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The effects of stringent Low Emission Zones in The Netherlands on levels of $PM_{2.5}$

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Contents

1 Introduction on particulate matter in The Netherlands

Particulate matter that is emitted by human sources arises from processes that often have a positive economic contribution for nations like increased road transport or industrial facilities (Malina and Scheffler, 2015). However, high concentrations of particulate matter can have negative effects on air quality and public health. Particulate matter is an indicator of air pollution that is brought into the air by natural and human activities (Kim et al., 2015). These particulates can travel over long distances and can stay in the air for a long time. The size of the particles differs and smaller particles have a higher potential for causing health problems. There are fine particles that are smaller than 2.5(μm) in diameter and small particles with a diameter of 2.5 to 10 (μm) that can be inhaled by humans. The aerodynamic diameter is an important criterium to describe a particles transport abilities through the atmosphere and the inhaling ability through a respiratory organism (Kim et al., 2015). The relationship between sources of particulate matter and human health effects that arise from this particulate matter are not easily detected (Kim et al., 2015). That is because of the long travel potential of the particulates. This also means that decreasing the concentration of particulate matter is a matter that transverses borders of regions and nations. Therefore, there are international standards for maximum amounts of particulate matter that are tolerated. The European Union has subjected memberstates to particulate matter standards.

Inhaling large concentrations of particulate matter, nitrogen dioxide and ozon can lead to inflammations in the lungs. This could lead to a decrease of the lung capacity, allergic reactions and other negative effects for the lungs, especially for people who have for example asthma or COPD (chronic obstructive pulmonary disease) (Gezondheidsraad, 2018). Therefore, Decreasing the amount of particulate matter in the air might have several advantages for the health of citizens in The Netherlands and even outside of The Netherlands. Particles can differ in their risks for health effects (Kim et al., 2015). The most harmful effects of particulate matter might be related to the size of the particles. This is because a smaller size might increase their ability to penetrate the lower airways and therefore their ability to impose harmful health effects. Furthermore even low exposures to particulates might have significant effects on health (Kim et al., 2015).

In The Netherlands almost half of all particulate matter arises from natural sources. The other half is emitted by human acitivities (Infomil, n.d.-a) [1]. Large contributors to particulate matter emitted by human activities are water and road transport, industry and agriculture. There are several policies that would reduce particulate matter from these sources. Low emission zones (LEZs) could for example lower emissions in areas that are heavily polluted by particulate matter (Malina and Scheffler, 2015). These LEZs are often located in urban areas and their succes is determined by how many types of vehicles are forbidden to enter the LEZ (Gehrsitz, 2017). In more stringent zones in which more vehicles are restricted to enter the amount of particulate matter is more often decreased significantly. Another policy to reduce particulate matter levels would be to reduce precursor emissions that lead to the formation of particulate matter in the atmosphere. An important precursor of particulate matter is ammonia, that is often emitted by agricultural companies (Erisman and Schaap, 2004). Furthermore a Diesel Particulate Filter (DPF) helps to reduce emissions from diesel motors. There are many more policies to reduce concentrations of particulate matter. In different types of areas different kinds of policies or technical improvements might be needed to decrease air pollution. In this report we will focus on LEZs in The Netherlands and determine whether they have a positive effect on air quality and if there are possible improvements for these LEZs. The goal of this report is therefore answering the following question:

Does the existence of (stringent) Low Emission Zones in The Netherlands that restrict access for high particulate matter emitting cars and vans decrease the (local) concentrations of particulate matter more than less stringent Low Emission Zones?

To answer the research question of this report first a literature review on particulate matter will be done in Section 2. This literature review will encompass important definitions on particulate matter and describe causes of high concentrations of particulate matter in The Netherlands. Furthermore

[1] Infomil is a central point of information for legislations in The Netherlands, and is funded by Rijkswaterstaat

policies to reduce PM levels will be discussed, and the possibilities of different types of Low Emission Zones will be discussed. Then in Figure 10 a conceptual overview of the model will be given. In Section 3 the data sources of this report will be discussed and visualized. The measurement data on particulate matter comes from an experimental data platform created by the Dutch National Institute for Public Health and the Environment. Then in Section 6 the statistical techniques to investigate the effects of a (more stringent) low emission zone will be discussed.

2 Literature Review

2.1 Technical summary of definitions on particulate matter

Particulate matter encompasses all particles in the air that are small enough to be inhaled by humans. These particals could be made from different materials. Particulate matter can be at most 10 micrometers (μm) in diameter (Infomil, n.d.-b). The two most important measures for particulate matter are PM_{10} (particulate matter with a maximum diameter of 10 μm), and $PM_{2.5}$ (a maximum diameter of 2.5 μm). $PM_{2.5}$ has more harmfull health effects than PM_{10} (Infomil, n.d.-b). Particulate matter can be composed of different materials that float through the air (Infomil, n.d.-a). These materials include soot particles, drifting sand, vehicle emissions, sea salt, plant materials, cement particles and (small) pieces of roads or tires. Particulate matter can also arise from reactions from different gasses in the air. Particulate matter is composed of primary and secundary particles (Infomil, n.d.-a).

Primary particulate matter arises because of frictions. These frictions come from rubbing materials in industrial processes, or winds that rub particles accross the side of buildings or rocks. Primary pariculate matter also arises from the burning of fossil fuels like coal, oil or gas. Primary particulate matter directly enters the air as small particles.

Secundary particulate matter arises when molecules of acidifying substances bind to salts. These substances can also get attached to primary particulate matter. Therefore, to reduce secondary particulate matter emissions it is necessary to lower precursor emissions (Erisman and Schaap, 2004). Ammonia is an important precursor emission for $PM_{2.5}$ (Erisman and Schaap, 2004).

