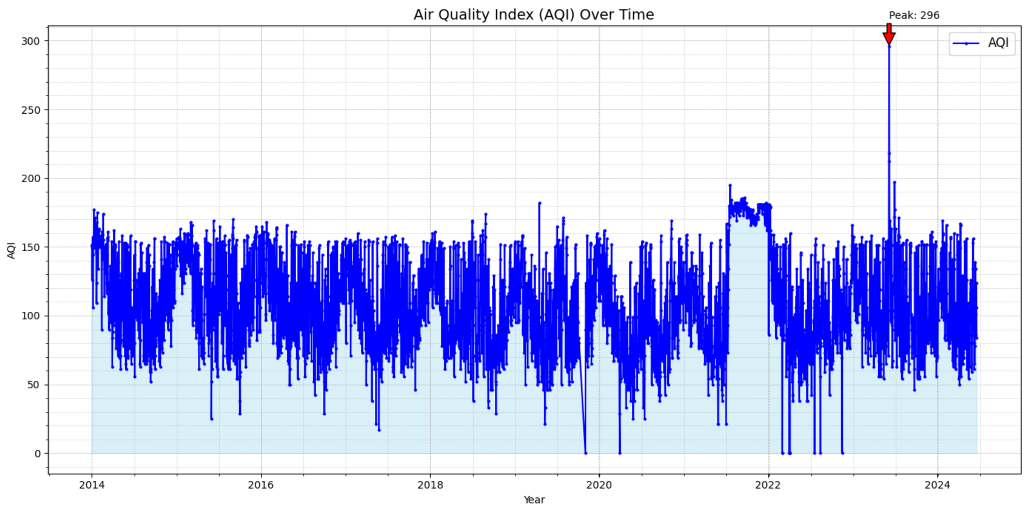

Figure 27: Air Quality Index (AQI) over time

The visual representation underscores the variability and periodicity in air quality, reflecting seasonal changes and sporadic pollution spikes. The peak AQI of 296, highlighted in the chart, signifies a severe pollution event that likely had substantial health impacts on the local population. Such visual analyses are crucial for understanding long-term trends and the effectiveness of air quality regulations and interventions.

Then, to prepare the data for forecasting, it was necessary to handle missing values to ensure a complete and continuous time series. The imputation process involved several steps to achieve this:

1. Setting the Date Index and Resampling: The ‘date‘ column was set as the index, and the data was resampled to a daily frequency using the ‘asfreq('D')‘ method. This step ensured that the dataset had consistent daily records, filling in any missing dates with NaN values.

2. Extracting Relevant Columns: The columns containing the pollutant measurements (‘pm25‘, ‘o3‘, ‘no2‘, ‘co‘) were selected for imputation. This subset of the dataframe was prepared for the imputation process.

3. Applying the KNN Imputer: The K-Nearest Neighbors (KNN) Imputer was applied to the selected columns. The ’n_neighbors’ parameter was set to 5, meaning that the algorithm used the five nearest neighbors to fill in the missing values.

By setting the date as the index and resampling to a daily frequency, a continuous time series was created. The KNN imputer then filled in the missing values based on the values of the nearest neighbors, resulting in a complete dataset for subsequent forecasting analysis.

To delve deeper into the analysis, Facebook Prophet was employed to forecast PM2.5, O3, and the Air Quality Index (AQI). This methodological approach is particularly suitable for time series forecasting due to its ability to handle various sources of uncertainty and capture complex seasonal patterns inherent in air quality data. Facebook Prophet operates by decomposing time series data into components such as trend, seasonality, and holiday effects. This decomposition allows the model to provide forecasts that account for these components, thereby offering more accurate predictions compared to traditional time series models. For each pollutant and AQI, the following steps were taken:

- Model Training: The historical data was used to train separate Prophet models for PM2.5, O3, and AQI. These models learned from the observed patterns and trends in the data over time.

- Forecasting: Once trained, the Prophet models were utilized to generate forecasts into the future. These forecasts incorporated seasonal variations, trend changes, and holiday effects specific to air quality dynamics in New York City.

