UNIVERSITY OF GOTHENBURG
SCHOOL OF BUSINESS, ECONOMICS AND LAW

Low emission zones in Sweden – Evidence from Uppsala

Author: Herman Andersson

Abstract:

High pollution levels have been a problem in many cities in the world. The high pollution levels affect public health and create high social and economic costs. In Sweden alone, the estimated number of premature deaths associated with air pollution was equal to 7,600 in 2015. One way of tackling the problem is the so-called low emission zones that prohibit the oldest and dirtiest vehicles from entering the most polluted areas of the cities. This thesis aims to investigate the effect of low emission zones using a difference in difference model for the city of Uppsala. Since nitrogen dioxide has been the main air pollutant target for Swedish cities, the analysis focuses on the nitrogen dioxide concentration. The results indicate that low emission zones in Uppsala do not seem to have an effect. This is to say, the low emission zone has failed to deliver on the policy target of lowering the nitrogen dioxide concentration.

Supervisor: Jessica Coria
Master's thesis in Economics, 30 hec
Spring 2019
Graduate School, School of Business, Economics and Law, University of Gothenburg, Sweden

Acknowledgements

I would first and foremost like to take this opportunity to show the sincerest gratitude to my supervisor Jessica Coria, for her support and valuable feedback throughout the process of the thesis. I would further like to thank Sara Andersson at the municipality of Uppsala for answering all my questions and providing the information needed from the municipality. I would also like to thank Joakim Viberg, spokesperson at the Swedish Association for Road Transport Companies, for taking the time to answer all my questions. Last but not least, I would like to thank my fellow students Annabelle Moine, David Schönfelder, Natalia Vdovina and Nguyen Cao for the support and motivation during the thesis. I could not have done it without you.

Table of content

1 Introduction 4
2 Background 7
2.1 Low emission zones in Sweden 7
3 Literature review 11
3.1 Changes in the vehicle fleet 11
3.2 Effect on air pollution 12
4 Economic theory 14
4.1 First best and emissions tax 15
4.2 Low emission zone and second-best 15
4.3 Low emission zone vs traffic tolls. 17
4.4 Situation in Uppsala 19
4.4 Hypothesis 19
5 Methodology 20
5.1 Changes in traffic volume 20
5.2 The effect of weather 20
5.3 Estimation strategy 21
5.4 Model specification 27
5.5 Data and descriptive statistics 28
6 Results 29
6.1 Altering the time period 32
6.2 Wind direction 33
6.3 Discussion 35
7 Conclusions 39
Sources: 40
Appendix 44
A1 regressions 44
A2 Tables 45

1 Introduction

Concerns about high levels of air pollution have increased in recent decades. The negative health effect from air pollution is well documented in the literature (see for example Dockery at al. (1993); Pope at al. (2002); Chay and Greenstone, 2003). Gustafsson et al. (2018) estimate that in Sweden alone the total number of premature deaths associated with increased levels of air pollution was equal to 7,600 in 2015. The authors further estimate that the socioeconomic cost associated with nitrogen oxides (NOx) and particle matters smaller than 2.5 micrometres (PM2.5) was 56 billion Swedish kronor for the same year.

Due to the significant negative health impact of air pollution, the pressure from the public and regulatory authorities to improve air quality has increased. The Clean Air Directive from the European Union made it mandatory for cities in the member states to limit emissions of particulate matter smaller than 10 micrometres (PM10) and nitrogen dioxide (NO_2) (European Parliament and Council Directive 2008/50/EC). The directive also opened the possibility of financial penalties for cities that did not meet the minimum requirements for air quality (see Wolff and Perry (2010) for further details about the European Clean Air Directive).

To tackle the high levels of air pollution and improve public health have several policy alternatives have been developed. One of the more radical policy options is to prohibit the oldest and dirtiest vehicles from entering the central parts of the cities in so-called low emission zones. The idea behind the zones is that new vehicles have lower emissions from using newer and cleaner technology. New and improved emission technology will be implemented slowly with the natural replacement rate. The low emission speeds up the process by prohibiting the oldest vehicles from entering the city centre. The benefit of new technology will, therefore, be moved forward in time. In other words, the average age (and emissions) of the vehicles within the zone will decrease, and the benefits from cleaner vehicles will come faster. The purpose of this thesis is to empirically evaluate if the low emission zone has influenced the pollution levels.

The regulations for low emissions differ between countries and over time. In Sweden, heavy vehicles over 3.5 tonnes are affected by the low emission zone. In Germany, lighter vehicles such as cars are also included. Swedish low emission zones are regulated through a national framework that makes the regulations equal within the country. Hence, it is not possible for one Swedish city to differ from another (Holman et al. 2015). The main rule in Sweden is that vehicles older than six years from the first registration date are not allowed to enter the zone. For vehicles with Euro III[1] engines or higher, the main rule is extended to eight years after the first registration (SFS 1998:1276. 4 chap. 22-23§).

---

[1] The Euro class system regulates the emission level from vehicle engines on the European market. See section 2 for definition and discussion.

The first low emission zones were implemented in Stockholm, Gothenburg and Malmö in 1996 under the name environmental zone (miljözon). Since 1996 the policy has spread to over 200 European cities (see www.urbanaccessregulations.eu for complete list). Besides the three first cities, Swedish cities like Lund (in 1999), Helsingborg (in 2008), Uppsala (in 2013), Umeå (in 2014) and Mölndal (in 2015) have implemented the policy. In the European cities, the primary target for the low emission zone has been to lower the concentration of particulate matter and in some cases, nitrogen oxides (Holman et al. 2015). Interestingly, it seems like the policy target has been the reverse in many of the Swedish cities, with focus on lowering the nitrogen dioxide levels. An explanation of the focus could be that complying with the Clean Air Directive for nitrogen dioxide has been a problem for several Swedish cities. When previous policies have not been effective, low emission zones have been a policy alternative for lower emission levels. (see, e.g. County Administrative Board of Skåne, 2009; Umeå municipality, 2012; Uppsala municipality, 2014). The focus of this thesis will, therefore, be on low emissions zones' effect on nitrogen dioxide.