2.2 (Inter)national standards on particulate matter

In order to regulate the spread of particulate matter, the European Union has determined to subject member states to standards for the maximum amount of particulate matter that is tolerated. The measurement of particulate matter is based on uncertainty, since measurements of particulate matter are always measurements of certain points at certain times. This means the measurements should be made by certain standards that are determined by the European Union.These standards determine that the uncertainty of measurements, including the uncertainty due to random sampling, meets the quality objective of 25% and the minimum time coverage of the measurements is 90%(European Parliament and Council of the European Union, 2008). This means that 10% of the captured data can be thrown out of the measurements in order to decrease the average measurement. For particulate matter, the 2008 directive defines two different measurement criteria for PM_{10} and $PM_{2.5}$. The Dutch Wet Milieubeheer has implemented the European guidelines corresponding to the spread of particulate matter. For PM_{10} the guideline specifies the maximum measurement to be 40 microgram per m^3 as yearly average and 50 microgram per m^3 als an 24-hour average concentration, that is allowed to be higher than 50 microgram per m^3 for a maximum of 35 days a year. For $PM_{2.5}$ the yearly average concentration should not exceed 20 microgram per m^3 ("Wet Milieubeheer", 2023). An average yearly concentration of $PM_{2.5}$ or PM_{10} is determined by the average 24 hour concentrations for one year, measured at local temperature and outdoor pressure. This means that high levels of particulate matter during certain times of the day might not be captured because low levels during other times of the day compensate the high levels ("Wet Milieubeheer", 2023). Furthermore, it is not specified how many measurement stations and at what locations these stations should be build.

2.3 Summary of emissions of particulate matter in The Netherlands

More than half of all the particulate matter in The Netherlands comes from natural sources like sea salt and soil dust (Infomil, n.d.-a). The other half is emitted by human activities. The largest source of human particulate matter is road and water transportation (about 40%), mainly because of the use of diesel motors. Industrial facilities have a comparable amount of emission of particulate matter. Furthermore agriculture emits 23% of this human made particulate matter (Infomil, n.d.-a). However locally agriculture can contribute to large amounts of particulate matter. These agricultural clusters are mainly in the east of Noord-Braband and in the north of Limburg (Infomil, n.d.-a). Agriculture emits large amounts of atmospheric ammonia (NH_3), which acts as a precursor to $PM_{2.5}$ (Wyer et al., 2022). Ammonia could potentially contribute to 50% of European $PM_{2.5}$ air pollution (Wyer et al., 2022). In Figure 1 the distribution of particulate matter that is emitted by human activities is visualised (Infomil, n.d.-a).

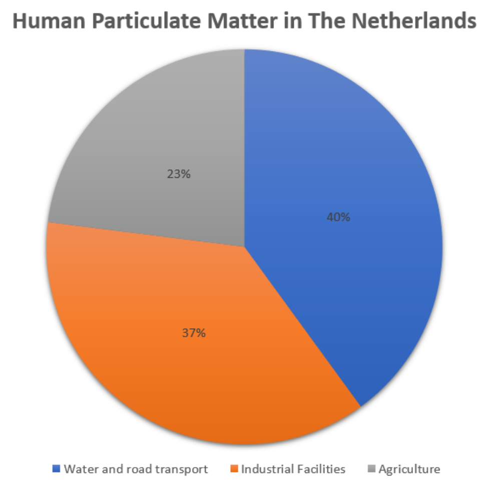

Figure 1: Emitters of particulate matter by human activities in The Netherlands (Infomil, n.d.-a).

2.3.1 Particulate matter from road and water transportation

Diesel particulate matter that is emitted by ship engines is a mixture of different materials with sizes spanning from a few nanometres to several microns (Di Natale and Carotenuto, 2015). Furthermore the emissions from diesel fuelled ships are comparable to heavy duty truck engines, but not to cars thanks to more restrictive environmental rules. The contribution of shipping to the overall particulate matter emissions is about 1-2% of global emissions (Di Natale and Carotenuto, 2015). However, these emissions are often concentrated in cities located by large ports and important water transport routes and therefore harmfull. This stresses the need for specific regulations to control emission of particulate matter from ships, similar to the automotive sector (Di Natale and Carotenuto, 2015). Furthermore, more measures to decrease PM levels in these areas like Low Emission Zones might increase air quality. Physical removal of diesel particulate matter before emission has been investigated from the 1980s (Mohankumar and Senthilkumar, 2017). Currently a diesel particulate filter (DPF) is used to decrease the amount of particulates that are emitted. There are multiple types of diesel particulate filters. Their main difference is the way in which the filter is cleaned, or regenerated, after it has filtered particulates. When the filter is not properly cleaned, this may cause the fuel consumption to increase (Mohankumar and Senthilkumar, 2017).
In Figure 2a and Figure 2b on the next page the influence of road transportation on the yearly average measurement of $PM_{2.5}$ in The Netherlands is visualised. These figures give us an indication that the road network influences the occurrence of particulates.

2.4 Policies to reduce concentrations of particulate matter from transportation

In order to decrease particulate matter emissions from vehicles, more stringent vehicle emission standards could be enforced by policy makers (Vijayaraghavan et al., 2012). As discussed in Section 2.3.1,

(a) Spread of (yearly average) particulate matter in The Netherlands in 2022

(b) Spread of $PM_{2.5}$ with the top 250 highway network of The Netherlands.

Figure 2: The influence of the road network on particulate matter, data retrieved from Atlas Leefomgeving (ALO), n.d.

Diesel Particulate Filters can be applied to reduce emissions from diesel fuelled vehicles (Mohankumar and Senthilkumar, 2017). Furthermore reducing the number of vehicles in cities could potentially decrease the amount of particulates, as these vehicles are emitters of PM. There are several policies to decrease the number of vehicles on the road. Depending on local infrastructure more public transport options or increasing the amount of safe alternative transport modes might help reducing the amount of vehicles. Alternatively cities could introduce Low Emission Zones to reduce high concentrations of particulate matter that are emitted by vehicles that emit large amounts of PM (Malina and Scheffler, 2015). The introduction of LEZs will be further discussed in Section 2.5.