- Visualization: The graphs generated using the Facebook Prophet model show predictions for various air quality measures. The black dots represent the actual measured values of the air quality metric over time. The blue line indicates the predicted values generated by the model. The light blue shaded area around the forecast line shows the range of uncertainty in the predictions, providing an upper and lower bound for expected values.

The forecasting results provided valuable insights into future air quality trends:

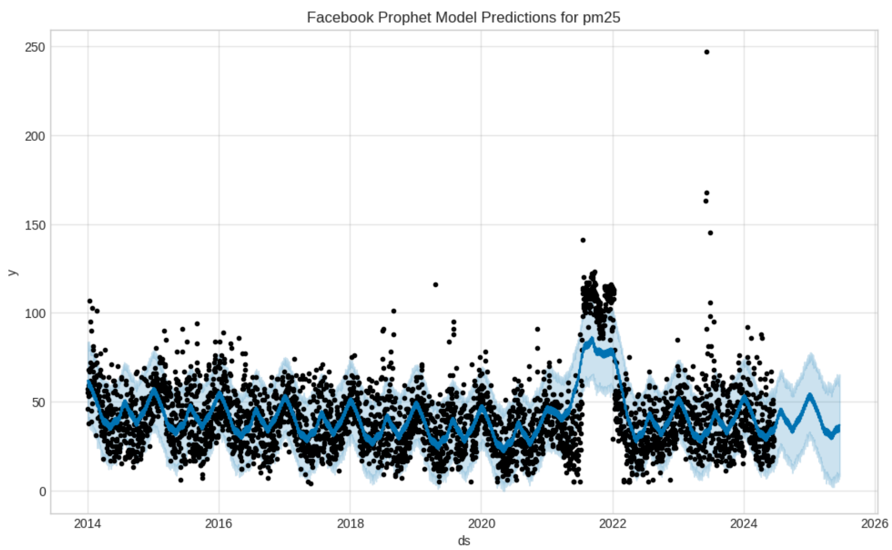

Figure 28: Facebook Prophet Model Predictions for PM2.5

The Figure 28 effectively demonstrates the forecasting capabilities of the Facebook Prophet model for PM2.5 levels over a span of more than a decade. One notable observation is the clear seasonal pattern, with regular peaks and troughs indicative of consistent annual fluctuations in PM2.5 concentrations. This seasonal trend suggests that certain times of the year consistently experience higher levels of PM2.5, likely due to specific weather patterns or recurring human activities. An interesting anomaly is observed around 2022, where there is a significant spike in PM2.5 levels, surpassing typical seasonal variations. This could point to an extraordinary event or a series of events leading to increased particulate matter in the air during that period. The model’s ability to highlight such deviations is valuable for identifying and analyzing unusual pollution events. The forecast extending to 2026 suggests a continuation of the established seasonal patterns, albeit with some degree of uncertainty as indicated by the shaded area around the predicted line. This uncertainty band is crucial for understanding the confidence range of the predictions and planning accordingly. Overall, the model provides a robust tool for predicting future PM2.5 levels, enabling proactive measures to mitigate air pollution and protect public health.