The discussion about low emission zones was actualised in 2018 when the Swedish government announced that municipalities will get the opportunity to include vehicles smaller than 3.5 tonnes from 2020 (Swedish government, 2018). The debate has been intense, and the tone has occasionally been sharp. A problem in the academic and public debate is the lack of knowledge of the effects of low emission zones. Even though low emission zones have been in effect since 1996, there are only a limited number of studies that have documented the effects on pollutions levels in Sweden. Given the sizeable adverse health effects of emissions, there is a need for further research on this subject.

For low emissions zones in Sweden, three relevant studies have been found. Rapaport (2002) and City of Stockholm (2008) evaluate the effect in Stockholm using simulation modelling. City of Gothenburg (2006) uses a comparable simulation model for Gothenburg. No studies for Swedish low emission zones using observed air pollution data have been found. As described by Holman et al. (2015) the modelling studies have several disadvantages, and there are indications in the literature that this type of models overestimates the reduction in pollution levels. The aim of the thesis is, therefore, to complement existing literature using panel data for nitrogen dioxide concentrations, and weather conditions from the Swedish Meteorological and Hydrological Institute (SMHI, 2019a; SMHI,2019b), in order to estimate the effect of the policy using observed data for nitrogen dioxide.

In the thesis, data from the city centre of Uppsala will be used. Uppsala is chosen as the city of interest since it is the most recent city that has implemented the policy and has suitable conditions. In the two most recent cities, Umeå and Mölndal, the measuring station for nitrogen dioxide are placed next to a state-owned road (Västra esplanaden and E6/E20). The low emission zones do only apply to streets owned by the municipality. The two roads are likely to have a significant impact on the local nitrogen dioxide levels. Since the streets are not affected by the policy it will not be possible to use the data from these two cities. The low emission zone in Uppsala was implemented 1 January 2013.

The hypothesis in the analyses is that the low emission zone has lowered the emissions in central Uppsala by prohibiting the oldest and dirties vehicles from entering. Hence, the average age and emissions from heavy vehicles would have decreased. The lower emissions from heavy vehicles will then affect the concentration levels of nitrogen dioxide. If the policy is effective, it will be possible to observe a decrease in concentration levels before and after the implementation. The null hypothesis H_0 will test the effect of the low emission zone against the alternative hypothesis H_A.

H_0: Low emission zones do not affect the concentration levels of nitrogen dioxide
H_A: Low emission zones have an effect reducing the concentration levels of nitrogen dioxide

The null hypothesis is tested in a difference in difference model using two identification strategies. The first strategy uses differences in the traffic pattern for heavy traffic between night and day hours. The low emission zone is assumed to not have an effect during the night, which makes it possible to use the night hours as control. The second strategy uses similar cities without low emission zones as the control group. The result of the regressions shows that it is not possible to reject the null hypothesis that the low emissions zone has no effect. Hence, it is not possible to show that the low emission zone has a positive effect on the nitrogen dioxide concentration in Uppsala. The results are robust for both identification strategies.

The thesis makes two primary contributions to the existing literature. Firstly, it contributes to the knowledge about low emission zones in Sweden. By complementing the simulation model in previous studies, the understanding of the effect of the Swedish regulation increases. Increasing the understanding of the effect is essential in order to understand the potential impact and when the policy is suitable. Without a good understanding of the low emission zones in Sweden, there is a risk that time and resources are invested in policies that have little or no effect.

Secondly, the thesis contributes to the relatively sparse literature about the effect of low emission zones in small and medium-sized cities. There is a tendency in the literature to focus on large capital cities such as London or Amsterdam. Uppsala, with its around 200,000 inhabitants (SCB, 2019) is a typical medium-sized city in a European perspective. The thesis will, therefore, add to the knowledge about the impact of low emission zones in small and medium-sized cities.

The thesis will proceed as follows. Section 2 discusses the regulations of low emission zones in Sweden. The section also includes an overview of the pollution levels in Uppsala and other traffic policies implemented around 2013. Section 3 makes an overview of the existing literature on low emission zones. Section 4 introduces a theoretical model that shows the rationality behind low emission zones and that the policy can be an optimal policy in a second-best setting. Section 5 presents the methodology and data that are used to obtain the results in section 6. The thesis ends with conclusions in section 7.

2 Background

This section will discuss the Swedish low emission zones regulations and the background to way Uppsala decided to implement the policy in 2013. The section starts with the technical aspect of the policy and the Euro class regulations of emission from heavy vehicles. After that is the nitrogen dioxide levels in Uppsala discussed. The section ends with a short overview of other policies implanted in Uppsala in the years before the low emission zone.

2.1 Low emission zones in Sweden

The law that regulates the low emission zones in Sweden is Trafikförordningen (SFS, 1998:1276), and it is effective all days and hours of the week. Trafikförordningen is designed to be what is known in the literature as a national framework for the policy. The purpose of this national framework is to simplify and harmonise the regulations within Sweden (Holman et al., 2015). It is, however, the local municipalities that have the right to declare a low emission zone. Hence, the municipalities make the decision but must follow the national framework when implementing them. It is therefore not possible for municipalities in Sweden to impose stricter or weaker restrictions than the national framework.

2.1.1 Regulations of vehicle emissions and the Euro class system

In the European Union, emissions from heavy vehicles are regulated by the Euro class system. The Euro classes are fixed standards that regulate the maximum level of emissions allowed for new vehicles. Table 1 shows an overview of the emission level and from what date a new engine type must meet the standard. It is important to note that the Euro class system is based on bench tests of the engine without the rest of the truck. Hence, the emission criteria in table 1 are not the maximum emissions for vehicles in real traffic and conditions (transportpolicy.net, 2019). It is, therefore, possible that the emissions in real driving deviates substantially from the emissions in the bench tests.

