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The effect of the Low Emission Zone in Rotterdam on air quality

Master Thesis Policy Economics
Arjen Treurniet (384451)
Supervisor: Dr. L.D.S. Hering
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Abstract

In this thesis, the effect of the Low Emission Zone (LEZ) in Rotterdam, which was introduced at January 1^{st}, 2016, is evaluated using a difference in differences approach with measured data on NO_2, NO and PM_{10}. There are data from 2013-2017 on 11 measuring stations in Rotterdam, Vlaardingen, The Hague and Amsterdam, from which 2 are in the LEZ and 2 are very close to the LEZ. No significant effect was found, which could very well be due to a shortage of measuring locations and confounding factors influencing the result. It could also be because the amount of NO_2 emitted by cars has not gone down much.

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1. Introduction

According to the World Health Organization (2016), polluted air kills 3 million people worldwide each year. The WHO also provides guidelines for air pollution (Krzyzanowski & Cohen, 2008).
Kampa & Castanas (2008) found an effect of carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NOx), particulate matter smaller than 10 µm (PM_{10}) and several other pollutants on health. The pollutants impair the functioning of human organs and they can cause cancer.
Tanaka (2015) evaluated the effect of Chinese air quality policies on infant mortality. He found that cleaner air reduced infant mortality significantly. The pollutant that was used for his evaluation is SO_2.

A WHO task group conducting a meta-analysis found that PM_{10} specifically has a negative effect on health (Anderson, Atkinson, Peacock, Marston, & Konstantinou, 2004). It raises mortality and cardiovascular diseases. Anderson (2009) conducted a historical research to the relation between air quality and mortality. There are some identification issues for the causal effect, but according to the author, it is likely that the strong correlation between episodes of very bad air and mortality is at least partly a causal relation.
Chay & Greenstone (2003) exploit the recession from 1981-1982 in the United States of America. This recession caused different declines in the levels of PM_{10} and particulate matter smaller than 2.5 µm ($PM_{2.5}$) in the air. They found a 0.35% decline in infant mortality if PM_{10} and $PM_{2.5}$ declined by 1%, which implies that during this recession 2500 fewer infants died as a result of pollution. The effect of pollution on infant mortality is also found by Jayachandran (2008).

Not only PM_{10}, also nitrogen oxides (NO_x, consisting of NO_2 and NO) have adverse health effects. Crouse et al. (2015) evaluate more than 2.5 million Canadians for 16 years. They find that pollution causes mortality due to lung cancer, cardiovascular disease and other diseases. The pollutants they investigated were NO_2, $PM_{2.5}$ and O_3. The authors were unable to distinguish between the causes of the different pollutants, because of the high correlations.

Traffic is an important cause of air pollution. Lenschow et al. (2001) use the chemical composition of PM_{10} and the difference between measuring stations near busy streets and urban background stations in Berlin to conclude that PM_{10} is for a large part caused by traffic.
Byrd, Stack, & Furey (2009) also used the chemical composition of PM_{10} to arrive at the conclusion that traffic influences it, but they did it for differential locations in Ireland. According to them, PM_{10} is a good unit to measure the effect of infrastructural projects.

In London and Milan, it was also measured that PM_{10} is for a large part caused by traffic (Charron, Harrison, & Quincey, 2007; Fuller & Green, 2006; Lonati, Giugliano, & Cernuschi, 2006).
Juda-Rezler, Reizer, & Oudinet (2011) also find that traffic causes PM_{10}. On top of this, they find that there is a strong positive correlation between PM_{10} and NO_2, which makes the case stronger for using NO_2 as outcome variable. They also found a strong positive relation between high air pressure and PM_{10}.

In line with the WHO guidelines mentioned in the first paragraph, due to the adverse health effects, there are European limit values, which the municipality of Rotterdam uses as a target for air quality in the city (Gemeente Rotterdam, 2018).

Because traffic causes pollution and because these limits will be exceeded without new policies (especially for NO_2), the municipality of Rotterdam introduced a Low Emission Zone (LEZ) (Gemeente Rotterdam, 2015). The general idea of an LEZ is, according to Ellison, Greaves, & Hensher (2013): “LEZs are areas where vehicles that do not meet a minimum standard for vehicle emissions are restricted from entering and are subject to large fines if they do enter.”

An LEZ is a zone within the city, in which the idea is that the air quality should become better than before. To reach this target, it is in the case of the LEZ in Rotterdam prohibited to drive a petrol car within the zone that was built before July 1st 1992. Diesel cars built before 2001 are also prohibited from driving into the LEZ. More details of the LEZ will be described in section 3.

Evaluating a Low Emission Zone using a difference in differences estimation strategy has not been done much before. In the Netherlands, it has never been done.

In this thesis, this LEZ is evaluated, using a difference in differences strategy with fixed effects. The research question is: "What is the effect of the Rotterdam Low Emission Zone on air quality?". Stations measuring NO_2, NO and PM_{10} within the LEZ, just outside the LEZ and in The Hague and Amsterdam are used to construct different treatment groups and control groups, each with its own advantages and disadvantages. The difference between treatment and control is compared before and after the introduction of the LEZ, using date and measuring station fixed effects and control variables for the weather. As mentioned before, if NO_2 does not have much adverse health effects in itself, it is strongly correlated with other pollutants that do. No effect was found of the LEZ, but that may be due to there being too little measuring stations, which is why confounding factors cannot be entirely written off as possible explanations for not observing an effect.

The structure of this thesis is as follows: in the next section related literature will be discussed, in section 3 the LEZ in Rotterdam will be described, in section 4 the estimation strategy is described. Section 5 contains a description of the data that is used for this thesis, in section 6 the results are summarized. Section 7 concludes.

2. Related literature

In this section, related literature will be discussed. First, other research evaluating Low Emission Zones is reviewed. From most of these papers, the estimation strategies are not extremely convincing. In the second subsection, some papers are discussed evaluating air quality policy using difference in differences strategies with air quality measures as outcome variables. In the third subsection a paper is discussed evaluating German LEZs using a difference in differences strategy. The estimation strategy for this thesis as explained in section 4 is strongly based on the papers reviewed in the last subsections of this section.

2.1 Evaluations of Low Emission Zones, not using differences in differences

There have been several evaluations of Low Emission zones. Most of these do not use very convincing estimation strategies, but it is good to summarize how evaluations of LEZs mostly takes place.
For London, an evaluation has been done by Ellison, Greaves, & Hensher (2013). They use compliance data and data for car ownership, next to PM_{10} and the sum of nitrogen oxide and nitrogen dioxide (NO_x). They find that just before the introduction of the London LEZ in 2008, a lot of older cars were replaced by newer ones. In the first year of the LEZ, the rate of car replacement was also a lot higher than the 'natural rate' constructed by using the replacement rate elsewhere in Britain. So according to Ellison et al. (2013) there was clearly an effect of the LEZ on car ownership. Using the Theil-Sen method to calculate deviations from a trend, they find a decline in PM_{10} and a smaller decline in NO_x.
Jones, Harrison, Barratt, & Fuller (2012) find a reduction in NO_x after the Low Emission Zone was introduced in London. They compare two locations in London before and after the introduction of the LEZ with one location in Birmingham. The introduction of the LEZ in London was at the same moment as the introduction of sulfur free diesel. Jones et al. (2012) conclude that the introduction of Sulfur free diesel had an influence on air quality. Because the reduction in pollution is larger in London, it is concluded that the LEZ might also have had an effect, but this is far from certain.
In a chemistry paper, Qadir, Abbaszade, Schnelle-Kreis, Chow, & Zimmermann (2013) compare values

of air quality before and after the introduction of a LEZ in Munich. They investigate the chemical composition of particles of PM_{10} to see what caused their existence. They find a 60% decline in the traffic caused particles after the introduction of the LEZ. Because it is just a before-after comparison, a causal interpretation of this figure is not possible, but other sources than traffic can be excluded, Fensterer et al. (2014) also investigate the effect of the Munich LEZ. Their outcome variable is PM_{10}. They measure this at two stations within the LEZ and one outside of it, before and after the introduction of the LEZ. They use two stations measuring PM_{10} within the LEZ and one station measuring PM_{10} in the suburbs of Munich, outside of the LEZ. The data they use go from 2006 until 2010. They use a simple linear regression with dummies for summers and winters with and without the LEZ. The station outside of the LEZ is taken into account as a control variable. They also controlled for time of the day, season, wind direction and public holidays. They find a significant reduction in PM_{10}.

Cesaroni et al. (2012) investigate the effect of two LEZs in Rome on PM_{10} and NO_2. Emission was modelled on the kind of cars that drove to the city. They compared this to emissions outside the two zones. The difference in calculated traffic related NO_2 was 58%, the difference in calculated traffic related PM_{10} was 33%.

Holman, Harrison, & Querol (2015) did a literature review on the effect of LEZs. They mention using NO or NO_2 as outcome variable possibly does not lead to any results, because there has not been a very large decline in emissions from cars over time. According to them, there might be a bigger effect in the summer, because the traffic related PM_{10} is a bigger part of the total amount in the summer. This is why there is also a robustness check including only the summer months. They mostly do not see very large results for studies that take the confounding factors into account, only on carbonaceous particles. It also seems to be that banning some old Light Duty Vehicles (LDVs) has a beneficial effect compared to banning only Heavy Duty Vehicles (HDVs). In Rotterdam also some LDVs are banned, so that could lead to a measurable effect on NO, NO_2 or PM_{10}.

2.2. Difference in differences approaches with air quality as outcome

Most studies that are done do not use measured air quality data or do not take confounding factors and trends into account correctly, or even both. That is why they might be indicative of the results, but it is not really possible to base the estimation strategy on them. There are however some studies that do use a difference in differences approach with measured pollutants as outcome variables. These are discussed in this subsection. The estimation strategy in this thesis is partly based on this research.

Bel & Holst (2018) estimate the effect of a Bus Rapid Transit (BRT) system in Mexico City on air quality, using a difference in differences approach with station, day of the week, month of the year and year fixed effects. In Mexico City a Bus Rapid Transit system was implemented. It consists of busses with separate bus lanes and bus stations. The advantage of this compared to conventional city bus systems is that they do not have to stop and pull up as much as a bus that drives in standard car lanes. This means that the busses pollute less and that they are faster, which should attract more users, which should make them drive less. Less car traffic leads to less pollution.

Because the system had clear lines, the authors could pick air quality measuring points in an area affected by the bus system and compare those to measuring points outside the affected area, using a difference in differences method. They constructed five different treatment groups (with different bandwidths) to estimate different patterns.

The outcome variables Bel & Holst (2018) used for air quality were CO, PM_{10} and SO_2. They used daily average concentrations. The control variables they used were a one day lag of the used outcome variable, the relative humidity, temperature, wind direction using Azimuth degrees, weekday dummies, month dummies and year dummies. They also included time fixed effects and measuring

station fixed effects.
They only evaluate the first line of the BRT system, using data from two years before it opened and two years after it opened.
They found significant negative effects of the BRT system on most outcome variables, which is a positive effect on air quality.

Bel & Rosell (2013) investigated the impact of a speed limit change on highways in the Barcelona metropolitan area, using a difference in differences approach with fixed effects, which is almost the same as in Bel & Holst (2018). Bel & Rosell (2013) include a municipality specific fixed effect and a time fixed effect, which they do not define more specifically. They also include temperature, humidity, rain, wind speed, air pressure and a one day lag of the pollutant in question. On some roads, the speed limit was lowered to 80 kilometers an hour, on some roads it was variable. When there was much traffic, the speed limit would be lower. The biggest difference with the approach by Bel & Holst (2018) is that there was less variation possible in the definition of the treatment and control groups and that only NO_x and PM_{10} were included as measures for air quality.
Bel & Rosell (2013) found a negative effect on NO_x and PM_{10} for the highways where there is a variable speed limit and a (surprising) positive effect for the highways where there is a speed limit of 80 kilometers an hour.

Van Benthem (2015) tries to find the optimal speed limit on highways in the western United States, for which he also estimates the effect of the speed limit on air quality, using a difference in differences strategy. The air quality data in his paper come from measuring stations at different distances from the relevant highway. He includes weather variables in his regression, just like dummies for the day of the week, the month of the year and the year. He finds a significant positive relation between the speed limit and CO, NO_2 and O_3.

2.3. Evaluation of a LEZ using Difference in differences

The only paper evaluating a Low Emission Zone using a difference in differences approach that I found is Malina & Scheffler (2015). In Germany, there are different LEZs, coordinated by the national government. This makes it possible to evaluate them at the same time. There is a stricter form and a less strict form. The stricter zones have the same requirements as the less strict zones, but there are some extra rules. This is why there is a dummy variable included indicating if there is an LEZ, which is one for all LEZs, and a dummy for the stricter LEZ, which is only one if the LEZ has stricter rules.
In the estimation strategy controls are included for temperature, rain, humidity, sunshine hours, wind force, wins speed, air pressure, snow depth, vapor pressure and interactions of weather controls. Fixed effects are included for the year and the measuring station.
Another important control variable is traffic volume. If the traffic volume shows differential trends at different locations, this can bias the results, if this is correlated with the existence of an LEZ at a certain location. A disadvantage of including traffic volume is that it can partly be caused by the LEZ itself. If ones car is not allowed into the zone, he might not go into the zone by car at all, instead of using a cleaner car. This might mean a decline in traffic volume caused by the LEZ. This could bias the coefficient on the LEZ towards zero.
The outcome of the paper was that PM_{10} levels were reduced significantly due to the LEZs. In a less strict zone, PM_{10} was reduced by 2.33 $\mu g/m^3$. In the stricter zones, the reduction of PM_{10} was 5.17 $\mu g/m^3$ higher.

3. The Low Emission Zone in Rotterdam

An LEZ is an area in which it is forbidden to drive certain polluting vehicles. The idea is that the air will be cleaner if less polluting cars drive into this area. If someone drives into the LEZ with a car that is not allowed into the zone, he will be fined. In this section the specifics of the LEZ in Rotterdam will be discussed, together with the predicted effect, the way it is enforced, some confounding factors possibly influencing the results of this thesis and some exemptions of the LEZ. The section ends with a summary of an evaluation initiated by the municipality of Rotterdam.

