KTH ROYAL INSTITUTE
OF TECHNOLOGY

Degree Project in Environmental Engineering and Sustainable Infrastructure
Second Cycle, 30 credits

Urban Planning for Better Air Quality

A case study of the Low-Traffic Neighbourhoods in London

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Stockholm, Sweden 2022

Abstract

Air pollution affects the environment negatively, boosts climate change, and is the cause of millions of deaths per year, first and foremost affecting the people living in urban areas. Since the early 20th century, many cities have been planned around cars, which are the main contributors to the bad air quality. However, after the Covid-19 pandemic, cities have been reshaped to enhance active travel and to provide more space for greenery. In London, this reassessment of the urban areas has led to the Low-Traffic Neighbourhoods (LTNs). The LTNs origins from 2019, however, most of them were implemented during the pandemic because of the crucial times demanding social distance, while also enabling people to walk and cycle more in their local borough. The LTNs only allow residents, emergency vehicles and blue badge carriers to enter, if travelling by a motorised vehicle. The scheme further aims for more greenery to be implemented. The aim of this thesis is to study the impact from the LTNs on the air quality of the local area, specifically regarding PM_{10} and NO_X, by using openly available data from the Imperial College London. Furthermore, the existing Green Infrastructure (GI) around each sensor, as well as the traffic, has been studied and compared to the air pollutant levels. This has been done to be able to analyse the air pollutants in relation to the surrounding GI and the level of traffic. The methodology further consists of mapping the air pollutants measured by the sensors; a statistical analysis; an interview with Sally Oldfield, the Nature Conservation Manager at Islington Ecology Centre; and field studies to the sensors used in the thesis, both the ones in LTNs and the ones in non-LTNs. The boroughs included in the study are the City of London, Islington, Wandsworth, and Westminster.

Previous research about the LTNs have focused on health and social issues, and the research about traffic schemes have focused on Low Emission Zones (LEZ) and Ultra Low Emission Zones (ULEZ). Studies on the air quality impact of the Covid-19 lockdowns have been done on New York, Madrid and Barcelona. The previous research on air pollutants in urban areas show a difficulty in mapping the movement of the pollutants hence the varied variables having an impact, such as wind, weather, the height and positions of the surrounding buildings. Research on the impact on the air quality from GI in general, has shown that the efficiency is dependent on the planning, type and size of the vegetation, as well as the distance to the emission source. However, the studies on GI are uncertain in how effective it is in terms of air quality improvement.

The result of this thesis shows a decline in NO_X- and PM_{10}-values after the implementation of the LTN by all sensors. The annual patterns further show that the yearly trends of the pollutants remained, however the magnitude is lower after the implementation of the LTNs. The daily patterns show varied results, where NO_X has clear connections to the traffic, and the sources of PM_{10} are uncertain. Lastly, the statistical analysis showed that the data series came from different distributions, except the PM_{10}-values by one of the sensors in Islington. Although a reduction was seen by all sensors, this might be because of, e.g., the Covid-19 pandemic. Furthermore, a correlation between GI and lower values of the pollutants could be seen by some sensors, however the results varied, making it difficult to distinguish any correlation. In conclusion, the absence of traffic can be seen to reduce the air pollutants NO_X and PM_{10}, where

GI might have a positive impact. Suggesting to reshape urban areas to enable active travel, and reduce the possibilities to travel by car, with the exception of blue badge carriers and emergency vehicles. Although the impact on air improvement from GI is uncertain, it is suggested to be incorporated in the planning due to its other benefits such as recreation, well-being, and biodiversity.

Keywords

Low-Traffic Neighbourhoods, London, Green Infrastructure, Urban Planning, Air Pollution

Sammanfattning

Luftföroreningar påverkar miljön negativt, påskyndar klimatförändringarna och är orsaken till miljontals dödsfall per år, vilket först och främst påverkar de människor som bor i städer. Sedan början av 1900-talet har många städer planerats kring bilar, vilka är de som bidrar mest till den dåliga luftkvaliteten. Dock har flera städer planerats om efter Covid-19-pandemin för att möjliggöra aktivt resande och för att ge mer utrymme för grönska. I London har denna förändrade stadsplanering lett till lågtrafikerade kvarter (Low-Traffic Neighbourhoods, LTN). Planen att implementera LTN:er i London fastställdes 2019, men de flesta LTN:er kom på plats under pandemin, då de speciella tiderna som krävde både socialt avstånd och möjligheten till att kunna röra sig i närområdet påskyndade implementeringen. LTN:er tillåter endast de som bor i området, utryckningsfordon och personer som har rätt till handikapparkering, att köra in bland kvarteren om de reser med ett motorfordon. LTN:er syftar vidare till att mer grönska ska få ta plats i området.

Syftet med denna uppsats är att studera LTN:ers inverkan på luftkvaliteten i det lokala området, särskilt avseende PM_{10} och NO_X, genom att använda öppet tillgängliga data från Imperial College London. Dessutom har den befintliga Gröna Infrastrukturen (GI) kring varje sensor, liksom trafiken, studerats och jämförts med luftföroreningsnivåerna. Detta har gjorts för att kunna analysera luftföroreningarna i förhållande till den omgivande GI och trafiknivån. Metoden består vidare av att kartlägga de luftföroreningar som mätts av sensorerna; en statistisk analys; en intervju med Sally Oldfield, naturskyddschef vid Islington Ecology Centre; och fältstudier till de sensorer som används i studien, både de i LTN och de i icke-LTN. De stadsdelar som ingår i studien är City of London, Islington, Wandsworth och Westminster.

Tidigare forskning om LTN:er har fokuserat på hälso- och sociala frågor, och forskningen om trafiksystem har fokuserat på miljözoner (LEZ) och ultralåga miljözoner (ULEZ). Studier av luftkvalitetseffekterna efter Covid-19-nedstängningarna har gjorts om New York, Madrid och Barcelona. Den tidigare forskningen om luftföroreningar i stadsområden visar en svårighet att kartlägga partiklarnas rörelse på grund av de olika variablerna som har en inverkan, såsom vind, väder, och höjd och placering hos de omgivande byggnaderna. Forskning angående påverkan på luftkvaliteten från GI i allmänhet har visat att effektiviteten är beroende av vegetationens placering, typ och storlek samt avståndet till utsläppskällan. Studierna om GI är dock osäkra över hur effektivt det är när det gäller förbättring av luftkvaliteten.

Resultatet av denna studie visar en nedgång i NO_X- och PM_{10}-värden efter implementeringen av LTN:er vid alla sensorer. De årliga mönstren visar vidare att de årliga trenderna för föroreningarna kvarstod, men nivåerna sjönk efter genomförandet av LTN:er. De dagliga mönstren visar varierande resultat, där NO_X har tydliga kopplingar till trafiken medan källorna till PM_{10} är osäkra. Slutligen visade den statistiska analysen att dataserierna kom från olika fördelningar, förutom PM_{10}-värdena vid en av sensorerna i Islington. Även om en minskning sågs vid alla sensorer kan detta bero på till exempel Covid-19-pandemin. Dessutom kunde en korrelation mellan GI och lägre värden av föroreningarna ses av vissa sensorer, men resultaten varierade vilket gjorde det svårt att säkerställa någon korrelation. Sammanfattningsvis kan

frånvaron av trafik ses minska luftföroreningarna NO_X och PM_{10}, där GI kan ha en positiv inverkan. En omformning av stadsområden för att möjliggöra aktivt resande och minska möjligheterna att resa med bil, med undantag för personer med rätt till handikapparkering och utryckningsfordon, föreslås. Även om möjligheten till luftförbättring från GI är osäker, föreslås det att ingå i stadsplaneringen på grund av dess andra fördelar så som rekreation, välbefinnande och biologisk mångfald.

Acknowledgement

This thesis marks the end of my master's studies in Environmental Engineering and Sustainable Infrastructure at KTH, The Royal Institute of Technology. I would like to express my deepest appreciation to my supervisor Joseph Mulligan who has shown an interest in this thesis throughout. Thank you for your guidance and support, and for sharing your deep knowledge in the field of sustainable urban planning.

I deeply appreciate all my friends at KTH and at the W-chapter. Without them I would not have made it through these five years. In times of doubt and happiness you have always shown friendship and support. I would like to thank my brother, Hampe Gustavsson, whose special interest in mathematical statistics has supported me with insights and interesting discussions. I am grateful to Sigvard Bast who has happily discussed this thesis whenever I have been struggling, always ready to share his wisdom over a cup of coffee. Lastly, I would like to extend my sincere thanks to Sally Oldfield who generously provided me with essential insight, which enriched this thesis.

Stockholm, 2022
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1. Introduction

Air pollution is a significant contributor to the environmental and climate crisis, as well as being directly damaging to human health, leading to increased mortality with estimates of nine million deaths per year due to air pollution (Manisalidis et al., 2020). Air pollutants contribute to acid rain, eutrophication, and loss of biodiversity, leading to imbalance in ecosystems. What is more, climate change caused by environmental pollution has an impact on the geographical distribution of several infectious diseases and natural disasters (Ibid). However, it is an unequal pollutant where the ones being exposed the most to it, are urban citizens and the urban environment (Manisalidis et al., 2020; Environmental Protection UK, n.d.; UK Air, 2022.). This is due to human activities at large scale, such as road emissions, power stations, and the industry, being main contributors, where cars are predicted to be responsible for roughly 80 percent of the air pollution globally (Manisalidis et al., 2020). Thus, the traffic dense cities are the culprits (Manisalidis et al., 2020; Environmental Protection UK, n.d.; UK Air, 2022.).

Since the early 20th century, cars have been one of the dominant and central factors in urban planning (Frazer, 2019), shaping the cities according to the movement of cars. The places that do advocate non-motorized movement by e.g., cycling or walking have been shown to have more efficient land use with a less negative impact on places and people, than their car-dependent counterpart (Babb, 2021). Cars are not only harmful because of the emissions, motor traffic is the cause of death by collision accidents, and it is harmful to humans due to noise pollution. What is more, enhancing the possibility to cycle and walk improves the mental and physical health of the population (Dajnak et al., n.d.; Laverty et al., 2021b).

As a result of the Corona pandemic, several cities have reshaped their urban planning in favour of pedestrians and cyclists, enhancing active- over car-based travel, and letting the grey areas become green (Cunningham, 2021; Oliver, 2021; Connolly, 2020; Dunning and Nurse, 2020; Aldred and Goodman, 2020). This has been done to help people move around while keeping distance, but the pandemic has also been used to implement already established plans yet to be launched **(**Dunning and Nurse, 2020). In London, this reassessment of the city has led to Low Traffic Neighbourhoods (LTNs) (Aldred and Goodman, 2020). The scheme originates from 2019, when Covid was unheard of, but thanks to the unique situation that the pandemic put the city in, the implementation was rapid and widespread (Laverty et al., 2021.). The LTNs are part of the aim to tackle the heavily polluted air of London, which is a project led by the current mayor Sadiq Khan. The project further includes school streets, Ultra Low Emission Zones (ULEZ), and reducing emissions from the taxi and bus fleet (Greater London Authority, 2019).

With the inspiration from Barcelona's superblocks (Figure 1), the LTNs are planned to connect residential streets in the same neighbourhood (Aldred et al., 2021). The superblock was established by the Barcelona Urban Ecology Agency, and the model is created to form an urban cell thought to evolve and develop in the city (Rueda, 2018; Staricco and Vitale Brovarone, 2022). By dividing the road network into the levels *Inside the superblock* and *Outside the* *superblock*, the greater part of the traffic can be directed to the main roads outside the superblock, leaving the inside to the traffic actually going to the neighbourhood, not only using it as a shortcut (Staricco and Vitale Brovarone, 2022). Figure 1 illustrates the levels, with the green square representing *Inside the superblock*, and the arrows illustrating the traffic going around. Furthermore, the motor traffic is moved from the residential streets by, e.g. modal filters; limiting the space for cars and parking; and with lower speed limits (Aldred and Goodman, 2020; Staricco and Vitale Brovarone, 2022). However, what the filter consists of might vary, some examples being CCTV, planters, or road signs (examples of modal filters can be found in Appendix 6). The type of traffic and to what extent that may pass can also vary between areas, but emergency vehicles and blue badge carriers, disabled drivers entitled to certain parking rights, are always allowed through into the LTNs (Department for Transport, 2021). Nonetheless, the planning of the LTN still emphasises walking and cycling as the primary types of transport. In Barcelona, this reduction of cars has led to a 60-70 percent increase in street space for other types of usage (Staricco and Vitale Brovarone, 2022). The possibility of replanning that this leads to, is part of the superblock model, which suggests changing the area into town squares, parks, and overall, more greenery in forms of corridors and patches (Muller et al., 2020), which is further addressed in the LTN scheme, where the greening is suggested as a way to further reduce the air pollution (Greater London Authority, 2019).

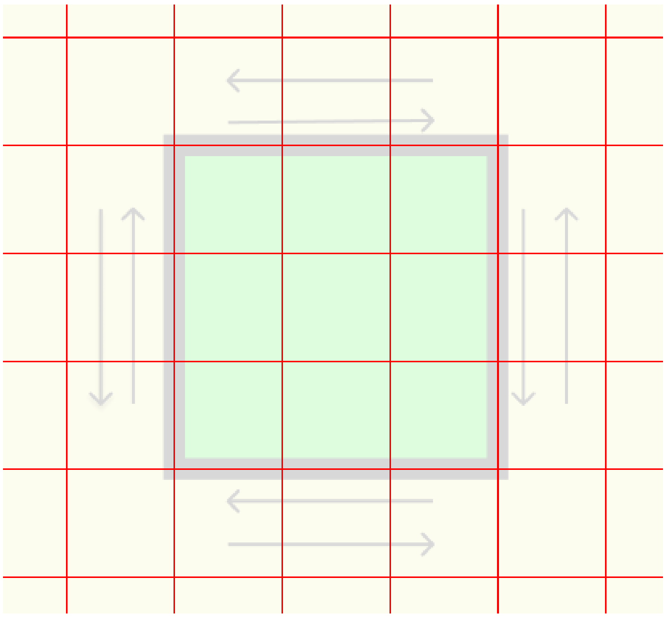

Figure 1. The Figure shows the superblock (the green square) with the traffic going around it, illustrated by arrows. The red lines represent streets, and each square is a block. The figure is drawn by Greta Gustafsson based on data from Rueda (2018).

So far, studies on LTNs have seen a decline in car ownership among the residents, emergency services having the same response time in LTNs as in non-LTNs, a reduced number of street crimes, and the risk of being harmed in a car accident has been calculated to have gone down by 75 percent (Laverty et al., 2021b). This stresses the need for a widespread implementation of schemes working towards less motorised traffic and a better air quality, including all areas and residents in the city. Socio-economic deprived areas have historically been more affected by air pollution and climate change, however, studies on LTNs have shown that the scheme has been implemented more in these areas, suggesting that the trend has changed (Laverty et al., 2021b; Aldred et al., 2021).

The road traffic in London is accountable for 50 percent of the predominant air pollutants, where cars are responsible for approximately 14 percent of NO_X, the umbrella term for NO and NO_2, and 56 percent of the emissions of $PM_{2.5}$ (Khan, 2018a). The levels of NO_2 in the city are above legal limits, and the levels of $PM_{2.5}$ are beyond the WHO-guideline value, leading to the damaging of human health, the environment, as well as being a contribution to climate change (Khan, 2018a; Greater London Authority, 2020). In the *Environmental Strategy of London* (Khan, 2018b), the mayor states that London is still too dependent on fossil fuel, meaning that the reduction of emissions is not happening at the pace it needs, to tackle global warming and climate change. Despite that, a study from the *London School of Hygiene and Tropical Medicine* (PA Media, 2022) showed that, thanks to the decreased car use because of the lockdown, European metropolises endured a reduction in air pollution with up to 60 percent (PA Media, 2022). Furthermore, the implementation of the ULEZ in London in April 2019, and the decline in travel due to the Covid-19 lockdown, have shown to have led to a significant drop in air pollution (Transport for London, 2020; Aldred and Goodman, 2020).

Although the emissions from motor traffic in London have been reduced thanks to policies such as the ULEZ, there will still be emissions from e.g. the industry, wood burning and the remaining traffic (Dajnak et al., n.d.). Emissions that contribute to the loss of biodiversity and a boost to climate change (Tallis et al., 2015). Therefore, the need for climate and environmental adaptation of London is continuing, where Green Infrastructure (GI) is seen as a means to replan the cities into resilient societies better prepared for the environmental and climate changes (Tallis et al., 2015). However, according to the UK National Ecosystem Assessment, the significance of green areas and natural sites in the urban context is not thoroughly understood, suggesting that their full potential is not attained (Khan, 2018b). Several studies on the performance of GI near busy roads, suggest that the presence of greenery do reduce air pollution, if carefully planned (Pugh et al., 2012; Al-Dabbous and Kumar, 2014; Abhijith and Kumar, 2019). In a study by Abhijith and Kumar (2019) on different types and combinations of vegetation near busy roads, it was found that when combining trees and hedges, as well as placing hedges on their own, the greatest reduction of pollutants was obtained.

The scheme of LTNs include both the removal of motorised traffic and the implementation of GI. However, how efficient and sustainable are the components of the LTN in the long run in regard to air improvement? The climate and environmental changes are pressing, and cities need to be prepared for the new circumstances. Which is why there is a need to know what actually works, and how well it performs. Should we remove all cars or turn our grey cities into urban forests?

1.1 Previous Research

This literature review of previous research will look at studies on LTNs, or superblocks as the original model is called. Moreover, it will explore studies on air pollution and the change of air pollution due to the reassessment of urban areas and/or the implementation of traffic schemes. Lastly, it will look at studies on GI and its possible impact on the air quality.

1.1.1 LTN

The studies on LTNs in London have so far looked at the change of travelling and car ownership, concluding a decrease in car ownership and an increase in active travel in LTNs (Aldred and Goodman, 2020; Goodman et al., 2020a), the impact on traffic injuries and street crimes (Laverty et al., 2021a; Goodman and Aldred, 2021), the impact on health and emergency service's response time (Goodman et al., 2020b; Laverty, 2021b; Dajnak et al., n.d.), and the equity of the distribution (Aldred et al., 2021). In conclusion, they have looked at health and social issues, not covering the environmental aspects. Furthermore, broad and informative studies on the superblock have been done on the original case of Barcelona, where Mueller et al. (2020) studied the health impact from the scheme, concluding that superblocks were beneficial for the citizens' health (Rueda, 2018; Mueller et al., 2020). According to Staricco and Vitale Brovarone (2022), the range of literature covering the superblock model is still limited, since it is a rather new concept, especially observational studies concerning the effect of the model in terms of environmental quality, mobility, and adaptation of the new public space (Staricco and Vitale Brovarone, 2022).

1.1.2 Traffic Schemes

Studies on the absence of motorised traffic and the possible effects on the air quality have been conducted during the past couple of years, concerning the unique situation of the Covid-19 lockdowns. These studies have looked at New York (Pitiranggon et al., 2022), Barcelona and Madrid (Baldasano, 2020) and in London regarding ozone, $PM_{2.5}$, NO_2, and CO (Ozone Zhang and Stevenson, 2022; Vega et al., 2021; Kazakos et al., 2021). However, to my knowledge, none of them have looked specifically at NO_x and PM_{10} in London, and most importantly, although they cover the field of air quality without the presence of traffic, the lockdowns were exceptional situations. That is, when studying the air quality in the absence of traffic after the pandemic, the background impact of normal traffic conditions is not included.

Furthermore, several studies on Low Emission Zones (LEZ) in different cities, not to be mixed up with the ULEZ which have other rules and limits, have been conducted. The LEZ in London covers almost the entire city and works like the ULEZ (described under *3.3 Local Politics*) however, with lower congestion limits (Transport for London, n.d.). A study by Zhai and Wolff (2021) looking at the change in PM_{10} after the implementation of LEZ, found that the policy first led to an increase in particulates by 14,8 percent in phase I where it only included heavy vehicles. However, when further including light weight vehicles, a reduction in PM_{10} by 5,5 percent was seen (Ibid). Moreover, a study on LEZ in Rome in regard to PM_{10} and NO_2 concentrations, saw a decrease after the implementation of the scheme. Continuing, the study looked at the areas where the LEZs were implemented, concluding that the socio-economic stronger areas were favoured (Cesaroni et al., 2012). In the case of the LEZ in the Netherlands, Boogaard et al. (2012) have studied the impact on PM_{10}, $PM_{2,5}$, soot, NO_x and NO_2 determining a moderate decrease in concentrations. Concluding that the scheme had been inefficient in improving the air quality (Ibid). A study on the combination of LEZ and on-street parking in Madrid in regard to the change in the use of private vehicles, saw a switch to less use of private vehicles in LEZ areas and where on-street parking was implemented. However, the citizens owning a cleaner vehicle were less willing to change to other modes of traffic, such as public transport or active modes. This was concluded to be because of the benefit of e.g. free parking for these vehicles (Gonzalez et al., 2022).

Prieto-Rodriguez et al. (2021) have studied the impact on NO_2 by the LEZ and the ULEZ in London, comparing the schemes. The study saw a decrease of NO_2 concentrations near roadsides after the implementation of the LEZ, with an additional decrease after the implementation of the ULEZ (Ibid). However, this is contradicted by a study on the effect of NO_2, $PM_{2,5}$ and O_3 concentrations following the ULEZ scheme in London. The researchers determined marginal effects on the air pollution, where some areas saw an increase and others a decrease. Concluding that the scheme had not been effective in improving the air quality (Ma et al., 2021). A study on LEZ and the superblocks in Barcelona, analysed both individually and in combination, concluded that if implemented by themself, none of the schemes had a significant impact on the emission levels. The study could only see an impact on local NO_X-levels, where the difference was both negative and positive. However, when implemented together, the schemes were seen to have a significant effect on the emission levels (NO_X and NO_2). Despite the combined impact, the study concluded that the schemes were insufficient in reaching the EU air quality standards and that more traffic restrictions need to be put in place (Rodriguez-Rey et al., 2022).

1.1.3 Green Infrastructure

One of the main focal points of this report is Green Infrastructure (GI), a concept without a strict definition, even in the context of LTNs. In the *London Environment Strategy* (2018b) GI is defined as the system of gardens, green spaces and parks, rivers and wetlands, woodlands, and attributes as for example trees in the street and green roofs. Furthermore, it is stated that these surfaces are designed, planned, and handled to improve healthier living and advocate cycling and walking, decrease the climate change impact as well as store carbon, increase the water and air quality, and enhance the ecological resilience and biodiversity. However, although this study has connections to the *London Environment Strategy*, it does not necessarily have to use the same definition of GI. Other studies have defined GI as strategic planning of semi-natural or natural areas in the urban context, incorporated to deliver ecosystem services in the form of e.g. climate adaptation and mitigation, recreational values, and improvement of air and water quality (Thomson and Newman, 2020). Further on, there are definitions highlighting that GI are natural areas built within the grey areas, where the green areas have been prioritised over the grey ones in places such as squares, cemeteries, or pocket parks, but also through green roofs and -walls e.g. (Evans et al., 2022). Other definitions emphasise connecting networks of greenery, implemented to preserve natural ecosystems, and consequently contribute with benefits for the human population (Washbourne, 2022; Staccione et al., 2022; Van Oijstaeijen et al., 2020). The definition of GI used in this thesis can be found under *2.2.3 Defining Green Infrastructure*.

Studies looking at the impact from green space, especially trees, in France and in New Zealand, found that the PM_{10}-concentrations in France declined by 17 ton or 3,35 percent, and the NO_2 dropped by 14 ton or 0,5 percent. Furthermore, the study in New Zealand measured a reduction in PM_{10} by 1320 ton and a decline in NO_2 by 2740 ton, when implementing 8,1 percent green space. However, these studies make different assumptions about e.g. leaf surface areas and deposition rates. Why Kumar et al. (2019) argues for more studies trying to quantify the air quality improvements from various forms of GI at regional and local scales (Ibid).