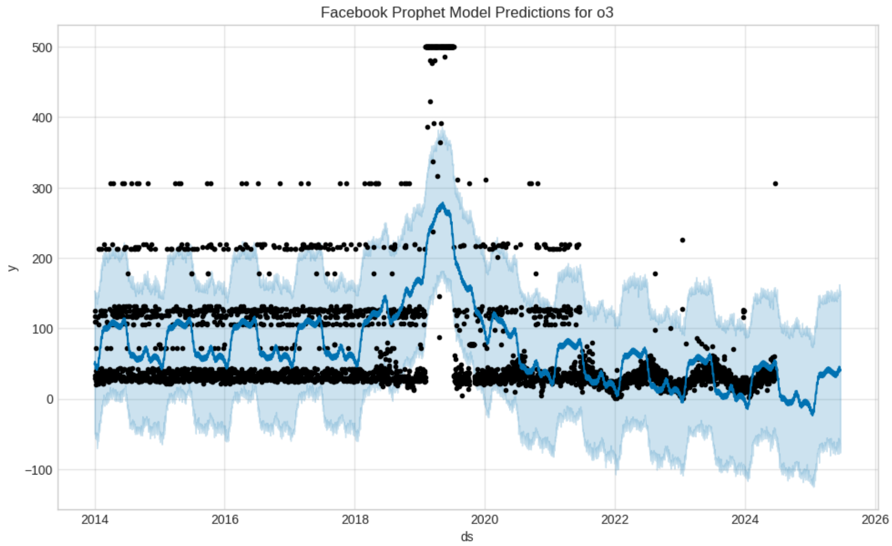

Figure 29: Facebook Prophet Model Predictions for O3

Figure 29 depicts the forecasts of ozone (O3) levels from 2014 to 2026 using the Facebook Prophet model. The model accurately captures the seasonal fluctuations in ozone levels, showing regular peaks and troughs that correspond to typical environmental and atmospheric processes. An interesting anomaly is evident around 2019-2020, where ozone levels experience a significant increase, surpassing the usual seasonal variations. This suggests an exceptional event or series of events that led to a notable rise in ozone concentration during that period. Following 2020, the model predicts a general decrease in ozone levels, indicating potential improvements in air quality measures or changes in emissions. The shaded areas around the predicted line represent the model's uncertainty intervals, providing a range within which actual ozone levels are likely to fall. These intervals signal the confidence in the model's predictions and reflect the complexity of factors influencing ozone levels, with wider intervals indicating increased uncertainty.

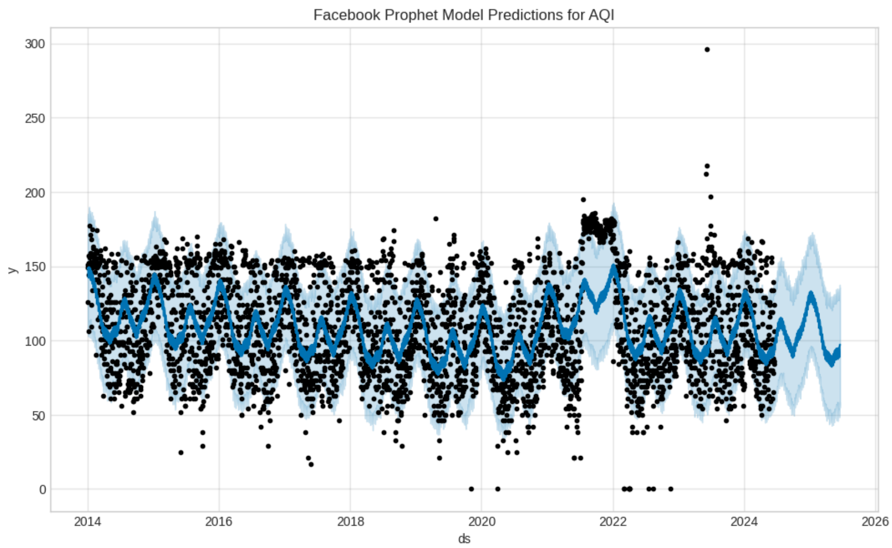

Figure 30: Facebook Prophet Model Predictions for AQI

Finally, the AQI predictions reveal significant seasonal patterns, with regular peaks and troughs that likely correspond to known seasonal changes affecting air quality. The model highlights substantial spikes in AQI values, including periods where the AQI reaches "Very Unhealthy" levels, indicating severe pollution events. These spikes are critical as they suggest potential times of increased health risks for the population. The uncertainty interval varies in width, reflecting the model's confidence levels; narrower intervals indicate higher confidence in predictions, while wider intervals suggest greater uncertainty. Despite some variability, the model's ability to forecast future AQI levels provides valuable insights for anticipating and managing air quality. The forecasts demonstrate a mix of periods with 'Good' to 'Moderate' air quality and occasional 'Unhealthy' to 'Very Unhealthy' conditions, underscoring the dynamic nature of urban air quality. These insights from the AQI forecast can help in planning and implementing air quality control measures and in issuing public health advisories during predicted high pollution periods.