3.1 Why does the LEZ in Rotterdam exist?

According to the 'Koersnota schone lucht' (Gemeente Rotterdam, 2015), the main objective for the LEZ is better air quality. The specific target is to lower the level of elementary carbon (EC) caused by traffic by 40% in 2018, compared to 2014. Another part of the objective is to lower the level of NO_2, but the target is not as specific as with EC.

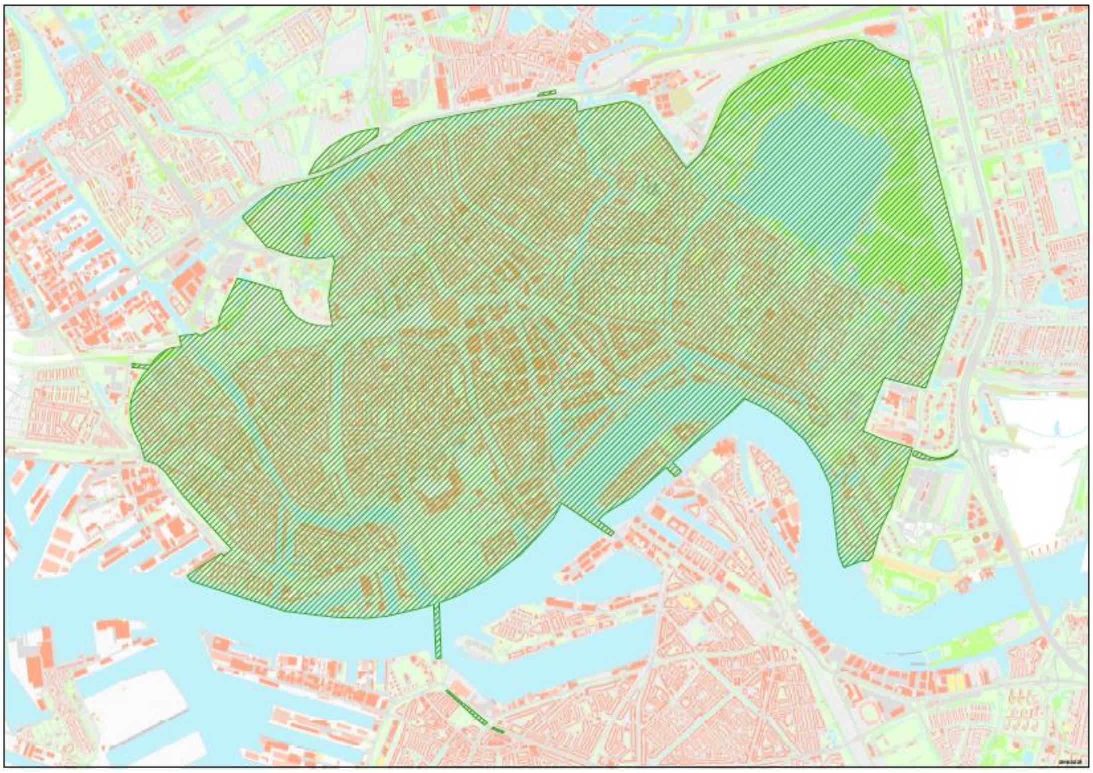
The general idea about air pollution is that it declines over time, because newer cars have cleaner engines. This is called the autonomous cleaning of the air.

The idea of the LEZ is that this air-cleaning process is accelerated. So there should be an autonomous downward sloping pollution curve, which is accelerated by the LEZ.

3.2 Where is the LEZ located?

As can be seen in figure 1, the LEZ is located within the motorway ring, on the north side of the river Maas. The routes to the south of the Maas, Willemsbrug, Erasmus bridge and the Maastunnel are included. The reason to choose for the north side of the river Maas is that the air quality is worse than on the south side and that because of this the need for cleaner air is higher at the north side. Also the zone at the north side should also have a positive effect on the air quality at the south side.

Figure 1[1]:



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[1] https://www.rotterdam.nl/wonen-leven/milieuzone/20160225_plaatje_milieuzone_site.pdf

3.3 The requirements for the LEZ

The requirements for driving into the LEZ are the following:

- For diesel trucks: a Euro IV standard
- For diesel cars and vans: first allowed on the road after January 1st 2001
- For petrol cars and vans: first allowed on the road after January 1st 1992

The numbers of cars registered on addresses within the LEZ that are not allowed into the LEZ are as follows: 1500 diesel cars, 400 petrol cars, 1200 diesel vans and 100 petrol vans. This is to the date of the 'Koersnota' (May 22nd 2015). Of course, these are only the cars registered within the LEZ. Many cars that drive into the LEZ are registered elsewhere.

3.4 Predicted effect

The municipality of Rotterdam predicted that the effect of the LEZ on NO_2 would be a reduction of 0.8 $\mu g/m^3$ on roads with a high traffic intensity and 0.3$\mu g/m^3$ on roads with low traffic intensity (Gemeente Rotterdam, 2015) Because the impact on roads with higher traffic intensity should be bigger, there are also regressions included using only measuring stations close to busy roads.

3.5 Enforcement

The LEZ is enforced using cameras on the boundaries. If someone illegally drives into the LEZ, he gets a 95 euro fine. The LEZ has been enforced since May 1st 2016[2]. This might influence the results of the regressions. Robustness checks are included not taking the first four months of 2016 into account. Another potential problem for the results is that the enforcement on petrol fueled cars from before 1992 was stopped at July 14th 2017 (Gemeente Rotterdam, 2017).

3.6 Other measures that might influence the results:

In the 'Koersnota', some more measures are mentioned that might influence the measured effect of the LEZ. There is also a compensation for people who have to buy a new car to get into the LEZ. This so-called Demolition scheme had been into place a few years before the introduction of the LEZ. This can cause a downward bias on the results.

The cars owned by the municipality are becoming less polluting and it is easy to get a charging station for an electric car. Another target is to stimulate electrical logistics in the city center. If these measures have an effect, it is likely that most of these influence the entire city of Rotterdam, not only the LEZ itself. This one of the reasons I will also use the two measuring stations just outside the LEZ as treatment group in the regressions.

Other plans mentioned in the 'Koersnota' are stimulating demolition of scooters and making the ships and busses use cleaner fuel. These measures were not in place during the investigated period in this thesis.

3.7 Exemptions

There are some exemptions for the LEZ, for example for cars older than 40 years. All exemptions can be found in Gemeente Rotterdam (2016).

3.8 Evaluation LEZ in Rotterdam

The municipality of Rotterdam evaluated the LEZ itself, supported by DCMR (Environmental agency for the Rijnmond area) and TNO (an independent research agency) (Gemeente Rotterdam, 2018). This evaluation is based on a traffic model and the traffic measured at six different locations. Every car is put into a category, measured by emission of NO_x and EC.

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[2] https://www.rotterdam.nl/wonen-leven/milieuzone/

They calculate the so called ‘autonomous cleaning’ of the air. This is the national average of traffic related emissions calculated using the number of cars in each category and the distance travelled. They also calculate the traffic related cleaning of the air within the LEZ. These differences are subtracted, which leads to the result that NO_x has decreased by 4% as a result of the LEZ and that EC has decreased by 13% as a result of the LEZ. The total traffic related decrease is 16% for NO_x and 36% for EC.
They also calculated by which kind of traffic the cleaning of the air was caused. No difference was made between the autonomous part and the part caused by the LEZ. According to Gemeente Rotterdam (2018), the share of petrol cars from before 1992 in the total decline in NO_x was 25%, which leads to the conclusion that the fact that these cars were admitted into the LEZ again by July 2017 is relevant.
There is a section in the evaluation which states how many cars that do not meet the requirements for the LEZ still drive into it. This number has significantly declined after the introduction of the LEZ. Also at the stations registering the cars outside the LEZ the number of cars not allowed into the zone declined strongly, but not as strongly as within the LEZ. The fact that the total number of not-allowed (petrol) cars declined makes it possible that the cost of allowing them in again is not as high as the initial benefit.

The difference between this evaluation and the method applied in this thesis is that in this thesis real measured data is used. The advantage of that is that there is no model underlying the results that could be flawed. The disadvantage is that there is more noise in the data, because NO_2 and PM_{10} are not only caused by traffic, but also by other factors. Also there are not very much locations where it is measured. I expect to be able to cancel the other factors out by using a difference in differences strategy with fixed effects.

3.9 Amsterdam as control group

In Amsterdam, there is also a Low Emission Zone for vans. This zone started on January 1st 2017[3]. This seems to have an effect on the amount of vans that went into the city and it might also affect the air quality. Partly because of this, Amsterdam is not included in all regressions.

4. Estimation Strategy

It has been mentioned before that the difference in differences method is used to estimate the effect of the LEZ in Rotterdam. In this section, this is explained in more detail.

In this thesis, the difference in differences method will be used, with time and location fixed effects. For the difference in differences method in its most basic form two groups are needed, a treatment group and a control group. There are also at least two time periods needed, before treatment and after treatment. First the difference between treatment and control is calculated before treatment. Then the difference between treatment and control is calculated after treatment. Then the difference between those differences is calculated. Hence the name: difference in differences.
In this thesis, this is about the difference between treatment (the LEZ) and control (outside of the LEZ). To be able to identify a causal effect using this method, one assumption is particularly important: the common trend assumption (Wooldridge, 2015). This means that it is assumed that trends move in the same direction. Graphically, the trends for the treatment and control group have the same slope

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[3] https://www.gezonderelucht.nl/actueel/milieuzone-amsterdam-zorgt-voor-tweederde-minder-vervuilende-ritten-bestelvoertuigen

before treatment. The difference in differences method cancels out different levels, that is why the difference between the differences is calculated, but differential trends are a problem. In this case this is about different levels of pollutants between treatment and control. As is shown in the next section, the levels of pollutants are higher in the treatment groups. The difference in differences method doesn't cancel out different slopes of the curves, which is why it is important that the trends are the same in the treatment and control groups.
The difference in differences method can only be applied if fixed effects are used. The idea is that a time fixed effect cancels out factors that are constant among different locations (in this case), but differ over time. A location fixed effect cancels out factors that differ per location, but stay constant over time. This is used as a method to cancel out differences in levels per station and per time period.

For this thesis, I will make use of different treatment groups to test the effect, as in Bel & Holst (2018). I will also use different control groups.

In Rotterdam, pollution was measured at the following locations: Schiedamsevest, Statenweg, Zwartewaalstraat and Pleinweg. In Vlaardingen, which is in the agglomeration of Rotterdam, pollution was measured at the Floreslaan. In The Hague, there are data from the De Constant Rebecquestraat and the Amsterdamse Veerkade (later sometimes referred to as Rebecquestraat and Veerkade, respectively). In Amsterdam data were measured at the following locations: Stadhouderskade, Jan van Galenstraat, Nieuwendammerdijk and Vondelpark/Overtoom. More details about the measuring stations can be found in the next section in table 1.

The different treatment and control groups I use are the following:

Treatment:

Treatment 1: The stations within the zone (Schiedamse Vest and Statenweg)
Treatment 2: Treatment 1 + Pleinweg and Zwartewaalstraat

Control:

Control 1: Pleinweg and Zwartewaalstraat
Control 2: Control 1 + Floreslaan
Control 3: Control 2 + Rebecquestraat and Amsterdamse Veerkade
Control 4: Control 3 + Jan van Galenstraat + Stadhouderskade + Nieuwendammerdijk + Overtoom
Control 5: Control 4 – Control 1
Control 6: Floreslaan, Rebecquestraat and Amsterdamse Veerkade
Control 7: Floreslaan

The reason for the fact that control 1 is partly the same as treatment 2 is that is really part of both groups. The LEZ should have an effect compared to stations just outside of the LEZ (which is where the Pleinweg and the Zwartewaalstraat are located). There is also a planned effect on the stations outside of the LEZ compared to stations with more distance to the LEZ. Hence, it makes sense to include these stations in some regressions as treatment group and as a control group in other estimations.

If treatment 1 is compared to control 4 and if treatment 2 is compared to control 5, the full dataset is used.

The regression equation I will use is:

$$Pollutant_{it} = \gamma Z_{it} + \beta \boldsymbol{X}_{it} + \theta_i + \delta_t + \varepsilon_{it}$$

Where $Pollutant_{it}$ is the relevant pollutant for measuring station i at time t. In most cases, the time is a day. In the appendix, sometimes hourly data were used. Then t is an hour. Z_{it} is an interaction dummy for being in the treatment group and the time period in which the LEZ has been introduced. It has a value of 1 if both is true. $\mathbf{X}_{it}$ is a vector of controls. These controls include the wind speed, temperature, amount of time it rained on a day, the millimeters of rain, air pressure and humidity. Next to this dummies for the day of the week, the month and the year will be included. Θ_i is a measuring station fixed effect and δ_t is a date fixed effect.

The weather variables are included because they can have an effect on air pollution. Temperature has an effect on chemical reactions happening for the different outcome variables, and if there is a very hot day, people might react to this by staying at home (which is good for air quality), or by driving to the beach (which is bad for air quality). A lot of this is captured by the date fixed effects, but some local differences are taken into account by including temperature.
Rainfall is good for air quality, because it takes pollutants out of the air. It is therefore very important to include it. There are two different measures included, one on the total amount of millimeters of rain and one on the amount of time it has been raining on a particular day.
Humidity also has a potential effect on pollutants, so it is also included in the estimation. Wind either blows pollutants away or it brings pollutants from elsewhere.
Air pressure has an effect on the levels op PM_{10}, according to Juda-Rezler et al. (2011). Therefore, it is included in the regressions.
For more information about the weather-related controls, see also Bel, Bolancé, Guillén, & Rosell (2015), Bel & Holst (2018), Bel & Rosell (2013) and Malina & Scheffler (2015).