1.2 Aim

This study aims to examine the air quality impact of LTNs in London, specifically regarding the air pollutants PM_{10} and NO_X in the local areas. This will be done by mapping the air pollution of different LTNs and non-LTNs, which will then be compared to each other, the non-LTN being used as a control variable. A statistical analysis of the available data will also be done. Furthermore, field studies will be conducted to study the area surrounding the sensor, with an emphasis on existing GI and the traffic, which will be used when analysing the values of the air pollutants as a way to study the impact of the GI and the presence or non-presence of traffic. Open-source data from the Imperial College London of PM_{10}- and NO_X-concentrations ranging from 2018 to 2022, will be used.

1.2.2 Research Questions

The abundant available air pollution data, with the study of GI through field visits allows for the following research questions:

- Has the implementation of Low-Traffic Neighbourhoods led to a decrease of the monitored NO_X- and PM_{10}-values?
- Is there a correlation between Green Infrastructure and lower values of NO_X and PM_{10}?

Analysis of the data and the findings from the field visits further enables a discussion about the effectiveness and possibilities of LTNs and GI in London, and what other cities can learn from this case.

2. Methodology and data

In the following section, the study area, methodology and data are presented. The four boroughs studied are presented below, with detailed information about their LTNs. Furthermore, the study consists of three data sets: air pollution data, field studies, and an interview. The air pollution data is open source collected from the Imperial College London. A statistical analysis in the form of a t-test has further been done on this data. Field studies to all sensors have been done to study the existing GI, the traffic conditions as well as verifying the sensors and LTNs positions. Lastly, an interview with Sally Oldfield, an ecologist working at the borough of Islington, has been done.

2.1 Study Area

The study area of the thesis is London, the capital and largest city of the United Kingdom (UK) with a population of around 9,5 million people (World Population Review, 2022). The city is in the southeast of England and is categorised into Inner London and Outer London, which together form Greater London. This thesis looks at the area of Greater London which measures 1580 km^2 and has 33 boroughs, although, out of coincidence, all boroughs studied are in Inner London, which measures 321 km^2 (Lu, 2020). A map of London can be seen in Figure 2.

London is a significant financial hub, and a prominent city for politics, and classical- as well as popular culture (Lu, 2020). As mentioned, the bad air quality of the city is not a new phenomenon. The combination of fog and smoke in the city during the 20th century, led to the, now common, term smog. Legislation restraining the emissions of pollutants has been in place since the reign of King James I, in the 16th to 17th century, with varying efficiency. After the historical event of the Great Smog in 1952, where thousands of people died because of the densely polluted air, the political action of the Clean Air Act was put in place. It was the first legislation in the UK to prohibit dark smoke, leading to stricter emission allowances and cleaner air (Rodriguez, 2014; Martinez, 2021).

Figure 2. The map shows London. It has been made by Greta Gustafsson in Google Maps based on data from London Air (Imperial College London, 2018), Safe Cycle London (Google Maps, 2021), and ULEZ Checker (Google Maps, 2019). A digital version of the map can be found here .

2.1.1 Selection of LTNs for Detailed Analysis

The extent of air pollution can vary greatly over space and time, which makes the positions of the monitor crucial. Studies have shown that monitors five metres apart from each other have given different values, indicating the obscure variation of pollution in the air (Hswen et al., 2019; Briggs et al., 2000). Nonetheless, it has been shown that the passive monitors, as the ones used by the Imperial College London (description under *2.3 Data* below), do contribute with accurate measurements with small errors (Briggs et al., 2000).

The Imperial College London has data points of 135 sensors around London (Imperial College London, 2018), hence there are a lot of sights to choose from, however not necessarily suitable for this thesis. When choosing which sensors to look at, the first step was to find the sensors being placed within an LTN, since it is essential for the study. After this, the measured pollutants of these sensors were checked as well as the time series. The sensors having neither NO_X or PM_{10}, nor data from 2018 to 2022 (the reasoning behind this is described in detail under *2.3 Data* below), were disregarded.

Sensors in non-LTN areas within the borough were found to be used as control variables. If this was not obtained, the LTN-sensor was disregarded. A control variable was used as a way to analyse if the change in air pollutants only occurred in the LTNs, or if it also had happened in areas where no change had been enforced. What is more, the linear distance between the sensor in an LTN and the sensor in a non-LTN differ between the boroughs. The control sensors are placed between 140 to 1750 metres away. This is because the closest non-LTN sensor/-s were chosen, however how close these were varied.

Regarding the boroughs with more than one control sensor, these areas were found to have several sensors with roughly the same distance to the LTN-sensor. In the case of Westminster one sensor was found to be in an area with existing GI, Cavendish Square, and one sensor in an area without any GI, Oxford Street East, why both were kept. In the case of the City of London, one sensor was found to be in an area with existing GI, the Aldgate School, whereas the other two non-LTNs sensors only had samples of PM_{10}, Upper Thames Street, or NO_X, Walbrook Wharf, why they were chosen to be kept. Lastly, the field studies verified the positions of the sensors and the LTNs. If the field study concluded that an LTN did not exist in the place where the reference had shown, or if the sensor could not be found at the specific positions, they were disregarded.

In conclusion, the areas chosen for this study follow all the following criteria: one sensor is placed within an LTN, with at least one other sensor being placed in a non-LTN; they have measured data of NO_X and/or PM_{10}; values ranging between 2018 and 2022. All sensors in the study are presented in table 1. Furthermore, the field study has confirmed their position, either if it is outside or inside an LTN. Even though the boroughs have different names for their LTNs, for example People-Friendly Street in Islington, LTN will be used for all of them in this report. The reason being that they all originate from the Liveable Neighbourhood guidance developed by the Transport for London (TfL) in 2019 (Aldred et al., 2021). Maps of the boroughs can be found below under each borough description. Pictures of the sensors and the surroundings can be found in Appendix 7.

Table 1. The table presents all sensors in the study. The sensors marked with an asterisk are the ones within an LTN.

Borough	Sensors	Implementation of LTN
the City of London	Beech Street* The Aldgate School Upper Thames Street Walbrook Wharf	18th of March 2020 (City of London, 2022)
Islington	Arsenal* Holloway Road	Completed by 11th of January 2021 (Islington, n.d.)
Wandsworth	Putney* Putney High Street	30th of August 2020 (Wandsworth-The brighter borough, 2021)
Westminster	Covent Garden* Cavendish Square Oxford Street East	Between March and September 2020, the time span means that the scheme was implemented during the month of September at the latest (Aldred et al., 2021). The date used in this study is the first of September 2020.

2.1.2 City of London

The City of London, Figure 3, is a central and busy borough, finance and business being significant in the area. However, there are two big housing estates in the borough: the Barbican estate and the Golden Lane estate, together being home to 5 500 residents (City of London, n.d.). The Beech Street sensor is placed in the LTN called Beech Street Zero Emission Scheme, see Figure 4 below or a detailed map of the scheme in Appendix 5, which was implemented on the 18th of March 2020. It is the first zero emission street in the UK (City of London, 2022) and only allows zero emission vehicles to enter (City of London, n.d.). The scheme ran from March 2020 to September 2021. However, it has got the approval to continue since improvements were seen, though the public will be consulted first, which will be done after the local elections on the 5th of May 2022 (The Electoral Commission, 2022; City of London, 2022). This is further confirmed in the *Mayor's Air Quality Fund Completion Report* (Greater London Authority, 2019) where it is stated that the scheme should be permanent by 2022.

Beech Street has historically had high levels of air pollution, due to a combination of extensive traffic and the street being in a tunnel. As of 2014, taxis were the most common vehicle type on Beech Street, followed by cars and large goods vehicles (City of London, 2022). Furthermore, greening will be part of the scheme. Focusing on the northern area of Beech Street (and along Golden Lane) GI will be planned with improved air quality, increased biodiversity, decreasing the surface water run-off, and mitigation of climate change, as the reasons behind it (City of London, 2022). However, during the field studies of this report, this was not seen.

Figure 3. The map shows the City of London.

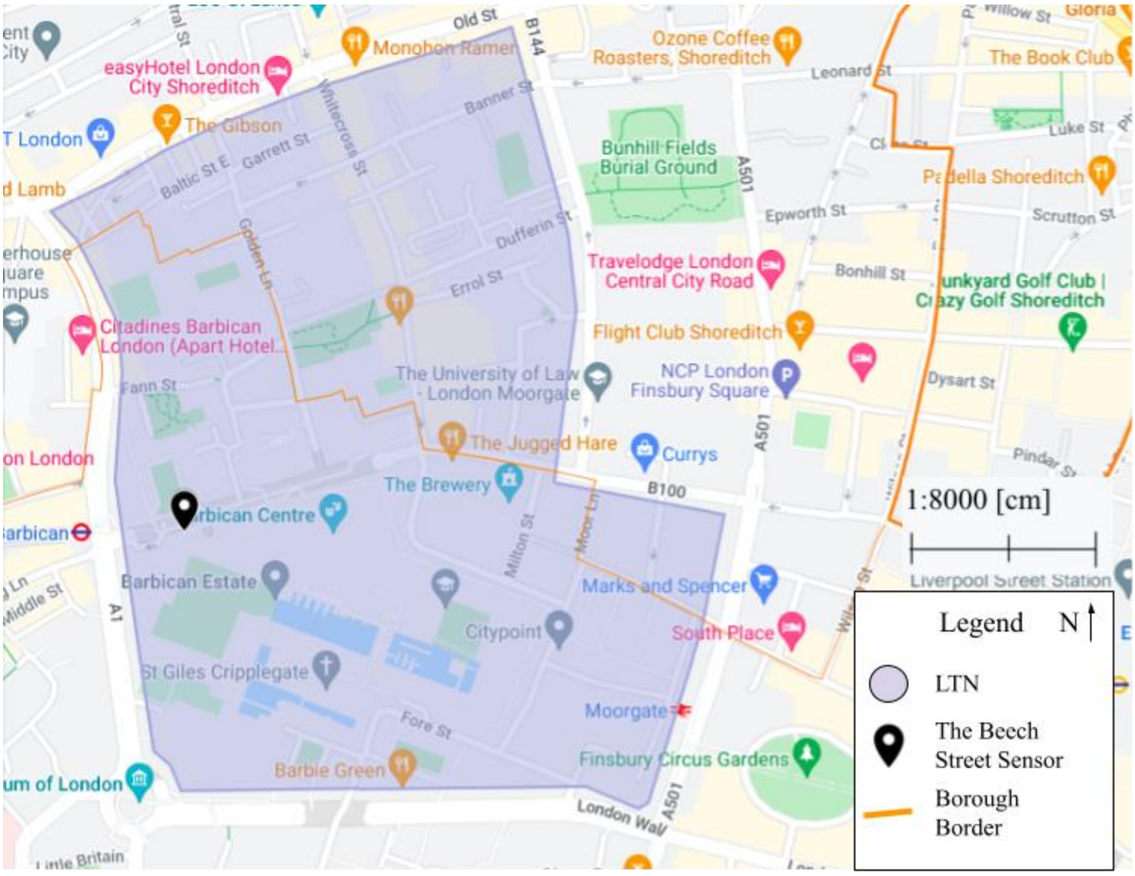

Figure 4. The map shows the LTN called Beech Street Zero Emission Scheme in the City of London .

2.1.3 Islington

The borough of Islington, Figure 5, in the north of London, has a significant cultural scene, as well as an extensive residential area (Mayor of London - London Assembly, 2022c). The borough describes LTNs, called People-friendly streets, as areas with well-planned traffic filters, placed to hinder or make it difficult for traffic to cut through. The purpose being to make the streets safer for pedestrians and cyclists, etcetera, when motor traffic is blocked from using the streets as shortcuts. However, motor vehicles can still enter the area, meaning that residents, emergency services and deliveries can still access (Islington, n.d.). The modal filters are a mixture of CCTV, bollards, and planters (Champion, n.d.; Field studies). Furthermore, the existing infrastructure in certain streets has been repurposed as modal filters. For example, no point entries hindering traffic going one way, now hinders all traffic, and width restrictions have been transformed to traffic filters. The name of the LTN in this study is Highbury west (Champion, n.d.), seen in Figure 6. A detailed map of the area can also be found in Appendix 5.

In the *Islington Air Quality Annual Status report 2019* (Islington, 2020), the borough states that they will use GI as a way to improve the air quality, by implementing green walls and screens, pocket parks and planters. It is further stated that research was done on the areas best suited to plant, including information about social deprivation, current canopy of low trees, and which areas near roads were best suited to help decrease the pollutants (Ibid). This is further mentioned in the Highbury West People-Friendly Streets Neighbourhood Scheme, where it is stated that if made permanent, the LTNs can be subject to implementation of more permanent changes such as tree planting, greening, and play-spaces (Champion, n.d.).

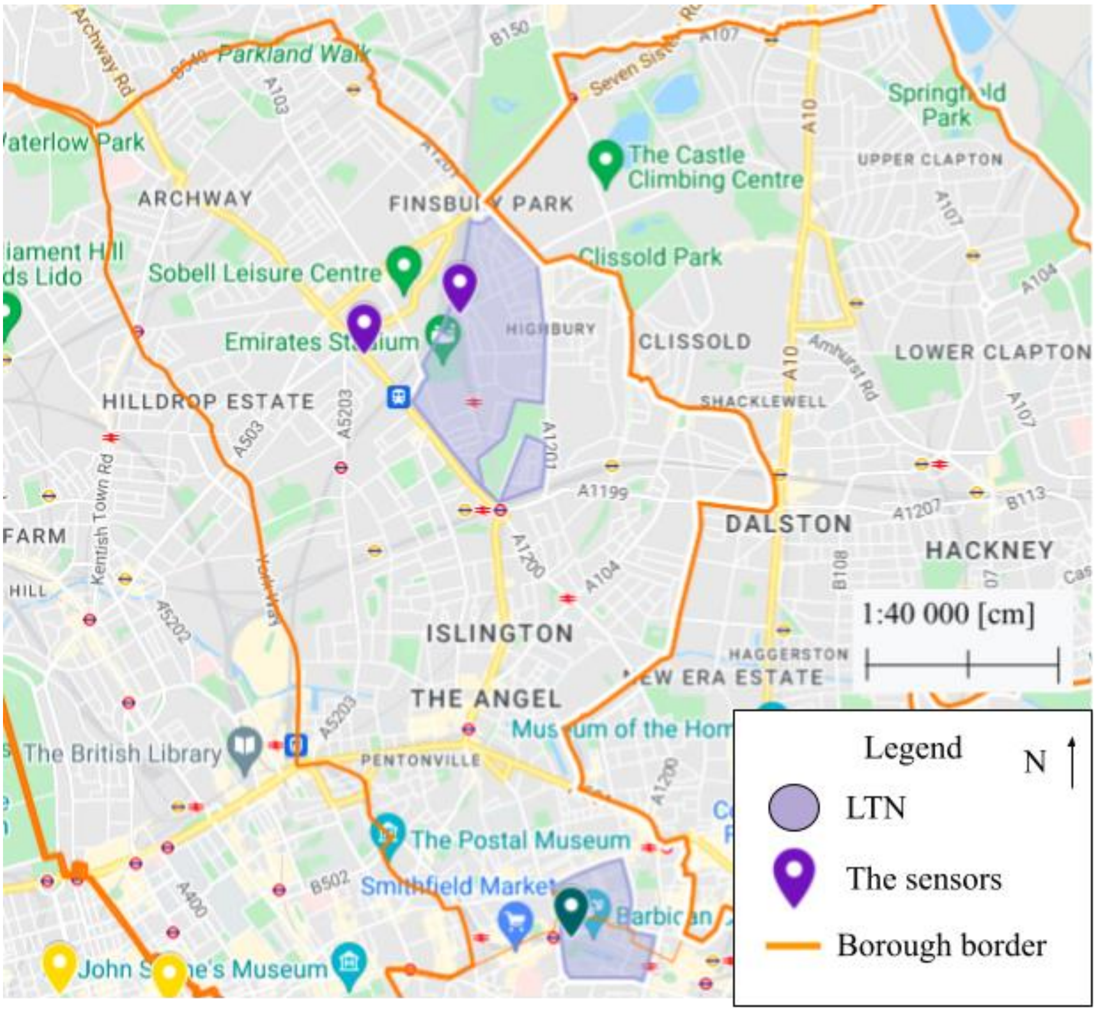

Figure 5. The map shows the borough of Islington.

Figure 6. Shows the LTN Highbury West in Islington.

2.1.4 Wandsworth

Wandsworth, Figure 7 below, is located in the southwest of London, with several open spaces and the busy railway station Clapham Junction (Mayor of London - London Assembly, 2022b). It is mainly a residential area, being the London borough with the most inhabitants, roughly 300 000 (edenharper, 2020.). The borough of Wandsworth describes the LTNs as areas designed to improve streets for cyclists and pedestrians, enable a stronger community, and decrease the through traffic on residential streets. The areas chosen to be replanned as LTNs are neighbourhoods that were either requested to be made into LTNs during Covid, or where residents had expressed a worry regarding high traffic volumes previously (Chadwick, 2020). The LTN in this study can be seen in Figure 8 below.

The Wandsworth council (2021) says that the air pollutants of concern in the area are PM_{10} and NO_2. To tackle these they have, among other political actions one of them being the LTN in this study, implemented a mechanical city tree on Putney High Street to help purify the air (Wandsworth Council, 2022). A mechanical tree is an air purification system, where air is drawn into a box which filters the air through layers of living moss, and then recirculates the air back into the atmosphere (Wandsworth Borough Council, 2021). However, it was not seen during the field studies, and it is unclear how close to the sensor it is positioned.

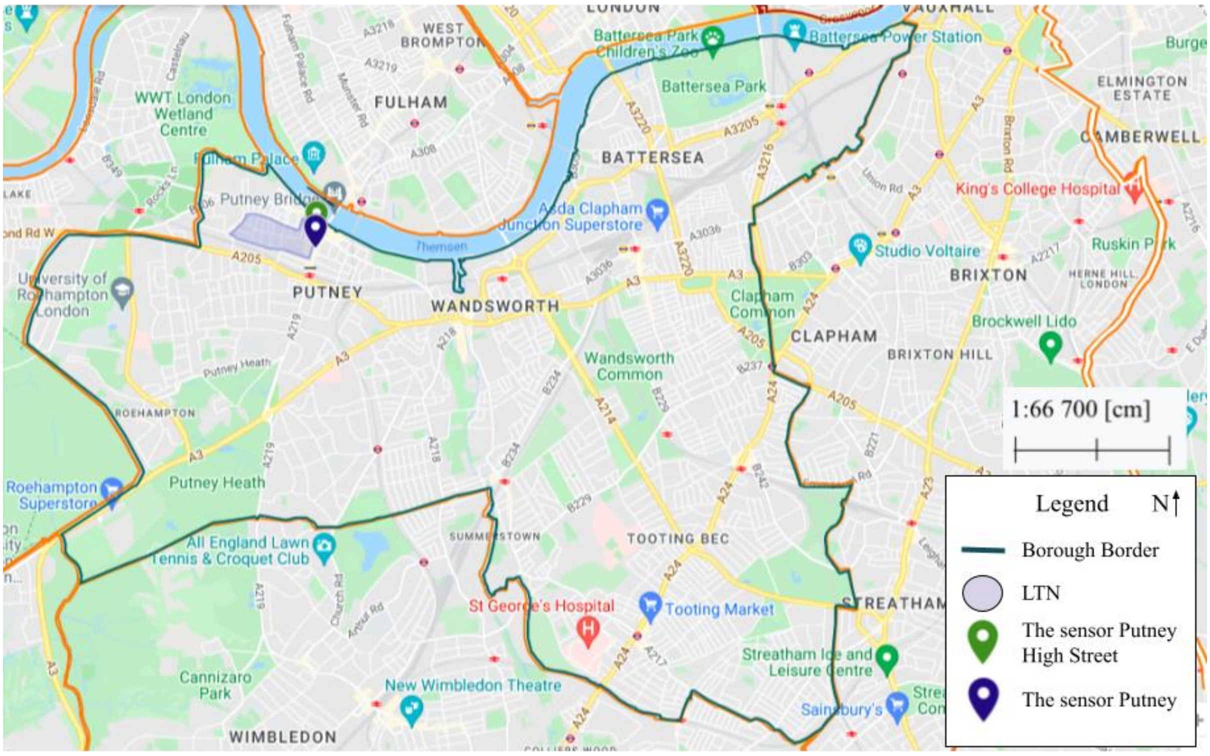

Figure 7. The map shows the area of Wandsworth.

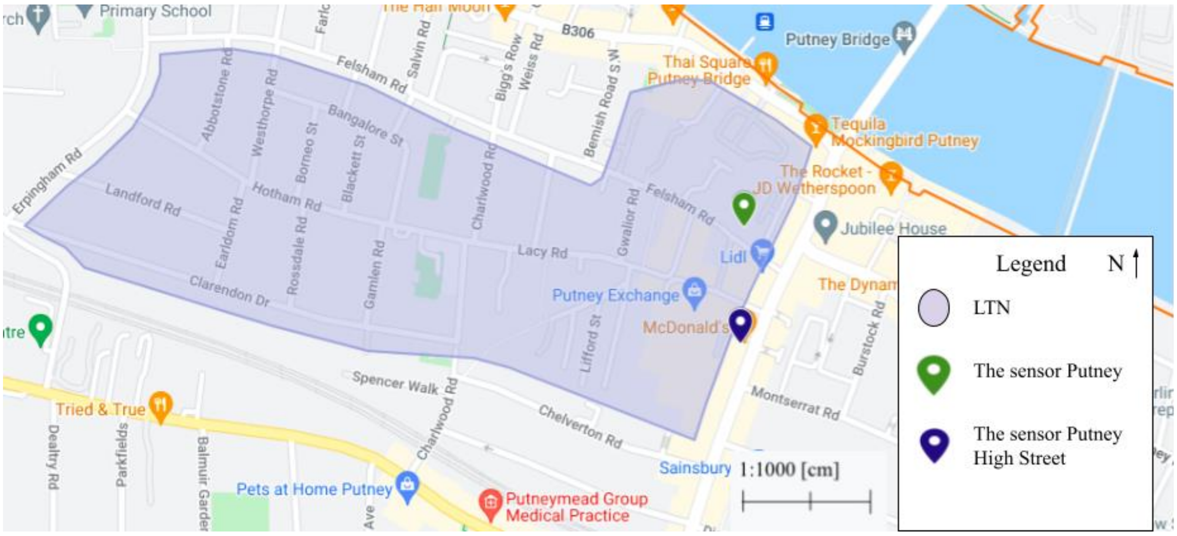

Figure 8. The map shows the LTN and sensors in Wandsworth.

2.1.5 Westminster

Westminster is a central and busy borough home to the house of parliament, Westminster Abbey, the theatre district, Buckingham palace etcetera. (The Editors of Encyclopaedia Britannica, n.d.). The Westminster LTN in this study is called the Northbank Business Low Emissions Neighbourhood (Northbank BLEN) (Mitchell, 2019). The area consists of an array of GI interventions, planning for delivery services, business engagement, and campaigns for behaviour change. The street interventions were done in gateways thought to help wayfinding and diminish anti-social behaviour, with robust and sturdy planters (The Pineapples, 2021). Furthermore, in the Air Quality Action Plan 2019 - 2024 it is stated that GI is a means to reduce the air pollution in the borough (Mitchell, 2019), which has led to 26 new trees, one parklet and 280 square metres of green walls (Greater London Authority, 2019).