Battery electric vehicle (EV) adoptation is promoted by the Dutch government by several financial stimulation policies (Ministerie van Infrastructuur en Waterstaat, 2020). However, the effectiveness on PM concentrations of policies that increase adaptation of EVs could be limited if the substitutional relationship between diesel fuelled vehicles (DV) and EVs is weak and EV purchases are mostly made by gasoline vehicle owners (Choi and Koo, 2021). This limits the effects of EV adaptation on particulate matter since diesel fuelled vehicles in general emit more particulates than gasoline vehicles (Infomil, n.d.-a).

2.5 Low emission zones to reduce particulate matter

In the European Union a common policy for reducing particulate matter concentrations is the introduction of Low Emission Zones (Malina and Scheffler, 2015). In Germany, the introduction of LEZs has decreased the concentration of PM_{10} in these areas. Furthermore, more stringent zones reduce PM_{10} concentrations more than three times as much as less stringent zones. More types of cars are left out in a more stringent zone than in a less stringent zone. Despite lowering the concentrations of particulate matter, the LEZs also have downsides. They are associated with substantial costs related to enforcement and replacement costs (Gehrsitz, 2017). High replacement costs might indicate lower income citizens might not be able to comply with LEZs. An LEZ that only bans the dirtiest vehicles is only associated with a decrease in PM_{10} of 1.5 to 2.5 percent while more restrictive zones can decrease PM_{10} levels by 3 to 4 percent (Gehrsitz, 2017). These effects need to take in account that control cities that do not introduce LEZs often introduce other policies to decrease concentrations of particulate matter. Therefore the percentages should be interpreted as relative effects of LEZs. Furthermore there is no indication that drivers circumventing LEZs increase pollution levels in surrounding areas (Gehrsitz, 2017).

The results of the Low Emission Zones in Germany are promising and it would be interesting to investigate the Low Emission Zones in The Netherlands. At the moment there are 4 cities in The Netherlands that have an LEZ for cars and vans ("Milieuzones in Nederland", n.d.). Furthermore there are 15 Dutch municipalities that have an LEZ for diesel fuelled heavy duty trucks. Some municipalities also restrict access for busses, taxi's, and mopeds. There are different restrictions for these LEZs, depending on different types of vehicles. The restrictions depend on the emission class that a vehicle is assigned. Some Dutch LEZs have been investigated in 2012 (Boogaard et al., 2012). The investigated LEZs only targeted old heavy duty trucks, which are a small fraction of the Dutch car park. This paper did not find any indication LEZs in The Netherlands that restrict old heavy duty vehicles (trucks) to enter would reduce air pollutants, among which particulate matter. Although $PM_{2.5}$ levels did decrease in some LEZs, there was no clear indication that this was a consequence of the LEZs. However, in one street not only an LEZ for old heavy duty trucks, but also traffic intensity was reduced, which did improve air quality in that street significantly (Boogaard et al., 2012). This is a promising result that might give an indication that more stringent LEZs could still positively influence air quality and reduce PM levels in The Netherlands.

2.6 Hypothesis

In this report we want to investigate whether the introduction of a stringent LEZ in Amsterdam significantly lowered levels of $PM_{2.5}$ compared to the less stringent LEZ that was enforced before. Based on earlier research described in Section 2.5 we formulate the following hypothesis:

A stringent LEZ in Amsterdam lowers levels of $PM_{2.5}$ significantly more than a less stringent LEZ

In order to test this hypothesis, we need to have measurements on levels of $PM_{2.5}$ in The Netherlands. In Section 3 the measurements that are used by this report will be described. Then, in Section 4 policy implications of the stringent LEZ compared to the less stringent LEZ will be discussed and measurement stations from Section 3 will be used to visualise some of the (stringent) LEZs.

3 Data

The data to investigate the development of particulate matter in this report comes from measurements on particulate matter from around 7700 measurement stations in The Netherlands (Samen Meten - Dataportaal, n.d.) [2]. The LEZ of Amsterdam will be investigated in this report. However measurements from neighbouring areas of the LEZ and other cities in The Netherlands will also be investigated and therefore we will look into measurements of an example city in The Netherlands to get a visualisation of the data. As an example city we will look into the data of Rotterdam. In Rotterdam the data portal receives measurements from 562 measurement stations for $PM_{2.5}$. In Figure 3 on the following page an overview of the measurements from the last couple of years of these stations is given for Rotterdam. It might be necessary to investigate the measurement data for outliers, as can be seen in Figure 3 on the next page because some measurements report unlikely high concentrations of $PM_{2.5}$. In Figure 4 on the following page an overview of the average spread of particulate matter for the entire city of Rotterdam is given. Figure 4 on the next page also shows that some measurement stations have large outliers. This report uses the following method to extract measurement stations that have large outliers from the data set entirely: if the average measurement of a station is larger than 12.14 $\mu g/m^3$(the maximum average measurement of particulate matter from Figure 6 on page 9), then we expect the measurement to be wrong and we therefore reject this measurement station. 12.14 $\mu g/m^3$ is the maximum yearly average measurement of $PM_{2.5}$ in The Netherlands in 2022 and all measurement stations that have an average yearly measurement that is larger than 12.14 $\mu g/m^3$ will be excluded and are called "outlier stations". In Figure 5 on page 9 the average amount of particulate matter in Rotterdam without these "outlier stations" is given. Now, we have filtered the measurement data in order to get more insightful data. We can investigate our objective LEZ in Amsterdam in the next Section with the help of this data.

[2]Samen Meten is an experimental data portal in which the Dutch National Institute for Public Health and the Environment (RIVM) collects measurements from a wide range of different contributers. Because of the experimental nature of the data portal, all measurements from the data portal are indicative.