4.1 Standard error issues

Because the values of different measuring stations are very likely to be correlated with each other, just like the values over time, the standard errors are likely to be biased (Driscoll & Kraay, 1998; Hoechle, 2007; Hoyos & Sarafidis, 2006).
Driscoll & Kraay (1998) construct a standard error that is robust to heteroskedasticity, spatial and serial dependence. This standard error is also used by Bel & Holst (2018) in their paper about the effect of the Mexican Bus Rapid Transit on air quality.
Bel & Rosell (2013) use the Wooldridge test to test for autocorrelation, the Wald test to test for heteroskedasticity, the Pesaran test for spatial correlation and the Breusch-Pagan test for cross-sectional dependence. They find all of these potential problems. The approach in trying to control for this in the standard errors looks very much like that in Bel & Holst (2018), they use panel corrected standard errors and Driscoll-Kraay standard errors.
Van Benthem (2015) tries to overcome the biased standard errors by clustering them by clusters per station per month. I will also do this in this thesis. All regressions are clustered by location, month and year.

5. Data

In this section, the data will be discussed. First, it will be made clear where the data come from. After this, characteristics of the measuring stations will be shown in table 1. Then some parts of the table will be discussed in more detail, followed by a description of the weather data. Next, the summary statistics are tabulated and discussed. The section continues with a graphical representation of the data and the implications for the common trend assumption. In the end it will be shown how highway traffic possibly influences the results.

There are data from January 1 2013 until December 31 2017. The data that will be used for air quality are provided by DCMR, the environmental service in the area around Rotterdam. They got part of the data from RIVM, the national institute for public health.

Table 1: Information about the stations

Location	**City**	**PM10 available**	**Treatment**	**Control**	**Aggregation**	**Intense traffic**
Statenweg (LEZ)	Rotterdam	Entire period	1, 2	No	Hour	Yes
Schiedamsevest (LEZ)	Rotterdam	From July 26, 2014	1, 2	No	Hour	No
Pleinweg	Rotterdam	Entire period	2	1, 2, 3	Hour	Yes
Zwartewaalstraat	Rotterdam	Entire period	2	1, 2, 3	Hour	No
Floreslaan	Vlaardingen	From July 28, 2014	No	2, 3, 5, 6, 7	Hour	Yes
De Constant Rebecquestraat	The Hague	From August 1, 2014	No	3, 4, 5, 6	Hour	No
Amsterdamse Veerkade	The Hague	From July 28, 2014	No	3, 4, 5, 6	Hour	Yes
Stadhouderskade	Amsterdam	Entire period (sometimes missing values for a week	No	4, 5	Day	Yes
Jan van Galenstraat	Amsterdam	No	No	4, 5	Day	Yes
Nieuwendammerdijk	Amsterdam	No	No	4, 5	Day	No
Overtoom	Amsterdam	Entire period (sometimes missing values for a week	No	4, 5	Day	No

Most of table 1 speaks for itself, except maybe the intense traffic. DCMR and RIVM measure air quality at different locations in cities, next to busy streets (street stations) and in streets with very low amounts of traffic (background stations)[4]. The busy streets are of course more directly influenced by traffic than the background stations, so that might be relevant for the measured effect. That is why there are also robustness checks included using only the stations next to busy streets.

The locations can be seen in figure 2. The green locations are the Schiedamsevest and the Statenweg, which are in the LEZ. The yellow locations are the Pleinweg and the Zwartewaalstraat, just outside of the LEZ. The other stations are indicated by a blue label.

The data on weather are daily. This means that in the hourly data, each day has 24 the same observations for weather. The weather data are obtained from the Dutch weather institute (KNMI). There are data on Wind speed, temperature, rain in one tenth of an hour, total millimeters of rain on a day, average air pressure and average humidity. The weather data are measured at fewer locations than air quality. In Rotterdam it is measured at the airport, in Amsterdam it is measured at Schiphol airport.
In The Hague, the weather is more of a problem. The measuring stations by the KNMI that are closest to The Hague are Valkenburg and Voorschoten. From both stations there is no data for the entire period. Because weather is not the variable of interest, but only a control, I think it is not a very big problem. I use the data from Valkenburg until July 15, 2014 and the data from Voorschoten from that date. Probably there are no very big discontinuities.

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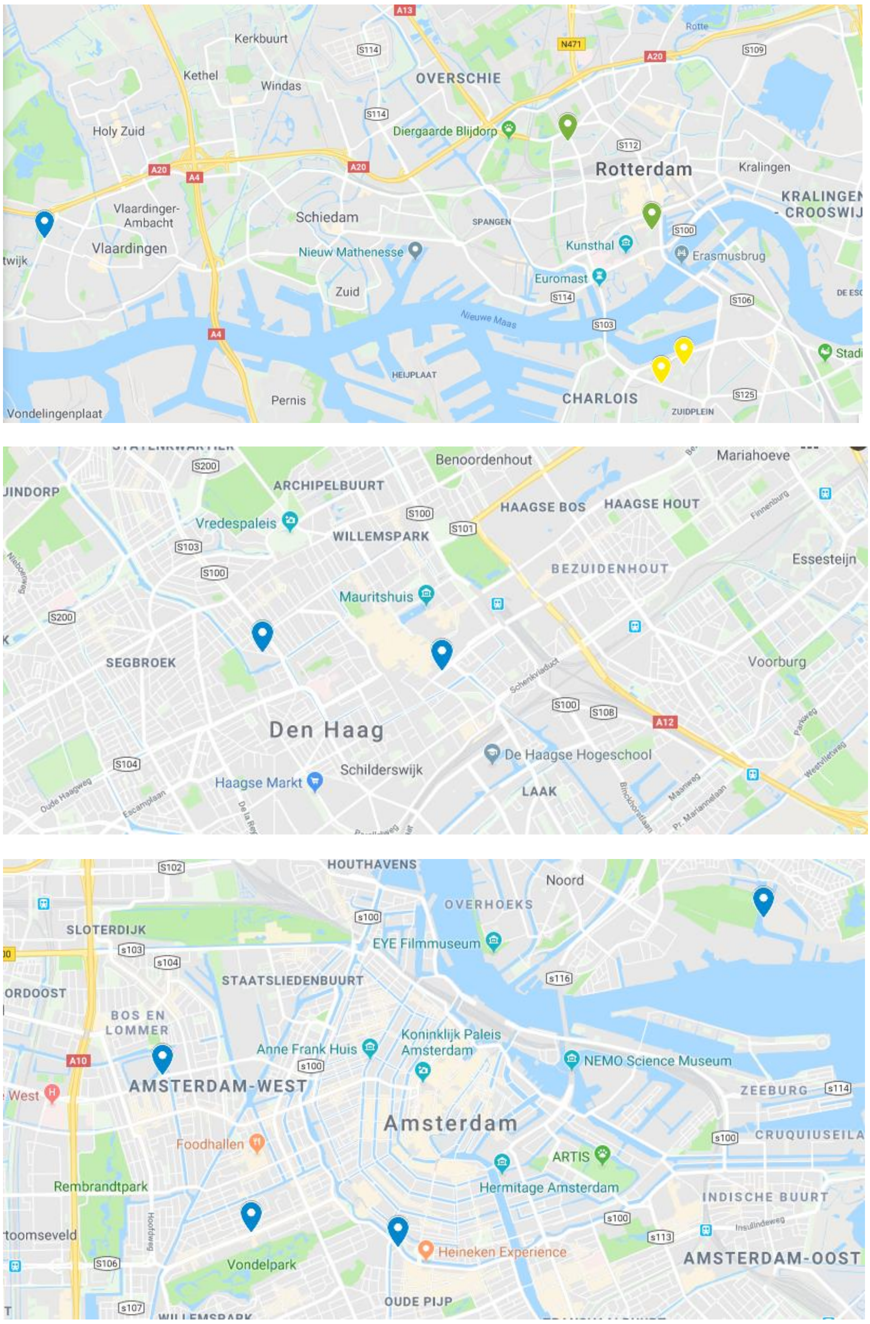
[4] Which station measures what can be found on luchtmeetnet.nl

Figure 2[5]:



5.1 Information about the variables

NO: Nitrogen oxide in µg/m^3. In hourly data this is a point value at the end of each hour, in the daily data this is an average from the measurements per hour.

NO_2: Nitrogen dioxide in µg/m^3. In hourly data this is a point value at the end of each hour, in the daily data this is an average from the measurements per hour.

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[5] Obtained from Google maps, filling in the locations myself: https://drive.google.com/open?id=1pVHVDhwxT6XObA-qXAqMoG8M2MqBYjkl&usp=sharing

PM_{10}: Particular matter smaller than 10 µm in µg/m^3. In hourly data this is a point value at the end of each hour, in the daily data this is an average from the measurements per hour.

Wind speed: average wind speed in meters per second

Temperature: average temperature in 0.1 degrees centigrade

Rain hours: total duration of rainfall in 0.1 hours

Rain millimeters: total amount of rain in 0.1 millimeters (-1 if it is below 0.05 millimeters)

Pressure: average pressure in 0.1 hectopascal

Humidity: average humidity in percentage[6]

Table 2: Summary statistics daily data

Variable	Obs	Mean	Std. Dev.	Min	Max
pm10	13,948	21.48823	10.54365	-1.49	115.8333
no2	19,793	33.58758	15.24841	2.3	102.7
no	19,799	16.68241	20.8825	-0.6	254.8042
windspeed	20,086	45.78532	21.08261	7	146
temperature	20,086	109.7255	58.68541	-75	270
rainhours	20,086	18.05327	29.5416	0	240
rainmillimillimeters	20,086	24.02435	49.43215	-1	776
pressure	20,086	10155	94.66449	9757	10443
humidity	20,086	80.98447	8.7113	33	99

Table 3: Summary statistics hourly data:

Variable	Obs	Mean	Std. Dev.	Min	Max
pm10	244,027	21.82368	15.64912	-30.13	1178.19
no2	301,178	34.48907	20.42392	-4.78	417.4
no	301,746	17.14459	30.55514	-7.8	1068.7

The thing that is most noticeable about the summary statistics is the fact that there are some negative values for NO_2, NO and PM_{10}. This can of course impossibly be the correct values. However, I keep them in the data set, because I assume the measuring errors are symmetric, so if I remove the negative values, the average will be too high. Robustness checks are included excluding these unreasonable negative values. Also one can see that the number of observations is not the same for every variable. This is because there are weather data from each day, while there are missing values for NO_2 and NO For PM_{10}, there are even more missing values, as can be seen in table 1.

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[6] http://projects.knmi.nl/klimatologie/daggegevens/selectie.cgi

5.2 Graphical description of the data

To test for a common trend between the treatment and the control stations before the introduction of the LEZ and to see if there is a change after the introduction of the LEZ, graphs were obtained from the data. Figures 3 to 8 display the levels of NO_2, NO and PM_{10} from 2013 to 2017. Monthly averages were used. In all graphs, the vertical line indicates the introduction of the Low Emission Zone. Treatment 1 and treatment 2 are compared to control 4 and control 5, respectively.

The levels of NO_2 and NO in the two treatment groups are higher than in the control groups. The levels of PM_{10} are the same in the treatment groups and the control groups. Keep in mind that for PM_{10}, there is some missing data, as shown in table 1.

As mentioned in section 4, the common trend assumption is a very important assumption in a difference in differences analysis. A way to test this assumption is to look into the trends before the introduction of the LEZ. There does not seem to be a trend for all three pollutants, so there also is no differential trend. The levels always move in the same direction for both treatment and control for all pollutants and for both treatment groups and control groups. From this I conclude that the common trend assumption is satisfied.

Not only do figures 3 to 8 show that there is a common trend before the implementation of the policy, it is also possible to use them for a small prediction of the effect of the LEZ. There is no visible change in NO_2 and NO after the implementation of the LEZ, as can be seen in figures 3, 4, 6 and 7. For PM_{10}, there might be a small measurable effect of the LEZ.