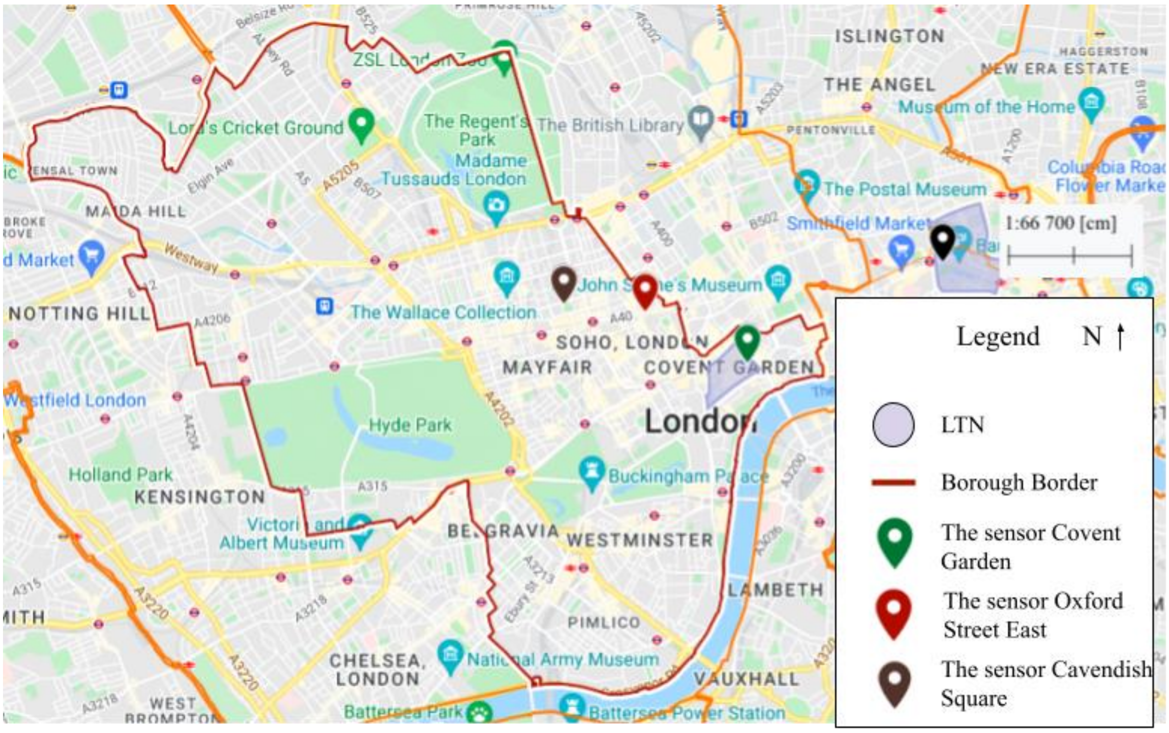

Figure 9. The figure shows the borough of Westminster.

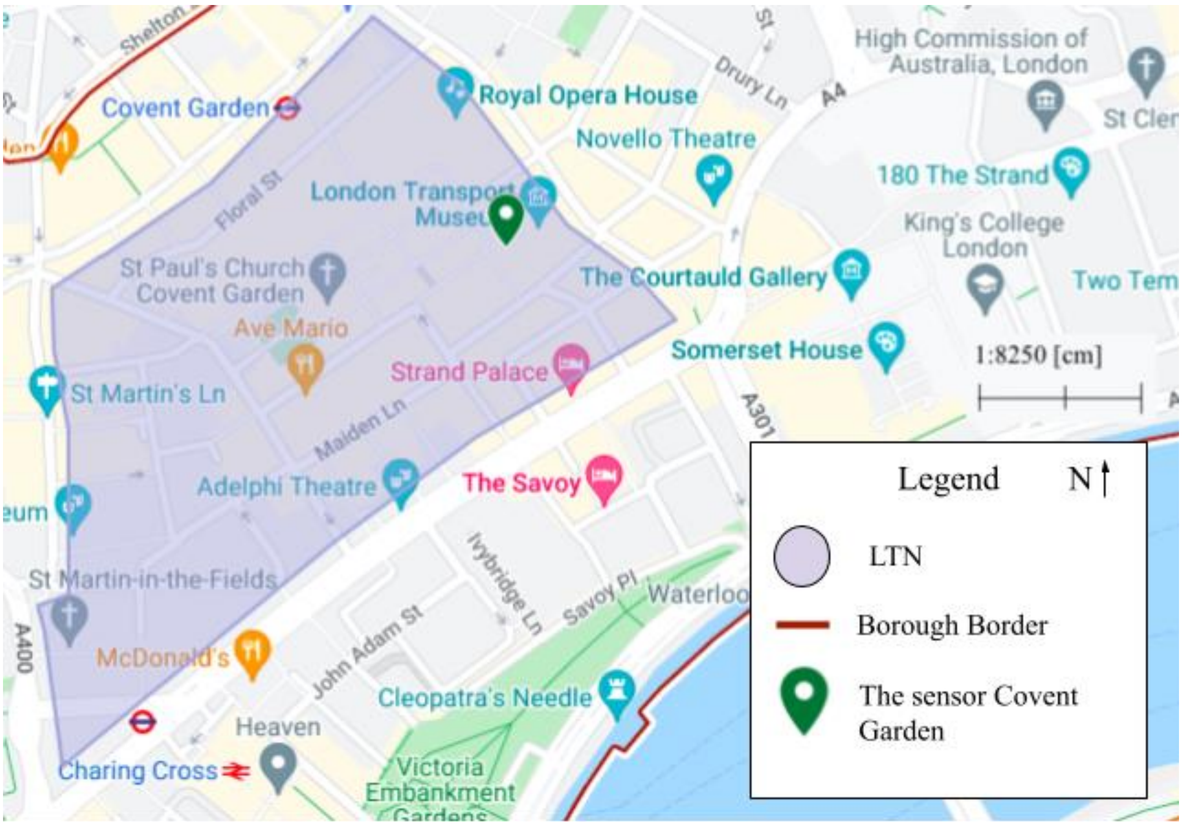

Figure 10. The figure shows the LTN in Westminster called Northbank BLEN, in purple.

2.2 Field Studies

Field studies were conducted to study the GI nearby the sensors. The factors chosen to look at follow the ones presented in *Handbook on Green Infrastructure* (Tallis et al., 2015), with a few exceptions. According to Tallis et al. (2015) the most important factors to look at when determining the impact GI have on air quality are the types of species; size, form, and structure; distance to the source of emission; and green-space management. However, this study will not determine the kind of species of the sites, nor the green-space management, since that would make the scope too wide.

The size, form and structure are important to look at since the size, shape, and ability of turbulence affect the possibility of reducing the air pollution. Regarding the distance to the source of emission, studies have shown that vegetation being placed closer to the source attracts more pollution (Tallis et al., 2015). The field studies have e.g. been the counting of the nearby trees and assessing their size, measuring the extent of lawns, shrubbery and bushes, and their distance to the road and the sensor. This has then been compared to the air pollution data, to see if there is a correlation between the extension and type of GI, and the measured values. Moreover, the field studies have also been a way to verify the positions of the sensors and the LTNs, to make sure that the data found match the reality. There have been areas where an LTN was thought to be, however when visited, it was not in place.

2.2.3 Defining Green Infrastructure

Kumar et al. (2019) states that the definition of GI is dependent on the context, signifying that it can refer to both engineered- or to strictly ecological solutions, with varied purposes and outcomes. Moreover, the *European Environment Agency* (EEA) (2011) has mapped different definitions of GI to where they serve the best purpose. They divide the definitions into the urban scale opposed to the landscape scale. The urban scale includes the foundation of a built-up area, something that can be part of the landscape scale as well, however the landscape scale further involves strictly farmed land or the desire to connect a different ecosystem to the one in place. Furthermore, the EEA divides the definitions into broad and narrow ones, where the broader definition includes terms to combine the green spaces and their interlinkage. Whereas the narrower definitions only state the linkages and the notion of relation (EEA, 2011).

The definition used in this report will be of the urban and narrow scale, since it will be situated in London which provides the foundation of built-up areas, and the study will be looking at one neighbourhood at a time, rather than the interconnections of green areas. Continuing, the reason behind why the vegetation has been put in the area will not be included, simply because that would demand more thorough research and possibly interviews with the specific planners, which would make the scope of this study too vast. The definition in the *London Environment Strategy*, stated above, includes rivers which will be excluded in this definition due to lack of time. Private back gardens will further be excluded because examining them would require access to them, an endeavour which has been deemed too ambitious for this study. Several definitions of GI include a statement of the GI being beneficial to humans. However, since the aim of this study is to quantify the vegetation's effectiveness in improving air quality, the outcome of the GI will not be included in the definition. The definition defined for and used in this study will therefore be:

Planned vegetation of varied quality in the form of trees, lawns, bushes, flowers, green walls, parks, parklets, planters, and vegetation barriers, placed in grey, urban areas with possible connections and relations.

2.3 Data

Open-source data of monitored values of NO_X and PM_{10}, conducted by the Imperial College London published at London Air, have been used (Imperial College London, 2022). The website and data were found through Google by searching for *air pollution London.* Imperial College London uses automatic sensors that are permanently placed in cabins that draw in the air at a specific sampling height (see table A1.1 in Appendix 1 for the height of each sensor). The data is then downloaded by the Environmental Research Group (ERG) who publish it (Imperial College London, 2018). The sample data used ranges between 2018 to 2022, why is described in the next paragraph. Although there are measured values for most dates, there are gaps in some data series. These gaps are due to damage in the equipment which has not been discovered immediately. This means that the faulty sensors can be running, or non-running, for days or months before being fixed, leading to incorrect or no sampling (Baker, 2022).

A similar study looking at the NO_2 and $PM_{2.5}$ values in New York after the Covid lockdown, also using open-source data of monitored air pollution values, tracked seasonal variations and long-term trends by using samples from the season just before the lockdown, that is the winter of 2018-2019. The season was used as a control variable to compare to the samples monitored during different stages in the lockdown (Pitiranggon et al., 2022). The same approach was used by a study looking at the change in air pollution during the lockdown in Barcelona and Madrid. However, this study only looked at the values during March for three consecutive years (Baldasano, 2020). In *Highbury West and Highbury Fields people-friendly streets trial* (Islington, n.d.), the authors handled the variation of factors such as the weather, by looking at data over a longer time, which in their case was one year prior to the scheme. On the other hand, Andrews and Pascarella (2021) states in the London Borough of Wandsworth - Air Quality Annual Status Report for 2020, that one year might not be enough to cover all weather variations. Based on these studies, this study will look at data from 2018, which is at least two years before the implementations, to cover for seasonal changes and trends such as the weather. Furthermore, the study on Spain used sensors placed at different latitudes, and with varied surroundings (suburban, urban background, and urban traffic) to include the variations of air pollution within the city (Baldasano, 2020). This study looks at sensors with surroundings classified as Roadside, Urban Background and Kerbside (definitions can be found in table A1.1 in Appendix 1), as well as sensors being placed in the North, Southwest, and central London.

2.3.1 Paired T-Test

A paired t-test is a test to determine whether there is a statistically significant difference between the means of distributions, based on the sample data. It is used when two samples are to be tested against each other and is commonly used on samples where an interaction has occurred, such as the implementation of a traffic scheme, and where the study wants to determine if the interaction had an impact. In other words, t-tests are used on before-and-after observations (Shier, 2004).

In the case of this study, the mean of the measured values from one sensor on a specific date after the implementation, e.g. 2020/08/01 and 2021/08/01, has been compared to the mean value from the same dates before the implementation, e.g. 2018/08/01 and 2019/08/01. This has been done on all measured values after the implementation, to the corresponding values the years before the implementation. Where there are gaps in the time series data, the value for the corresponding date has either been removed from the test, since no pair can be formed, or if there is a value for one of the years, that value has been used.

The t-test used in this study is one-tailed, hence a two-tailed test only determines if there is a difference, whereas a one-tailed test determines if there is a difference and if it is positive or negative. In the case of this study, the t-test is used to determine if the difference is negative. That is, a decline has happened. Furthermore, the significance level is 0,05 and the degrees of freedom (df) will vary between the sensors, please see table 3 for the specific dfs. When conducting a t-test, a few aspects are assumed. These are: normality in distributions among the calculated differences, this has thus been tested for all sensors; the samples are on an ordinal or continuous scale, in this case the samples are on a continuous scale; the samples are randomly picked, that is, the choices are unbiased; the sample size is of a rational size; and, the variance are homogenous, which has been tested (Maverick et al., 2021). Lastly, when doing a paired t-test, a null hypothesis (H_0) and a hypothesis (H) are required. These are:

H_0: *The measured values of PM_{10} respective NO_X have not decreased after the implementation of the LTN.*

H: *The measured values of PM_{10} respective NO_X have decreased after the implementation of the LTN.*

A t-test results in a t-value, which is compared to a t-value showing the significance limit for a specific degree of freedom. The calculations involve the determination of the difference of each pair (di), the mean difference of all samples (dm), calculating the standard deviation (Sd) (equation 1) and the standard error (Se) (equation 2), and finally the t-value (T) (equation 3).

$$Sd = \sqrt{\frac{\Sigma(di - dm)^2}{n}} \qquad (1)$$

$$Se = \frac{Sd}{\sqrt{n}} \qquad (2)$$

$$T = \frac{dm}{Se} \qquad (3)$$

2.4 Interview

A zoom-interview was held with Sally Oldfield, the Nature Conservation Manager at Islington Ecology Centre, on the 14th of April 2022. The interview was semi-structured, meaning that several questions were prepared beforehand. These were also sent to Oldfield by email before the interview. However, spontaneous questions were also part of the interview. The reasoning behind this was that it was determined beneficial since it would not limit the possibility of receiving information about the borough. Oldfield does not work directly with the LTNs in Islington, the borough where she works. However, since being an ecologist she works with the GI in the area and has insight in the LTN process.

2.5 Literature Review

A literature review has been done to study the research on LTNs and superblocks, air pollution in urban areas, and GI and the correlation with air quality. Grey literature about the LTNs has also been reviewed. The databases used are ScienceDirect, Google Scholar, Google, and DiVa. Search words have been e.g. LTN, LTN in Wandsworth, LTN in Islington, LTN in the City of London, LTN in Westminster, air pollution, air pollution in London, green infrastructure in London, the superblock etcetera.

3. Background

In the following section, general information about air pollution will first be presented which will further go into more detail about PM_{10}, NO_X, and Biologically derived Volatile Organic Compounds (BVOC). Continuing, research about improving the air quality with GI can be found. Following, a section about the local politics in London regarding different schemes is presented, and lastly, there will be a passage regarding the traffic data in the different boroughs for the time scope of the study, either 2020 to 2021, or 2019 to 2020.

3.1 Air Pollution

When talking about air pollution one refers to several components with the common attribute of being poisonous and harmful for the surroundings. The most common pollutants are ozone, O_3; Carbon Monoxide, CO; Sulphur Dioxide, SO_2; Nitrogen Oxides, NO_X; and PM_{10} and $PM_{2.5}$ (Aeroqual, 2021). The pollutants studied in this report are NO_X, the umbrella term for NO and NO_2, and PM_{10}, particulate matter of the size 10 micrometre or less. The WHO guideline values for the UK says that the NO_2 number should not exceed 200 µg/m³, a number that should not be surpassed more than 18 times per year. The PM_{10}-limit is set to 50 µg/m³, which should not be surpassed more than 35 times per year. However, the limit for the annual mean regarding both NO_2 and PM_{10} is 40 µg/m³ (Simons, n.d.). In this study, all NO_X-values have the reference unit of [µg/m³ as NO_2] why the NO_2-limit will be used.

There are several factors of uncertainty when studying air pollution and the correlation of sources, wind being one of them since it will have an impact on the movement, dispersion, and transport of particles (Liang and Gong, 2020). For example, pollutants travelling from outside of London will be included in the data series although not originating in the area (Dajnak et al., n.d.). However, wind can both increase and decrease the number of pollutants, since it can catch the particles on the ground as well as remove the particles from the area. Furthermore, there is no direct linkage between places with high or low wind speeds to the air quality of the city. Rather, a study on PM_{10}-movement in urban areas, one of them being London, showed that more significant predictors of PM_{10}-concentration were the change of temperature and atmospheric stability. London is in a high-pressure area, which is associated with stable stratification however not automatically stable condition (Kukkonen et al., 2005).

Meteorology is another uncertain variable, where temperature, cloud cover and solar radiation, and precipitation will have an impact on the pollutants (Querol et al., 2021). As mentioned under *Data* these factors are taken into consideration by looking at data series for several consecutive years. What is more, the area metrics and shape affect how air pollution changes (Liang and Gong, 2020). London is in a flat area with low hills to the south and west (Kukkonen et al., 2005), however it is still an urban area that is largely built up. Something that needs to be taken into consideration when analysing the result. Lastly, despite air pollution being tricky to study, analyses of the monitored data can give an estimation of the changes in the local air quality (Andrews and Pascarella, 2021).

3.1.2 NO_X

As mentioned, NO_X includes both NO and NO_2. In London, more than half of the NO_X comes from road traffic (Querol et al., 2021; Kukkonen et al., 2005), the reaction being favoured by the high temperatures in the engine (Aeroqual, 2021). The following sources are energy production and domestic sources, in that order of magnitude. Furthermore, the NO_X originating from traffic mainly contains NO; it has been measured to be between 75 and 90 percent of the NO_X, with NO_2 being the rest (Querol et al., 2021).

NO_2 harms the environment by forming ozone and photochemical smog (Aeroqual, 2021), and it is further harmful for humans, specifically regarding respiratory health (European Environmental Agency, 2021). Moreover, NO_X contributes to eutrophication of water and soil, and to acid deposition. Consequently, having a negative impact on both aquatic and land-based ecosystems, e.g. leading to poor water quality and lack of biodiversity (European Environmental Agency, 2021).

3.1.3 PM_{10}

All particles with a size up to 10 micrometres fall under the category PM_{10} (Naturvårdsverket, n.d.), meaning that both $PM_{2.5}$ and PM_1 are included. PM_{10} originates from human factors such as motorised traffic, waste management, and the industry. Additionally, it can be emissions from natural sources such as volcanic emissions, dust from soil, windblown seawater, and emissions from vegetation in the form of BVOC (described below) (Tallis et al., 2015). That is, PM is a heterogeneous variety of different particles having diverse origins, chemical compositions, and size (Grantz et al., 2003). PM_{10} will continue to be an emission from traffic, despite the implementation of zero emission zones, since the particles are released from tyre and brake wear, which is not excluded from electrical vehicles (Mitchell, 2019). What is more, it is a global emission, meaning that it does not mind travelling long distances. Studies have concluded that roughly 40 percent of the measured particulates originates from different global sources (Andrews and Pascarella, 2021).

The particles are harmful to humans since they harm the respiratory system (McDonald et al., 2007). It is further of environmental concern, since PM directly accumulated to the soil may affect the nutrient cycle specifically concerning nitrogen. The soil can further be disturbed by the presence of the PM since the pH-value of the soil may increase greatly due to its presence. What is more, the effect on ecosystems by the PM has been shown to have a linkage to climate change. The higher levels of PM can further diminish the radiation interception by vegetation canopies, and by an array of physical effects, the PM can cause less precipitation. Because of the impact on ecosystems, the higher levels of PM will ultimately lead to less biodiversity and the loss of ecosystem services (Grantz et al., 2003).

3.1.4 BVOC

An ecosystem disservice with vegetation is that they can be a source of air pollution. By emitting biological pollutants in the form of pollen, fungal spores, and the most significant one in regards to this report: BVOC (Tallis et al., 2015). BVOC are volatile compounds in the form of CO, non-methane volatile organic compounds, and NO. BVOCs are very reactive and therefore have a great impact on the physical and chemical properties of the atmosphere. They especially favour reacting with NO_X, forming tropospheric ozone and photochemical smog, and they might form secondary aerosols, a PM_{10}-element (CNR, n.d.). The studies on BVOC's impact on air quality show a complex system difficult to map. The results are further at variance if BVOC have a positive or negative impact on the air quality, making it a difficult variable to take into consideration (Tallis et al., 2015).

3.2 Improving the Air Quality With GI

Based on what is known today, diminishing the emissions by the source is the most adequate way to decrease air pollution. However, doing this will not reduce the pollutants all together, but more mitigations need to be put in place, such as implementation of vegetation in urban areas. The plants capture, absorb, or metabolise the pollution, and thus remove it from the atmosphere, as a way to restore balance in the ecosystem. The leaf petioles are especially good at catching pollution by assimilation and separation of gaseous pollution and particulates (Karmakar et al., 2021). The deposition is further divided into dry and wet, defining how the pollution moves from the atmosphere to the specific structure, e.g. vegetation, asphalt, brick, or water. Wet meaning that the pollutant was transferred with precipitation, and dry indicating movement with e.g. wind. The structure will further impact the removal of the pollutant. Smooth surfaces will enhance a short-term removal for dry deposition, meaning that the pollutant can revert to the atmosphere when the conditions are more favourable. Furthermore, when the pollutant is absorbed and becomes part of the structure, the removal is long-term, also known as sequestration. Lastly, the pollutant can use the surface as an artery to soil or water. Generally, rough areas are better at removing pollutants from the atmosphere, e.g. tree canopies are more efficient than asphalt (Tallis et al., 2015).

Studies on the removal of PM by greenery have determined a reduction by two to ten percent. Regarding the removal of NO_X, it depends on stomatal uptake, uptake by the leaf or young stems, which is smallest during the night-time and winter, when the levels of NO_X are the highest. However, when the vegetation does absorb NO_X, during daytime and summer, the levels of NO_X are the lowest (Department for Environment Food and Rural Affairs, 2018). Nonetheless, studies on trees in London have seen that they reduce 13 percent of PM_{10} and 14 percent of NO_2 of the road transport emissions (Khan, 2018b).

Concerning which vegetation is more efficient in improving the air quality, there are some guidelines. Trees are better than shorter vegetation, hence their large leaf area, surface roughness, and air turbulence in the canopies. Continuing on the same theme, large trees are better than small ones, and studies have shown that young trees with an open canopy are effective in removing PM_{10}, especially when placed in single lines along the road. This method might even be more efficient than arbitrarily placing out trees, and then increasing the size of the canopy. Grass and herbaceous vegetation can be favourable since they can be placed close to the emission source. The relationship between the emission sources, the local climate and the chemistry of the atmosphere has an essential impact on the movement of air pollution. Ultimately affecting the deposition, transport, and re-suspension of the pollution through water, soil and vegetation. Generally, this means that the closer the vegetation is to the emissions source, and the larger the area, the vegetation will have a greater positive impact on the air quality (Tallis et al., 2015).

The impact from GI regarding air quality improvement, is affected by the built environment in the surroundings in relation to the location, type, and structure of the GI. The typographies of built-environment can be categorised as street canyons or open-road. Open-road being roadside without influence from surrounding buildings, hence if houses exist in the areas, they are low-rise single-storey buildings. The open-road category is more common in rural or peri-urban areas. Whereas street canyons in general are located in urban centres with single to multi-storey houses going along the sides of the road, leading to the wind flows with more or less turbulence within the canyons, depending on the ratio between the height of the buildings and the street width. When this ratio is 0,5 or less, tall trees within the street canyon may enhance the concentrations of pollutants at ground level since they reduce the dispersion. Regarding GI in open-road areas, if the thickness, height, and coverage are adequate, it can decrease the concentration of downwind pollution by depositions and increased turbulence. However, profoundly porous vegetation placed with gaps, may lead to no or increased concentrations of downwind pollutants (Kumar et al., 2019).

In the *Environmental Strategy of London* (Khan, 2018b) it is stated that the GI of London today needs modification and improvement for the city to gain more biodiversity and provide wildlife corridors. Now, the GI often consist of low-grade amenity or grass landscape, without much function or purpose other than being an open area (Khan, 2018b). A new scheme called Biodiversity Net Gain is about to be rolled out, to make developers plan early on in ways that improve biodiversity. However, according to Oldfield (2022) the process of the scheme is difficult to adapt to an urban context (Ibid). Furthermore, the mayor proclaims in the *Environmental Strategy of London* (2018b) that he wants London to become the globally greenest city. This is further established in the *Transport Strategy* (2018a) where the aim that half of the city should consist of greenery, is stated. As of 2015 a third of the city was deemed to consist of public green areas. However, on the contrary, the number of green areas have declined during the last couple of years, and some of these green areas are lacking in quality because of financial shortage, which have led to a degeneration in biodiversity. The planning and implementation of GI in London is determined by the London Plan, the latest being published 2016, with the more specific policies regarding GI being All London Green Grid (ALGG), Open Space Strategies, Tree and Woodland Strategies, and London’s foundation (Carlsen et al., 2012).