The regulation of interest in this thesis is the level of nitrogen oxide (NOx). As can be seen in table 1, the NOx regulations have been strengthened over time, forcing the manufacturer to develop cleaner technology. For example, the allowed emission of nitrogen oxide decreased by 30 % between Euro III and IV. Euro V decreased the level by an additional 40%. Since the regulations and the euro classes become stricter over time, the emissions and levels per vehicle should also decrease when the vehicle fleet is renewed.

Table 1: Euro classes heavy vehicle, diesel engines, g/kWh (smoke in m^{-1})

Tier	Date	CO	HC	NOx	PM	Smoke
Euro I	1992 (<85 kW)	4.5	1.1	8.0	0,612	
	1992 (> 85 kW)	4.5	1.1	8.0	0.36	
Euro II	October 1996	4.0	1.1	7.0	0.25	
	October 1998	4.0	1.1	7.0	0.15	
Euro III	October 2000	2.1	0.66	5.0	0.10 0,13[1]	0.8
Euro IV	October 2005	1.5	0.46	3.5	0.02	0.5
Euro V	October 2008	1.5	0.46	2.0	0.02	0.5
Euro VI	January 2013	1.5	0.13	0.4	0.01	

Source: transportpolicy.net (2019)

Note: 1 for engines of less than 0.75 dm^3 swept volume per cylinder and a rated power speed of more than 3000 min^{-1}

2.1.2 Euro classes and low emission zones

The main idea of the low emission zone is that the benefit of newer and cleaner engines should come earlier when the trucks need to meet stricter regulations. The low emission zone is, as can be seen in table 2, based on the Euro class standard by setting a lower limit for vehicles entering the zones. The main rule prescribes that all vehicles may enter the zone six years after the first registration, irrespective of the Euro class. However, vehicles with Euro III or newer may enter the zone up to eight years after the first registrations. Furthermore, it is possible for vehicles with Euro IV and V engines to enter until 2016 and 2020 irrespective of first registration date. As can be seen in table 2, vehicles older than six years can be converted to Euro 4 or higher and still enter the zone.

Table 2: Entering requirements for Swedish low emission zones

Main rule

- *Vehicle may enter the zone 6 years after the first registration*

Exceptions from main rule

- *Vehicle with Euro III may enter the zone 8 years after the first registration.*
- *Vehicle with Euro IV may enter the zone until 2016 or 8 years after the first registration. If the Vehicle is* converted *to Euro IV, it may enter until 2016.*
- *Vehicle with Euro V may enter the zone until 2020 or 8 years after the first registration. If the Vehicle is converted to Euro V, it may enter until 2020.*
- *Vehicle with Euro VI or better has no time limits for entering*

Source: SFS 1998:1276, 4 chap. 22-23§

2.2 Low emission zone in Uppsala

The primary purpose behind the decision of implementing a low emission zone in Uppsala was to lower emissions of nitrogen dioxide to meet the environmental quality standards (EQS). Uppsala adopted its first action plan to lower pollution levels in 2006 when the Swedish government demanded that Uppsala acted in order to improve its air quality. In the updated action plan of 2009, there was a discussion of the possibility of introducing a low emission zone in 2010 (Kommunledningskontoret, 2009). Due to problems with adopting the local buses, the implementation was delayed until the first of January 2013. The zone was defined within the streets Kyrkogårdsgatan-Drottninggatan-Nedre Slottsgatan-Munkgatan-Östra Ågatan-Strandbodgatan-Väderkvarnsgatan-Råbyvägen-Luthagsesplanaden (Gatu-och trafiknämnden, 2011).

The dominating source of nitrogen dioxide in central Uppsala in 2011 was traffic emissions, which stood for 57 % of the total 1,700 tonnes. The most significant contributor to the total traffic emissions of nitrogen dioxide in 2011 was heavy diesel trucks with 46 % of the emissions. Another 16 % of the traffic emissions in 2011 were from heavy buses. Hence, the category of vehicle that is affected by the low emission zone stood for 62 % of the traffic emissions. The remaining emissions were from cars and light trucks under 3.5 tonnes, not affected by the low emission zone (Uppsala municipality, 2014).

It is important to note that not all heavy trucks and buses are affected by the low emission zone, only the vehicles that do not meet the criteria described in table 2 are prohibited from the zones. The low emission zone prohibited vehicles with Euro III registered before 1 January 2005 from entering the zones. The same was true for older Euro classes. Hence, all Euro III engines or older were prohibited except for vehicles registered before October 2005 when the Euro IV become mandatory. The age and Euro class of the vehicles that entered Uppsala in 2013 are however not known. It is therefore not possible to know how many trucks and buses were affected by the policy. Trafikanalys (2014) presents statistics on the age structure of trucks registered in Sweden. Based on survey data, Trafikanalys estimates that 85 % of all transport kilometres made by Swedish trucks were with trucks eight years or younger. How well the national statistics represent central Uppsala and the composition of Euro class is not known. However, national statistics indicate that relatively few trucks were affected.