Figure 3: NO_2, treatment 1 versus control 4

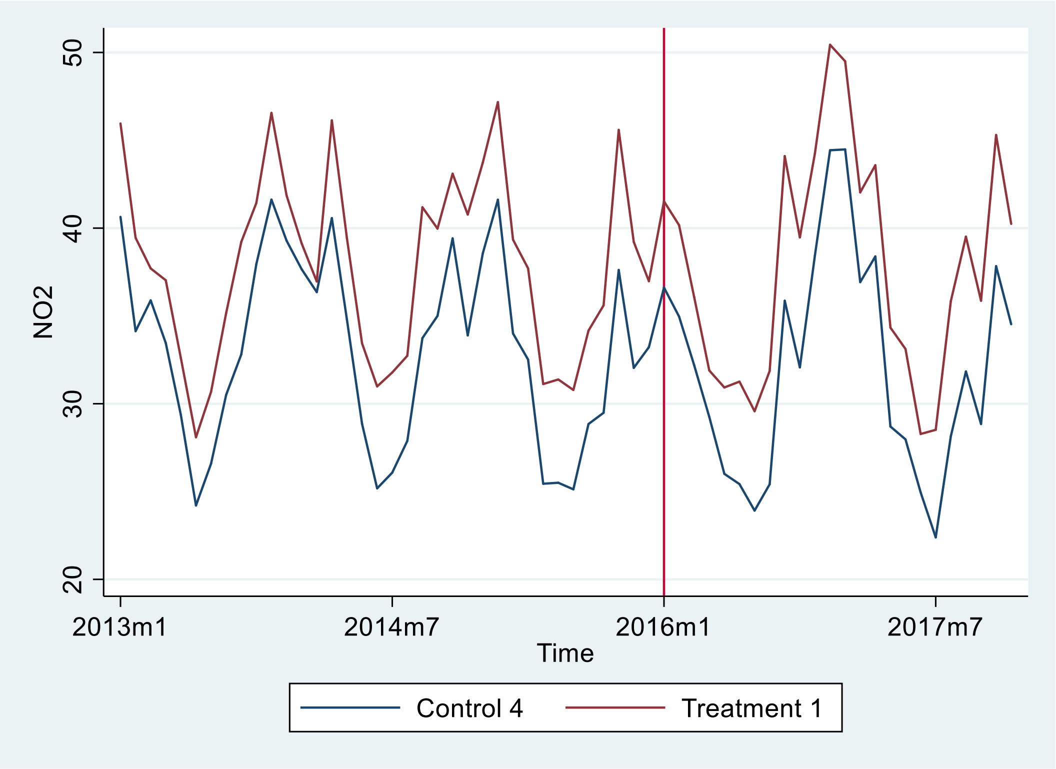


Figure 4: NO, treatment 1 versus control 4

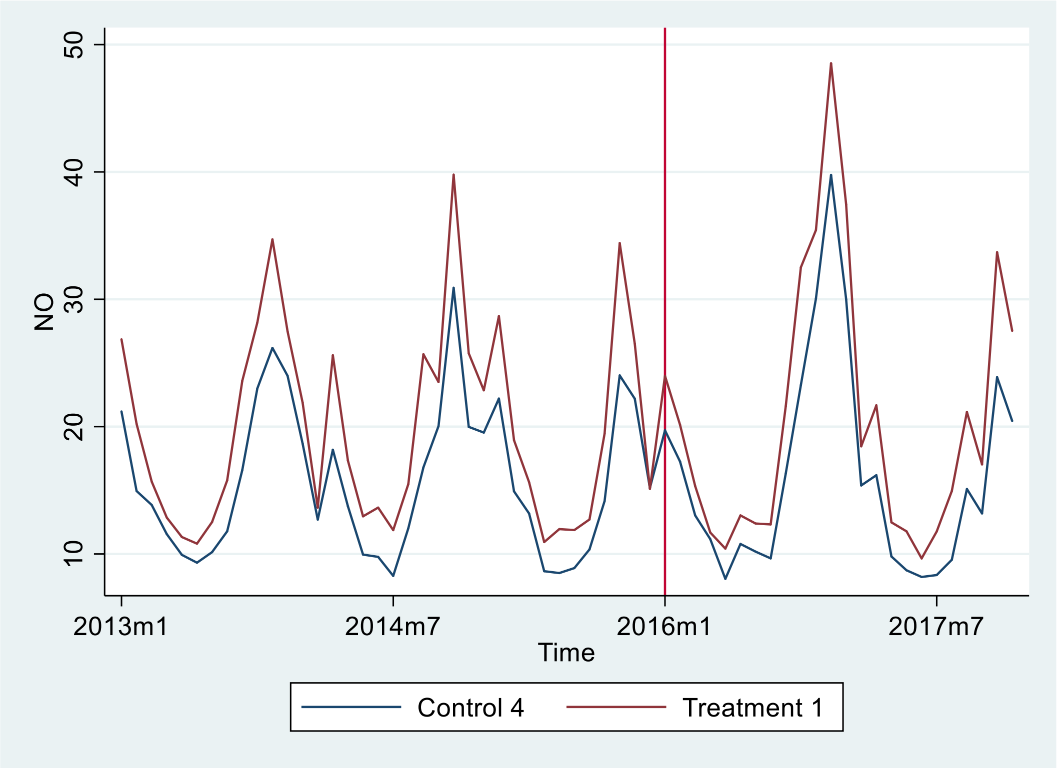


Figure 5: PM$_{10}$, treatment 1 versus control 4

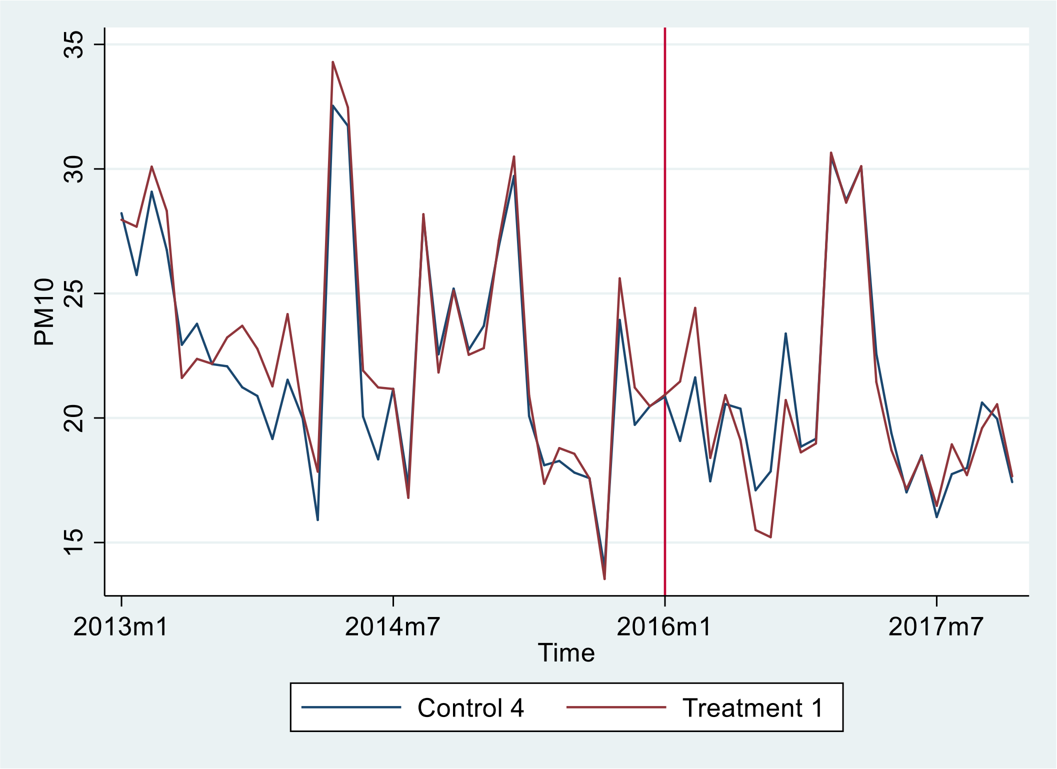


Figure 6: NO$_2$, treatment 2 versus control 5

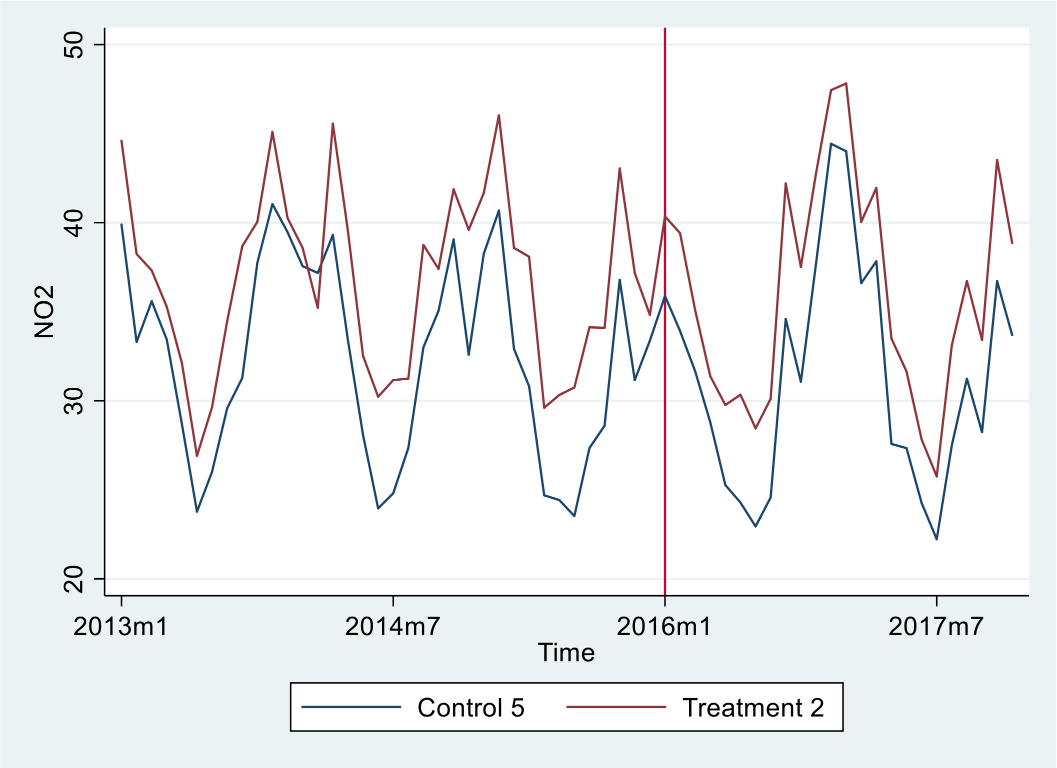


Figure 7: NO, treatment 2 versus control 5

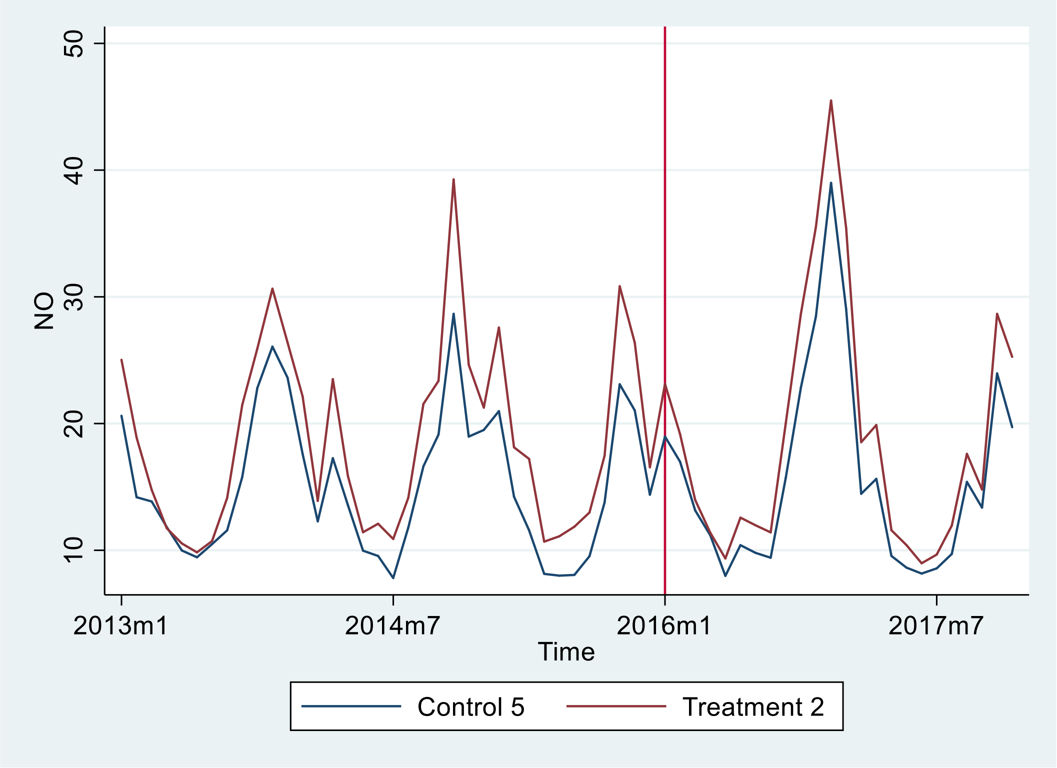
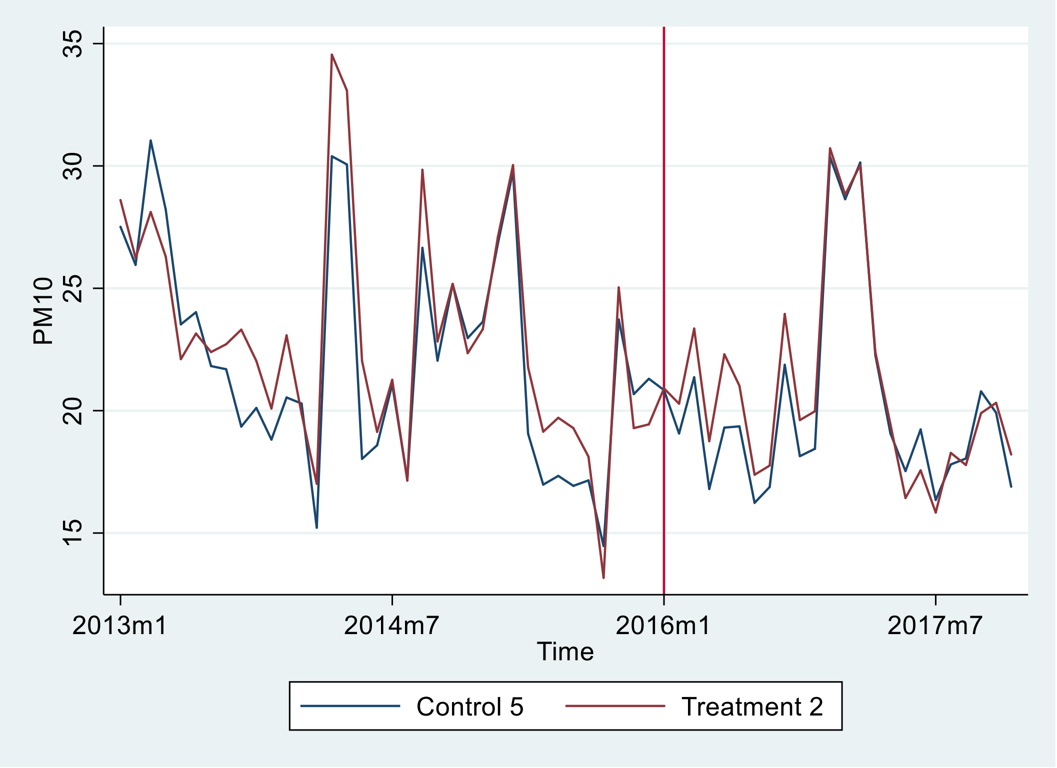


Figure 8: PM_{10}, treatment 2 versus control 5



5.3 Highways

Because traffic on highways also emits NO_x and PM_{10}, there are trends about traffic intensity on highways around Rotterdam, The Hague and Amsterdam in figure 9[7]. Because highways have nothing to do with the LEZ, it is important that the trend is equal for different cities.