When planning for GI in Islington, several stakeholders are involved such as the tree, net-zero, and air pollution group, as well as groups looking specifically at traffic, parks, and children’s areas. The area is rather built up, leading to new GI being implemented where there used to be car parks, or by developing the already existing parks by introducing e.g. meadows. Development areas and areas where new housing estates are to be planned, are also seen as large areas with the possibility of including more GI in the borough. Additionally, the borough looks at the connection between green areas when planning for more, especially if the sites are determined to be extra important for nature conservation. However, Oldfield (2022) stresses the need to implement greenery where there are not any, since the borough aims for every resident to have easy access to nature. Furthermore, the borough aims for more tree canopy cover to tackle air pollution, although the canopies already cover 25 percent of the area, they are aiming for 30 percent coverage by 2050. To reach this, they are planning to plant more trees on public areas, as well as on private land (Oldfield, 2022). Estimates of the pollution removals from public trees in the borough, says that 8,1 tonnes a year are removed thanks to trees (Islington, 2020). Moreover, the borough is planning for more hedges, since tree canopies can trap the pollutants, whereas hedges enhance more air flow (Oldfield, 2022).

3.3 Local Politics

The boroughs in London own and administrate 95 percent of the streets. This means that the developments and policies might vary within the city. However, TfL works together with the boroughs hence there are still overall objectives affecting the entire city (Khan, 2018a). Moreover, TfL funds the projects and provides guidance for the boroughs, where the LTNs are an example. The LTNs originate from the Liveable Neighbourhood guidance from 2019, developed by TfL. The implementation of LTNs is further supported by the Healthy Street concept, working to advocate well-being by for example day-to-day exercise (Aldred et al., 2021). In May 2020 a Strategic Neighbourhood Analysis Guidance was established by the TfL to help boroughs distinguish areas suitable to become LTNs. The guidance uses several parameters such as cycling and walking fractures; cycling connectedness; number of car owners, schools, and children; population density and total size; etcetera. Although only guidance and not mandatory, it is assumed to be used when suggesting new schemes (Aldred et al., 2021). As of October 2020, 152 LTNs had been given funding from the TfL (Greater London Authority, 2020).

The Department for Transport (2021) states that the local authorities ought to continue with the work of releasing more road space for pedestrians and cyclists, and sustain the changes made under the pandemic to make them permanent, even as the pandemic fades out. The department further highlights the importance of giving the new schemes time, not condemning them too early before they have had time to settle and letting them be tested to more normal traffic. If a borough decides to cancel a scheme, it should be done with substantial proof of it not working. Furthermore, a cancellation must be discussed with the public just as carefully as an implementation would have been. The default setting being to keep, and cancellation the exception (Ibid).

During the past years several measures to tackle the air pollution in London, other than the LTNs, have been put in place. The first ULEZ-scheme was implemented on the 8th of April

2019 (Mayor of London - London Assembly, 2019), shown as red in Figure 2 above. The second ULEZ-scheme was implemented on the 25th of October 2021 (Mayor of London - London Assembly, 2022a), shown as the blue area in Figure 2 above. An ULEZ indicates an area where all motorised vehicles must meet specific emissions standards. The standards to be met to pass the ULEZ zone without being charged are Euro 4 for petrol vehicles, and Euro 6 for diesel vehicles. If the vehicle cannot live up to these standards, the driver will have to pay a day charge to enter the area, much like a congestion charge (Mayor of London - London Assembly, 2019). The ULEZ operates all year around during all hours of the day, except Christmas Day (Mayor of London - London Assembly, 2022a).

Figure 11 shows a timeline of the implementations of the ULEZs as well as when the different LTNs have been implemented. However, only the first Covid-Lockdown is included. The reasoning being this is because the first lockdown was the one closing down the society, whereas the other two, in force on the fifth of November 2020 and sixth of January 2021 (IfG n.d.) were enforced during the pandemic. What is more, how much the society opened up between the lockdowns varies and is uncertain. Continuing, according to Chadwick (2020) the impact from the Covid-pandemic on traffic is infrequent and uncertain, why the impact should be treated with caution. For example, the use of home delivery and residential boilers potentially increased during the lockdowns, leading to a change of emissions sources (Ibid).

Figure 11. The timeline highlights the different schemes implemented in London, as well as the first lockdown due to Covid-19. The Figure is drawn by Greta Gustafsson based on data from IfG (n.d.).

3.3.4 Local Opinions

In Islington, the LTNs have got both praise and critique (Oldfield, 2022). The borough has seen a grassroot movement of residents being positive to the scheme, seeing it as a way to reshape the streets. The old parking spaces have now been filled with planters, something that has not only been seen as positive. The neighbours seizing the moment for more greenery, might have neighbours thinking otherwise, and although the authorities have the right to remove the planters, it is not what they are aiming for. Instead, the borough of Islington came up with the project Greening Together. Residents can apply for funding to implement planters or parklets the size of a car parking space, through the project. However, the neighbours must be consulted beforehand. By doing this, the borough expects more greenery, however, it will be maintained by the residents themself. A project connecting to Greening Together is Green Together Champion, premiering this spring in Islington. By asking the residents to volunteer and help with projects such as the implementation of planters and parklets, as well as spreading awareness and inspiring people to do more greening in their surroundings (Ibid).

Nonetheless, not everyone is happy about the LTNs, some residents expressing a lot of anger and negativity about it by protesting and marching. However, Oldfield (2022) thinks that most people are quiet and happy about it, saying that the people being pessimistic about the scheme are a loud minority, something that is further stated in an article by Voce and Walker (2021). Additionally, an article by Kersley (2022), discusses that LTNs and other car free areas tends to become more popular if you live in one, and as times past (Ibid). No matter the case, in May 2022, there was a local election in London concerning all boroughs, which was thought to show the true opinion of the borough residents. The politicians in Islington who implemented the scheme said that if re-elected, they would continue with it (Oldfield, 2022). It can be noted that the same approach, that is letting the local election be a way to receive the opinions of the residents, was used in the City of London too (see *2.1.1 the City of London*). According to Nick Bowes, chief executive of the centre for London think tank, it is likely that the LTN was a crucial issue in the election in several boroughs, saying that the LTNs could be the subject of many surprising winners in the local elections (Donovan, 2022). Looking at the outcome of these elections, the candidates being positive to the LTNs, were the winners in most boroughs (Speed, 2022). Lastly, there are cases of LTNs already being cancelled as a result of protests from the residents, although the guidance from the Department of Transport to let the scheme be tested to normal traffic post the pandemic (Charsley, 2021; Holmes, 2020; Aldred et al., 2021).

3.4 Traffic Data

The traffic data only concerns motorised traffic, excluding trains, the under- and overground, cyclists, pedestrians, and e-scooters. The observed traffic changes in Islington after the implementation of the LTN, looking at November 2020 to December 2021, were an increase by 21 percent on Holloway Road and, the streets around the Arsenal sensor all saw a decline in traffic, ranging from 52 to 90 percent observed decrease. Overall, there was a decrease in traffic by 72 percent within the LTN, and the roads surrounding the LTN had more or less the same traffic volumes as before the scheme (Islington, n.d.).

On Beech Street the numbers of cars went down by 75,37 percent to 77,98 percent when comparing pre- and post-scheme, March 2020 to September 2021, depending on the connecting street. Furthermore, when looking at the total number of cars, motorcycles, light and other goods vehicles, taxis and public service vehicles, the decline was 70,34 percent to 73,66 percent, depending on the connecting street (City of London, 2022). After the implementation of the scheme, the average traffic volumes of weekdays were 350 vehicles, which is less than 5 percent of the pre-scheme volumes, when around 9500 vehicles entered. This is partly because of the scheme, and partly because of the pandemic (City of London, n.d.).

The traffic data corresponding to the sensors in Wandsworth and Westminster is limited. Only one sensor in each area was found to have corresponding traffic data. On Putney High Street, the decrease between 2019 and 2020, based on traffic data representing an average day during the year, was 22 percent (Department for Transport, n.d.a.). On Oxford Street East, the decline in traffic during the same time period was 24 percent (Department for Transport, n.d.b).

4. Results

The result of the study is presented in the following section. Firstly, the field study will be summarised, which will be followed by a presentation of the measured values before and after the implementation of the LTNs. Continuing, the annual and daily patterns will be presented, and lastly the result from the statistical analysis can be found. The study looks at the time-period 2018-2022. However, it should be noted that the traffic data, presented in the background, compares 2020 to 2021, or 2019 to 2020, whereas the difference in percentage, found under *4.2 Values Pre and Post the Implementation of LTN*, compares 2018-2021. Lastly, the statistical analysis compares 2018 to 2022. More details about the time periods can be found under each section.

4.1 Field Study

A table of the findings from the field study can be found in Appendix 1, this paragraph being a summary. It was found that Beech Street; Upper Thames Street; Walbrook Wharf; Putney High Street, figure 12b; and Oxford Street East were all near busy roads without any GI in the surrounding area. Additionally, the Beech Street sensor was placed in a tunnel. Furthermore, Holloway Road, figure 12a, was also near a busy street, however with significant GI in the surrounding area consisting of several large trees being placed along the street, shrubbery along the pavement and lawns leading up to the houses. What is more, the Cavendish Square sensor was placed under a large tree between two busy streets, as well as being next to a park, about 100 metres in diameter, with several large and small trees, hedges going along the edge of the park, and lawns. The sensor Aldgate School, figure 13a, was placed in a quieter neighbourhood, next to a neat and organised park with stone paved floors and lawns, bushes, herbaceous plants, and small trees. The sensor being placed in the most unique area was Arsenal, figure 13b, hence it was placed by the entrance of a nature reserve. Thus, the area was free of traffic with a significant amount of varied, forest-like, GI. All sensors having GI in their surroundings, were placed close to the greenery. The modal filters of the areas were planters that more or less were blocking the road, bollards and CCTV; examples of modal filters from Wandsworth and Islington can be found in Appendix 6. Pictures of the sensors and their surroundings can be found in Appendix 7.

Figure 12a. The figure shows the Holloway Road sensor and the single lined trees going along the road. Picture taken by Greta Gustafsson.

Figure 12b. The figure shows the Putney High Street Sensor, which is the green-grey box behind the blue post. Picture taken by Greta Gustafsson.

Figure 13a. The figure shows the Aldgate School Sensors: the black box behind the bars. The Picture is taken by Greta Gustafsson.

Figure 13b. The figure shows the Arsenal sensor, which is the green box in the middle of the picture. Picture taken by Greta Gustafsson.

4.2 Annual Means Pre and Post the Implementation of LTN

The values in table 2 show the change in percentage of the annual mean before and after the implementation of the LTN, as compiled by the author from the available data, when comparing the annual means. Since the implementation of LTN happened at different times in different boroughs, the start of a year occurs at the same date as when the LTN was implemented, and thus, the dates in the analysis vary between the boroughs. This means that the analysis for each sensor includes at least one entire year with the LTN in place, and two years prior with one year being unaffected by the Covid-19. The value of the annual means can be found in Appendix 2.

Table 2. The table shows the change in percentage of the annual means of NO_X and PM_{10} for all sensors in the study, before versus after the implementation of the LTN in the specific borough. The sensors in the LTNs are marked with asterisk, and the largest decreases are marked by bold letters.

Area	Sensor	NO_X-change [µg/m^3 as NO_2]	PM_{10}-change [µg/m^3]
the City of London	Beech Street*	**-79,0%**	**-23,3%**
	The Aldgate School	-41,6%	-17,1%
	Walbrook Wharf	-62,6%	
	Upper Thames Street		-17,9%
Islington	Arsenal*	-24,1%	-3,0%
	Holloway Road	**-41,7%**	**-6,8%**
Wandsworth	Putney*	**-15,9%**	**-12,3%**
	Putney High Street	-8,7%	-9,6%
Westminster	Covent Garden*	-41,8%	
	Cavendish Square	**-42,3%**	
	Oxford Street East	-38,0%	

All sensors, independently if they were in an LTN or not, saw a reduction in air pollutants when comparing the values before and after the implementation of the LTN. Overall, the more central boroughs, the City of London and Westminster, saw a greater decrease in NO_X-values. Which is further the case regarding PM_{10} in the City of London. The sensor with the most significant change in NO_X-levels is Beech Street with a decline of 79 percent. The sensor is the only one placed in a zero-emission area, meaning that no non-electrical motor vehicles are allowed to enter. It is further placed in a tunnel without any GI nearby and is placed in an area subject to the first ULEZ implemented in 2019. The measured decrease exceeds that of the combined reduction of motorised vehicles (see numbers under *Traffic data*). Beech Street is further the sensor with the greatest reduction of PM_{10}, although the changes in PM_{10}-levels were similar within the boroughs. The biggest difference being between Beech Street and the Aldgate School in the City of London, 23,3 respectively 17,1 reductions. It can be noticed that in two of the areas with the most pre-existing GI in their respective borough; the Aldgate School and Arsenal, showed the lowest change in PM_{10}, Arsenal being the sensor with the overall lowest difference in percentage in PM_{10}. Continuing, in the City of London and Wandsworth, the sensors within the LTN had the greatest reduction in PM_{10}-levels.

The greatest change in NO_X-values happened by the sensors placed near busy roads, Beech Street, Walbrook Wharf and Putney High Street, with the exception of Oxford Street East. The sensors placed in more quiet streets, such as Arsenal and the Aldgate School, did not see as great decrease. Looking at the annual values (Appendix 2), areas such as Arsenal and the Aldgate school, started off with, in this context, fairly low NO_X-values, whereas Beech Street, Walbrook Wharf, and Putney High Street had values around four times that of the recommended maximum mean. Thus, the rate of the reduction in this case being higher for the areas with the highest values to begin with. Furthermore, the Arsenal sensor had a lower decrease regarding both NO_X and PM_{10}, than the corresponding sensor in the non-LTN, Holloway Road. When looking at the traffic data, Holloway Road saw an increase in traffic after the implementation of the LTN, whereas the area around Arsenal saw a decline in traffic by 52 to 90 percent. Furthermore, the sensor being placed in an LTN in Westminster, Covent Garden, had a lower decline than the sensor in a non-LTN, Cavendish Square. Covent Garden being in a less busy area with less GI, and Cavendish Square being in a busy area although placed next to a significant amount of GI.

4.3 Annual Patterns

The annual patterns are presented in the following paragraph. The y-axes in all graphs have the unit of [$\mu g/m^3$] and the x-axes show every other month during the time period. What can be observed in all areas is that the annual trends and patterns of both PM_{10} and NO_X remained the same even after the LTN (and the first ULEZ), however the values went down, especially the peaks. The WHO-guideline to have a maximum mean value of 40 [$\mu g/m^3$] regarding both NO_X and PM_{10}, is further exceeded in all areas. This can be seen in Figure 14 and 13 below. The annual trends are more apparent in the NO_X-series than in the PM_{10}-series, Figure 16 and 15. It can further be noticed that the NO_X-values went up during the autumn and winter, and down during the summer and spring, Figure 15. The same pattern can be seen regarding the PM_{10}-values, however with shorter intervals and not as obvious, Figure 16 and 15. Graphs of the remaining sample series can be found in Appendix 3.

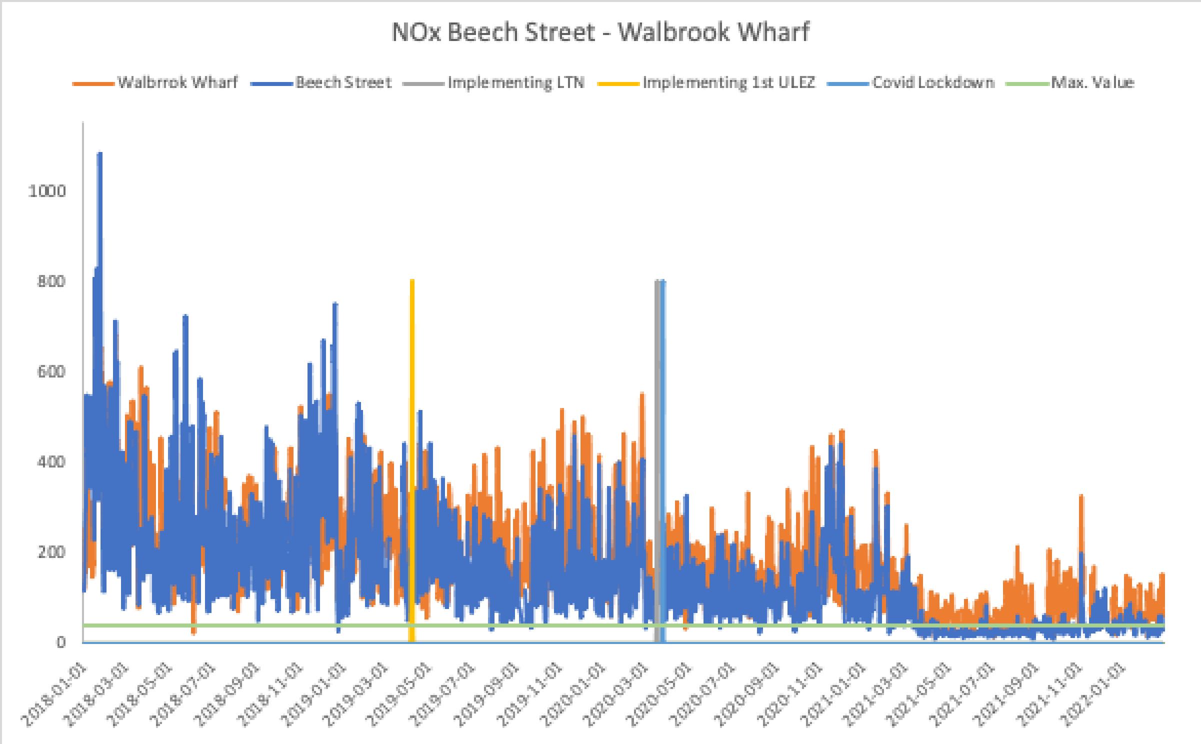

Figure 14. The graph shows the trends, from 2018 to the beginning of 2022, in sensored NO_X-particles by the sensors Beech Street and Walbrook Wharf in the City of London.

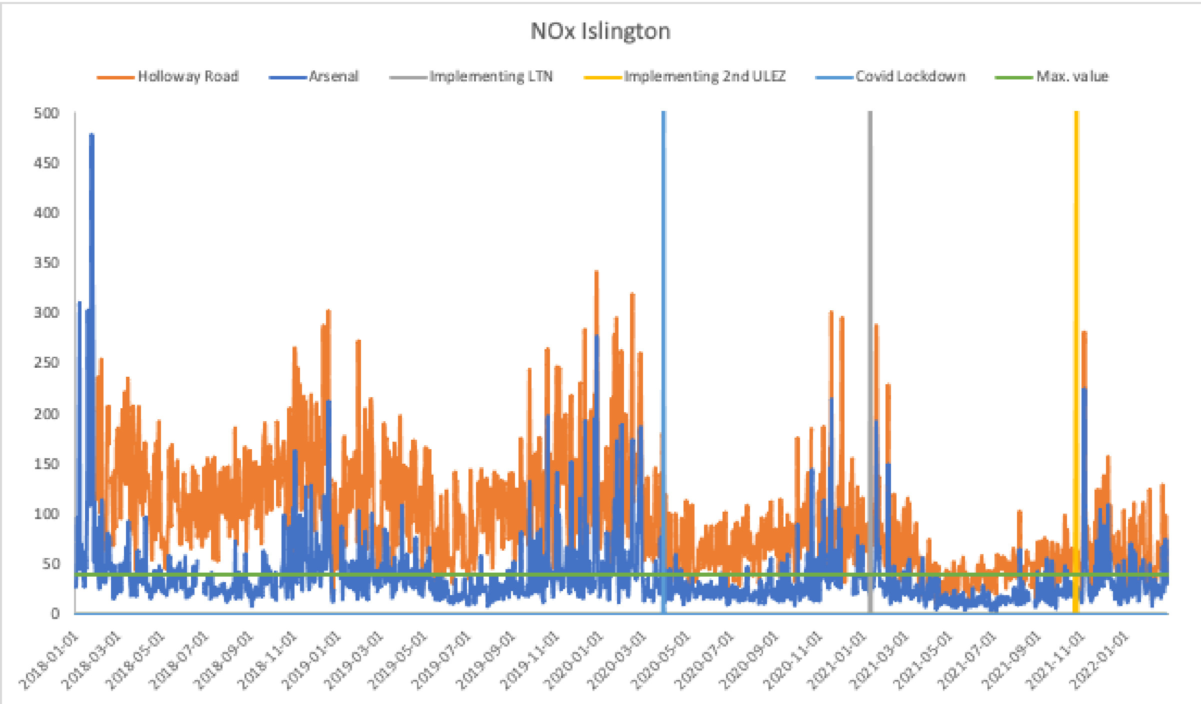

Figure 15. The graph shows the trends, from 2018 to the beginning of 2022, in NO_X-levels for both sensors in Islington, Holloway Road and Arsenal.

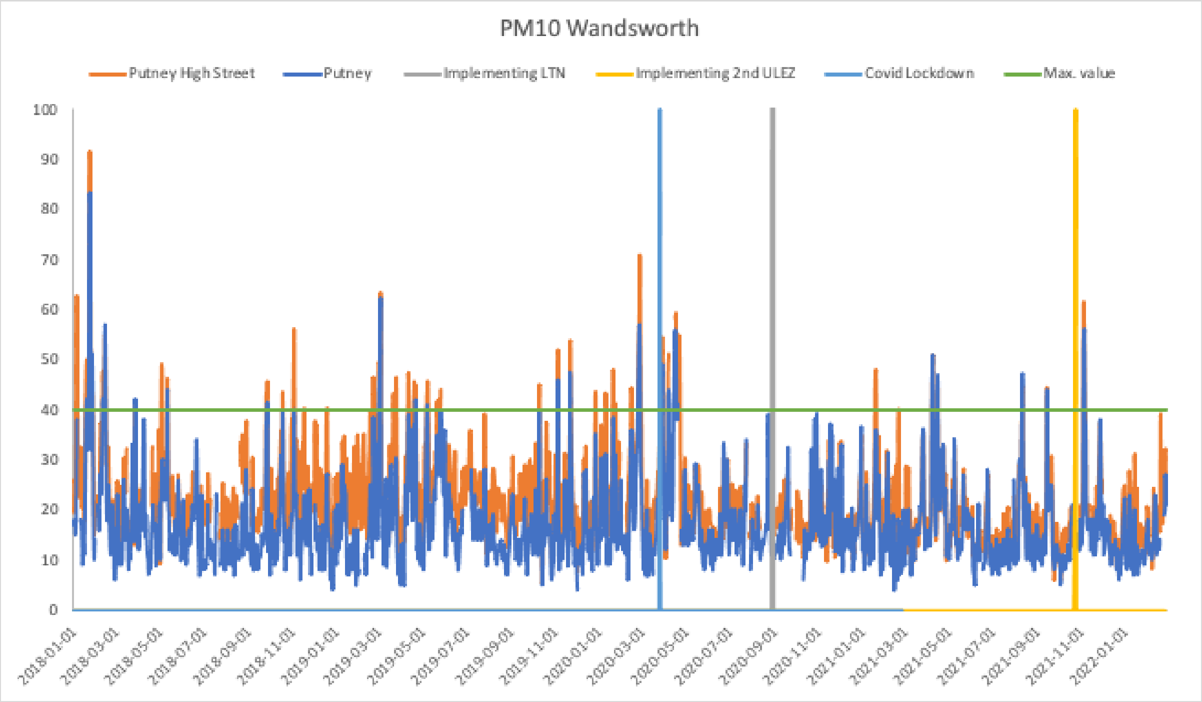

Figure 16. The graph shows the trends, from 2018 to the beginning of 2022, in PM_{10}-levels for both sensors in Wandsworth, Putney High Street and Putney.