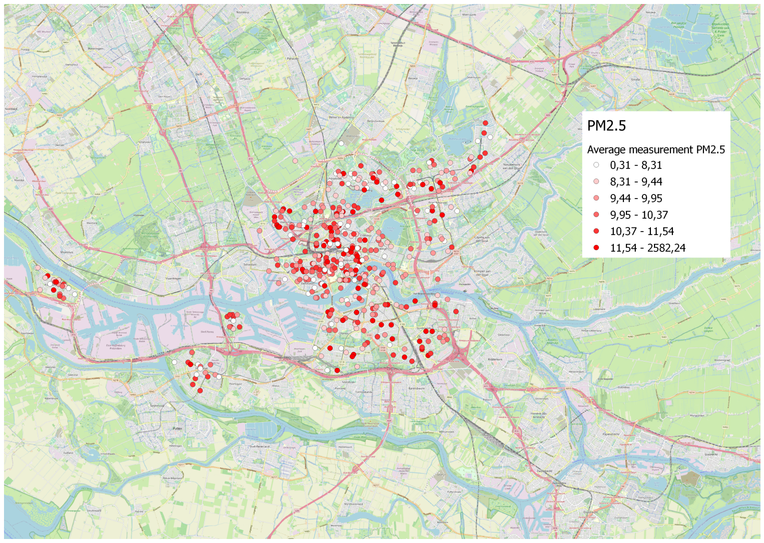

Figure 3: Spread of (yearly average) particulate matter in Rotterdam from 1 Januari 2021 up until 27 April 2023, data to construct this image was retrieved from the data portal Samen Meten (Samen Meten - Dataportaal, n.d.).

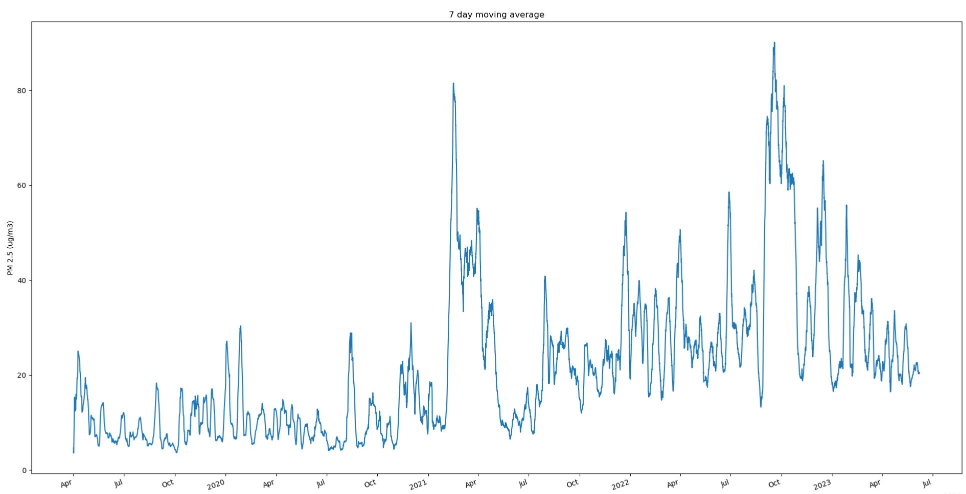

Figure 4: 7 Day moving average of the spread of particulate matter in Rotterdam from april 2019 up until june 2023 that averages the measurement data of $PM_{2.5}$ from all measurement stations in Rotterdam, data to construct this image was retrieved from the data portal Samen Meten (Samen Meten - Dataportaal, n.d.).

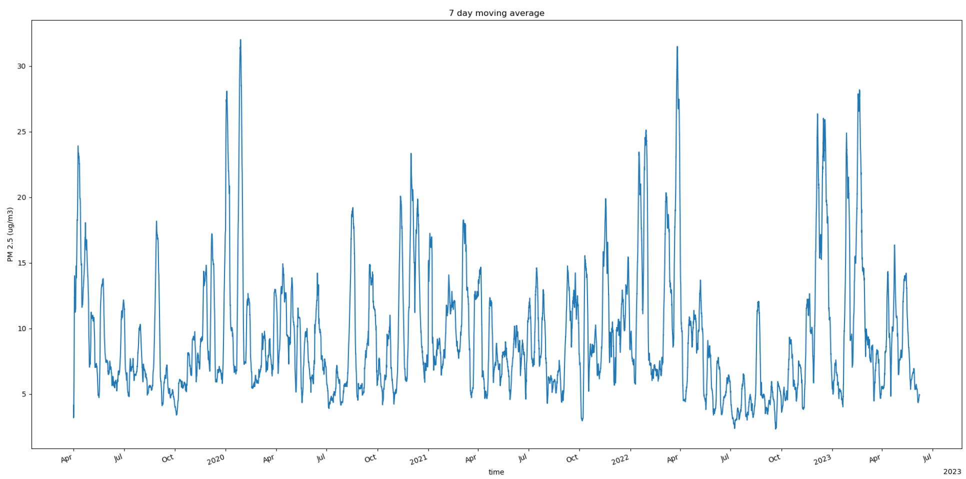

Figure 5: 7 Day moving average of the spread of particulate matter in Rotterdam from april 2019 up until june 2023 that averages the measurement data of $PM_{2.5}$ from all measurement stations in Rotterdam that do not have an average measurement of particulate matter higher than 12.14 $\mu g/m^3$, data to construct this image was retrieved from data portal Samen Meten (Samen Meten - Dataportaal, n.d.)

Figure 6: Spread of (yearly average) particulate matter in The Netherlands in 2022 in $\mu g/m^3$ (Atlas Leefomgeving (ALO), n.d.)

4 Stringent Low Emission Zones in The Netherlands

This report attempts to investigate whether a stringent LEZ that bans both old heavy duty trucks and personal cars and vans fuelled by diesel is more effective in reducing PM levels than less stringent LEZs in which old personal cars and vans are not excluded. There are four stringent LEZs in The Netherlands, and this report will focus on one of these LEZs (in Amsterdam). First the LEZs of Arnhem, Utrecht and The Hague will be discussed. Then we will look into the LEZ of Amsterdam which will be investigated further. The LEZs of Arnhem and Utrecht will not be investigated further due to insufficient data. Furthermore the LEZ of Amsterdam will be investigated instead of the LEZ of The Hague because of the high number of measurement stations in and around Amsterdam.