2.2.1 Nitrogen dioxide levels and EQS in Uppsala

In Uppsala, the concentration of nitrogen dioxide is measured at Kungsgatan 42 in the central part of the city. To comply with EQS regulation for nitrogen dioxide the yearly, daily and hourly observations must be below the target values. The yearly average cannot exceed 40 µg/m^3, where the yearly number of days with a mean above 60 µg/m^3 is not allowed to be more than 7. The corresponding numbers for hourly values are 90 µg/m^3 and 175. Hence, 98% of the daily and hourly values must be below the regulatory levels. Furthermore, the highest hourly peaks cannot be above 200 µg/m^3 more than 18 times per year. The regulation must be met for any outdoor environment that the public normally has access too. Examples of not publicly accessible areas are within industry properties and tunnels. (Naturvårdsverket, 2019)

Diagram 1 contains data over the compliance with the EQS regulations three years before and after the implementation of the low emission zone. The black bar represents the yearly averages; the blue bar represents days above an average of 60 µg/m^{3,} and the white bar represents numbers of hours above 90 µg/m^3. The lines in the diagrams indicate the EQS levels. Observe that the black and blue bars are measured on the left axis and the white on the right axis. The diagram shows that the yearly average was violated in 2010. The daily levels were violated in 2010, 2011 and 2013, and the hourly values in 2010 and 2011. Overall, the year 2012 was the first year since the first action plan implemented in 2006 when the quality standard was not exceeded for nitrogen dioxide (Uppsala municipality, 2014). The standard was once again violated due to high daily values in 2013 but stayed below the regulated level in 2014 and 2015.

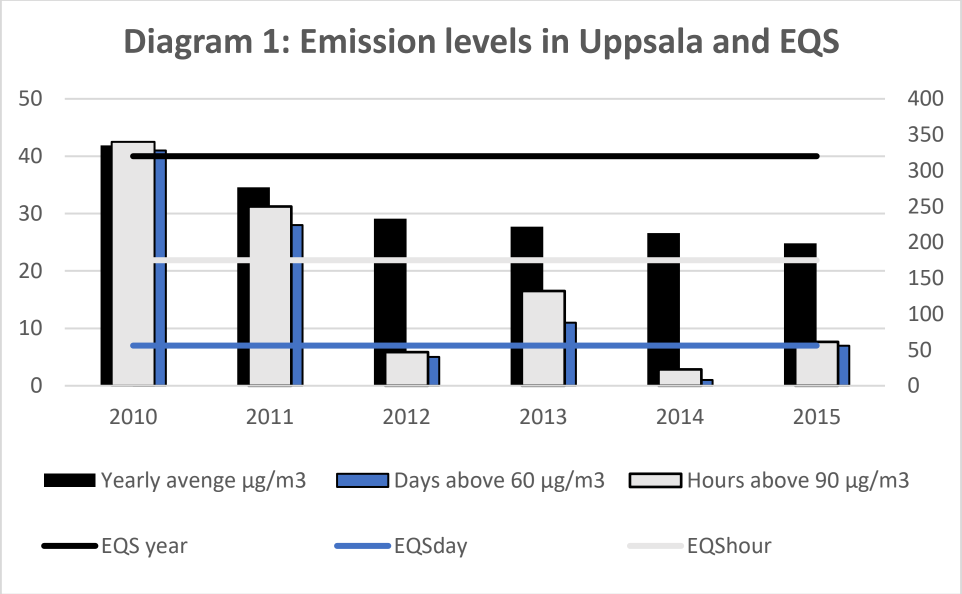


Diagram 1 shows the yearly average of NO2 levels (black bars), the number of days above 60 µg/m^3(blue bars) and the number of hours above 90 µg/m^3(white bars). The horizontal lines represent the EQS level, 40 µg/m^3 yearly averages (black line), 7 days (blue line) and 175 hours (white line). Observe that the black and the blue bars and lines are measured on the left axis and the white on the right. Source: SMHI (2019a)

The data in diagram 1 is from the urban traffic station Kungsgatan 42, in central Uppsala. The station is the only station in Uppsala classified as urban traffic, meaning that the station is representative for the local pollution level on street level. According to Naturvårdsverket (2019), the station should be placed so that it is representative for at least 100m of the street around the station and where both pollution levels and exposure by city inhabitants are high. Analyses by Uppsala municipality (2014, p16) show that in 2013, Kungsgatan was the most critical street when it comes to violating the nitrogen dioxide regulations. Hence the station at Kungsgatan is the most polluted part of the city and therefore a good location to evaluate both the effectiveness of low emission zones and compliance with the EQS standard.

What is striking in diagram 1 is that both the yearly averages and the number of days and hours of higher values decrease from 2010 to 2012. One likely exploitation is to the downward sloping trend in emission levels are decreasing traffic volumes. Uppsala municipality (2014) estimates that car traffic has decreased by 25-35 %. Hence the levels decreased substantially in the years before the implementation of low emission zones. Uppsala has since 2006 tried to lower its emissions with several policies. One that is likely to have had a significant effect is the ban of motor vehicles with studded tires on Kungsgatan implemented in October 2010.

Another change is the reopening of Strandbogatan on 25 October 2011, that had been closed for four years. According to Sundblom (2014), the opening reduced traffic at Vaksalagatan (intersecting Kungsgatan at the measuring station) by around 30%. Sundblom also mentions the decrease in speed limits and the expansion in Gottsunda shopping centre outside the central part of the city (which took place in 2011) as an explanation for lower traffic volumes around Kungsgatan.

3 Literature review

The low emission zone policy aims to lower air pollution by creating a change in the vehicle fleet towards newer and cleaner vehicles. The changes are created by excluding vehicles that do not meet the entering requirements. The first questions are therefore if the policy creates a change in the vehicle fleet. Hence, does the low emission zone lead to a shift from older to newer vehicles? The second question is how a change in the vehicle fleet affects air pollution?