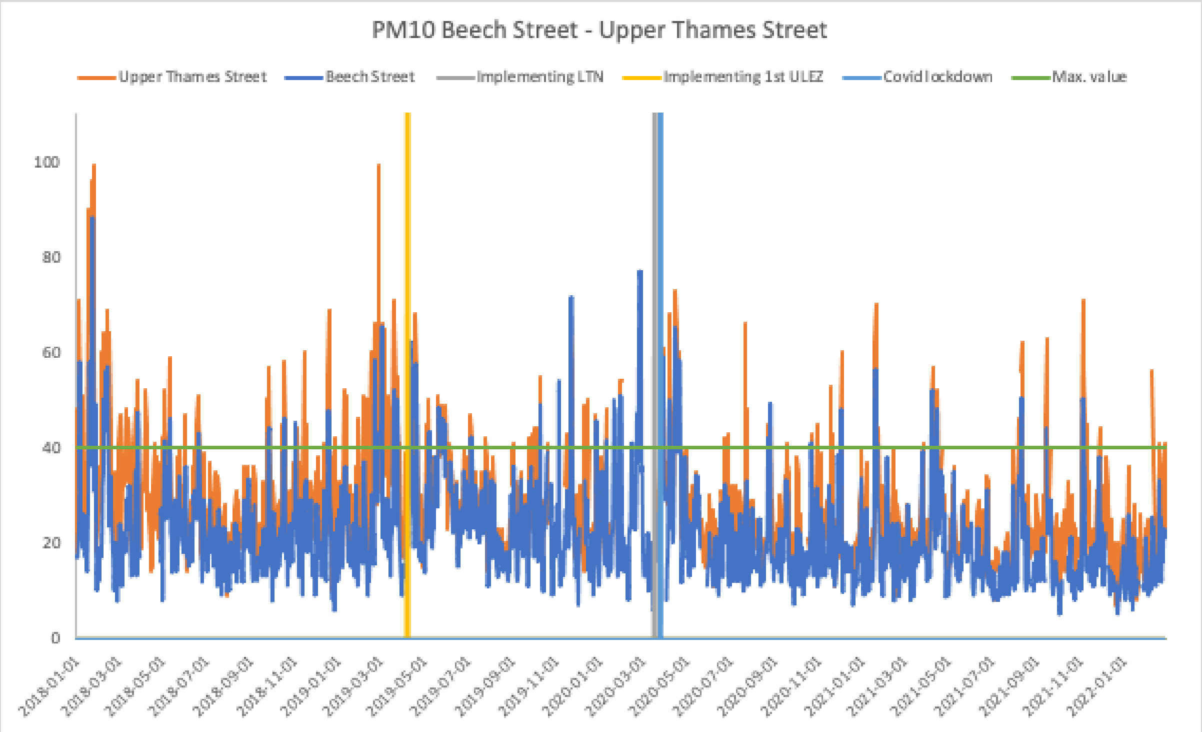

Figure 17. The graph shows the trends, from 2018 to the beginning of 2022, in PM_{10}-levels for Beech Street and Upper Thames Street, the City of London.

4.4 Daily Patterns

The daily patterns of the sensors in the LTNs are presented in the following paragraph. The y-axes in all graphs have the unit of [µg/m^3] and the x-axes show every 15 minutes during a 24-hour period. The daily patterns of April first and October first during the years 2018-2021 for all sensors in an LTN, were studied. The dates were chosen as they are not bank holidays, and because one value was during the spring whereas the other one happened during the autumn. Aside from that, the choice was random. Graphs of the remaining samples can be found in Appendix 4. The daily trends varied significantly between the sensors. The ones showing a correlation with the rush hours, 07.30 to 09.00 and 17.00 to 19.00, were the NO_X-samples during the first of October at Beech Street (Figure A4.2), Arsenal (Figure A4.4), and Covent Garden (Figure 21 below). The sensor in Putney showed this correlation for NO_X both at the first of April and the first of October (Figure A4.6 and 16 below). The PM_{10}-patterns seem to be more constant during the day, without clear peaks, this can be seen during the first of April at Beech Street (Figure 19 below) and in Putney (Figure A4.7). If there are peaks, they are more like outbursts spread out during the day. This can be seen during the first of October on Beech Street (Figure A4.3), and the first of April and October in Arsenal (Figure 20 below and A4.5).

Regarding the changes between the years, the NO_X-values changed significantly, whereas the PM_{10}-levels were more similar. The greatest differences can be seen between the NO_X-values on the first of October in Covent Garden (Figure 21 below), were the values for 2021 are close to zero, and the first of April on Beech Street (Figure A4.1.), where the NO_X-values for 2020 and 2021 are close to zero. The PM_{10}-values at the first of October in Putney (Figure A4.8) are similar between the years, except for 2019, where the values are abnormally high in comparison. However, it is not necessarily the most recent years that show the lowest PM_{10}-values, which can be seen during the first of April on Beech Street (Figure 19 below), and in Putney at the first of April and October (Figure A4.7 and Figure A4.8), where the values are about the same level as, or higher than, before the LTN was implemented. Lastly, a few graphs show a great drop in the NO_X-levels during the morning hours on the first of April 2021, this could be seen in Arsenal (Figure 22 below), in Putney (Figure A4.6) and Covent Garden (Figure A4.9), sensors that are far away from each other however with common parameter of being in an LTN.

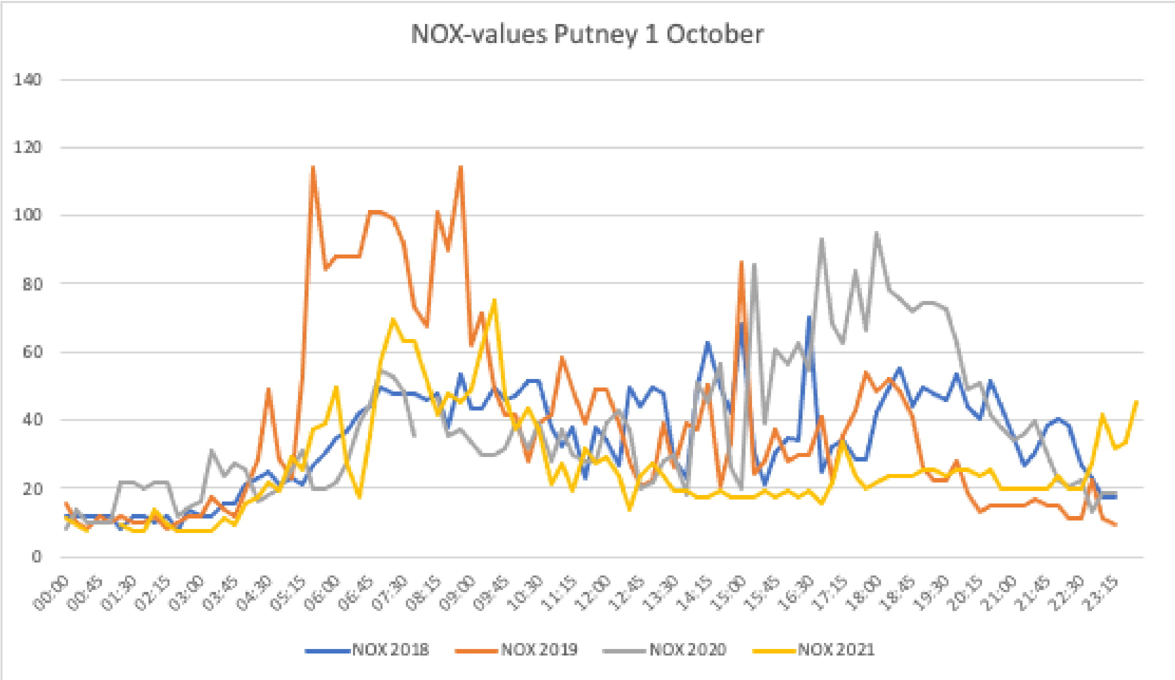

Figure 18. The figure shows the NO_X-values by the sensor Putney in Wandsworth on the first of October 2018-2021.

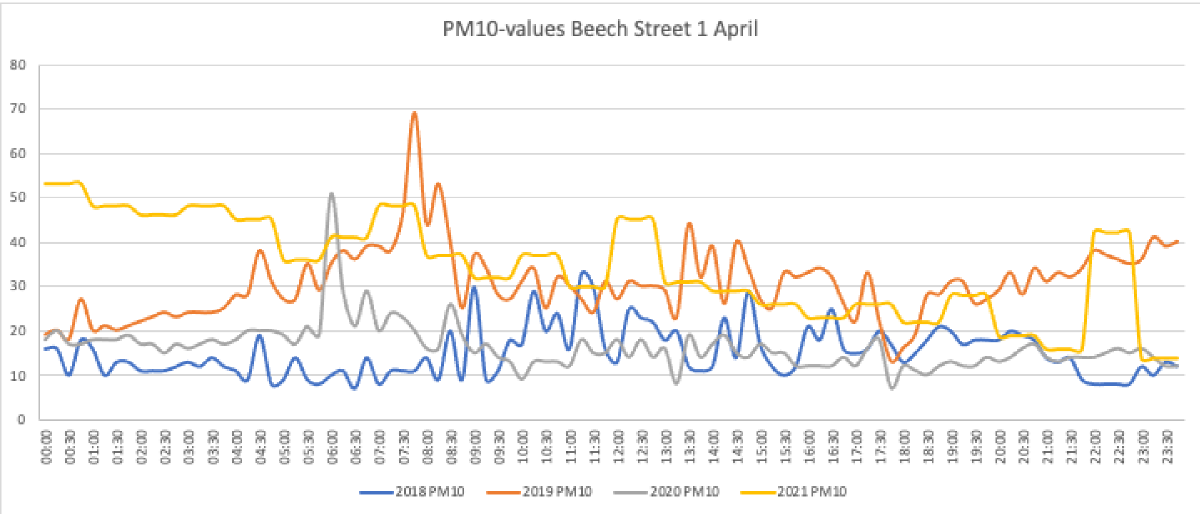

Figure 19. The figure shows the PM_{10}-values by the sensor Beech Street in the City of London on the first of April 2018-2021.

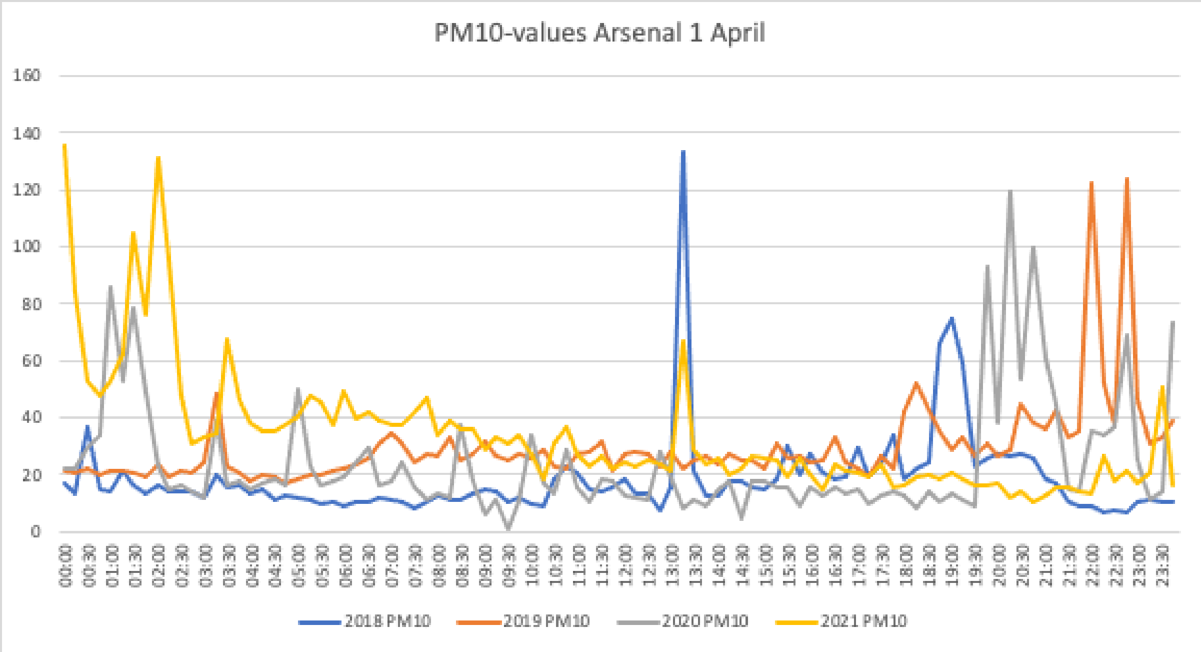

Figure 20. The figure shows the PM_{10}-values by the sensor Arsenal in Islington on the first of April, 2018-2021.

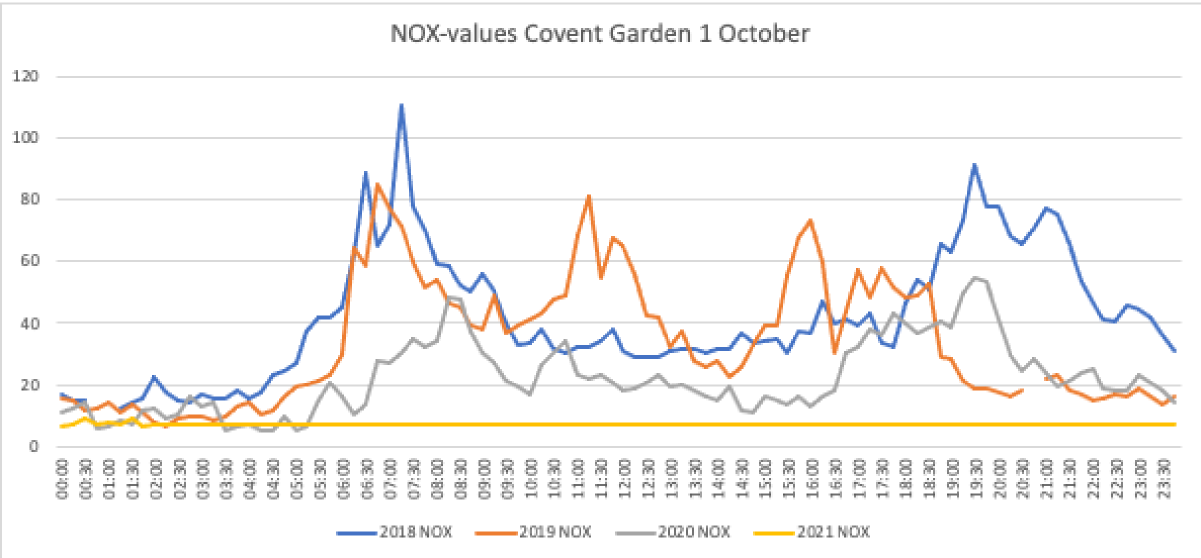

Figure 21. The figure shows the NO_X-values by the sensor Covent Garden in the City of London on the first of October 2018-2021.

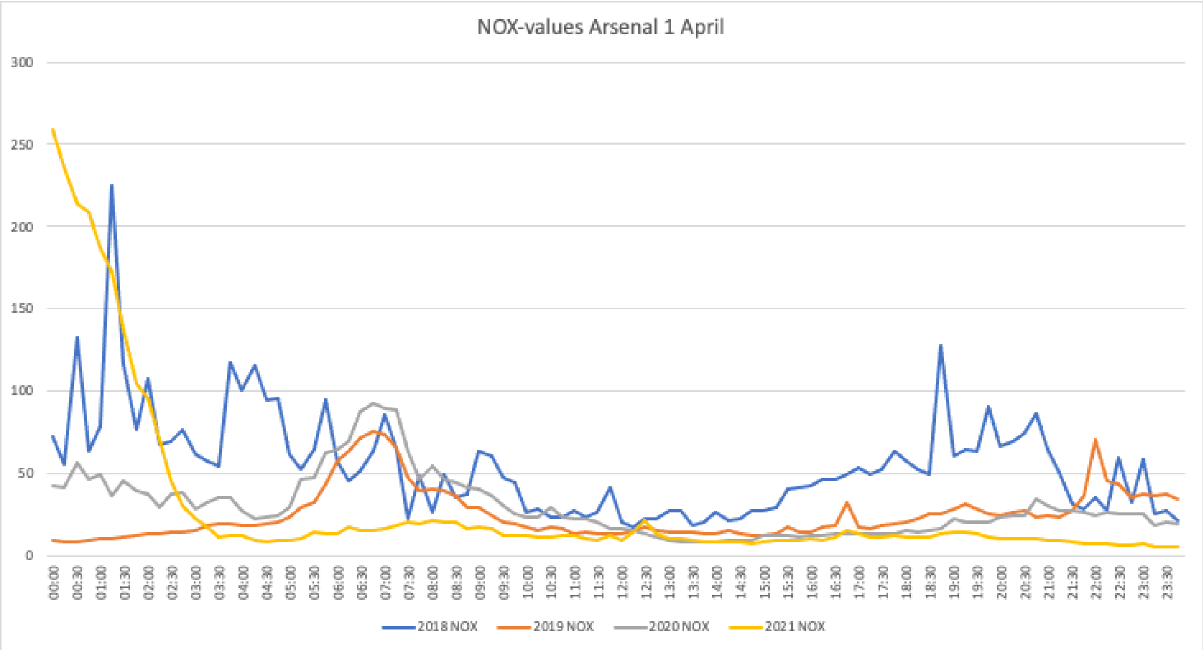

Figure 22. The figure shows the NO_X-values by the sensor Arsenal in Islington on the first of April 2018 - 2021.

4.5 Statistical Analysis

To look at the significance of the measured data before and after the implementation of the LTN, a paired t-test has been done. The result is presented in table 3 below. All data series except PM_{10}, in Arsenal were shown to come from different distributions, that is, it can be concluded that there has been a reduction of pollutant levels after the implementation of the LTN. The significance level (p) of the test was 0,05, which means that this reduction in levels can be said with a 95 percent confidence, hence the results are not 100 percent certain. This means that the null hypothesis:

H_0: *The measured values of PM_{10} respective NO_X have not decreased after the implementation of the LTN.*

(presented under 2.3.1 *Paired T-Test* in the Methodology and Data chapter) can be rejected for all samples except PM_{10} in Arsenal. However, how certain the results are, vary between the sensors. The certainty is determined by looking at the T-value. A T-value further away from the T(df) indicates a higher certainty. In the case of this study, the T-values with the highest significance are the lowest ones, with Beech Street being the most significant one for both pollutants and the PM_{10}-levels by Putney being the least significant. This implies that the implementation of LTN could be a significant breaking point for lower pollutant-levels. The null hypothesis could not be rejected for Arsenal in Islington regarding PM_{10}, which means that it cannot be said with certainty that the pollutant levels have gone down after the implementation of the LTN. This indicates that, although the trend has been lower levels, the LTN does not seem to be a significant breaking point affecting the trend.

Table 3. In the table the specific details of the statistical analysis for each sensor and pollutant can be seen, as well as the time period used for the specific test. The individual details of the statistical analysis presented in the table are degree of freedom (df), the T-value for that df resulting from the test) (T-value), and the T-value which determines the significance limit of the test (T(df)).

Borough, sensor	Pollutant	Time period	df	T-value	T (df)	T-value < T(df) for significance
the City of London, Beech Street	NO_X	2018/03/23 - 2022/02/28	364	-30,05	-1,6491	Yes
	PM_{10}		361	-13,75	-1,6491	Yes
Islington, Arsenal	NO_X	2018/01/12-2022/02/28	314	- 4,14	-1,6497	Yes
	PM_{10}	2018/01/11-2022/02/28	265	-1,62	-1,6506	No
Wandsworth, Putney	NO_X	2018/08/30-2022/02/20	345	-5,81	-1,6493	Yes
	PM_{10}	2018/08/30-2022/02/27	314	- 4,01	-1,6497	Yes
Westminster, Covent Garden	NO_X	2018/09/01- 2022/02/28	355	-10,76	-1,6492	Yes

5. Discussion

The analysis of the difference in percentage showed that a decrease in NO_X- and PM_{10}-values had happened at all sensors, both the ones in the LTN and the ones in non-LTNs. This was seen both in the difference in percentage and in graphs and was further checked for the sensors in the LTNs by the statistical analysis, which confirmed that the results were statistically significant at all sensors except one: the PM_{10}-values at the Arsenal sensor. The sensor seeing the greatest decrease was the NO_X-values by Beech Street, a sensor in an LTN. The decrease was 79 percent, which exceeded the decrease in traffic, that being between 75,37 to 77,98 percent. The Beech Street sensor is the only one placed in a road tunnel, and there is no GI nearby, however this specific LTN meant that only non-emission vehicles could enter without getting a fine. Traffic tunnels are normally heavily polluted due to the particles being stacked inside (Xu et al., 2022; Smirnova et al., 2020), hence this result might be an indication of non-emission zones being very effective, due to the great reduction in an atmosphere normally being one of the most affected by air pollutants. It can also be an indication of the movement of air pollutants in urban traffic tunnels.

The most central boroughs, the City of London and Westminster, saw the greatest decrease in NO_X-values, as well as PM_{10}-values in the City of London. These are also the areas being in the first ULEZ implemented in 2019 which could suggest a doubled effect from both schemes by the sensors in an LTN. Regarding the sensors in non-LTNs this result might rather be an indication of the effect of the ULEZ. An earlier study on LEZ in combination with the superblocks in Barcelona, described under *1.1.2 Traffic Schemes,* saw a significant improvement when the schemes were implemented together, however minor effects of the schemes individually (Rodriguez-Rey et al., 2022). However, the City of London and Westminster are also areas where there are a lot of businesses and workplaces. Areas where people did not go during the lockdown, which might be the reason behind the great drop in levels. Both Islington and Wandsworth being more of residential areas, where people stayed during the pandemic.

5.1 PM_{10}

Regarding the changes in PM_{10}-levels, the decline was moderate in all areas compared to the decline in NO_X, again Beech Street seeing the greatest decrease. The area with the most GI, Arsenal, had the lowest decline with three percent. This could indicate other PM_{10}-sources in the area, such as BVOC or dust, hence the extensive GI near the sensor. Furthermore, the decrease of PM_{10} at Arsenal was not considered statistically significant, meaning that the reduction of PM_{10} cannot be said to have happened after the implementation of the LTN. It should be noted that the Arsenal sensor had around the same levels of PM_{10} as Holloway Road, the other sensor in Islington. Holloway Road being a sensor classified to have *quite a lot of GI* (Appendix 1).

Furthermore, the Aldgate School, a sensor categorised as *having a significant amount of GI* (Appendix 1), had the lowest decline of PM_{10}-levels in the City of London, however, the difference to Upper Thames Street, a busy road without any GI, is only 0,8 percentage points. The Aldgate school sensor had a lot of grass and herbaceous vegetation, seen as effective in reducing air pollutants (please see *3.2 Improving the air quality with GI* under background), which would suggest a greater decrease than the other sensors in the City of London, hence they did not have any GI at all. However, the opposite was seen as they saw a greater decline. Nonetheless, one of the sensors in the LTNs had a greater decrease of PM_{10}-levels than the non-LTN sensors in the area. That is Putney, a sensor categorised as *there is GI* (Appendix 1). The other sensor in the borough, Putney High Street, being a busy road without any GI.

When looking at the daily and annual patterns and trends of PM_{10} by all sensors, it was seen that the trends between the different sensors were similar, and that the different levels between sensors in LTNs and non-LTNs were small. What is more, a study on peak values of PM_{10} in London showed that the greatest peaks were situated during late winter or early spring (Kukkonen et al., 2005). Although great peaks can be seen during this period in the annual graphs, they are not distinct. It was further difficult to track any trends in the daily patterns dependent on time and factors such as rush hour, between the years. Indicating that the source of PM_{10} varies throughout the day, without any clear patterns, hence strengthening the fact that the sources are many and varied.