4.1 Low Emission Zone - Arnhem, Utrecht and The Hague

From 2014 onwards the municipality of Arnhem has subjected the inner city to a LEZ for heavy duty trucks (“Gemeente Arnhem - Milieuzone wijzigen in verband met landelijke harmonisatie”, 2020). From January 2019 onwards the LEZ also included diesel fuelled private cars that were older than 2005. From 29 oktober 2020 onwards the LEZ included private and business diesel cars and heavy duty trucks with an emission class lower than 4 [3]. For foreign vehicles the emission class is determined by their age and should not be older than 2005 (Rijksoverheid, 2023). To compensate owners of old diesel fuelled company cars that either live in the LEZ or have their company in the LEZ, the municipality gives 1.000 euros if they demolish their vehicle. There are several exemptions for the LEZ. Diesel fuelled oldtimers (more than 40 years old) receive a nationwide exemption for LEZs. Furthermore old diesel fuelled campers of citizens of the LEZ get an exemption for the LEZ in which they live. Also vehicles that are wheelchair accessible, or vehicles that are made for disabled people can receive an exemption. Lastly any diesel fuelled car can receive an exemption for the LEZ from the municipality (“Gemeente Arnhem - Milieuzone wijzigen in verband met landelijke harmonisatie”, 2020) for 12 times a year. In Arnhem only three measurement stations are within the LEZ. This means the results for Arnhem in this report might not have significant value and therefore the LEZ of Arnhem is not investigated further in this report.

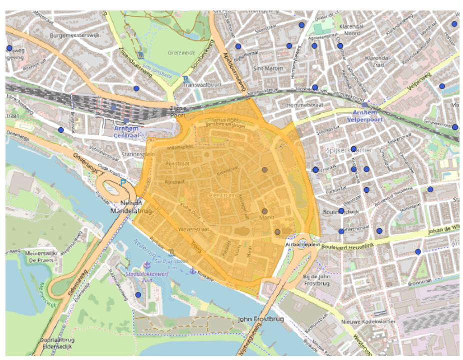

Figure 7: LEZ in Arnhem in orange with the measurement stations in blue (Samen Meten - Dataportaal, n.d.), (Gemeente Arnhem, 2023)

In the city center of Utrecht there is an LEZ for cars, vans, heavy duty trucks and busses (Gemeente Utrecht, 2023). The LEZ of Utrecht has been in place from 2015 onwards for cars and vens, and has therefore been a stringent LEZ for a long time (Zuithof, 2017). Since the measurement stations of Samen Meten do not have much data on this time period, the effects of the LEZ of Utrecht will not be investigated further in this report.

From July 1 2021 diesel fuelled cars and vans with an emission class lower than 3 are no longer admitted in the city center of The Hague (Gemeente Den Haag, 2021). There are again excemptions for the LEZ, largely comparable to the exemptions of the LEZs in Arnhem (oldtimers, vehicles for disabled people, diesel fuelled campers of citizens). Furthermore diesel fuelled cars can ask the municipality for an exemption for the LEZ for 6 days a year.

[3]Emission classes determine how clean a vehicles emissions are, a higher emission class indicates less harmfull emissions

4.2 Low Emission Zone - Amsterdam

From Oktober 9 2008 Amsterdam has a Low Emission Zone that rejects heavy duty trucks with an emission class lower than 4 (Het Parool, 2010) inside the city center. In the following years the municipality of Amsterdam has also included diesel fuelled taxi's, vans and old mopeds. A significant change in the LEZ was made in 2020. From November 2020 onwards the municipality of Amsterdam has a Low Emission Zone for diesel fuelled passenger cars (Gemeente Amsterdam, 2023a). Only diesel fuelled passenger cars and diesel fuelled vans with an emission class higher than 4 can enter the LEZ (comparable to the LEZ in Arnhem). Furthermore there are some exemptions in the LEZ of Amsterdam for oldtimers, vehicles that transport disabled people and campers of citizens of the LEZ (comparable to the exemptions mentioned in Section 4.1). The effectiveness of the (stringent) LEZ in Amsterdam on PM levels will be examined for the time period before introduction of LEZ and the time period after introduction. This way this report wants to investigate if the PM levels have decreased due to the more strict entrance rules of the LEZ. In a couple of years, in Amsterdam only emission free vehicles can enter the city (Gemeente Amsterdam, 2023a).
Since most stringent LEZs in The Netherlands are comparable in terms of regulations and enforcement and most measurement data is available for the LEZ in Amsterdam, this LEZ will be investigated further. First a conceptual model will be given in the next Section.

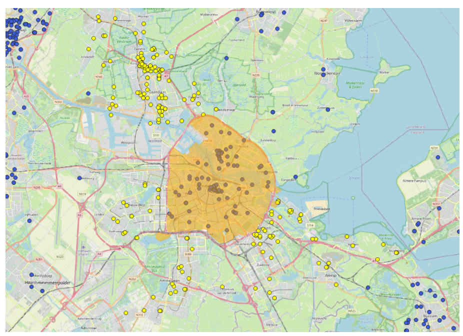

Figure 8: LEZ in Amsterdam in orange with the measurement stations in blue and the neighbouring measurement stations in yellow (Samen Meten - Dataportaal, n.d.), (Gemeente Amsterdam, 2023b)