3.1 Changes in the vehicle fleet

A typical strategy for estimating changes in vehicle distribution is to look at how the age distribution of the vehicles registered in the city changes. The strategy will only give a partial answer since the low emission zone is also trafficked by vehicles from other cities. Furthermore, the registration data does not provide any information on how many kilometres the vehicles are driving within the zone. Hence the registration data does not give a full picture but an indication of the effect. City of Stockholm (2001) shows that the age distribution for heavy vehicles in 1995 was similar for Stockholm and the rest of Sweden. In the year 2000, the distribution had changed, and Stockholm had a distribution with more newer vehicles and fewer older ones than the national average. Especially vehicles registered in 1996 and 1997 stand out. The low emission zone in Stockholm implemented a low emission zone in 1996. City of Gothenburg (2006) finds a similar pattern for the city of Gothenburg.

Ellison et al. (2013) investigate the changes in age distribution in London after the implementation of the low emission zone in 2008. The authors find a decrease in pre-Euro III vehicles 20 % above the natural replacements rate. In other words, there was a sharp decrease in older vehicles when the low emission zone was implemented. After the implementation, the replacements rate returned to the same trend as the rest of the UK. Hence, the replacement decision was not just moved forward, but the operators continued to renew the fleet at the same rate as before even after the jump in 2008.

Wolff (2014) uses an alternative strategy to estimate the impact on the vehicle fleet. With a regression model using data from the German vehicle register, does he estimate how distance to the nearest low emission zone affects the incentives to replace dirty vehicles with cleaner ones. Wolff (2014) concludes that the incentives to upgrade to cleaner vehicles increases by 1 % for every kilometre closer a commercial vehicle is to a low emission zone. For private vehicles, the number was found to be 0.6%. Wolff (2014) concludes that low emission zones influence the vehicle owner’s decision to replace their vehicles.

The conclusions from the studies presented above are that the low emission zone influences the age distribution of vehicles. Hence, the literature indicates that the policy creates a transition in the vehicle fleet from older to newer vehicles.

3.2 Effect on air pollution

The evidence from the Swedish and European studies presented above indicates that emissions from the vehicle fleet are lower after the implementation of the low emission zone. However, air quality depends on more factors than total emissions. In this thesis and a large part of the literature is air quality defined in terms of concentration levels of pollution, normally on street level. Hence, the amount of pollution in the air that city inhabitants breathe. Air quality defined as concentration level depends on more variables than total emissions, such as meteorological conditions, physical planning and background levels (see, e.g. Carslaw and Beevers, (2002) and Ellison et al. (2013) for further discussion). The effect on air quality is, therefore, an empirical question. Two general approaches for evaluating the effect of low emission zones are simulations through computer programs and the use of observed data for air quality.

3.2.1 Simulation models in Sweden

All three relevant evaluations of Swedish low emissions zones use the simulation approach. Rapaport (2002), City of Stockholm (2008) and City of Gothenburg (2006) create different scenarios based on the age distribution of the vehicle fleet. The age distribution for the city of interest is collected from the vehicle register. Based on this data, the concentration levels are simulated using assumptions about variables such as traffic volumes and weather conditions. From the municipalities without low emission zones, an alternative scenario is constructed without the policy. The underlying assumption is that the difference in distribution between cities with and without low emission zones is due to the effect of the zone. By comparing the two scenarios, the effect of the low emission zone can be calculated.

Rapaport (2002) estimates a decrease in nitrogen oxide emissions of 5 % in Stockholm for the year 2001. The author calculates the effect on street level for Hornsgatan, one of Stockholm’s most trafficked and polluted streets. Rapaport (2002) estimates a decrease of 1,5 % for Hornsgatan. Hence, a decrease in total emissions of 5 % only led to a decrease in the concentration level of 1,5 %. Rapport concludes that the low emission zone only had a modest effect on the nitrogen dioxide concentration in 2001.

City of Stockholm (2008) estimates the effect for heavy trucks in Stockholm for the year 2007 with and without a low emission zone. The report estimates a reduction in total emission of between 3 and 4 %. It is important to note that the report does not estimate the changes in concentrations levels as Rapaport (2002) but only the amount of emissions. The same is true for City of Gothenburg (2006) that evaluates the effect in Gothenburg for the year 2004 and finds a decrease of 7,8 %. How the decrease from the two studies translates into changes in concentration levels on street levels is not known. The results from Rapaport (2002) can be an indication, but the specific levels are not known.

The benefit of simulations models is that the researcher has control over all parameters and factors in the model. Identification of the causal effect is therefore not a problem in the simulation models. The problem with simulation models is to assign values for all the ingoing parameters and factors. The simulations assume that it is possible to find correct values for all parameters and how they interact. One example of this problem is how to find the emission factor for different vehicles, i.e., how much vehicles emit and how emissions change with newer engines. The emission factor has shown to be underestimated in several studies. Beevers et al. (2012) and Carslaw & Rhys-Tyler (2013) find that differences between new and older engines are smaller than expected in real driving in the UK. Velders et al. (2011) conclude that the Euro-V truck's emissions were three times higher than expected under normal driving in Dutch cities. The studies show the difficulties in simulation models and raise the concerns that the effect from the Swedish low emission zones might be overestimated. It is, therefore, essential to compare the results from simulations models with studies using observed data in order to understand the true effect of low emission zones.

3.2.2 Estimation strategies using observed pollution levels

The problem with using data on observed pollution levels is to disentangle the effect of low emission zones and other parameters. The literature contains several strategies to overcome this problem. Boogaard et al. (2012), Ellison et al. (2013) and Panteliadis et al. (2014) calculate the difference in concentration levels before and after implementation of the zones both for traffic stations within the low emission zones and for background stations outside the zones. By comparing the decrease in concentration levels within and outside the zones the effect of the policy can be calculated. Elias et al. (2013) found no significant decrease in nitrogen oxide for the London low emission zone. The same result is fund by Boogaard et al. (2012) for five Dutch cities, including Amsterdam. Panteliadis et al. (2014) on the other hand, find a significant decrease of 4,9 % for Amsterdam.