This thesis shows a difficulty in determining the origin of PM_{10} and how it can be removed from the atmosphere. GI may not be effective in removing the PM_{10}-particles (*3.2 Improving the air quality with GI*), it may further even be a source of the emission in the form of BVOC, however the current research is uncertain if BVOC has a negative or positive impact on the air quality (please see *3.1.4 BVOC*). Still, the lower decrease of pollutants in areas with more GI can be due to the GI having removed the particles during a longer time period before the implementation of the LTN. Looking at the numbers of the annual means (Appendix 2), the sensors with more GI in their surroundings had lower values to begin with, however the annual means by the sensors with less GI is not much higher. Continuing, the one sensor where the change in PM_{10}-concentrations as a result of the LTN could not be statistically assured was Arsenal, the sensor with the most pre-existing GI. Thus, this could be an indication of the GI improving the air quality, making the impact from the LTN minimal in regard to PM_{10}.

This suggests that future studies should look at the air quality near areas where GI has been newly implemented, to study the impact more clearly from GI on PM_{10}. What is more, this may also show that the lack of traffic is a more efficient way to reduce the PM_{10}, which was seen in the study by Pitiranggon et al. (2022) studying the impact of the lockdown in New York, where Pitiranggon et al. (2022) concluded a decline in $PM_{2,5}$ (which are part of PM_{10}) as a result of the absence of traffic.

5.2 NO_X

As mentioned, the levels of NO_X decreased by all sensors, which was further analysed statistically. When further looking at the annual trends, it can be seen that the levels went down significantly after the implementation of the LTN, however this can also be seen to happen after the Covid lockdown in some cases. However, according to Chadwick (2020) the impact of Covid is uncertain, hence it is a factor that should be handled with care (Ibid). Furthermore, the annual trends of NO_X were seen to continue even after the implementation, however with lower values, suggesting that the LTN scheme has had an impact. It can further be noticed that the annual trend of NO_X peaks during autumn and winter and goes down during the summer and spring. According to a study on annual NO_X-trends, the increased numbers in the winter can partly be explained by an increased use of fossil fuel from driving and domestic heating (Roberts-Semple et al., 2012).

Regarding the daily trends of NO_X, correlation with the rush hours were seen. What is more, in some graphs, high levels of NO_X during the morning hours followed by a great drop, was seen during the first of April 2021. According to a study by Pancholi et al. (2018) on seasonal and daily behaviours of NO_x and O_3 in western India, the early morning peak can be explained by a combination of emission from vehicles from the night before, a tendency for elevated levels during these hours, and low Planetary Boundary Layer (PBL) leading to a decreased mixing of air pollutants (Ibid). The connections between NO_X and the traffic are further stated in the studies on NO_2 after the lockdowns in New York, and Barcelona and Madrid, where both studies noticed a decline in concentrations after the removal of traffic (Pitiranggon et al., 2022; Baldasano, 2020).

5.3 Urban Planning and GI

Photos of all sensors and their surroundings can be found in Appendix 7. Regarding the type of GI of the areas, it varied between the sensors. Both Covent Garden and the Aldgate School had clearly planned GI in the forms of e.g., planters or flowerbeds. In the case of Covent Garden, Figure 23a, a connection between the GI could not be seen, rather, the GI was inconsistent. The area consisting of different planters, pots with flowers and single trees, and hanging flowerpots. Continuing, a connection in the GI of the Aldgate School, Figure 23b, could be seen, the area being more of a park than Covent Garden. Although the ground was stone-paved, connecting hedges and bushes could be noticed. What is more, the Aldgate School sensor was placed closer to the connecting GI, than the Covent Garden sensor, although the difference is small. Despite these differences, the areas have almost the same reduction in NO_X, around 40 percent (PM_{10} is not applicable hence Covent Garden does not measure that). Although Covent Garden is in an LTN, and the Aldgate School is not, they are both categorised as Urban Background (Imperial College London, 2018). This might thus be an indication of this type of GI being efficient in removing NO_X from the atmosphere.

Figure 23a. The figure shows a pot with flowers and a tree in Covent Garden.

Figure 23b. The figure shows a flowerbed in the park next to The Aldgate School.

Both Islington and Wandsworth, two similar areas, had one sensor in an LTN, and one sensor placed next to a busy road. When compared, it can be noticed that the sensors in Islington had a significantly greater decrease in NO_X-values compared to the sensors in Wandsworth, however the sensors in Putney measured a greater decrease in PM_{10}-values compared to the sensors in Islington. This can be compared to Putney High Street, Wandsworth, seeing a decrease in traffic by 22 percent, whereas Holloway Road, Islington, saw an increase in traffic by 21 percent. Although being similar areas, both sensors in Islington had more GI in their surroundings compared to the sensors in Wandsworth, which might suggest that the GI has had a positive impact on the NO_X-levels. Regarding the PM_{10}-levels, Holloway Road has several large, single trees placed along the road, which has been shown to decrease the PM_{10}-particles (please see 3.2 *Improving Air quality with GI* under background). The difference in traffic between Holloway Road and Putney High Street was 40 percentage points, whereas the difference in PM_{10}-reduction was 2,8 percentage points, which might confirm that the trees have had an impact.

Two areas had two sensors in non-LTNs, Westminster and the City of London. The sensor being placed near a busy street in the City of London, Walbrook Wharf, saw a more significant reduction in NO_X-values than the sensor placed next to a park, the Aldgate School. This is the opposite of what can be said about the sensors in Westminster, where the sensor having more GI in the surroundings, Cavendish Square, had a greater decrease in NO_X-values than the sensor placed next to a busy street without any GI, Oxford Street East. However, the difference between the non-LTN sensors in Westminster is low, ranging between 38 to 42,3 percent, while the sensors in the City of London have a range between 62,2 to 41,6 percent decrease. Furthermore, Cavendish Square was categorised as *quite a lot of GI*. The area consisting of a park with several large and small trees, lawns, and hedges. Whereas the Aldgate School was categorised as *a significant amount of GI*, the GI being neat and organised, with small trees, shrubbery, bushes, and lawns. That is, the Aldgate School sensor was categorised to have more GI, however, Cavendish Square might have GI more suitable to improve the air quality even though it was further from the sensors, hence the trees were significantly larger and the lawns more extensive (please see *3.2 Improving the Air Quality with GI*). On the contrary, the Aldgate School is the only one of these sensors to be categorised as Urban Background, which could further indicate that removing the traffic close to the sensor, is the most efficient way to reduce air pollutants.

These findings suggest that GI can be a way to improve the air quality, in LTNs as well in non-LTNs. Also, as has been mentioned above under *5.1 PM_{10}*, the initially lower concentrations in the areas with GI might be an indication of the effect from the vegetation. However, the PM_{10} are tricky to study, and might originate from other sources, or be removed due to other factors. Nonetheless, the absence of traffic has been shown to improve the air quality significantly in regards to NO_X, suggesting that it is the more effective option when replanning for better air quality.

It should also be mentioned, that although this thesis studies air pollutants, both GI and the presence or non-presence of traffic serves other purposes as well, making the question about their existence broader. In a society where motorised traffic has been diminished, the question about the possibilities of air purification from GI may not be on the agenda. Instead seeing GI for its other possibilities such as recreation and improved well-being, biodiversity, or preventing cities from flooding. What is more, even though GI is a source of PM_{10} it is uncertain if it is harmful, and if it were to be one of few PM-sources, the levels might be on a less crucial level. Suppose we cannot remove the pollutants altogether, the question ends up being about which pollution sources we want. Cars or greenery? London is a large and busy city, with a wide variety of industries and activities, people, and communities. If the implementation of traffic schemes that are transforming boroughs to go from car-centred to people-centred can be successful here, it can be an indication of the possibility of success in other cities elsewhere.

5.5 Limitations, Uncertainties and Future Studies

There are several limitations and sources of uncertainty in this study that should be addressed. The traffic data used comes from different sources and are based on different time spans. This might lead to less accurate numbers, hence the methodology may differ between the sources, which would mean less specific comparisons between the sensors. What is more, it is only the total number of vehicles that have been included, not the type of vehicle. Although an area has a higher number of vehicles, these might be electrical or hybrid ones, run on petrol or diesel, or the flow of the traffic in the street might differ, variables that are not included in the analyses however might change the assessment of the results. It would therefore be suggested, for future studies, to also include the types of vehicles and not only the number, to get a deeper insight of their impact on the air quality.

As mentioned, there are gaps in the data series which vary between the samples. Due to this, the number of samples are not consistent between the sensors, and the amount of data used will further be different among the boroughs. Furthermore, when using data from another source, insight in the methodology is limited. Although the Imperial College London has been deemed a trustworthy source, there might be unknown limitations in the calibration and sampling.

There are several factors not included in this study. Although the two factors regarded as the ones that can improve the air quality, stopping the emissions and vegetation, are studied, several factors that might have an impact on the dispersion and movement of the pollutants are not. These are factors such as wind; weather, although the methodology was constructed to include it by looking at data from several years, it cannot be certain that this was obtained; how the houses are positioned around the sensor etcetera. What is more, as mentioned, the PM_{10}-sources are varied, meaning that it does not only originate from traffic. However, traffic is the only PM_{10}-source that has been studied. Construction sites, particles from other cities and countries, dust, BVOC, etcetera, are not included in the analyses.

Regarding the statistical analysis, it stated that there has been a decline after the implementation in all but one sensor. Nonetheless, the cause of the decline might not be the LTNs, but can be Covid, the type of traffic, weather etcetera. Therefore, it can only be stated that a decrease in NO_X- and PM_{10}-values has happened, however why cannot be certain. It was not feasible within the timeframe of this thesis to take all these factors into account, and it is therefore suggested that future studies look at the details of a statistical analysis. What is more, since the Covid pandemic might have had an impact on the timespan studied, it is suggested to analyse the impact from the LTNs in a wider timespan, when more time has passed. This could lead to a more certain analysis of the scheme. Furthermore, using normalisation instead of or complementing to the t-test, hence the special time of the pandemic, might have given other values more reasonable with normal conditions. It should further be noted that the other methodological choices made may have had an impact on the thesis. For example, looking at other sensors based on different criteria, using another timespan, using another definition and categorisation of GI etcetera.

6. Conclusions

This study has shown that there has been a decline in the measured values of NO_X and PM_{10} after the implementation of the Low-Traffic Neighbourhoods, however this was seen for all areas in the study, including the non-LTNs. Thus, it cannot be established that this is because of the implementation of the LTNs. There are several other parameters which might have had an impact on the measured values, not the least the Covid-19 lockdowns. However, no matter the reason, the considerable reduction in traffic following March 2020, due to the LTNs and/or Covid-19, and the great reduction of NO_X, indicates that the absence of traffic has improved the air quality. Nonetheless, an unknown combination of these factors has led to a reduction in NO_X and PM_{10}, improving the air quality, leading to a better environment for the residents and nature in London, consequently improving the health of all Londoners. As suggested, future studies looking at the subject in more detail, will perhaps determine which factors played which part and to what extent.

The correlation between GI and the values of NO_X and PM_{10} varies between the boroughs, making it difficult to distinguish any pattern. There are several examples where GI could have had an impact, e.g., Holloway Road, suggesting that it has been beneficial. The areas with the most GI had the lowest decline, however they also had the lowest values to begin with, which might indicate that the GI has helped clean the air before the implementation. However, all these findings might be because of other, unstudied, factors. Though, the presence of GI does not seem to make the air quality worse. Suggesting that future urban planning should focus on removing the cars and incorporating GI, if not to improve the air, GI has several other benefits such as recreation.

Hence the rather short time interval where the Covid-pandemic has had an unknown influence, this study is perhaps a way to look at the effect from the implementation of the LTNs in the short run, whereas the effects in the long run should be studied as well. Given the scheme more time to settle, as well as the society to form post the pandemic, the effect from the LTN can further be studied. As has been mentioned, future studies are also suggested to study areas where the GI has been newly implemented, to study the impact in more detail. Lastly, studies with other methodologies are also suggested since those choices might have had an impact on the result.

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Appendix

Appendix 1: Field study results

The classifications used originate from the London Air-website (Imperial College London, 2018). The definitions are: Kerbside - the inlet of the sample is within 1 metre from the kerb of a busy road and the sampling height is in 2 to 3 metres of the ground; Roadside - the inlet of the sample is between 1 to 5 metres from the kerb and the sampling height is within 2 to 3 metres of the ground; Urban Background - these sensors are far away from great sources and are often typical examples of the city-wide background concentrations found in e.g. residential areas (Imperial College London, 2018). The categories used to determine the traffic are Car free, Traffic exists, and Busy Road. To determine the GI, the categories used are A significant amount of GI, Quite a lot of GI, There is GI, and No GI. Pictures from the sensors can be found in Appendix 7.

Table A1.1 The table consists of detailed information about the surroundings of the sensors, in regard to GI and traffic, as well as additional information about the sample heights and distance to road.

Borough	Sensor	Description	Categories and keywords
the City of London Beech Street/Barbican area implemented 18th of March 2020 (City of London, 2022)	Beech Street	The sensor is placed next to a tunnel where pedestrians, cyclists and motorised vehicles can enter through. Although the area is an LTN, the traffic is significant. There is no GI in the surrounding area. The distance to the road is 1 metre and the sampling height is unknown. It is classified as Roadside (Imperial College London, 2018).	Busy Road in an LTN Roadside No GI
	The Aldgate School	The sensor is placed on a school yard, which is further positioned next to a park. It is surrounded by shrubbery, however I could not see how deep they were. Furthermore, there are small bushes and herbaceous vegetation going along the school yard fence. The park consists of stone paved floors and lawns, as well as shrubbery. There are 10 trees in the park that look fully grown, however still fairly small.	Car Free Urban Background A significant amount of GI (park) Bushes Shrubbery Small sized trees Lawns Herbaceous plants Planned greenery (neat and organised)

		The distance to the road is 40 metres and the sampling height is unknown. It is classified as Urban background (Imperial College London, 2018). The linear distance to Beech Street is 1,5 km.	
	Upper Thames Street	The sensor is placed under a viaduct next to a busy road without any GI. It is classified as Roadside (Imperial College London, 2018). The linear distance to the Aldgate school is 820 metres and 1,3 km to Beech Street.	Busy road Roadside No GI
	Walbrook Wharf	The sensor is placed next to a busy road without any GI. The distance to the road is 4 metres, the sampling height is 2 metres, and it is classified as Roadside (Imperial College London, 2018). The linear distance to Beech Street is 1,13 km.	Busy road Roadside No GI
Islington Completed by 11th of January 2021 (Islington, n.d.)	Arsenal	The sensor is placed at the entrance of a natural reserve (Gillespie Park), which thus indicates a lot of GI surrounding it. I could not see behind the sensor due to a fence, but it looked like there was vegetation in the form bushes. Overall, the area was signified by a lot of shrubbery and several trees of varied kinds however all of them being leafy trees. The nearest road, which is part of an LTN area, is 15 metres from the sensor (Imperial College London, 2018). Other than that, the traffic seems to be limited except for the vehicles going to and from the ecology centre. The sampling height is 2,5 metres. It is classified as Urban Background (Imperial College London, 2018).	Car free/No traffic Urban Background A significant amount of GI (natural reserve) Varied vegetation Forest-like No lawns Extensive areas of vegetation
	Holloway Road	The sensor is placed next to a bus station on a busy road. However, there are several trees and bushes along the road.	Busy Road Roadside Quite a lot of GI

		The trees come in lines crossing the road and are placed approximately 10 metres apart. The trees were fully grown with extensive crowns. The shrubbery was about 1,3*1,3 m^2 high and deep, and went along the road. Behind the bushes there were lawns going up to the surrounding houses. Linear distance to Arsenal is 700 m. The distance to the road is 3 metres, the sampling height is 3 metres, and it is classified as Roadside (Imperial College London, 2018).	Shrubbery Single large trees Lawns Planned greenery (neat and organised)
Wandsworth 30th of August 2020 (Wandsworth- The brighter borough, 2021)	Putney	The sensor is placed in front of a garden. There is a hedge, approximately 1-1,3 metres high, directly behind the sensor, which is then followed by a lawn, ~7 metres wide. There are also 3 larger trees and 2 smaller ones in the garden. The sensor is placed one block from Putney High Street, by the entrance of the LTN. The distance to the road is unknown and the sampling height is 2,75 metres. It is classified as Urban Background (Imperial College London, 2018)	Low traffic in an LTN Urban Background There is GI Planned greenery Lawns Hedge Single trees
	Putney High Street	The sensor is placed next to a busy road with no GI. The distance to the road is 0.5 metres and the sampling height is 1 metre (Imperial College London, 2018). The linear distance to Putney is 140 m. It is classified as Kerbside (Imperial College London, 2018).	Busy road Kerbside No GI
Westminster LTNs implemented between March and September 2020 (Aldred et al., 2021).	Covent Garden	The sensor is placed on a square with stone paved floors. The square has several restaurants with outdoor seating, some of them being lined with planters. These outdoor seatings are approximately 5*10 m^2 respectively, 7*4 m^2. There are small trees, ivy and tulips in planters, placed around the square. The trees are placed roughly 3 metres apart, and there are 15 of	Car free Urban Background There is GI Planned greenery Planters with varied vegetation Flowers Herbaceous vegetation

		them. Between the trees there are hanging flowerpots with ivy. There are 6 modal filters, all of them being planters of various sizes and mixed vegetation. One of the modal filters has a small tree in the planter. The distance to the road is 50 metres and the sampling height is 2 metres. It is classified as Urban Background (Imperial College London, 2018)	Several small trees
	Cavendish Square	The sensor is placed on a street island between two, somewhat, busy roads, under a big tree. Next to the sensor, on the other side of the road, there is a park, about 100 metres in diameter. The park is aligned with hedges. The greater part of the park is covered by lawns, except for paved walkways. There are 10 very big trees, as well as 6 smaller ones. The linear distance to Covent Garden is 1,75 km. The distance to the road is 5 metres, the sampling height is 1,7 metres, and it is classified as Roadside (Imperial College London, 2018).	Busy road Roadside Quite a lot of GI (park on the other side of the road) Hedges Lawns Several very large trees Several small trees
	Oxford Street East	The sensor is placed on a busy street without any GI. The linear distance to Covent Garden is 1 km. The distance to the road is 1,2 metres, the sampling height is 1,7 metres, and it is classified as Roadside (Imperial College London, 2018).	Busy road Roadside No GI

Appendix 2: Annual means

Table A2.1 The table consists of the annual means of NO_X and PM_{10} by the different sensors. The date format is year/month/day. Note that the sensors in Westminster do not measure PM_{10}.

Area	Sensor	NO_X [µg/m^3 as NO_2]			PM_{10} change [µg/m^3]		
the City of London		2018/03/18 - 2019/03/17	2019/03/18-2020/03/17	2020/03/18-2021/03/17	2018/03/18-2019/03/17	2019/03/18-2020/03/17	2020/03/18-2021/03/17
	Beech Street	169,14	125,79	30,94	25,19	20,60	17,56
	The Aldgate School	51,87	43,21	27,77	21,35	17,74	16,20
	Walbrook Wharf	224,77	169,78	73,81			
	Upper Thames Street				30,92	26,41	23,54

Area	Sensor	NO_X				PM_{10}			
Islington		1018/01/11-2019/01/10	2019/01/11 - 2020/01/10	2020/01/11-2021/01/10	2021/01/11-2022/01/10	2018/01/11-2019/01/10	2019/01/11 - 2020/01/10	2020/01/11-2021/01/10	2021/01/11-2022/01/10
	Arsenal	39,12	37,24	26,18	25,96	19,57	19,15	17,31	18,10
	Holloway Road	111,61	88,57	54,80	49,55	20,46	20,12	18,29	18,29

Area	Sensor	NO_X			PM_{10}		
Wandsworth		2018/08/30 - 2019/08/29	2019/08/30-2020/08/29	2020/08/30 - 2021/08/29	2018/08/30-2019/08/29	2019/08/30 - 2020/08/29	2020/08/30-2021/08/29
	Putney	53,72	43,49	40,90	18,14	16,81	15,33
	Putney High Street	173,37	144,60	145,08	23,35	19,24	19,25

Area	Sensor	NO_X		
Westminster		2018/09/01-2019/08/31	2019/09/01-2018/08/31	2020/09/01-2021/08/31
	Covent Garden	60,16	39,54	29,03
	Cavendish Square	112,46	72,21	53,31
	Oxford Street East	124,87	73,28	61,45

Appendix 3: Graphs 2018-2022

The Appendix consists of the graphs of the annual patterns of PM_{10} and NO_X by the different sensors presented under 4.3 Annual Patterns. All y-axes have the unit of [µg/m^3] and all x-axes show every other month from January 2018 to March 2022.

City of London

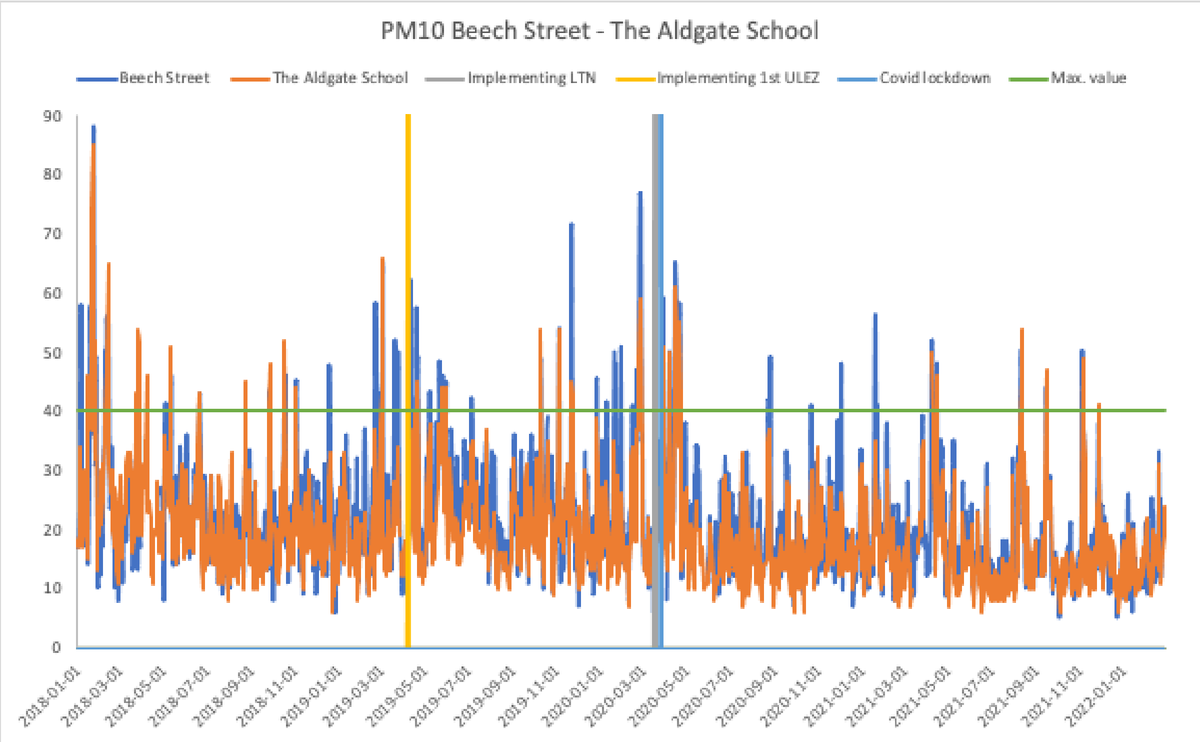

Figure A3.1. The graph shows the PM_{10}-values for Beech Street and the Aldgate School.