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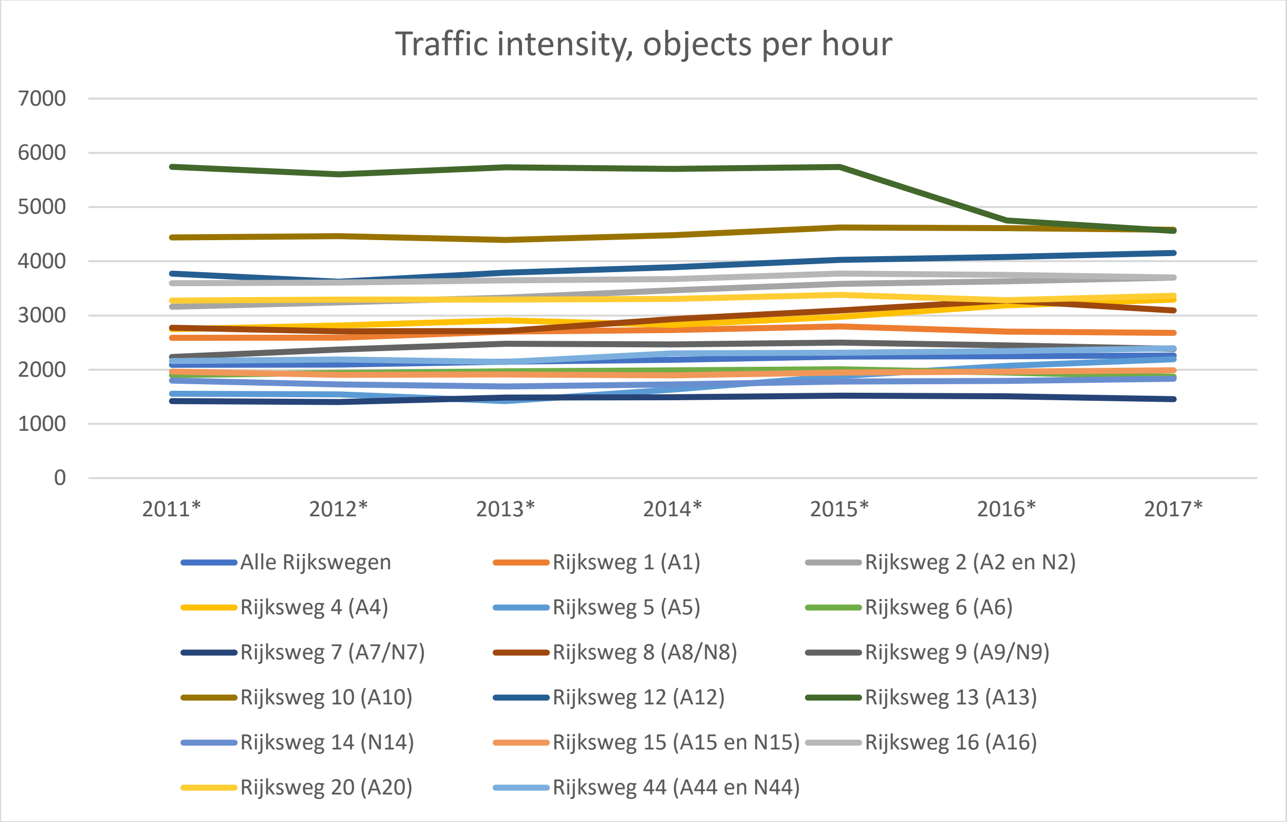
[7] http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=82855NED&D1=0&D2=a&D3=12,25,38-51,64,77,l&HDR=T,G2&STB=G1&VW=T

Figure 9: Traffic intensity on highways



Because the A13 runs from the Hague to Rotterdam, it is a potential problem that a shock can be seen from 2015 to 2016. This is most probably attributable to the opening of the A4 in December 2015.[8] This is also problematic because it happened simultaneously to the introduction of the LEZ in Rotterdam. This means that if measuring units from The Hague or Amsterdam are used as a control, the measured effect can also be because of the lower traffic intensity on the highway A13.

6. Results

In this section, the results from the regression estimations are described. To test for the ideal regression specification, different regressions were done, with different fixed effects (see Appendix 2 for the tables). From this, I concluded that it seemed best to use Location and Date fixed effects, to be able to make full use of the time dimension. If the date is included as a fixed effect, including national holidays, month of the year and day of the week is not necessary, because this is all captured by the date fixed effect, as this is all the same everywhere in the Netherlands. As can also be seen in appendix 2, using data per hour has almost no effect on the coefficients. Adding an hour fixed effect does not have a large effect too, which means that using hourly data is not necessary.

I tested for the ideal regression using only NO_2, because there is a specific target for NO_2, not for NO or PM_{10}. Also the data for NO_2 are more complete than for PM_{10}.

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[8] https://www.omroepwest.nl/nieuws/3017349/A4-Midden-Delfland-tussen-Delft-en-Schiedam-helemaal-open

Table 4: NO_2 using daily data, with and without weather, different treatment and control

	1 no2 T1-C3	2 no2 T1-C3	3 no2 T1-C4	4 no2 T2-C6	5 no2 T2-C6	6 no2 T2-C5
treatment1	1.769*	1.421*	1.275			
	(0.695)	(0.566)	(0.668)			
treatment2				1.774	1.181	0.854
				(1.019)	(0.742)	(0.846)
windspeed	-0.470**		-0.377**	-0.476**		-0.378**
	(0.113)		(0.0889)	(0.115)		(0.0902)
temperature	-0.103		-0.137**	-0.114		-0.139**
	(0.0783)		(0.0484)	(0.0802)		(0.0472)
rainhours	0.0296		0.0212	0.0283		0.0210
	(0.0221)		(0.0130)	(0.0259)		(0.0135)
rainmillimeters	-0.00132		-0.00223	-0.00108		-0.00223
	(0.00702)		(0.00708)	(0.00683)		(0.00683)
pressure	0.190		-0.355**	0.195		-0.356**
	(0.148)		(0.0948)	(0.148)		(0.0948)
humidity	-0.244		-0.0887	-0.263		-0.0923
	(0.172)		(0.105)	(0.169)		(0.103)
N	12714	12714	19793	12714	12714	19793
adj. R-sq	0.870	0.859	0.861	0.870	0.859	0.861

Standard errors between parentheses, *: p-value below 0.1, **: p-value below 0.05 and ***: p-value below 0.01. Daily data was used, standard errors clustered by location, year and month. In every column, fixed effects are added for location and date. In column 1 and 2, treatment 1 is compared to control 3, in column 3, treatment 1 is compared to control 4, in column 4 and 5, treatment 2 is compared to control 6, in column 6, treatment 2 is compared to control 5.

In table 4, it is clear that there seems to be no negative relation between the introduction of the LEZ and the amount of NO_2 in the air, also corrected for weather circumstances. The difference in the coefficient between treatment 1 and treatment 2 is not very big. However, if the treatment includes the two stations just outside the LEZ, the positive relation is not significant anymore. For the weather, only windspeed is always significant. Air pressure and temperature are significant in column 3 and column 6, when all data is used. The reason for this is that there is more variation in weather if Amsterdam is included in the regressions.

The most striking result is that for different specifications, there is a significant positive relation between the introduction of the LEZ and the level of NO_2. As can be read in the related literature section, it could be expected that the effect on NO_2 was small or absent, but a positive effect is a puzzling outcome. Probably this has to do with confounding factors, like highways, the port of Rotterdam or rising amounts of traffic on the roads in the treatment group, because there is no reason for a positive relation and there are limitations to the data because of the small amount of measuring stations. To test for the port of Rotterdam hypothesis, there are regressions with only Rotterdam and only Rotterdam and Vlaardingen in table 5.

The coefficients on treatment 2 are also positive in all regressions, but they are all insignificant. Adding Amsterdam, as in column 4 and 8 of table 5 lowers the coefficients on treatment a little, rendering the one on treatment 1 insignificant.

Table 5: NO_2 using different treatment/control combinations

	1	2	3	4	5	6	7	8
	no2	no2	no2	no2	no2	no2	no2	no2
	T1-C1	T1-C2	T1-C3	T1-C4	T1-C5	T2-C7	T2-C6	T2-C5
treatment1	1.013	1.239*	1.769*	1.275	1.311			
	(0.647)	(0.458)	(0.695)	(0.668)	(0.818)			
treatment2						1.191	1.774	0.854
						(0.716)	(1.019)	(0.846)
windspeed			-0.470**	-0.377**	-0.283**		-0.476**	-0.378**
			(0.113)	(0.0889)	(0.0750)		(0.115)	(0.0902)
temperature			-0.103	-0.137**	-0.160**		-0.114	-0.139**
			(0.0783)	(0.0484)	(0.0496)		(0.0802)	(0.0472)
rainhours			0.0296	0.0212	0.0192		0.0283	0.0210
			(0.0221)	(0.0130)	(0.0137)		(0.0259)	(0.0135)
rainmillimeters			-0.00132	-0.00223	-0.000608		-0.00108	-0.00223
			(0.00702)	(0.00708)	(0.00611)		(0.00683)	(0.00683)
pressure			0.190	-0.355**	-0.431**		0.195	-0.356**
			(0.148)	(0.0948)	(0.133)		(0.148)	(0.0948)
humidity			-0.244	-0.0887	-0.0680		-0.263	-0.0923
			(0.172)	(0.105)	(0.101)		(0.169)	(0.103)
N	7272	9092	12714	19793	16164	9092	12714	19793
adj. R-sq	0.895	0.889	0.870	0.861	0.870	0.889	0.870	0.861

Standard errors between parentheses, *: p-value below 0.1, **: p-value below 0.05 and ***: p-value below 0.01. Daily data were used, standard errors clustered by location, year and month. In every column, fixed effects are added for location and date. In the third row of the table is shown which treatment and which control group are used. The weather data are removed in column 1, 2, and 6 because they are the same for all stations in Rotterdam and are therefore collinear with the date fixed effect.

Also with the specifications in table 5, regression 2 and 3 result in a significant positive effect of treatment on NO_2. Because only Rotterdam and Vlaardingen -which is even closer to the port of Rotterdam- are included in regression 2, changes in emission from the port cannot be the reason the coefficient on treatment is (significantly) positive. There still seem to be confounding factors resulting in the positive effects. The effect on treatment 2 is positive but insignificant using different control groups, Amsterdam still renders the effect on treatment insignificant.

Table 6: NO using different treatment/control combinations

	1	2	3	4	5	6	7	8
	no	no	no	no	no	no	no	no
	T1-C1	T1-C2	T1-C3	T1-C4	T1-C5	T2-C7	T2-C6	T2-C5
treatment1	1.149	1.288**	0.900	0.362	0.167			
	(0.947)	(0.444)	(0.569)	(0.627)	(0.680)			
treatment2						1.000	0.172	-0.426
						(1.040)	(1.116)	(0.678)
windspeed			0.0854	0.0260	0.0682		0.0873	0.0294
			(0.0533)	(0.113)	(0.0930)		(0.0579)	(0.115)
temperature			0.0241	-0.130	-0.205		0.0276	-0.124
			(0.133)	(0.104)	(0.128)		(0.141)	(0.130)
rainhours			-0.0206	0.0270	0.0217		-0.0202	0.0273
			(0.0214)	(0.0336)	(0.0389)		(0.0229)	(0.0403)
rainmillimeters			0.00946	-0.00419	-0.00361		0.00938	-0.00420
			(0.00571)	(0.00463)	(0.00460)		(0.00548)	(0.00465)
pressure			0.116	-0.247	-0.318*		0.114	-0.244
			(0.297)	(0.137)	(0.148)		(0.300)	(0.138)
humidity			0.205	0.147	0.192		0.211	0.157
			(0.262)	(0.194)	(0.223)		(0.265)	(0.199)
N	7273	9093	12718	19799	16170	9093	12718	19799
adj. R-sq	0.797	0.805	0.802	0.774	0.765	0.805	0.802	0.774

Standard errors between parentheses, *: p-value below 0.1, **: p-value below 0.05 and ***: p-value below 0.01. Daily data were used, standard errors clustered by location, year and month. In every column, fixed effects are added for location and date. In the third row of the table is shown which treatment and which control group are used. The weather data are removed in column 1, 2, and 6 because they are the same for all stations in Rotterdam and are therefore collinear with the date fixed effect.

Table 6 is exactly the same as table 5, but for NO, instead of NO_2. Also for NO, there are mostly positive effects, but there is only one significant effect, in regression 2, comparing treatment 1 to control 2. Only one of the weather variables has a significant effect on NO, only pressure in regression 5, comparing treatment 1 to control 5. In column 8, finally a negative coefficient on treatment is visible, but that is far from significant. So also for NO, the conclusion so far must be that I cannot measure an effect.

Table 7: PM_{10} using different treatment/control combinations

	1	2	3	4	5	6	7	8
	pm10	pm10	pm10	pm10	pm10	pm10	pm10	pm10
	T1-C1	T1-C2	T1-C3	T1-C4	T1-C5	T2-C7	T2-C6	T2-C5
treatment1	-0.739	-0.594	-0.566	-0.237	0.0499			
	(0.607)	(0.370)	(0.364)	(0.291)	(0.358)			
treatment2						0.192	-0.0208	0.528
						(0.511)	(0.760)	(0.627)
windspeed			0.0647	0.00834	0.0355		0.0654	0.00680
			(0.0406)	(0.0314)	(0.0409)		(0.0367)	(0.0379)
temperature			0.0667*	0.0703	0.0839		0.0624**	0.0635
			(0.0275)	(0.0466)	(0.0607)		(0.0220)	(0.0530)
rainhours			0.00193	-0.0230*	-0.0332**		0.00203	-0.0231*
			(0.0135)	(0.00964)	(0.00985)		(0.0151)	(0.00892)
rainmillimeters			0.00225	0.00256	0.00363		0.00235	0.00256
			(0.00490)	(0.00422)	(0.00280)		(0.00501)	(0.00278)
pressure			-0.277	0.0334	0.0956		-0.273	0.0304
			(0.162)	(0.0620)	(0.0803)		(0.162)	(0.0564)
humidity			-0.0700	-0.00437	0.0405		-0.0790	-0.0175
			(0.0891)	(0.0600)	(0.0815)		(0.0847)	(0.0656)
N	6666	7901	10385	13948	10343	7901	10385	13948
adj. R-sq	0.912	0.886	0.878	0.880	0.881	0.886	0.877	0.880

Standard errors between parentheses, *: p-value below 0.1, **: p-value below 0.05 and ***: p-value below 0.01. Daily data were used, standard errors clustered by location, year and month. In every column, fixed effects are added for location and date. In the third row of the table is shown which treatment and which control group are used. The weather data are removed in column 1, 2, and 6 because they are the same for all stations in Rotterdam and are therefore collinear with the date fixed effect.