A more complex difference in difference strategy is used by Wolff (2014) for estimating the effect on PM10 levels in nine German cities. The cities with low emission zones are used as a treatment group. Cities that did not meet the regulatory standards for clean air and did not implement low emission zones are used as a control group. Wolff uses two identification strategies. The first strategy matches cities based on the concentration levels in 2005 and the second matches nearby cities that will implement the policy in the future but not jet taking the decision. The model includes a large number of meteorological conditions, dummy variables for public holidays, school vacations and controls for day of the week. Station and time fixed effect are also added to the model. Wolff (2014) finds a significant decrease in PM10 concentration of 9%.

Malina and Scheffler (2015) use another estimation strategy. The authors use a robust fixed effect panel data model with controls for traffic volume, weekdays, meteorological conditions, month and yearly fixed effects. Malina and Scheffler (2015) investigate the effect for 25 German cities. The model specifications allow the authors to investigate how the effect differs when the regulations are getting stricter by including a dummy variable for different stages of the low emission zone. The authors find that the PM10 concentration decreases by 2.3 µg/m^3 when the city implements a stage 1 low emission zone. When the regulation becomes stricter, the concentration levels decrease by an additional 5,1 µg/m^3. Hence, the estimated effect increased three times by stricter regulations. The combined effect corresponds to a decrease of around 13% for a stage 2 low emission zone. The results from Malina and Scheffler (2015) indicate that the entering requirements are an important factor for the effect of the policy.

3.2.3 Conclusions from European studies

As shown by the papers above, the effect of low emissions zones differs between the studies. Holman et al. (2015) make an overview of published papers from Denmark, Germany, the Netherlands, Italy and the UK. The authors conclude that there is evidence of decreasing nitrogen dioxide and PM10 concentrations in German cities by up to 4% and 7 %, respectively. The results in other countries are mixed, with the general result that no effect can be proven. It is important to note that the criteria for entering the low emission zones differ between countries and over time. The different criteria make the studies not perfectly comparable between countries. However, the literature indicates that the effect on nitrogen dioxide concentration outside Germany is small.

It is important to note that the main focus of the literature has been on PM10 and NOx concentrations. Cyrys et al. (2014) argue that the impact of low emission zones is more significant than the general decrease in PM10 indicates. The authors mention other particles such as black smoke and elemental carbon as examples of particles that are strongly correlated with traffic emissions and have a significant health impact. Cyrys et al. (2014) conclude that the low emission zone policy decreases these particles. The health effects are, therefore more substantial than the general decrease in PM10 and nitrogen dioxide levels indicates. Hence, it is not enough to look at PM10 and nitrogen dioxide levels when evaluating the full health impacts of low emission zones.

4 Economic theory

This section discusses the economic theory behind low emission zones. The section starts with a discussion about the first-best setting and emissions taxes and how this solution can be hard to reach in practice. After that, the low emission zone is modelled in a second-best setting. The section ends with a comparison between low emission zones and road tolls, and the conditions for emission zones in Uppsala.

4.1 First best and emissions tax

Road traffic from vehicles creates several negative externalities that lower the total welfare within a city. Examples of negative externalities are noise, accidents and emissions. The externality that will be in focus in this thesis are emissions of nitrogen dioxide created in the combustion engine of the vehicles. From a theoretical point of view, there are two basic strategies to lower emissions. The first is to adopt policies that affect the emission per unit (per kilometre driven) or the amount driven (the number of kilometres).

In a first-best setting, policies should find the optimal combination of reduction per unit and amount driven in order to maximise social welfare. It is well documented in the economics literature that an emissions tax solves this problem by affecting both the incentives to lower emission per kilometre and the kilometres driven. Pigou showed already in 1920 that the first-best solution is an emissions tax equal to the marginal external damage, also known as a Pigou tax (Pigou, 1920).

The main problem with an emissions tax is how to measure the emissions. As pointed out by Proost (2011), this is less of a problem if the amount of emissions is proportional to the amount of fuel. This is, for example, the case for carbon dioxide (CO_2). Nitrogen emissions do, however, depend on several factors, such as engine specifications, exhaust system and engine temperature, to take a few examples. The relationship between emissions and fuel is, therefore, weaker for nitrogen dioxide than for carbon dioxide. Fullerton and West (2002) discuss several solutions as to how the emission measuring problem can be solved and the first-best can be achieved. One solution is, for example, to differentiate a fuel tax to every vehicle and its specific amount of emissions. The authors also show that the practical problems with such a tax are large, making it tough to implement in practice.

4.2 Low emission zone and second-best

An alternative to a first-best emissions tax is to look for the second-best policies that either affects the emissions per kilometre or the kilometres driven. One example of the first is low emission zones that set a standard for what emissions the vehicle engine can have when entering the city centre. Hence, the policy forces the vehicle owner to lower the emissions per driven kilometre, but it gives no incentives to lower the amount driven. Because only one of the two strategies to lower emissions is affected, a low emission zone is by definition a second-best solution.

De Borger and Proost (2013) have developed a general model where different policies can be analysed. A slightly modified version of De Borger's and Proost's model will be presented here. The different elements of the model will first be parented before the full maximisation problem is discussed in equation 3. The demand for traffic (V) measured as kilometres driven is assumed to be a downward-sloping function of the generalised price P. Rewriting the demand function to its inverse, demand becomes $P^V(Y)$. The externality cost (E) is assumed to be a function of the traffic volume according to equation 1.

$$E = e(1 - \alpha z)V \qquad (1)$$

In equation 1, e is the externality per kilometre driven before the municipality implements a low emission zone. The parameter z is the level of the emission standard and α how effective the standard is to lower the emission. The emission standard z is zero if now vehicles are affected by the policy. The external cost is assumed not to take any negative values, the maximum z levels are therefore defined to be smaller than $\frac{1}{\alpha}$ .The alfa parameter takes the value one if the standard and the real emissions follow the same trend. Hence, if the standard and the emissions are proportional. If alfa is zero, there is no connection between the standard and the real emissions. The emission per kilometre driven is therefore reduced from e to $e(1 - \alpha z)$ when the policy is implemented.