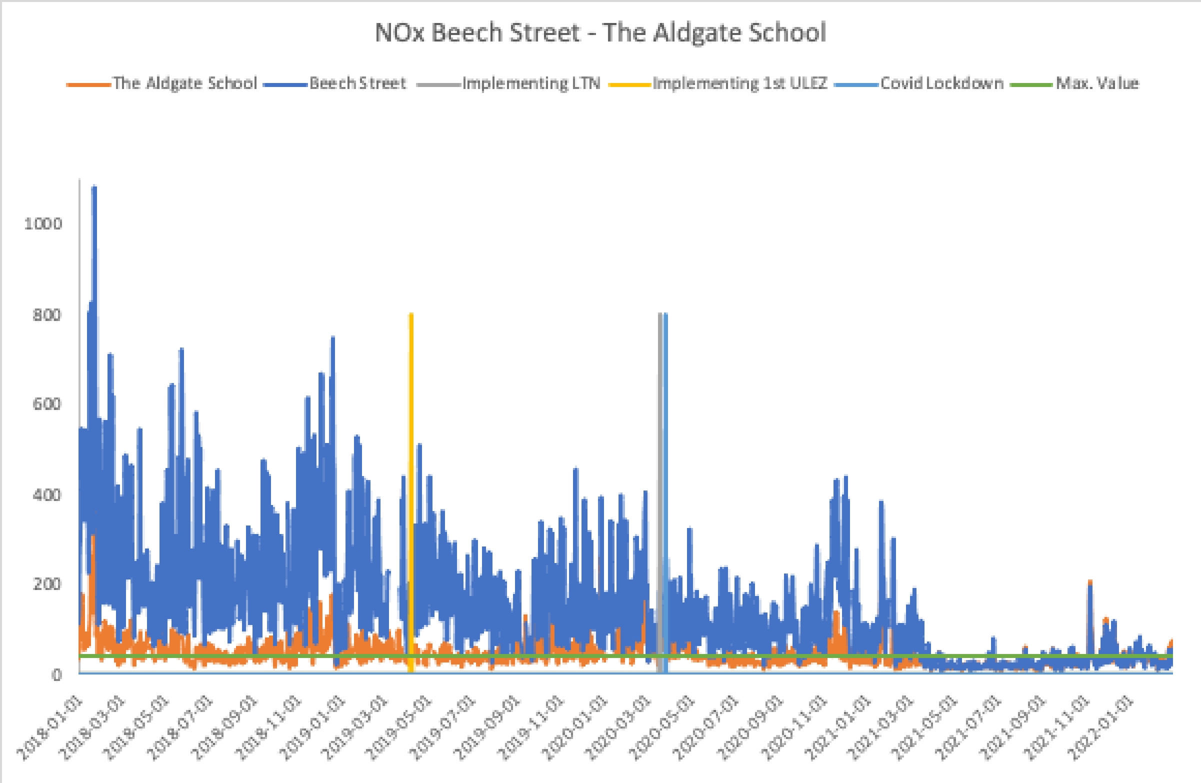

Figure A3.2. The graph shows the NO_X-values for Beech Street and the Aldgate School.

Islington

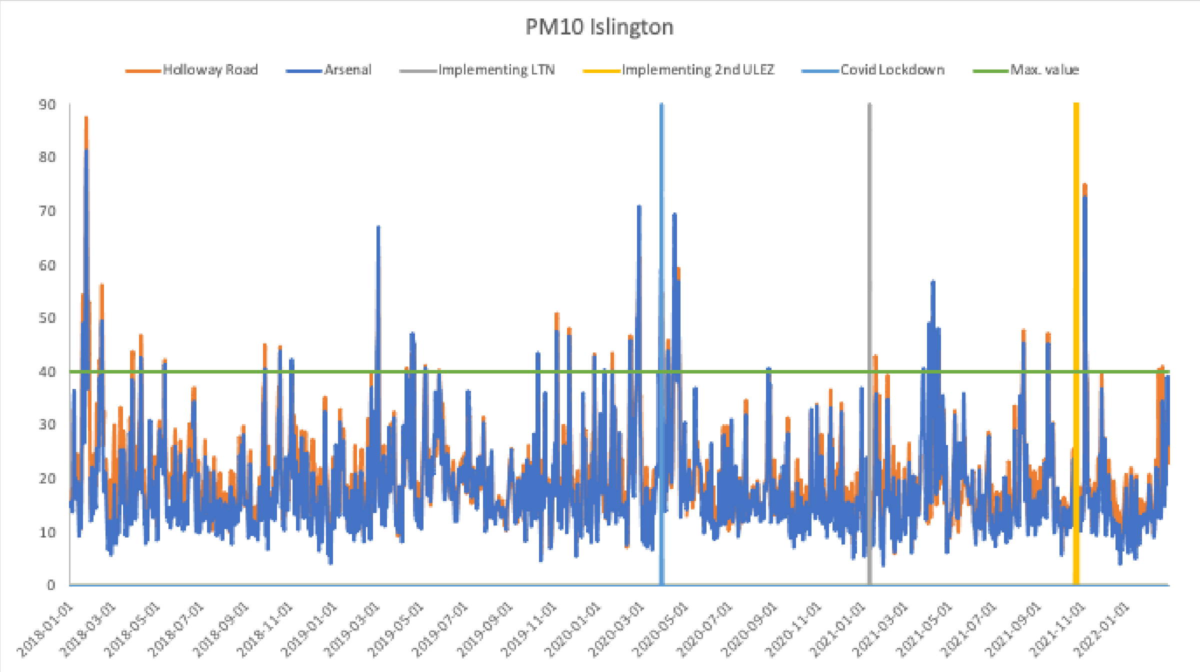

Figure A3.3. The graph shows the PM_{10}-values for Arsenal and Holloway Road, the sensors in Islington.

Wandsworth

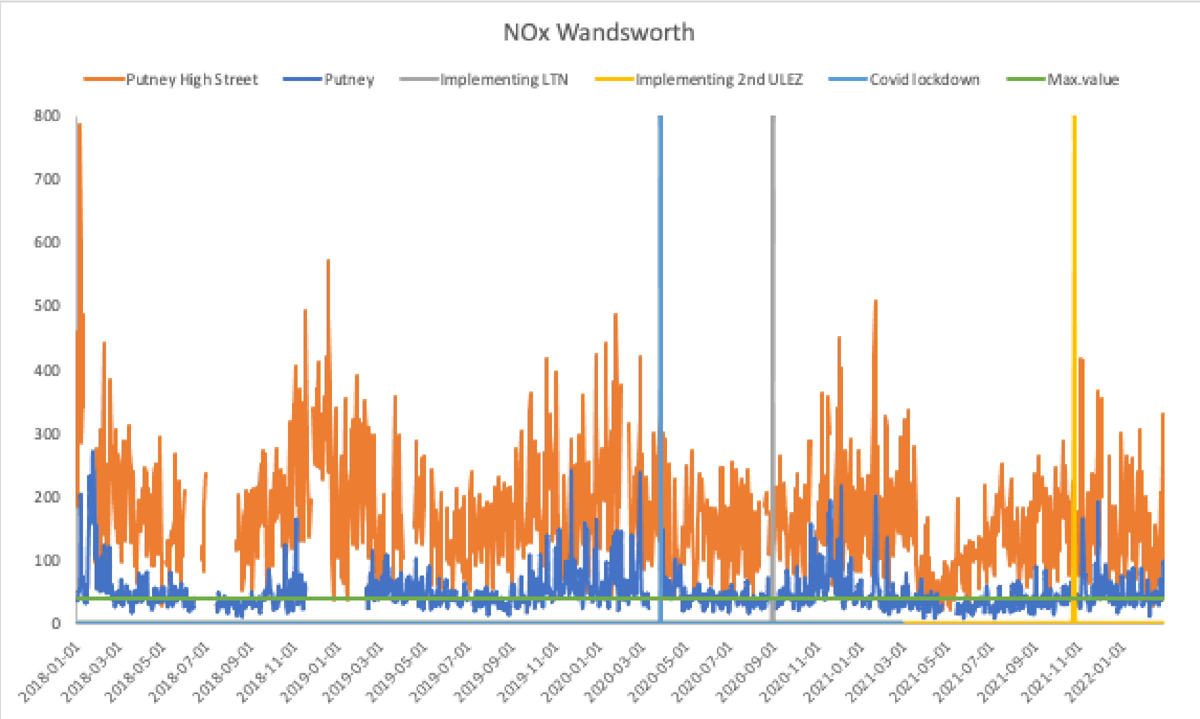

Figure A3.4. The graph shows the NO_X-values for Putney and Putney High Street, the sensors in Wandsworth.

Westminster

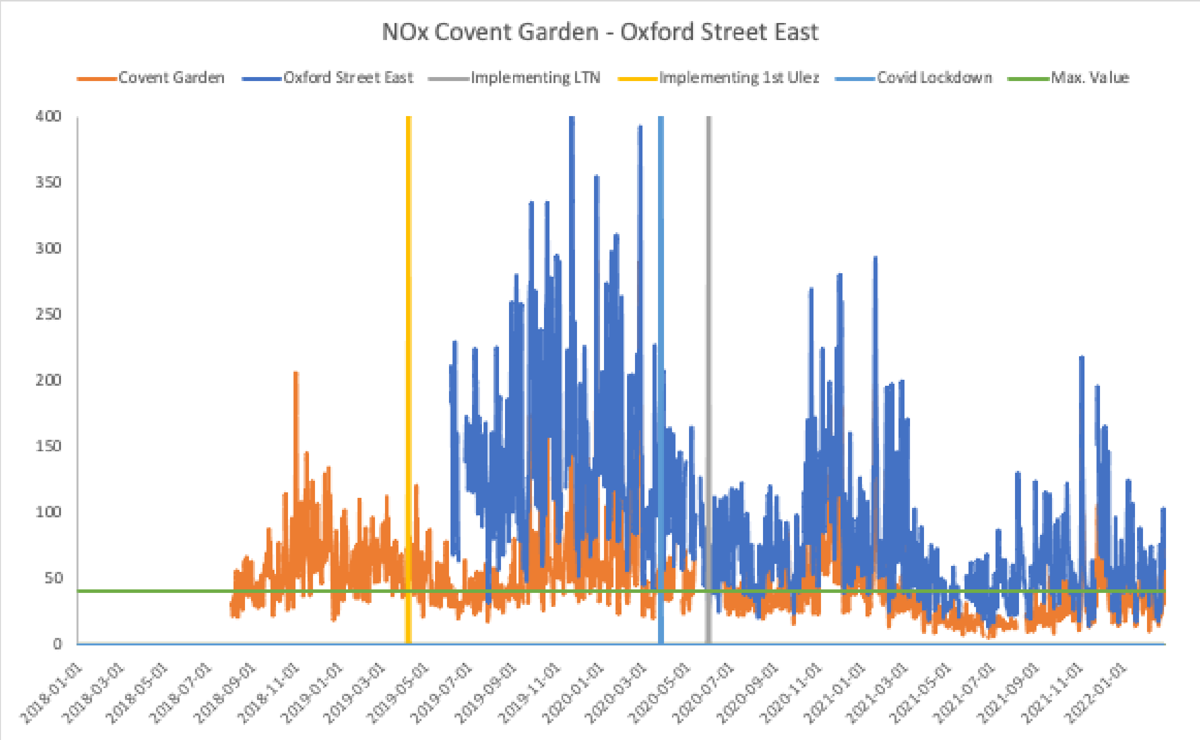

Figure A3.5. The graph shows the NO_X-values of Covent Garden and Oxford Street East.

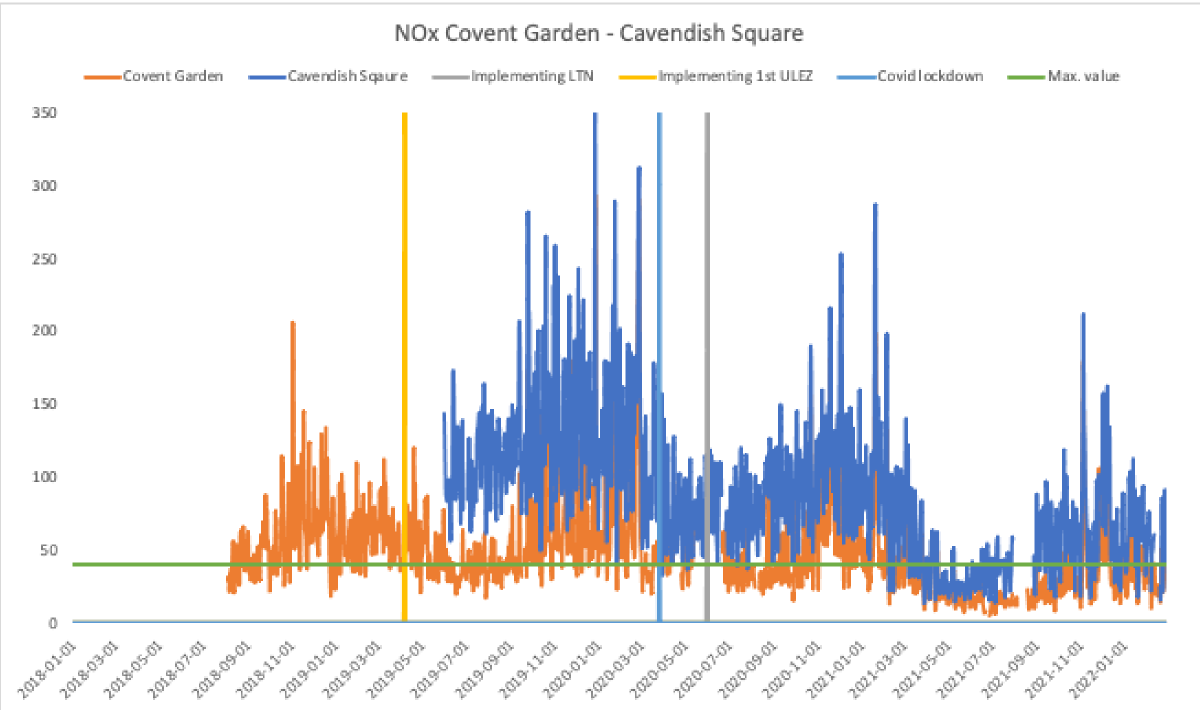

Figure A3.6 The graph shows the NO_X-values of Covent Garden and Cavendish Square.

Appendix 4: Graphs of daily patterns

The Appendix consists of the graphs of the daily patterns not presented under 4.4 Daily Patterns. All y-axes have the unit of [µg/m^3] and all x-axes show every 30-minutes during the 24-hour period.

City of London - Beech Street

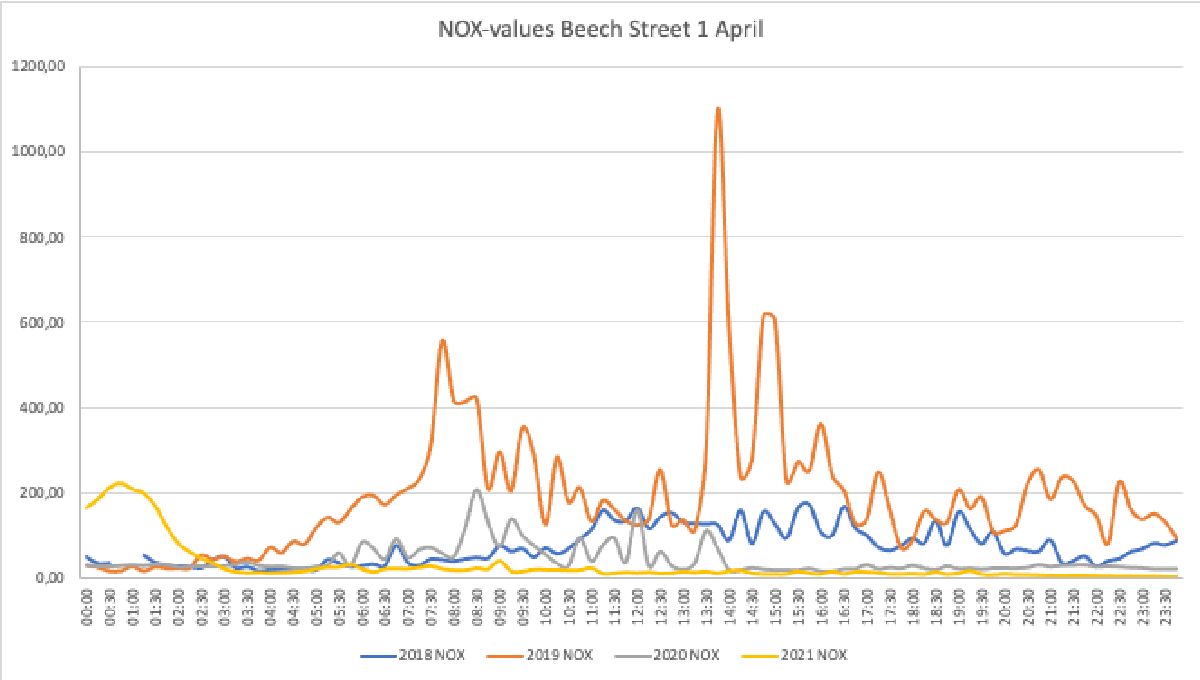

Figure A4.1. The figure shows the graph of the NO_X-values by Beech Street on the first of April 2018-2021

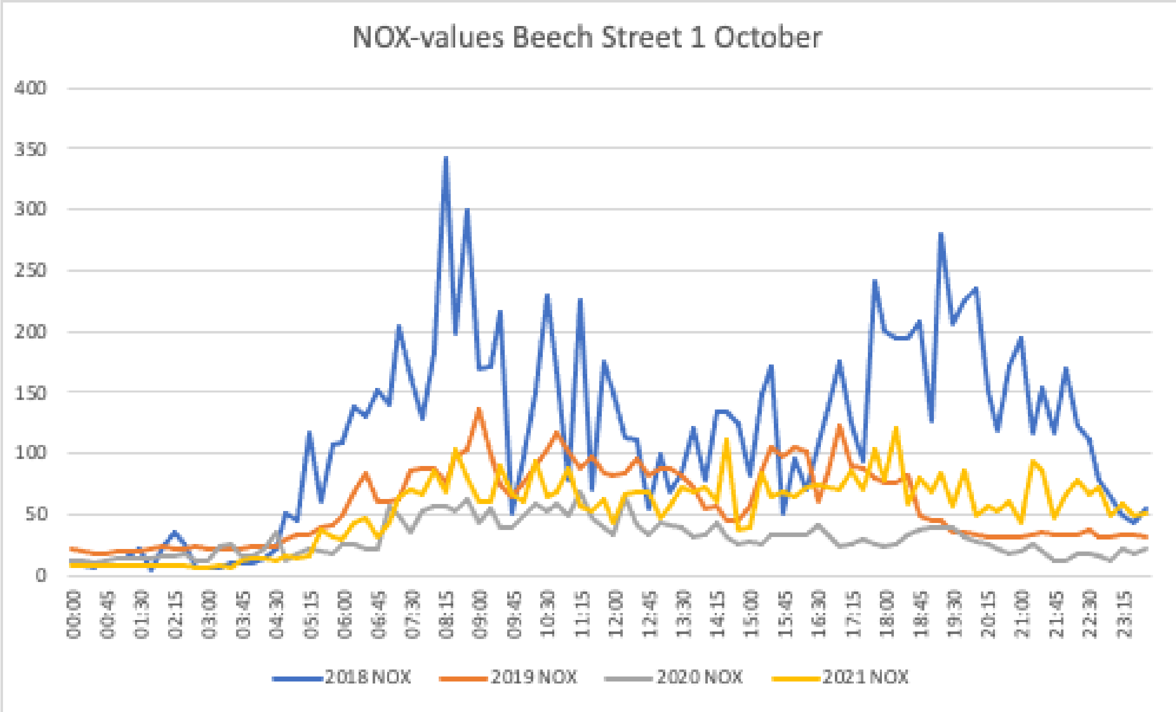

Figure A4.2. The figure shows the NO_X-values by Beech Street on the first of October 2018-2021

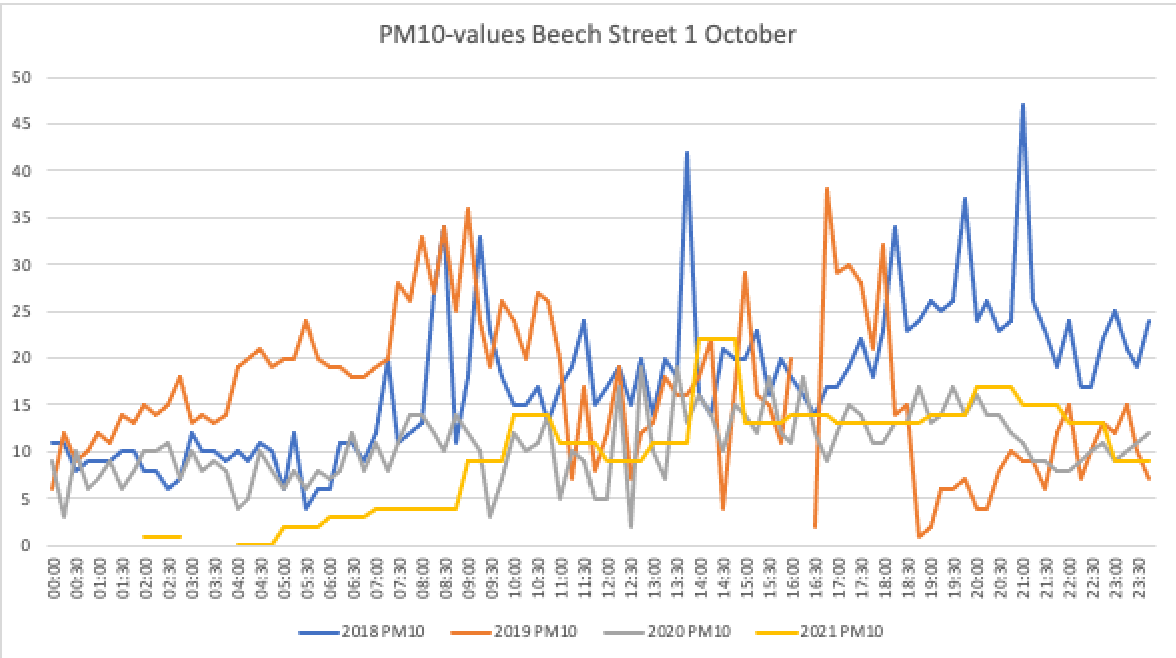

Figure A4.3. The graph shows the PM_{10}-values by Beech Street on the first of October 2018-2021

Islington - Arsenal

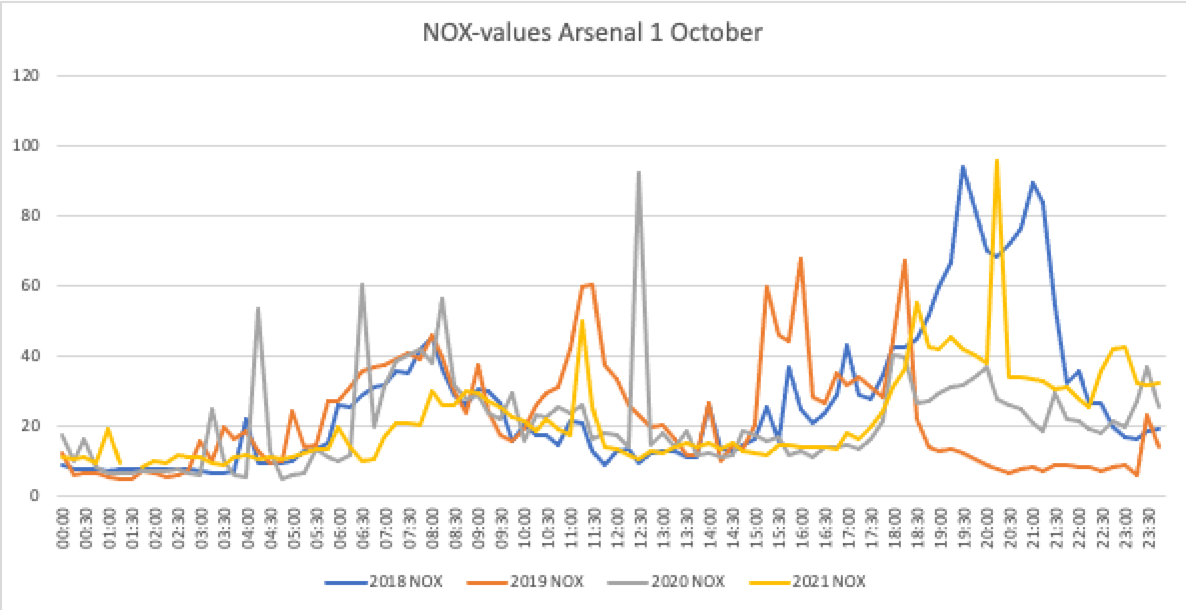

Figure A4.4. The figure shows the NO_X-values by Arsenal on the first of October 2018-2021