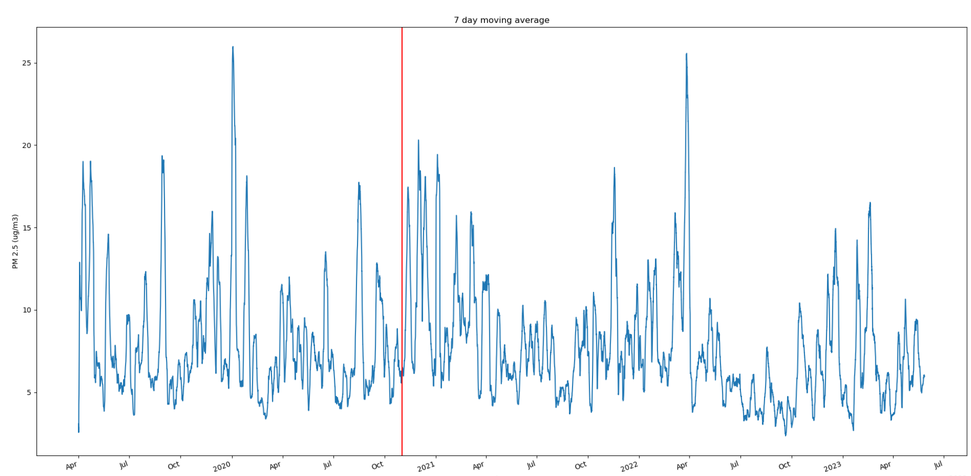

Figure 9: Average measurement of $PM_{2.5}$ depicted as a 7 day moving average inside the LEZ of Amsterdam with the red line specifying when the stringent LEZ was enforced

5 Conceptual model

In Figure 10 on the following page a conceptual model to determine the effect of stringent LEZs in The Netherlands is given. LEZs are expected to decrease levels of $PM_{2.5}$ and PM_{10} and this is the effect that we want to measure with our model. The effect of an LEZ is expected to depend on the type of LEZ that is implemented. That means that an LEZ that allows less types of vehicles inside the LEZ might have a larger negative effect on PM levels, as is expected by Section 2.5 on page 6. Furthermore, the change in PM levels might be influenced by other factors. Firstly, a change in population density can influence PM levels as an increase in population density is associated to higher levels of PM. A 1 percent increase in population density was estimated to increase both PM_{10} and $PM_{2.5}$ by 0.08 percent (Borck and Schrauth, 2021). On the other hand a lower density might have an opposite effect and result in less particulates. Secondly, other policies that lower (or upper) PM levels in an area could influence measurements of $PM_{2.5}$ and PM_{10} (Gehrsitz, 2017). Thirdly a change in oil prices might influence the concentration of particulate matter, since a higher oil price might result in less driving vehicles in the city (in the long run). In general in the short run fuel demand is considered relatively inelastic. On the other hand, in the long run fuel prices are expected to influence fuel demand significantly (Sterner, 2007). Therefore oil prices might influence PM levels in the long run.

The change in PM levels in the stringent Low Emission Zone will be modeled with the use of neighbouring areas and other cities that have no Low Emission Zone. The levels of PM of the neighbouring areas and other cities will be used to model levels of PM in the stringent LEZ before and after the stringent LEZ is introduced. However, a neighbouring city might take alternative measures against high PM levels, which might affect the prediction of PM levels in the cities with a stringent LEZ. These alternative measures might include decreasing the amount of traffic which results in a decrease in PM levels (Boogaard et al., 2012).

The use of neighbouring measurements from Figure 8 on the preceding page to determine the effect of stringent LEZs is important in this report since PM levels can be influenced by many other factors or policies (as described in Figure 10). Neighbouring cities or areas could therefore decrease the influence of other effects in the analysis of the change in PM levels resulting from LEZs, as these cities would ideally face similar conditions as the objective city apart from the stringent LEZ in the objective city. Furthermore, spacial correlation between neighbouring cities for $PM_{2.5}$ levels can be expected from research on PM levels of neighbouring areas in China (Wu and Guo, 2021). Therefore we expect the neighbouring measurements points in Amsterdam to correlate with the PM levels inside the LEZ. The neighbouring measurement points are shown in Figure 8 on the previous page. Furthermore oil prices should be similar for all neighbouring cities and cities of interest. The effect of oil prices is expected to be different in the long run and in the short run, and would therefore be difficult to model directly (Sterner, 2007). The neighbouring cities are selected based on the LEZ measures that they take (that is, no LEZ measures should be taken in the neighbouring cities). Alternative (local) measures to decrease PM levels should also be taken into account but might be difficult to consider (Gehrsitz, 2017). Therefore this is considered to be an omitted variable for this research. However, since all neighbouring cities are located in one country, nationwide measures to reduce PM levels like promoting battery electric vehicle adoptation or increasing nationwide investments in emission free transport modes as discussed in Section 2.4 will be similar for neighbouring areas/cities and the objective city. Also, the measurement data includes a time during which nationwide pandemic measures were taken that influenced the number of vehicles in The Netherlands (Velders et al., 2021). For example during the spring of 2020 levels of $PM_{2.5}$ were 20% lower than expected by model simulations with expected emissions for that time period. This effect will be taken into account by using the neighbouring cities/areas as predictive variables because all areas faced similar measurements. Because these policy measures cannot be determined numerically and the relationship between these variables and PM levels would be very complex, they cannot be modeled directly.

Measurement data of other cities in The Netherlands on PM levels will be used in order to estimate PM levels in the LEZ of Amsterdam (Alkmaar, Amersfoort, Dordrecht, Lelystad, Groningen and Zoetermeer). The other cities/areas that are used to predict levels of $PM_{2.5}$ in the objective city are selected based on a few characteristics. All neighbouring cities/areas are located within The Netherlands and the number of measurement points should be higher than 20 since otherwise the average measurement of $PM_{2.5}$ might be influenced by insufficient data. Furthermore the other cities do not have an LEZ.