The cost associated with driving is captured by equation 2, where G is the generalised cost of driving.

$$G = c + \frac{1}{2}dz^2 \qquad (2)$$

The (monetary) generalised cost is divided into two parts. The first term c captures the cost of driving without the low emission zone policy. Note that the c parameter captures both monetary and time cost of the driving. The second term is the cost associated with complying with the policy. Hence, the second term captures the additional cost of driving associated with a low emission zone. In order to comply with the low emission zone regulation, the driver needs to upgrade his or her vehicle to the standard. It could be argued that this should be treated as a fixed cost, as the driver needs to invest in either a newer vehicle with lower emission or upgrade the current one. By imposing the assumption that all vehicles drive the same number of kilometres within the city centre, the cost of complying with the regulation can be treated as a variable cost. The parameter d captures the cost of complying. This is a strong assumption, but it will simplify the calculation and the analysis. Note that the interpretation of the second term will be that the compliance cost rises with harder regulations.

The goal of the municipalities is to maximise social welfare by maximising equation 3. Hence, the social planner can maximise the total social welfare by choosing the optimal level of the emissions standard (z).

$$\max_{z} \int_0^V P^y(V)dy - \left[c + \frac{1}{2}dz^2\right]V - e(1 - \alpha z)V + FC \qquad (3)$$

The first term represents the gross consumer surplus from driving in the city centre. The second term represents the cost of driving, and the third term is the negative externality that reduces social welfare. The last term FC represents the public investment cost of the policy. It should be noted that the cost of implementing a low emission zone is fixed and independent of the regulation level. Hence, the cost associated with policies such as information and putting up signs is the same independently of the level of z.

Using the fact that in equilibrium, the generalised price is equal to the generalised cost (equation 4), the maximisation problem in equation 3 can be solved and simplified into equation 5.

$$p^y(V) = G = c + \frac{1}{2}dz^2 \tag{4}$$

$$\left(\frac{\alpha e}{d} - z\right)V = e(1 - \alpha z)\frac{\partial V}{\partial P}z \tag{5}$$

Finding a meaningful expression for the optimal level of z is not possible because the right-hand side of equation 5 is quadratic in z. The simplifying assumption that the traffic is perfect in elastic makes it possible to solve for z and find a meaningful expression for the optimal regulatory level. If the traffic is perfectly inelastic, the right-hand side of equation five will be zero, which yields:

$$z = \frac{\alpha e}{d} \tag{6}$$

Given the assumption of perfect inelastic traffic, the optimal regulatory level of the low emission zones increases with alfa and e and decreases with d. In other words, if higher standards are effective in lowering emissions and high emission levels without regulations, the emissions standard should be stricter. A higher compliance cost will, on the other hand, lead to a less strict standard. It can also be noted that under the assumption about price elasticity, the low emission zone will achieve the first-best solution. Because the kilometres driven cannot be affected, the only way of lowering emissions is to lower emissions per kilometre driven. As can be seen from equation 5, the optimal level of z will be higher if the assumption about perfect inelastic traffic is relaxed, hence $z > \frac{\alpha e}{d}$.

4.3 Low emission zone vs traffic tolls.

One advantage with the basic model developed by De Borger and Proost (2013) is that it allows comparing different policies within the same framework. An example of a policy that can be used instead is road tolls. The road toll is in this context a fee for entering the central part of a city. By making it more expensive to enter the kilometres driven will go down, and the emissions will decrease. The road toll can be seen as an opposite strategy to a low emission zone since it only affects the kilometres driven but gives no incentive to lower the emissions per kilometre. Equation 7 describes the equivalent maximising problem for road tolls, as equation 3 did for low emission zones.

$$\max_F \int_o^{V_{toll}} p^y(V)dy + [c + F]V_{toll} + FV_{toll} - eV_{toll} + FC_{toll} \tag{7}$$

A significant difference between tolls and low emissions zones is that the generalised user cost will now depend on the road toll F. Note the assumption made earlier that all drivers drive the same amount in the city centre. This assumption makes it possible to define F as the cost per kilometre driven in the city centre. A second difference is that the third term represents the public revenue from the road toll. A fee for driving in the city centre will lower the demand for driving within the city and affect the traffic volume V. The subscript toll indicates that it is the traffic volume under the road toll policy.

By adding the subscript LEZ for the low emission zone equation, it becomes possible to compare the total social welfare (W) between the two policies. In order to compare the two options, note that an optimal fee should be where the marginal cost of emission equals the fee, hence where F=e. The third and the four the term will, therefore, cancel each other out. The welfare difference will then be:

$$\begin{aligned} W_{LEZ} - W_{toll} = \left\{\int_0^{V_{LEZ}} P^y(V) - \left[c + \tfrac{1}{2} dz^2\right] V_{LEZ}\right\} - \Big\{\int_0^{V_{toll}} P^y(V) - \\ [c + F] V_{toll}\Big\} - e(1 - \alpha z) V_{LEZ} + FC_{LEZ} - FC_{toll} \end{aligned} \tag{8}$$

By rearranging terms, assuming a linear demand and after some algebra, equation (8) can be simplified to[2]:

$$\begin{aligned} W_{LEZ} - W_{toll} = \frac{1}{2}\alpha e z V_{LEZ} + \frac{1}{2}\frac{\partial V}{\partial P}\left\{\left[e - \frac{1}{2} dz^2\right]^2 + e(1 - \alpha z) dz^2\right\} \\ + FC_{LEZ} - FC_{toll} \end{aligned} \tag{9}$$

In equation 8 the first term is the net consumer surplus for driving in the low emission zone, the second term is the net consumer surplus for driving under a road toll scheme. From the simplified expression in equation 9 it is possible to conclude that a higher traffic elasticity (note that $\frac{\partial V}{\partial P}$ has a negative sign) makes road tolls preferable. This is natural since the toll has a larger effect on traffic volume, thus it is more effective. This is shown in the equation by a decrease in the second term. Equation 9 further shows that if alfa is high and d is low, the social welfare will be larger for low emission zones. Hence, the first term in equation 9 is larger than the second. In other words, the stronger the connection is between the real emissions and the standard, the more preferable the low emission zone becomes. On the other hand, higher compliance costs make the road toll preferable.