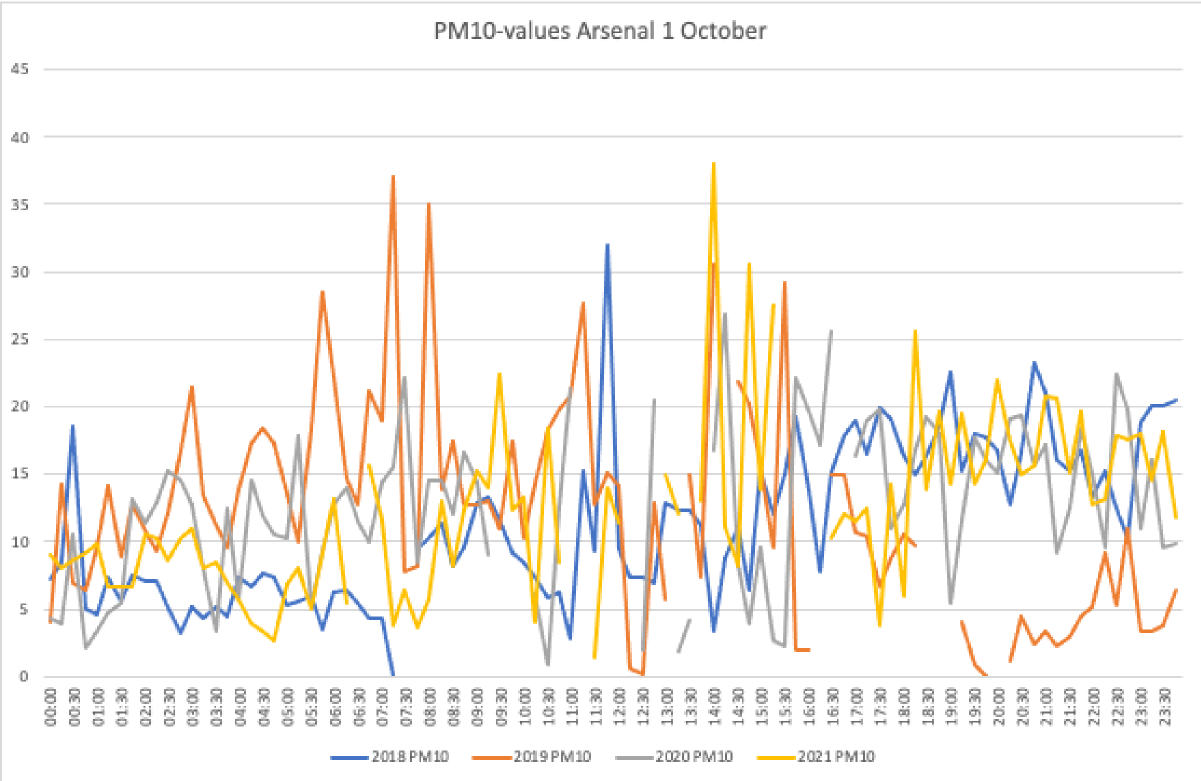

Figure A4.5. The graph shows the PM10-values by Arsenal on the first of October 2018-2021

Wandsworth - Putney

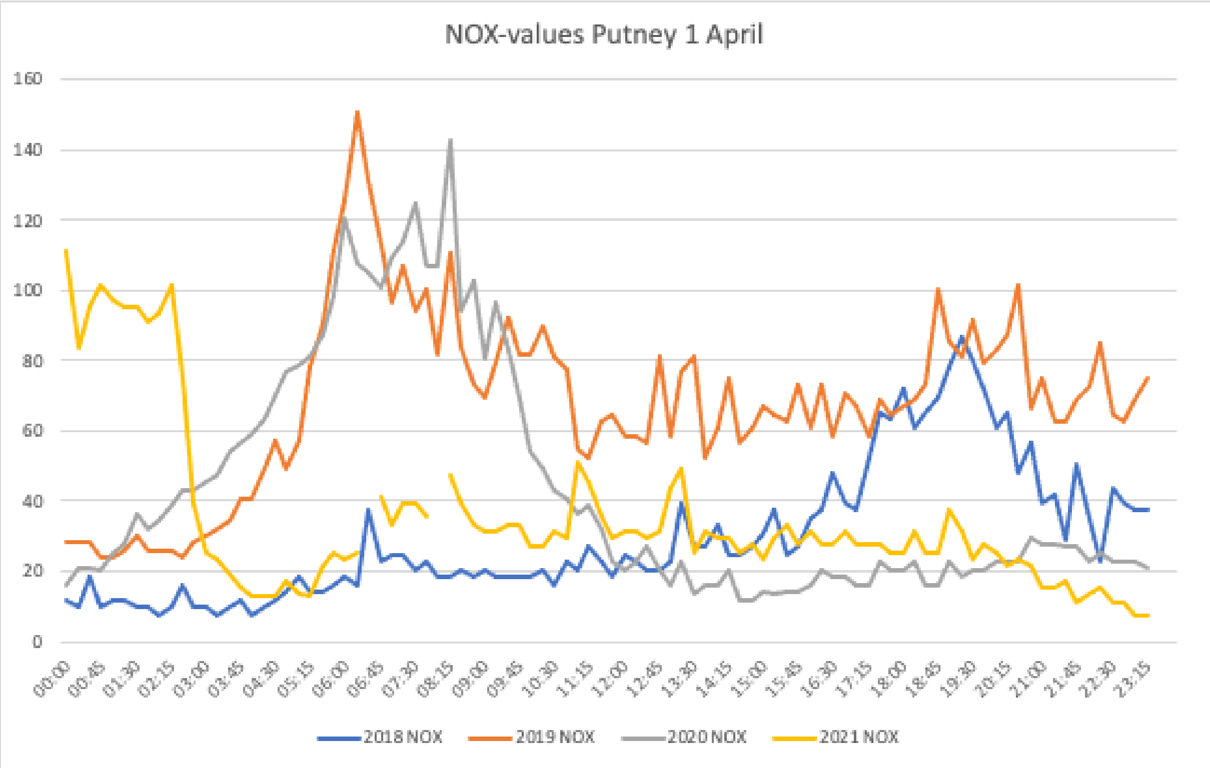

Figure A4.6. The graph shows the NO_X-values by Putney on the first of April 2018-2021

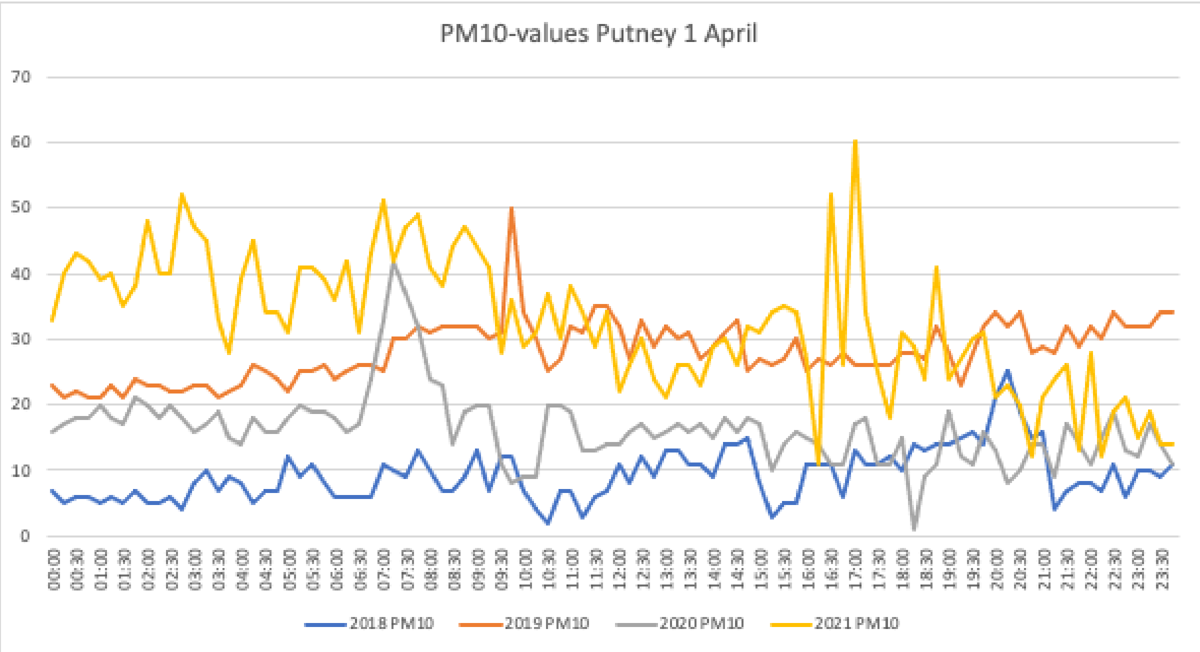

Figure A4.7 The graph shows the PM_{10}-values by Putney on the first of April 2018-2021

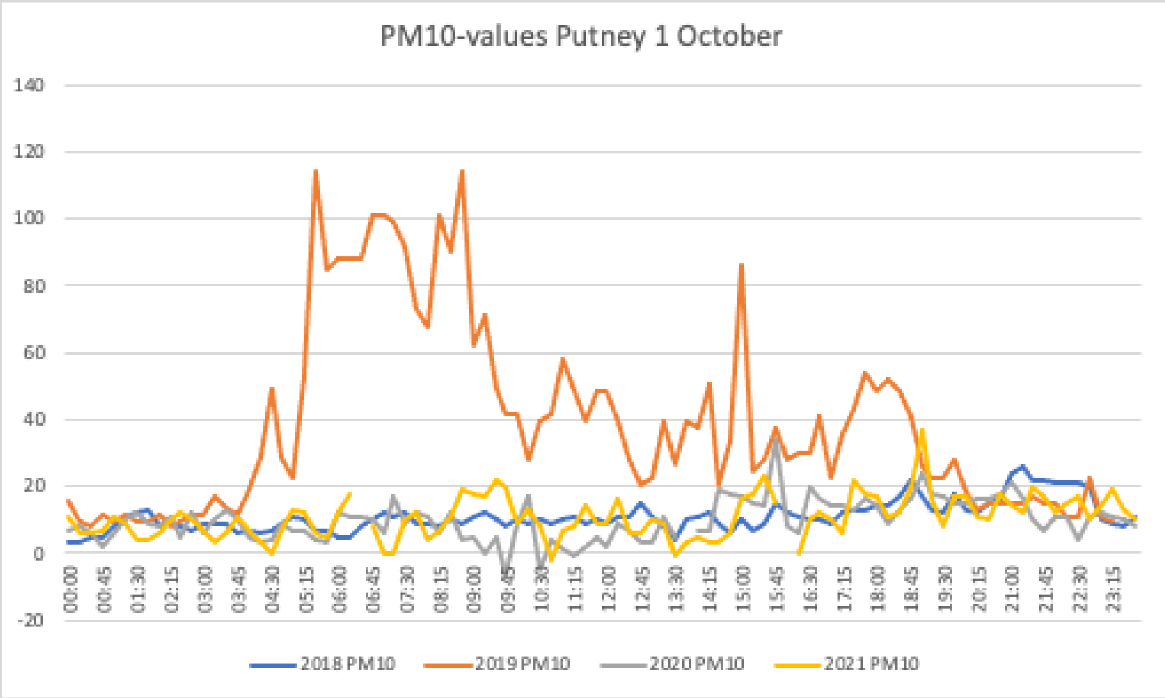

Figure A4.8. The graph shows the PM_{10}-values by Putney on the first of October 2018-2021

Westminster - Covent garden

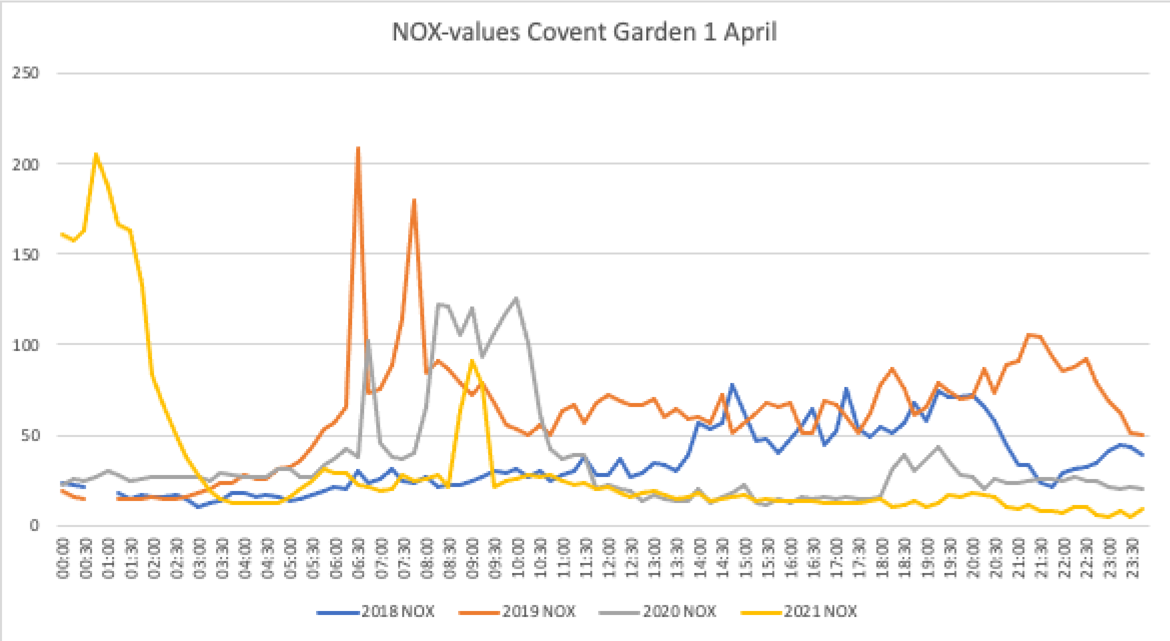

Figure A4.9. The graph shows the NO_X-values by Covent Garden on the first of April 2018-2021

Appendix 5: Figures of the LTNs

the City of London - Beech Street

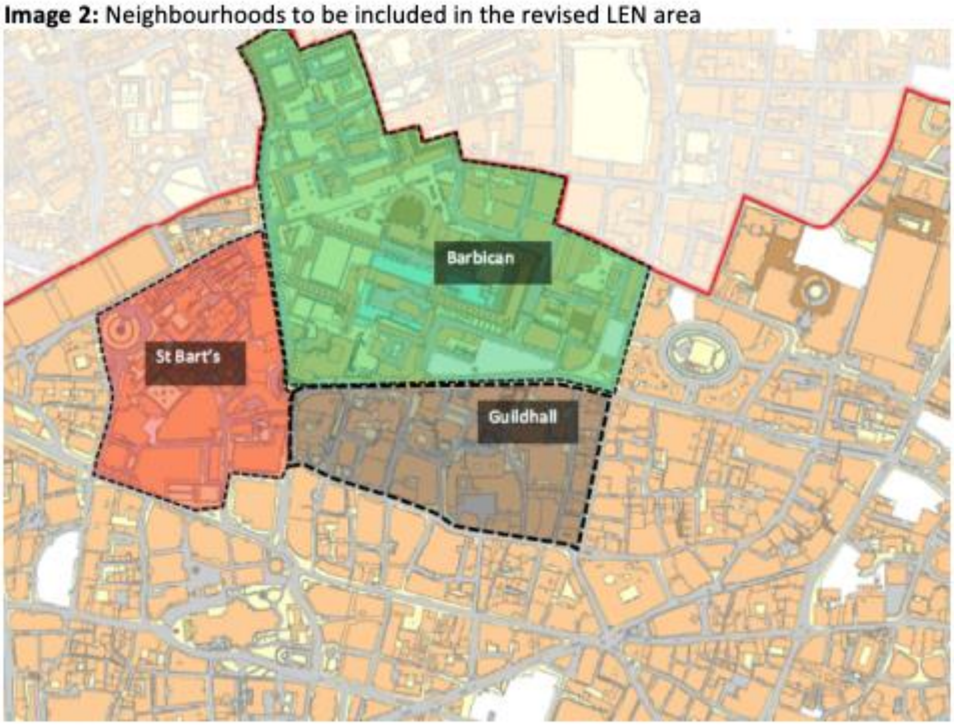

Figure A6.1. Detailed map of the LTN called Beech Street Zero Emission scheme, in the City of London. Image source (City of London, n.d.).

Islington - Arsenal

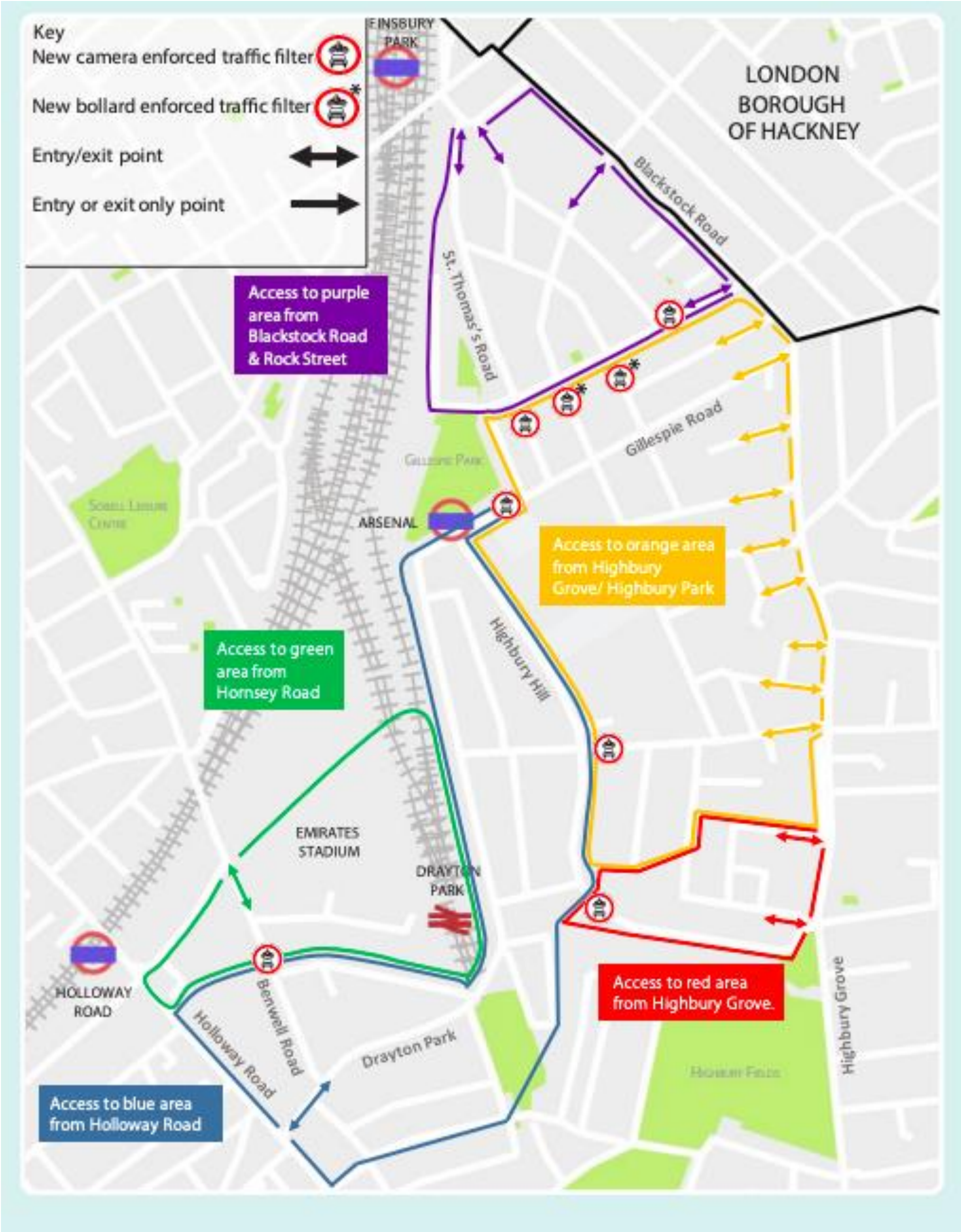

Figure A6.2. Detailed map of the LTN called Highbury West, in Islington. Image source (Champion, n.d.).

Appendix 6: Examples of modal filters

Figure A7.1. The figure shows an example of modal filters by the entrance to the area Highbury west in Islington. Picture taken by Greta Gustafsson.

Figure A7.2. The figure shows modal filters by the entrance to the area Highbury West in Islington. Picture taken by Greta Gustafsson.

Figure A7.3. The figure shows an example of modal filters in Wandsworth, however not by the entrance to the LTN of the study. Picture is taken by Greta Gustafsson.

Figure A7.4. The figure shows an example of the modal filters by the entrance to the LTN in Wandsworth that is part of this study. Picture taken by Greta Gustafsson.

Figure A7.4. The figure shows an example of modal filters in Hackney (not a borough that is part of the study). Picture taken by Greta Gustafsson.

Figure A7.5. The figure shows an example of modal filters in Soho, a part of Westminster not included in the study. Picture taken by Greta Gustafsson.

Appendix 7: A selection of pictures of the sensors and the surrounding area

Figure A7.1. The figure shows the Beech Street Sensor, the black box in the middle of the picture, in City of London. Picture taken by Greta Gustafsson.

Figure A7.2. The figure shows the entrance to the tunnel where the Beech Street sensor is placed. Picture taken by Greta Gustafsson

Figure A7.3. The figure shows the surrounding park of the Aldgate School sensor in City of London. The sensor is to the left, behind the fence. The picture is taken by Greta Gustafsson.

Figure A7.6. The figure shows the surroundings of the Arsenal Sensor. The sensor is the green large box in the middle of the picture. Picture taken by Greta Gustafsson.

Figure A7.4. The figure shows the park opposite the Aldgate School sensor in City of London. Picture taken by Greta Gustafsson.

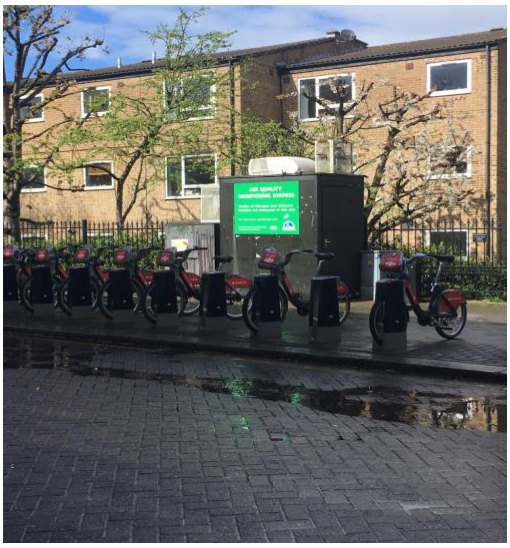

Figure A7.7. The figure shows the Putney sensor in Wandsworth. The sensor is the big, black box with a green sign on it. Picture taken by Greta Gustafsson.

Figure A7.8. The figure shows the Cavendish Square sensor in Westminster. The sensors is the black box under the tree. Picture taken by Greta Gustafsson.

TRITA-ABE-MBT 22605