PM_{10} seems to be a bit more dependent on rain than NO_2 and NO. As opposed to what was predicted by Juda-Rezler et al. (2011), air pressure does not have a significant effect. There is also a small negative relation between the introduction of the LEZ and the level of PM_{10} in the air, although it is not significant in any of the regression specifications.
Of course, one should take into account that there are some locations that do not measure PM_{10} and that some locations have started measuring it later than 2013 (see table 1 in section 5 for the details). Table 7 is a too small basis to conclude that the LEZ has a negative effect on the amount of PM_{10}, but there is some indication. Comparing treatment 1 to control 5 (which means the stations within the LEZ compared to all stations, except Pleinweg and Zwartewaalstraat) results in a coefficient that is very close to zero. It seems that PM_{10} has gone down most in treatment 1 compared to control 1 (which is the same as the difference between treatment 1 and treatment 2). This can therefore also be concluded from the fact that treatment 2 has very far from significant results. The effect on PM_{10} is therefore not only too small to conclude that there is an effect, it is also ambiguous.

6.1 Analysis

These results pose the question why there is no measured effect of the Low Emission Zone on air quality. There are various possible reasons for this. These can be classified in two different categories. The first category is reasons why there really is no effect of the LEZ on the pollution variables used in this thesis. The second category is reasons why there is no measured effect, while there might be an effect in reality.

There are two reasons why there really could be no effect on NO_2, NO and PM_{10}. The first is that these are not the right values to measure. Malina & Scheffler (2015) argue that NO_2 is indeed not the best pollution variable to use. The municipality of Rotterdam also states that these might not be the right variables (Gemeente Rotterdam, 2018). It states that elementary carbon is the best form of pollution to use as an outcome variable. Another reason for the absence of an effect is that older cars do not influence pollution much. Traffic is only a part of pollution and these cars are only a small part of traffic. So it might be that the LEZ should be stricter to generate an effect.

There are many reasons why there is no measured effect, but there could be an effect in reality, all of them amounting to shortcomings in the data. The first and most likely reason for not measuring an effect is that there are too few measuring stations. Other things causing pollution close to a measuring station alter the results significantly, while they do not have a large effect on pollution in the LEZ as a whole. In this case, that might be going on. In column 1 of appendix table 4, there is a significant positive effect measured from the LEZ on NO_2, if only the high traffic stations are taken into account. This might mean that the Statenweg deviates from the trend, which causes unreliable results.
Another possibility for the lack of a measured effect is a kind of anticipation effect. (Part of) the real effect had taken place before the implementation of the LEZ. Theoretically, this could be tested using the announcement date as the start of treatment, but before the LEZ was announced, the demolition scheme had been in place, which foreboded the LEZ. It is therefore not clear what date can be used as alternative starting date, which makes it impossible to test for anticipation effects.

6.2 Robustness checks

To test for the robustness of the results (or the lack of results) some robustness checks were done, as can be seen in Appendix 2, in tables 3, 4 and 5.
In appendix table 3, some regressions were done using the natural logarithm of the pollutants. Possibly the results are more a relative change than a change in the level. Almost all regressions still did not have a significant coefficient on treatment. Only treatment 1 has a significant negative effect on PM_{10}, which would mean that PM_{10} has gone down by 1.36% within the LEZ, compared to all other

measuring stations. However, based on only this specification, this far from certain.

As briefly mentioned in the previous subsection, a robustness check was done comparing only stations alongside busy roads (which stations these are can be found in table 1). The estimations that were done using this subsample can be found in appendix table 4. The advantage of this is that these stations are relatively more influenced by traffic, so the effect should be bigger, if there really is an effect. The very large disadvantage of this specification is that there are only 6 measuring stations left and only 1 station in treatment 1. Using this specification does not alter the results a large margin, except for the significant positive effect of treatment 1 on NO_2, which has probably to do with confounding factors close to the Statenweg.

Because negative values for the different pollution measures are unreasonable, there is also a robustness check done excluding these negative values. This can be found in appendix table 5. It did not change the results.

7. Conclusion

This thesis evaluates the Low Emission Zone in Rotterdam, using measured data on NO_2, NO and PM_{10}. This is done using the difference in differences strategy, with different treatment groups and control groups. Weather related control variables were taken into account. The different specifications of the treatment and control groups did not yield any result on all these air quality measures. This could be because the effect is very minimal, but it could also be because there are not enough stations measuring NO_2, NO and PM_{10}. But as stated in section 2, it could very well be that there really is not much of an effect on NO_2, because cars have not improved very much regarding the NO_2 emission levels (Gemeente Rotterdam, 2018; Holman et al., 2015). Therefore, the conclusion must be that it is possible that there is an effect that could not be measured the way it is done in this thesis, but that it is not likely this effect is very substantial. It is also possible that the effect of the LEZ partly took place before the actual introduction of the zone, because of the demolition scheme mentioned in section 3.6.

The difference between the lack of results from this thesis and the significant results from Malina & Scheffler (2015) has two important reasons. Firstly, they evaluated many LEZs simultaneously, so they had a lot more differentiation in measuring stations. The second reason is that they included traffic volume in the regression. I mentioned the disadvantage of this, but it might be good to also evaluate the LEZ including traffic volume.

This leads to some recommendations for future research. To be able to conduct a good difference in differences analysis, more measuring stations are needed. Only two stations within the LEZ and two just outside of it is not enough to estimate a precise effect. Also the stations are mostly meant to compare busy streets to the city background, instead of comparing streets that are much like each other. So to be able to conduct a better difference in differences analysis, it would be good to measure air quality data at more locations, and find locations that are comparable to each other in amount of traffic. If something happens close to those stations that could influence pollution, it should be clearly documented, so researches can control for this. I also recommend measuring elementary carbon, as the effect on elementary carbon is claimed to be higher than the effect on NO_2 and PM_{10} (Gemeente Rotterdam, 2018).

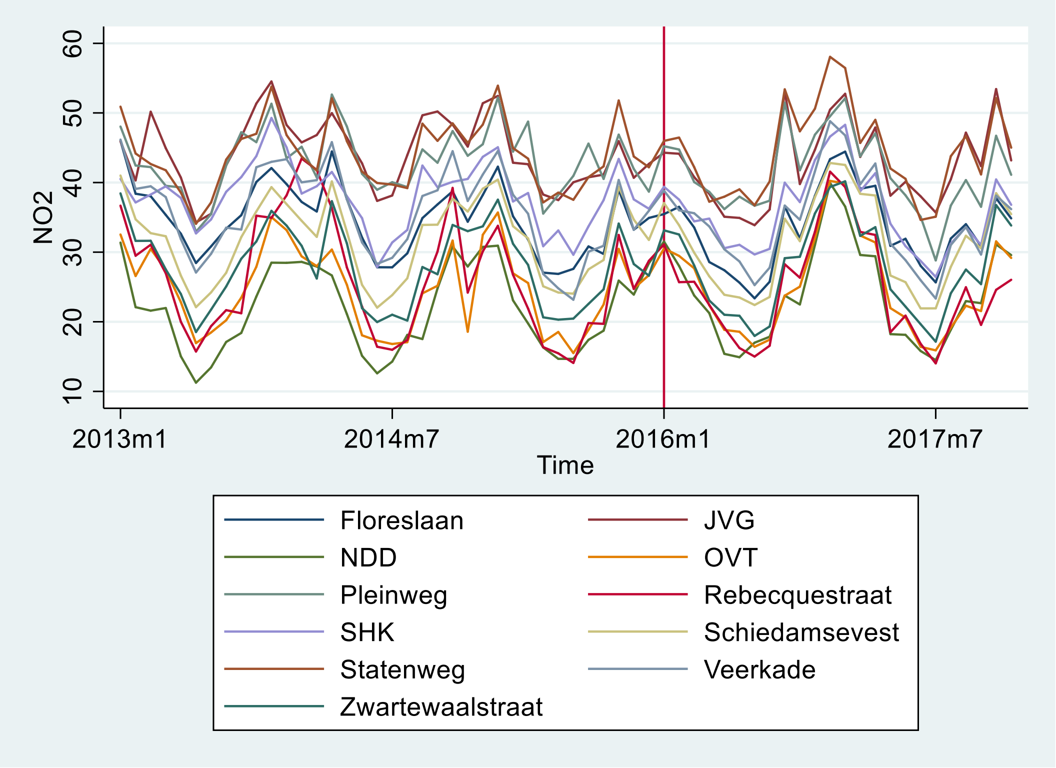
Another possibility, combined with measuring at more locations, is to conduct an experiment. In a sample of comparable cities, LEZs should be introduced, after which the cities with and without LEZs can be compared to each other. For this cooperation is needed on the national level or even at the European level, so it can be hard to do it, but I think it is not impossible.

Even if there is an effect of the LEZ on air quality, this does not necessarily mean that the LEZ is a good

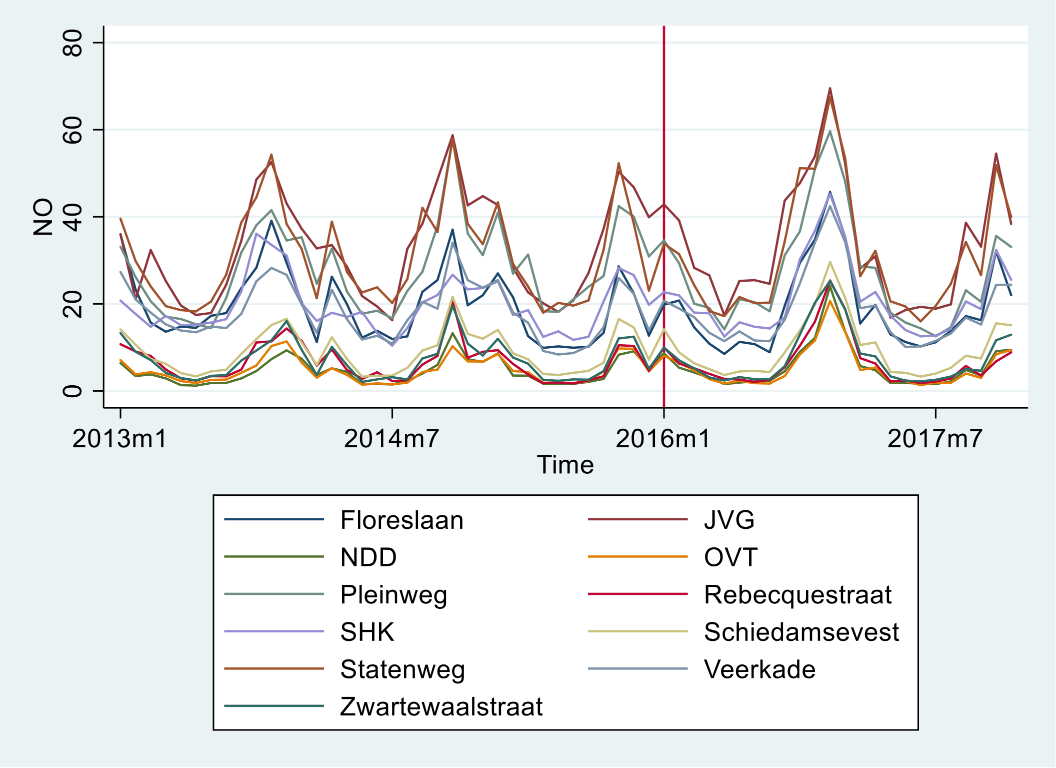
idea. A cost benefit analysis should be done weighing the costs and benefits of the LEZ. There also might be other air quality measures that cost less and have the same effect. An LEZ can have adverse effects, for example for the transportation sector (Cruz & Montenon, 2016).
This thesis does not have reliable enough results to give clear policy recommendations, other than the call for more research. The careful recommendation I can give is that there should be thought about other ways to improve air quality in cities, because LEZs might not have the intended result, especially on NO_x.