Evaluation metrics such as Mean Absolute Error (MAE), Mean Squared Error (MSE), and Root Mean Squared Error (RMSE) quantified the accuracy of the forecasts:

- PM2.5: MAE of 13.90, MSE of 318.29, and RMSE of 17.84.
- O3: MAE of 23.03, MSE of 1020.51, and RMSE of 31.95.
- AQI: MAE of 27.16, MSE of 1042.53, and RMSE of 32.29.

The Mean Absolute Error (MAE) provides insight into the accuracy of predictions for each pollutant and the Air Quality Index (AQI). For PM2.5, the MAE of 13.90 micrograms per cubic meter indicates that, on average, the forecasts deviate by approximately this amount from the actual measurements. This suggests a relatively close alignment between predicted and observed PM2.5 levels, reflecting a reasonable level of accuracy. Moving to O3, the MAE of 23.03 micrograms per cubic meter suggests slightly less accuracy compared to PM2.5 forecasts. This metric indicates a moderate average error in predicting ozone levels, implying challenges in capturing seasonal variations and unexpected spikes accurately. For the AQI, which integrates multiple pollutants into a composite index, the MAE of 27.16 points suggests a higher average error compared to individual pollutants like PM2.5 and O3. This metric underscores the complexity of predicting overall air quality conditions accurately, reflecting the challenges in integrating diverse pollutant data and their impacts on public health.

The Mean Squared Error (MSE) provides a measure of the average squared deviations between forecasts and actual values. With PM2.5, an MSE of 318.29 indicates significant variability in predicting particulate matter levels, despite the relatively lower MAE. This suggests notable discrepancies between forecasts and observed PM2.5 concentrations, highlighting the need for refining models to better capture fine particulate dynamics. Similarly, the MSE of 1020.51 for O3 underscores challenges in accurately modeling ozone concentrations over time. This metric reflects larger squared errors compared to PM2.5, indicating greater variability and difficulty in predicting ozone levels, which are influenced by complex meteorological factors and emissions patterns. For the AQI, the MSE of 1042.53 reveals substantial variability and discrepancies in predicting the composite air quality index. This metric highlights the ongoing complexities in integrating pollutant data into a cohesive index that accurately represents overall air quality conditions, crucial for public health assessments and regulatory decisions.

The Root Mean Squared Error (RMSE), derived from the MSE, provides a clearer picture of the average deviation between forecasts and actual values. With PM2.5, an RMSE of 17.84 micrograms per cubic meter indicates the typical magnitude of errors in predictions, showing a reasonable level of accuracy despite the variability. For O3, the RMSE of 31.95 micrograms per cubic meter reflects a larger average deviation compared to PM2.5, suggesting greater uncertainty in forecasting ozone levels accurately. This metric underscores the challenges in capturing the complex dynamics of ozone concentrations in urban environments. Similarly, an RMSE of 32.29 AQI points for the composite AQI indicates the average deviation from observed values, reflecting significant uncertainties in predicting overall air quality conditions. This metric highlights the need for continued improvements in modeling approaches to enhance the precision of AQI forecasts and support effective public health and environmental management strategies.

In summary, while the forecasts for PM2.5 demonstrate relatively better accuracy compared to O3 and AQI, all three metrics reveal challenges in accurately predicting urban air quality dynamics in New York City. These results underscore the ongoing need for refining modeling techniques to better capture and forecast air pollution variations, essential for mitigating health impacts and improving overall environmental quality.

6 Policy suggestions and Conclusion

Addressing urban air pollution requires a multifaceted policy approach that combines regulation, technological innovation, community engagement, and sustainable urban planning [12]. Based on the findings of this study, the following policy suggestions are recommended:

1. Enhance emission standards and regulations by implementing stricter standards for vehicles and industrial sources. This includes adopting Euro 6/VI standards or equivalent for vehicles and imposing stringent limits on industrial emissions of pollutants such as PM2.5, NOx, and VOCs. Regular inspections and monitoring should be conducted to ensure compliance.

2. Encourage the adoption of renewable energy sources, such as wind, solar, and hydroelectric power, by providing subsidies and tax incentives to businesses and households. Also, develop and implement a plan to gradually phase out the use of fossil fuels in favor of cleaner alternatives. Encourage the use of natural gas as a transitional fuel while renewable infrastructure is developed.