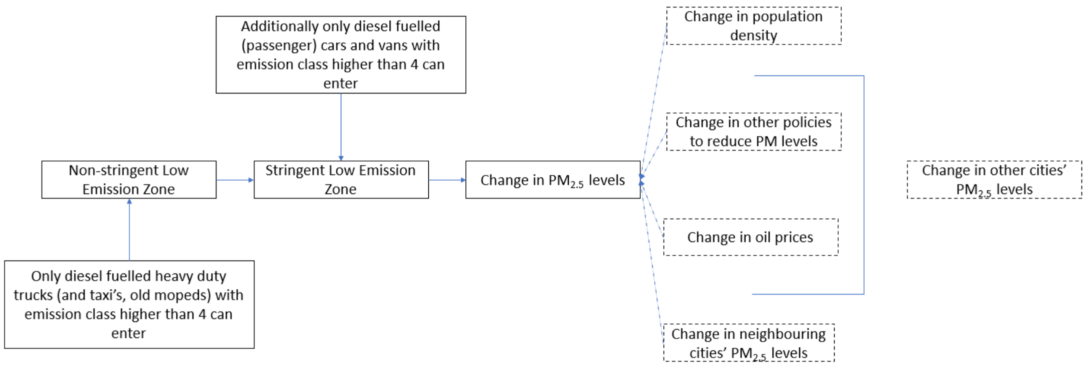

Figure 10: A conceptual model to investigate the effect of sringent Low Emission Zones in The Netherlands on levels of $PM_{2.5}$ compared to less stringent LEZs, while keeping in mind the control variables that are also expected to influence PM levels.

6 Methods

In this report we want to investigate whether stringent LEZs that include diesel passenger cars and vans decrease levels of $PM_{2.5}$ significantly more then a less stringent LEZ in Amsterdam. In order to investigate the effect of a stringent LEZ, this paper will use a predictive model based on data before and after the introduction of a stringent LEZ (where before the LEZ was less stringent). In Equation (1) Y encompasses $PM_{2.5}$ levels of the objective city "Y" for which we want to determine wheter PM levels decrease after the introduction of a stringent LEZ. $X_1 \dots X_n$ are PM levels of predictive cities that will be used as predictive variables in the two regression models. Furthermore N_1 is the neighbourhood area of Amsterdam from Figure 8 on page 11. $C_1 \dots C_n$ are the regression coefficients.

$$Y = C_1 \cdot N_1 + C_2 \cdot \text{stringentLEZ} + C_3 \cdot X_1 \cdots + C_n \cdot X_n + \epsilon \tag{1}$$

For each predictive city and for the neighbourhood measurement stations in Amsterdam, the average measurement of $PM_{2.5}$ of all measurement stations located inside the area is calculated for each hour. Then, we can use Ordinary Least Squares (OLS) to find a regression model for levels of $PM_{2.5}$.

Linear regression models assume that the variance is independent of time and the measurement errors should be independent and normally distributed around 0. To check the distribution of the measurements of $PM_{2.5}$ we can make a qqplot of the measurement data. Figure 11 gives us an indication that the measurement data of $PM_{2.5}$ might not be normally distributed. However, the logarithm of the measurement data does seem to approach a normal distribution according to Figure 12. Also, since we want to measure relative changes in PM levels, a logarithmic model would be preferable. Therefore, we will continue with this logartithmic model to test if the introduction of the stringent LEZ has significantly lowered PM levels. Furthermore, we investigate if the residuals of the logarithmic model are normally distributed, as demanded by linear regression. We again use a qq plot to visualize whether the errors of the logarithmic model are normally distributed. In Figure 13 on the following page we see that the normality assumption of the residuals is reasonable, however the ends of the Figures do show signs of another distribution. Despite this shortcoming, we continue with the logarithmic model in our further tests.

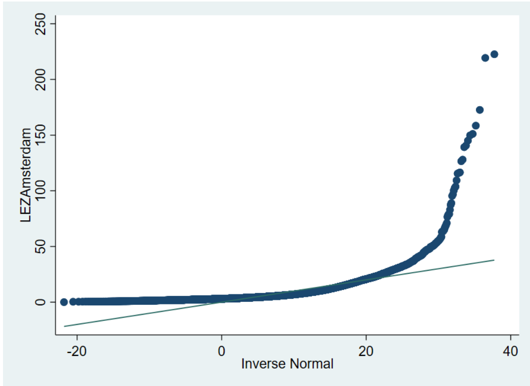

Figure 11: A qq plot that shows the distribution of the measurement data against a normal distribution

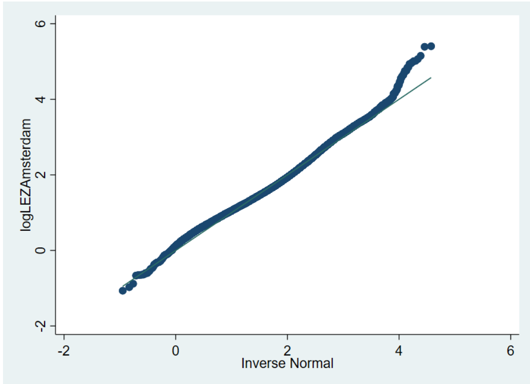

Figure 12: A qq plot that shows the distribution of the logarithm of the measurement data against a normal distribution

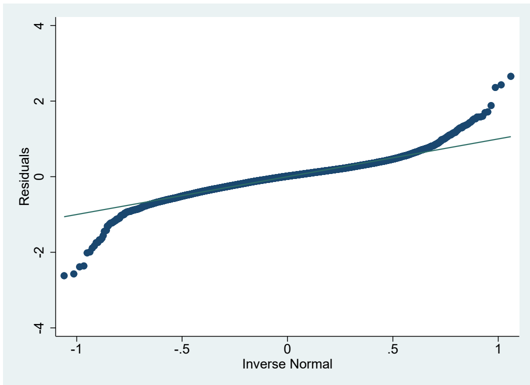

Figure 13: A qq plot that shows the distribution of the residuals of the logarithmic model against a normal distribution

7 Results

In Figure 14 on page 16 the model from Table 1 is used to visualize how well the logarithmic model fits the measurement data. From Figure 14, no clear conclusion can be derived about the difference between the logarithmic model and the measurement data. Furthermore, the logarithmic regression model is given in Table 1.