Appendix 1: extra figures

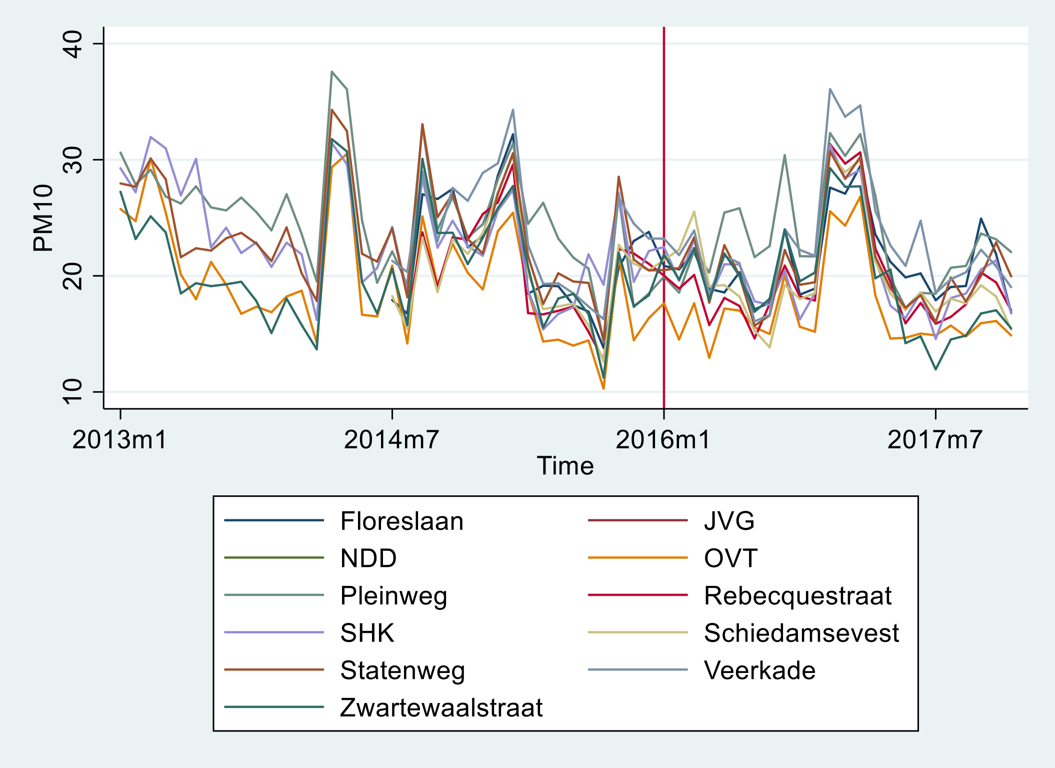
Appendix figure 1: NO$_2$ per station



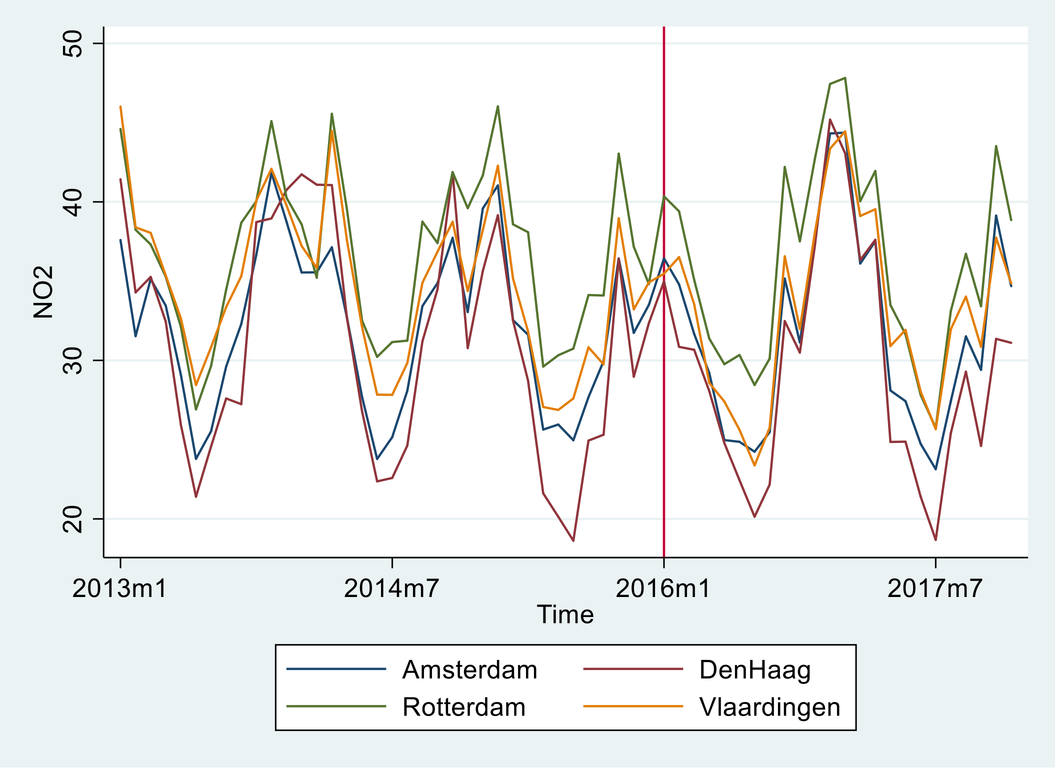
Appendix figure 2: NO per station



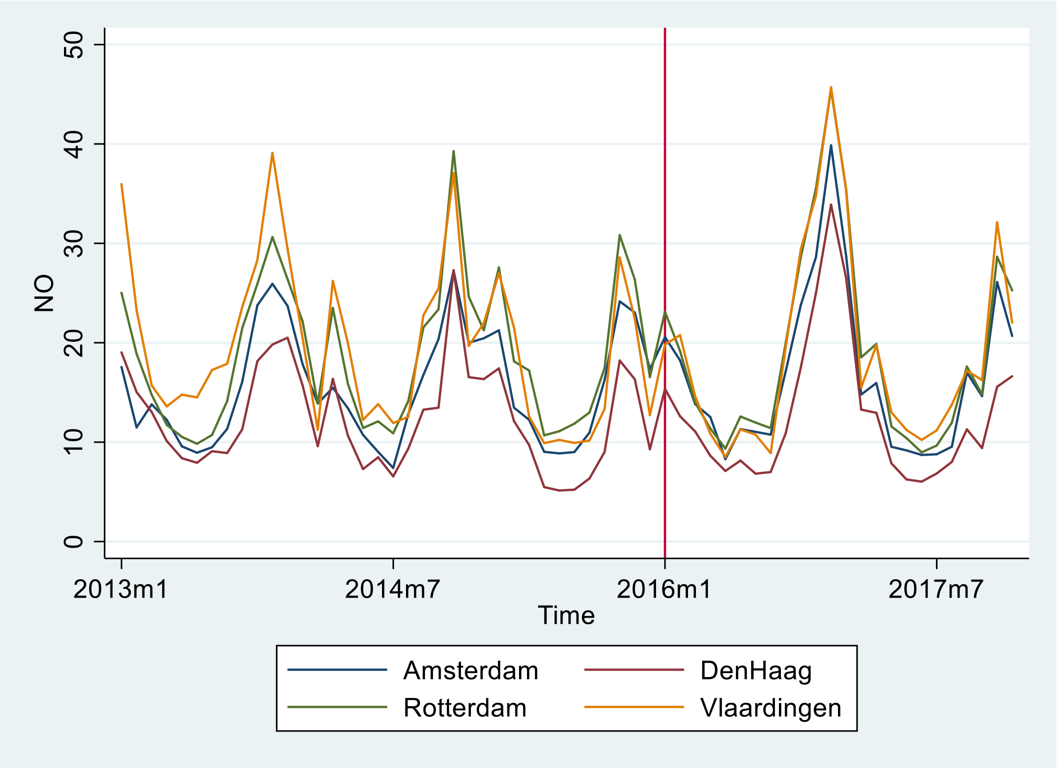
Appendix figure 3: PM$_{10}$ per station



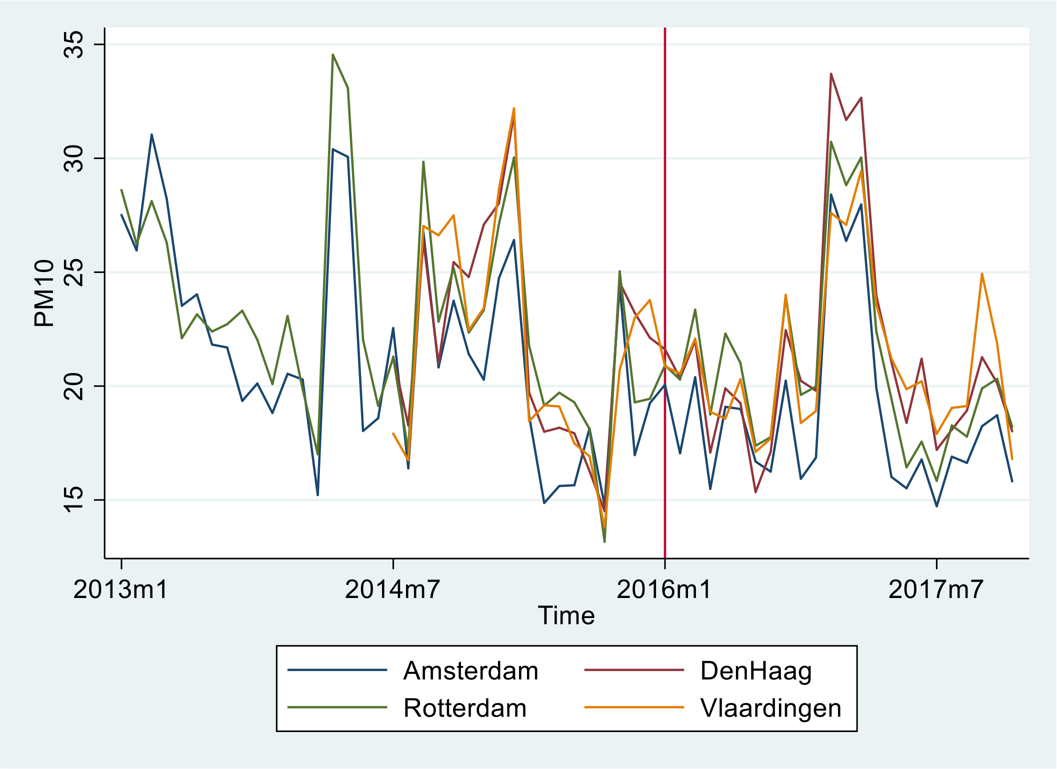
Appendix figure 4: NO$_2$ per city



Appendix figure 5: NO per city



Appendix figure 6: PM$_{10}$ per city



Appendix 2: extra regression tables

Appendix table 1: hourly data, different fixed effects

	1 no2	2 no2	3 no2	4 no2	5 no2	6 no2
	T1-C3	T1-C3	T1-C3	T1-C3	T1-C3	T2-C6
treatment1	1.671*	1.682*	1.586	1.569**	1.580**	
	(0.656)	(0.655)	(0.893)	(0.604)	(0.602)	
treatment2						1.601
						(0.979)
windspeed	-0.391***	-0.391***	-0.319***	-0.423***	-0.423***	-0.393***
	(0.0541)	(0.0543)	(0.0306)	(0.0288)	(0.0289)	(0.0545)
temperature	-0.0309	-0.0307	-0.0706***	0.0527**	0.0526**	-0.0322
	(0.0229)	(0.0231)	(0.0120)	(0.0170)	(0.0170)	(0.0236)
rainhours	0.000918	0.000937	-0.0301**	-0.0190	-0.0190	0.000684
	(0.0102)	(0.0102)	(0.0116)	(0.0118)	(0.0119)	(0.0107)
rainmillimeters	0.00622	0.00629	-0.00460	0.00774	0.00774	0.00637
	(0.00320)	(0.00325)	(0.00679)	(0.00435)	(0.00432)	(0.00336)
pressure	-0.0271***	-0.0271***	-0.0109	-0.00999	-0.01000	-0.0274**
	(0.00565)	(0.00565)	(0.00549)	(0.00504)	(0.00497)	(0.00690)
humidity	-0.0921	-0.0922	0.261**	0.0652	0.0651	-0.0937
	(0.0900)	(0.0903)	(0.0882)	(0.0571)	(0.0571)	(0.0901)
Location FE	Yes	Yes	Yes	Yes	Yes	Yes
Date FE	Yes	Yes	No	No	No	Yes
Hour FE	No	Yes	No	No	Yes	No
Year FE	No	No	Yes	Yes	Yes	No
Month FE	No	No	No	Yes	Yes	No
Weekday FE	No	No	No	Yes	Yes	No
N	301178	301178	301178	301178	301178	301178
adj. R-sq	0.491	0.532	0.256	0.340	0.380	0.491

Standard errors in parentheses: * p<0.1, ** p<0.05, *** p<0.01. All standard errors are clustered by location, year and month. In the third row of the table is shown which treatment and which control group are used. Because this table is about experimenting with fixed effects, extra rows are added showing which fixed effects are included.

Appendix table 2: daily data, different fixed effects

	1	2	3	4
	no2	no2	no2	no2
	T1-C3	T1-C3	T1-C3	T2-C6
treatment1	1.769*	1.588	1.593*	
	(0.695)	(0.930)	(0.650)	
treatment2				1.774
				(1.019)
windspeed	-0.470**	-0.311***	-0.414***	-0.476**
	(0.113)	(0.0306)	(0.0289)	(0.115)
temperature	-0.103	-0.0693***	0.0545**	-0.114
	(0.0783)	(0.0121)	(0.0178)	(0.0802)
rainhours	0.0296	-0.0295*	-0.0179	0.0283
	(0.0221)	(0.0120)	(0.0122)	(0.0259)
rainmillimeters	-0.00132	-0.00567	0.00659	-0.00108
	(0.00702)	(0.00687)	(0.00475)	(0.00683)
pressure	0.190	-0.0105	-0.00936	0.195
	(0.148)	(0.00559)	(0.00500)	(0.148)
humidity	-0.244	0.273**	0.0812	-0.263
	(0.172)	(0.0898)	(0.0593)	(0.169)
Location FE	Yes	Yes	Yes	Yes
Date FE	Yes	No	No	Yes
Year FE	No	Yes	Yes	No
Month FE	No	No	Yes	No
Weekday FE	No	No	Yes	No
N	12714	12714	12714	12714
adj. R-sq	0.870	0.455	0.606	0.870

Standard errors in parentheses: * p<0.1, ** p<0.05, *** p<0.01. All standard errors are clustered by location, year and month. In the third row of the table is shown which treatment and which control group are used. Because this table is about experimenting with fixed effects, extra rows are added showing which fixed effects are included.

The point of including these two tables is twofold. First, it shows that including location and date fixed effects seems not to give very strange results, comparing it to other fixed effects. Because it obviously makes full use of the time dimension, it is best to use that as fixed effect, as to compare only differences on the same day. Also these tables are included to show that using hourly data does not provide extra information. Adding an extra fixed effect for hour does not alter the results much.

Also the coefficients for daily data are very much like the ones for hourly data. Appendix table 2 uses regression specifications and treatment/control combinations that are the same as in appendix table 1. Column 1 of appendix table 2 is the same as column 1 of appendix table 1. Column 2 of table 2 is the same as column 3 in table 1, column 3 of table 2 is the same as column 4 in table 1 and column 4 in table 2 is the same as column 6 in table 1.