3. To improve public transportation, it is important to invest in expanding and modernizing public transportation systems. This will help reduce reliance on private vehicles. We should promote the use of electric buses and trains, which produce significantly lower emissions compared to their diesel counterparts. Incentives should be provided for the development of charging infrastructure. Furthermore, infrastructure for non-motorized transportation such as cycling and walking should be developed. This includes the creation of bike lanes, pedestrian zones, and bike-sharing programs.

4. Urban green spaces should be increased, including parks, green roofs, and urban forests, to act as natural filters absorbing pollutants and provide residents with healthier environments.

5. Support for vulnerable populations: Targeted interventions should be developed for communities that are disproportionately affected by air pollution, such as low-income neighborhoods and areas near industrial zones. Resources should be provided to improve indoor air quality and mitigate pollution exposure. Additionally, access to healthcare and social services should be enhanced for vulnerable populations. This includes providing free or subsidized medical check-ups, health education, and support for individuals with pollution-related health conditions.

6. Finally, it is important to believe in community engagement and education. For example, launching extensive public awareness campaigns to educate residents about the sources and health impacts of air pollution. It is important to utilize various media platforms to reach a wide audience. Additionally, engaging communities in participatory decision-making processes to ensure that policies reflect local needs and priorities is crucial. This can include public consultations, workshops, and forums.

The study highlights the complex nature of urban air pollution in New York City, underscoring the significant health and environmental challenges posed by pollutants like PM2.5 and ozone. Despite advancements in forecasting and monitoring, substantial gaps remain in accurately predicting and mitigating these pollutants' impacts. Effective policy implementation is critical to addressing these challenges and collaborative efforts across sectors—policy-making, urban planning, public health, and community engagement—are essential for creating sustainable and equitable urban environments. The success of these initiatives relies on continuous refinement of strategies based on emerging data and technological advancements. By prioritizing equity, sustainability, and community involvement, cities can improve residents' quality of life and mitigate the adverse effects of air pollution.

For those interested in exploring the data and methods used in this study, the complete codebase is available on GitHub. You can access the code here: GitHub Repository

References

[1] I. Manisalidis, E. Stavropoulou, A. Stavropoulos, and E. Bezirtzoglou, "Environmental and health impacts of air pollution: A review," *Frontiers in Public Health*, 2020.

[2] National Geographic Education, "Air pollution," https://education.nationalgeographic.org/resource/air-pollution, 2024, accessed: June 23, 2024.

[3] J. Fairburn, S. Schüle, S. Dreger, K. Hilz, and G. Bolte, "Social inequalities in exposure to ambient air pollution: A systematic review in the who european region," *Int J Environ Res Public Health*, 2019.

[4] Marketing and Communication Team of Kunak, "Air quality in communities, an environmental justice issue," https://kunakair.com/air-quality-in-communities, 2024, accessed: June 23, 2024.

[5] "Using the air quality index," https://www.airnow.gov/aqi/aqi-basics/using-air-quality-index/, n.d., accessed: June 23, 2024.

[6] "The official website of the city of new york," https://www.nyc.gov/, n.d., accessed: June 25, 2024.

[7] "World air quality historical database," https://aqicn.org, n.d., accessed: June 25, 2024.

[8] "Open data for all new yorkers," https://data.cityofnewyork.us/Environment/Air-Quality, n.d., accessed: June 25, 2024.

[9] "New york city's zoning and land use map," https://zola.planning.nyc.gov/, n.d., accessed: June 26, 2024.

[10] "Summer ozone season: Why is ozone worse in hot weather?" https://www.usairpurifiers.com/blog, n.d., accessed: June 26, 2024.

[11] U. E. P. Agency, "Technical assistance document for the reporting of daily air quality – the air quality index (aqi)," *n.d*, 2018.

[12] F. Chen, W. Zhang, M. F. B. Mfarrej, M. H. Saleem, K. A. Khan, J. Ma, A. Raposo, and H. Han, "Breathing in danger: Understanding the multifaceted impact of air pollution on health impacts," *Ecotoxicology and Environmental Safety*, vol. 280, p. 116532, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0147651324006080