From Table 1 we derive that enforcement of the stringent LEZ would lead to a significant decrease in concentrations of $PM_{2.5}$ of around 8 percent $((e^{-0.0821} - 1) \cdot 100)$ compared to when a less stringent LEZ is introduced in Amsterdam. We obtain this number with the coefficient associated with the variabel "stringentLEZ". This result confirms the hypothesis of this report that a more stringent LEZ in Amsterdam lowers levels of $PM_{2.5}$ significantly more than a less stringent LEZ.

The model in this report does not use changes in population density as a predictive variable for levels of $PM_{2.5}$, but this variable was mentioned in the conceptual model of Figure 10. This variable is not used in the regression analysis since only yearly data on population density inside the LEZ of Amsterdam is available, but our model requires daily data. A linear interpolation of population density could alternatively be applied, but there is no indication that population density increases linearly. Levels of population density have increased in Amsterdam in the time period of 2019 up until 2023 (CBS, 2023). However, levels of particulate matter have significantly decreased according to Table 1 after the stringent LEZ was enforced. Because a positive sign is attributed to population density and concentrations of $PM_{2.5}$, this report assumes omitting this variable will not change the result that the stringent LEZ has singificanly lowered levels of $PM_{2.5}$ (Borck and Schrauth, 2021) compared to the less stringent LEZ that Amsterdam had before.

Table 1: Logarithmic model for PM levels inside the LEZ of Amsterdam where the variable "stringentLEZ" is activated when the stringent LEZ is introduced (distribution of the residuals can be found in Figure 13 on the previous page)

VARIABLES	$\log(PM_{2.5})$
logAlkmaar	0.0396***
	(0.0320 - 0.0471)
logAmersfoort	0.0424***
	(0.0331 - 0.0518)
logDordrecht	0.0383***
	(0.0319 - 0.0447)
logLelystad	0.0724***
	(0.0659 - 0.0789)
logGroningen	0.0246***
	(0.0180 - 0.0313)
logZoetermeer	-0.0528***
	(-0.0581 - -0.0474)
logAmsterdam (around LEZ)	0.800***
	(0.788 - 0.811)
stringentLEZ	-0.0821***
	(-0.0901 - -0.0741)
Constant	0.0993***
	(0.0883 - 0.110)
Observations	23,738
R-squared	0.848

Confidence interval in parentheses
*** p<0.01, ** p<0.05, * p<0.1

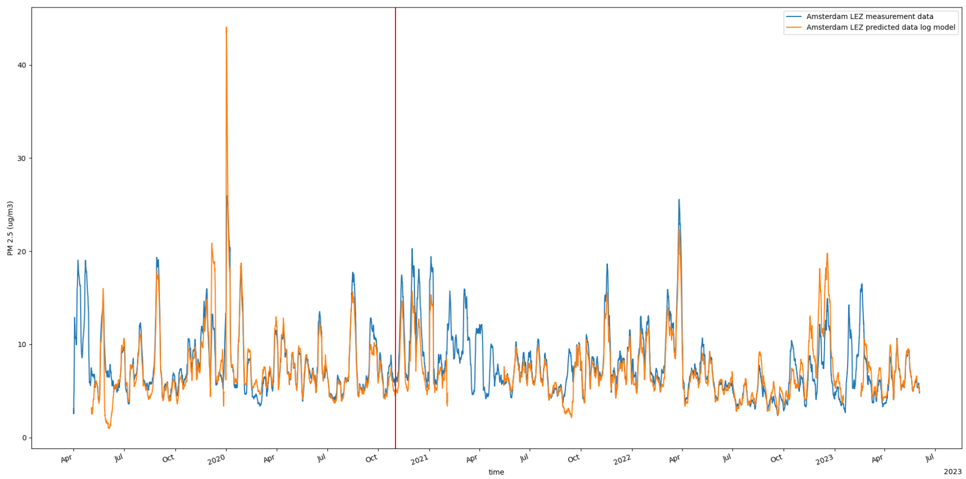

Figure 14: Prediction of logarithmic model from Table 1 for levels of $PM_{2.5}$ inside the LEZ of Amsterdam with the red line specifying the moment the LEZ was introduced. If no data was available at a specific time for one of the predictive variables, no prediction was made for that time period

8 Conclusion

Reducing concentrations of Particulate Matter, especially $PM_{2.5}$, could have positive effects on the health of citizens in The Netherlands (Kim et al., 2015). In this report several ways to reduce concentrations of particulate matter were discussed, and the introduction of a stringent LEZ was further investigated. Other reports suggested that stringent LEZs would decrease concentrations of PM_{10} more than three times as much as less stringent zones (Malina and Scheffler, 2015). These research outcomes led to the following research question in this report:

Does the introduction of (stringent) Low Emission Zones in The Netherlands that restrict access for high particulate matter emitting cars and vans decrease the (local) concentrations of particulate matter more than less stringent Low Emission Zones?

In order to investigate the effects of a stringent LEZ, measurements of $PM_{2.5}$ in Amsterdam before and after the existing less stringent LEZ was turned into a stringent LEZ were used. According to the results of Section 7 the model of this report suggested a significant reduction in levels of $PM_{2.5}$ of around 8 percent after a more stringent LEZ is introduced in Amsterdam (compared to when the LEZ was less stringent). That means that the hypothesis that a stringent LEZ in Amsterdam lowers levels of $PM_{2.5}$ significantly more than a less stringent LEZ is confirmed according to the model of this report. Therefore, in order to reduce levels of $PM_{2.5}$, more stringent LEZs would be preferred instead of less stringent LEZS in The Netherlands.

The data that is used for this report is freely accessible and could therefore be used by others. Unfortunately, as was mentioned in Section 3, the data contains measurement errors. To prevent these outliers measurement stations would need to be regulated more strictly. In future work more investigation would need to be done to confirm whether the use of neighbouring areas and cities that are further away (but comparable in terms of nationwide or regionwide circumstances) to predict levels of $PM_{2.5}$ is usefull.

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