Appendix table 3: logarithmic outcome variables for all three pollutants

	1 logno2	2 logno2	3 logno	4 logno	5 logpm10	6 logpm10
	T1-C4	T2-C5	T1-C4	T2-C5	T1-C4	T2-C5
treatment1	0.0332		0.0240		-0.0136**	
	(0.0260)		(0.0344)		(0.00362)	
treatment2		0.0280		-0.00882		0.0372
		(0.0317)		(0.0390)		(0.0348)
windspeed	-0.0170**	-0.0171**	-0.00547	-0.00535	0.000333	0.000228
	(0.00501)	(0.00504)	(0.00676)	(0.00679)	(0.00167)	(0.00196)
temperature	-0.00449**	-0.00459**	-0.00515	-0.00496	0.00431	0.00385
	(0.00157)	(0.00154)	(0.00441)	(0.00459)	(0.00262)	(0.00256)
rainhours	0.000746	0.000740	0.000916	0.000925	-0.00125***	-0.00126**
	(0.000591)	(0.000599)	(0.00121)	(0.00119)	(0.000264)	(0.000331)
rainmillimeters	-0.000144	-0.000143	-0.000312	-0.000313	0.000146	0.000146
	(0.000256)	(0.000264)	(0.000425)	(0.000552)	(0.000167)	(0.000136)
pressure	-0.0126*	-0.0127*	-0.000879	-0.000777	0.00399	0.00378
	(0.00559)	(0.00560)	(0.0162)	(0.0162)	(0.00557)	(0.00429)
humidity	-0.00201	-0.00220	0.0105	0.0108	0.000261	-0.000628
	(0.00432)	(0.00446)	(0.00967)	(0.00956)	(0.00360)	(0.00292)
N	19793	19793	19777	19777	13947	13947
adj. R-sq	0.842	0.842	0.862	0.862	0.852	0.852

Standard errors between parentheses, *: p-value below 0.1, **: p-value below 0.05 and ***: p-value below 0.01. Daily data were used, standard errors clustered by location, year and month. In every column, fixed effects are added for location and date. In the third row of the table is shown which treatment and which control group are used. The columns can be compared to columns 4 and 6 of table 5, 6 and 7 respectively.

Appendix table 4: only street stations

	1	2	3	4	5	6
	no2	no2	no	no	pm10	pm10
	T1-C4	T2-C5	T1-C4	T2-C5	T1-C4	T2-C5
treatment1	2.591***		0.287		-0.464	
	(0.0630)		(0.158)		(0.443)	
treatment2		1.449		-0.993		0.182
		(1.139)		(0.940)		(0.369)
windspeed	-0.362**	-0.363**	-0.00673	-0.00132	0.0202	0.0191
	(0.0927)	(0.0883)	(0.210)	(0.180)	(0.0458)	(0.0602)
temperature	-0.0689	-0.0702	-0.160	-0.151	0.0823	0.0787
	(0.0555)	(0.0463)	(0.200)	(0.273)	(0.0602)	(0.0578)
rainhours	0.0206	0.0205	0.0249	0.0253	-0.0316	-0.0318
	(0.0239)	(0.0172)	(0.0411)	(0.0481)	(0.0189)	(0.0169)
rainmillimeters	0.000153	0.000154	-0.00358	-0.00361	0.00585	0.00585
	(0.00860)	(0.00587)	(0.00969)	(0.00437)	(0.00343)	(0.00378)
pressure	-0.339**	-0.340**	-0.344	-0.340	0.00561	0.00320
	(0.0898)	(0.0866)	(0.236)	(0.237)	(0.0765)	(0.0746)
humidity	-0.113	-0.116	0.229	0.246	-0.0128	-0.0195
	(0.125)	(0.0902)	(0.289)	(0.294)	(0.0776)	(0.0731)
N	10806	10806	10807	10807	7876	7876
adj. R-sq	0.850	0.849	0.798	0.798	0.855	0.855

Standard errors between parentheses, *: p-value below 0.1, **: p-value below 0.05 and ***: p-value below 0.01. Daily data were used, standard errors clustered by location, year and month. In every column, fixed effects are added for location and date. In the third row of the table is shown which treatment and which control group are used. The columns can be compared to columns 4 and 6 of table 5, 6 and 7 respectively. Only 6 measuring stations are used for these regressions. Treatment 1 is only one station in this case.

Appendix table 5: negative outcome variables removed

	1	2	3	4	5	6
	no2	no2	no	no	pm10	pm10
	T1-C4	T2-C5	T1-C4	T2-C5	T1-C4	T2-C5
treatment1	1.275		0.365		-0.239	
	(0.668)		(0.626)		(0.291)	
treatment2		0.854		-0.423		0.526
		(0.846)		(0.680)		(0.626)
windspeed	-0.377**	-0.378**	0.0268	0.0302	0.00795	0.00641
	(0.0889)	(0.0902)	(0.113)	(0.116)	(0.0313)	(0.0379)
temperature	-0.137**	-0.139**	-0.130	-0.124	0.0703	0.0635
	(0.0484)	(0.0472)	(0.104)	(0.130)	(0.0466)	(0.0530)
rainhours	0.0212	0.0210	0.0270	0.0273	-0.0229*	-0.0230*
	(0.0130)	(0.0135)	(0.0338)	(0.0404)	(0.00949)	(0.00877)
rainmillimeters	-0.00223	-0.00223	-0.00417	-0.00418	0.00253	0.00253
	(0.00708)	(0.00683)	(0.00464)	(0.00466)	(0.00421)	(0.00277)
pressure	-0.355**	-0.356**	-0.246	-0.243	0.0333	0.0304
	(0.0948)	(0.0948)	(0.137)	(0.138)	(0.0620)	(0.0564)
humidity	-0.0887	-0.0923	0.148	0.158	-0.00452	-0.0176
	(0.105)	(0.103)	(0.194)	(0.200)	(0.0603)	(0.0657)
N	19793	19793	19783	19783	13947	13947
adj. R-sq	0.861	0.861	0.774	0.774	0.880	0.880

Standard errors between parentheses, *: p-value below 0.1, **: p-value below 0.05 and ***: p-value below 0.01. Daily data were used, standard errors clustered by location, year and month. In every column, fixed effects are added for location and date. In the third row of the table is shown which treatment and which control group are used. The columns can be compared to columns 4 and 6 of table 5, 6 and 7 respectively.

References

Anderson, H. ., Atkinson, R., Peacock, J., Marston, L., & Konstantinou, K. (2004). Meta-analysis of time-series studies and panel studies of particulate matter (PM) and ozone (O3). *Report of a WHO Task Group*, 1–68. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Meta-analysis+of+time-series+studies+and+panel+studies+of+Particulate+Matter+(+PM+)+and+Ozone+(+O+3+)#0

Anderson, H. R. (2009). Air pollution and mortality: A history. *Atmospheric Environment*, *43*(1), 142–152. https://doi.org/10.1016/j.atmosenv.2008.09.026

Bel, G., Bolancé, C., Guillén, M., & Rosell, J. (2015). The environmental effects of changing speed limits: A quantile regression approach. *Transportation Research Part D: Transport and Environment*, *36*, 76–85. https://doi.org/10.1016/j.trd.2015.02.003

Bel, G., & Holst, M. (2018). Evaluation of the impact of Bus Rapid Transit on air pollution in Mexico City. *Transport Policy*, *63*(November 2017), 209–220. https://doi.org/10.1016/j.tranpol.2018.01.001

Bel, G., & Rosell, J. (2013). Effects of the 80km/h and variable speed limits on air pollution in the metropolitan area of barcelona. *Transportation Research Part D: Transport and Environment*, *23*, 90–97. https://doi.org/10.1016/j.trd.2013.04.005

Byrd, T., Stack, M., & Furey, A. (2009). The assessment of the presence and main constituents of particulate matter ten microns (PM10) in Irish, rural and urban air. *Atmospheric Environment*, *44*(1), 75–87. https://doi.org/10.1016/j.atmosenv.2009.09.037

Cesaroni, G., Boogaard, H., Jonkers, S., Porta, D., Badaloni, C., Cattani, G., … Hoek, G. (2012). Health benefits of traffic-related air pollution reduction in different socioeconomic groups: The effect of low-emission zoning in Rome. *Occupational and Environmental Medicine*, *69*(2), 133–139. https://doi.org/10.1136/oem.2010.063750

Charron, A., Harrison, R. M., & Quincey, P. (2007). What are the sources and conditions responsible for exceedences of the 24 h PM10limit value (50 µg m-3) at a heavily trafficked London site? *Atmospheric Environment*, *41*(9), 1960–1975. https://doi.org/10.1016/j.atmosenv.2006.10.041

Chay, K. Y., & Greenstone, M. (2003). Mortality: Evidence From Geographic. *Quarterly Journal of Economics*, *118*(3), 1121–1167. https://doi.org/10.1162/00335530360698513

Crouse, D. L., Peters, P. A., Hystad, P., Brook, J. R., van Donkelaar, A., Martin, R. V., … Burnett, R. T. (2015). Ambient PM2.5, O3, and NO2exposures and associations with mortality over 16 years of follow-up in the canadian census health and environment cohort (CanCHEC). *Environmental Health Perspectives*, *123*(11), 1180–1186. https://doi.org/10.1289/ehp.1409276

Cruz, C., & Montenon, A. (2016). Implementation and Impacts of Low Emission Zones on Freight Activities in Europe: Local Schemes Versus National Schemes. *Transportation Research Procedia*, *12*(June 2015), 544–556. https://doi.org/10.1016/j.trpro.2016.02.010

Driscoll, J. C., & Kraay, A. C. (1998). Consistent Covariance Matrix Estimation with Spatially Dependent Panel Data. *Economic Systems Research*, *10*(4), 307–324. https://doi.org/10.1016/S0099-1767(98)90076-9

Ellison, R. B., Greaves, S. P., & Hensher, D. A. (2013). Five years of London's low emission zone: Effects on vehicle fleet composition and air quality. *Transportation Research Part D: Transport and Environment*, *23*, 25–33. https://doi.org/10.1016/j.trd.2013.03.010

Fensterer, V., Küchenhoff, H., Maier, V., Wichmann, H. E., Breitner, S., Peters, A., … Cyrys, J. (2014).

Evaluation of the impact of low emission zone and heavy traffic ban in Munich (Germany) on the reduction of PM10 in ambient air. *International Journal of Environmental Research and Public Health*, *11*(5), 5094–5112. https://doi.org/10.3390/ijerph110505094

Fuller, G. W., & Green, D. (2006). Evidence for increasing concentrations of primary PM10 in London. *Atmospheric Environment*, *40*(32), 6134–6145. https://doi.org/10.1016/j.atmosenv.2006.05.031

Gemeente Rotterdam. (2015). Schone lucht, voor een aantrekkelijk en gezond Rotterdam 2015 - 2018. Koersnota.

Gemeente Rotterdam. (2016). Beleidsregels en ontheffingenbesluit ontheffingen Milieuzone Rotterdam 2016, wijziging 1 [Besluit]. *Gemeenteblad 55682*, (55682), 1–15.

Gemeente Rotterdam. (2017). Gemeente Rotterdam - Verkeersbesluit [Besluit]. *Staatscourant 45491*, (45491), 13–15.

Gemeente Rotterdam. (2018). *Vervolg - evaluatie Koersnota Luchtkwaliteit*.

Hoechle, D. (2007). Robust standard errors for panel regressions with cross-sectional dependence. *Stata Journal*, *7*(3), 281–312. https://doi.org/The Stata Journal

Holman, C., Harrison, R., & Querol, X. (2015). Review of the efficacy of low emission zones to improve urban air quality in European cities. *Atmospheric Environment*, *111*, 161–169. https://doi.org/10.1016/j.atmosenv.2015.04.009

Hoyos, R. E. De, & Sarafidis, V. (2006). Testing for Cross-section Dependence in Panel Data Models. *The Stata Journal*, *6*(4), 482–496. https://doi.org/The Stata Journal

Jayachandran, S. (2008). *Air quality and early-life mortality: evidence from Indonesia's wildfires*.

Jones, A. M., Harrison, R. M., Barratt, B., & Fuller, G. (2012). A large reduction in airborne particle number concentrations at the time of the introduction of " sulphur free" diesel and the London Low Emission Zone. *Atmospheric Environment*, *50*, 129–138. https://doi.org/10.1016/j.atmosenv.2011.12.050

Juda-Rezler, K., Reizer, M., & Oudinet, J. P. (2011). Determination and analysis of PM10 source apportionment during episodes of air pollution in Central Eastern European urban areas: The case of wintertime 2006. *Atmospheric Environment*, *45*(36), 6557–6566. https://doi.org/10.1016/j.atmosenv.2011.08.020

Kampa, M., & Castanas, E. (2008). Human health effects of air pollution. *Environmental Pollution*, *151*(2), 362–367. https://doi.org/10.1016/j.envpol.2007.06.012

Krzyzanowski, M., & Cohen, A. (2008). Update of WHO air quality guidelines. *Air Quality, Atmosphere and Health*, *1*(1), 7–13. https://doi.org/10.1007/s11869-008-0008-9

Lenschow, P., Abraham, H. J., Kutzner, K., Lutz, M., Preuß, W., & Reichenbächer, W. (2001). Some ideas about the sources of PM10. *Atmospheric Environment*, *35*(1), 23–33. https://doi.org/10.1016/S1352-2310(01)00122-4

Lonati, G., Giugliano, M., & Cernuschi, S. (2006). The role of traffic emissions from weekends' and weekdays' fine PM data in Milan. *Atmospheric Environment*, *40*(31), 5998–6011. https://doi.org/10.1016/j.atmosenv.2005.12.033

Malina, C., & Scheffler, F. (2015). The impact of Low Emission Zones on particulate matter concentration and public health. *Transportation Research Part A: Policy and Practice*, *77*, 372–385. https://doi.org/10.1016/j.tra.2015.04.029

Qadir, R. M., Abbaszade, G., Schnelle-Kreis, J., Chow, J. C., & Zimmermann, R. (2013). Concentrations and source contributions of particulate organic matter before and after implementation of a low emission zone in Munich, Germany. *Environmental Pollution*, *175*(2), 158–167. https://doi.org/10.1016/j.envpol.2013.01.002

Tanaka, S. (2015). Environmental regulations on air pollution in China and their impact on infant mortality. *Journal of Health Economics*, *42*, 90–103. https://doi.org/10.1016/j.jhealeco.2015.02.004

Van Benthem, A. (2015). What is the optimal speed limit on freeways? *Journal of Public Economics*, *124*, 44–62. https://doi.org/10.1016/j.jpubeco.2015.02.001

Wooldridge, J. M. (2015). *Introductory Econometrics* (6th ed.). Boston, MA: Cengage Learning.

World Health Organization. (2016). *Ambient Air Pollution: A global assessment of exposure and burden of disease*. *World Health Organization*. https://doi.org/9789241511353