A low emission zone and road tolls are not necessarily in conflict with each other. The two-policy options can work well together where the drivers can make the choice of either complying with the emissions standard or paying a fee. De Borger and Proost (2013) show that a solution where the local drives choose to comply, and the outside drivers prefer to pay the fee can be an optimal solution. Ellison et al. (2013) report that London chose this solution

---

[2] See De Borger and Proost (2013) page 59 for derivation of the steps.

when implementing a low emission zone in 2008. The heavy vehicles that did not meet the standard had to pay a fee of £200 per day inside the city centre.

4.4 Situation in Uppsala

The conclusion from the discussion above is that low emission zones can be an optimal policy tool in a second-best setting where an emissions tax is not feasible. The model above has shown that traffic elasticity, efficiency of standards and compliance cost are determining features for the low emission zone. To decide these variables for Uppsala is beyond the scope of this thesis. However, some factors should be noted. Firstly, through traffic with heavy vehicles are forbidden in central Uppsala, which means that all vehicles have a destination within the central parts. Hence trucks might not pass through but are allowed in to deliver goods. Lowering the traffic volume requires either a change in the demand for goods in the city centre or a change in the logistic chain. The changes could be in the form of more coordination between the delivery trucks or fewer delivery dates. Both solutions are likely to be relatively expensive, and the fee needs to be high in order to affect the logistic chain. Given this, it is not unreasonable to believe that traffic elasticity for heavy vehicles is low.

The sizes of the alfa and d parameters of the model above are also uncertain. The definition of the emissions standard and potential problem with the Euro class system has been discussed above. The compliance cost can be significant for the individual vehicle owner, but the fact that other cities have implemented the same policy before Uppsala indicates that the cost is manageable. The overall conclusion is, therefore, that there is support in the economic literature for Uppsala's decision to implement a low emission zone for heavy vehicles. This conclusion is correct given that the traffic elasticity and compliance cost are low, and the alfa parameter is high. However, the final effect on pollution levels is an empirical question that cannot be determined in a theoretical model.

4.4 Hypothesis

The main goal of a low emission zone in Uppsala and several Swedish cities has been to lower the level of nitrogen dioxide (County Administrative Board of Skåne, 2009; Umeå municipality, 2012; Uppsala municipality, 2014). The theoretical model above is suitable for analysing any traffic-generated pollutant, but since the regulatory focus in Sweden has been on nitrogen dioxide, this will be the pollutant of interest in this thesis. The main goal of the regulators has not necessarily been to reach the second-best optimal level of emissions within the cities, but to lower the emissions enough to meet the environmental quality standard. If the policy is effective, it will be possible to observe a reduction in concentration levels before and after the implementation. The hypothesis tested in the thesis is, therefore, if the low emission zones have had any impact on the concentration levels of nitrogen dioxide. Formally the null hypothesis H_0 will be tested against the alternative hypothesis H_A.

H_0: Low emission zones do not affect the concentration levels of nitrogen dioxide
H_A: Low emission zones have an effect reducing the concentration levels of nitrogen dioxide

5 Methodology

This section will discuss the estimation strategy that will be used in the thesis. Several factors are important when estimating the effect of low emission zones. As described in section 2.2 has the traffic volume been changing around the nitrogen dioxide measuring station at Kungsgatan 42. Traffic volume is likely to be the main explanation for the reductions in nitrogen dioxide concentration since 2010. Another critical factor is the meteorological conditions that impact how the air mixes and emissions disperse. This section will start with a discussion about changes in traffic volume and the effect of weather. After that is the estimation strategy to overcome these problems presented and discussed.

5.1 Changes in traffic volume

As discussed in section 2 traffic around Kungsgatan has changed significantly during the years before 2013 when the low emission zone was implemented. Based on 12 of the traffic counts station that Sundblom (2014) presents the average vehicles per day decreased by 9 % between autumn 2012 to autumn 2013[3]. The station located on Vaksalagatan (the closest to the nitrogen dioxide measuring station) showed a traffic decrease of 16 % and the next closest at S:t Olofsgatan had a similar decrease of 17 %.

The municipality of Uppsala did unfortunately only count the traffic at central locations once a year. Factors like weather and the date of counting may have affected the results. The observed traffic volume is therefore not perfectly comparable across the years. The lack of comparability makes it impossible to draw any conclusions about changes in traffic volume. However, keeping in mind the relatively large changes around Kungsgatan in the years before the introduction of the policy (discussed in section 2.2) a reduction in traffic volume is expected. It is also known from the traffic count that the number of vehicles decreased 7 percentage points more on Vaksalagatan than the average for the city centre. The combined picture says that it is reasonable to believe that there has been a decrease in traffic volume around Kungsgatan between 2012 and 2013. Unfortunately, can the changes in traffic volume not be controlled for due to lack of data.

5.2 The effect of weather

It is important to note that it is not the amount of emissions of nitrogen dioxide that is in focus but the concentration. The amount of emissions is an essential factor for the concentration, but weather will have a significant effect on how the emissions are dispersed. For example, concentration of emissions is lower at higher wind speeds since the nitrogen emissions become blended and diluted with large amounts of air. If the air instead is stationary, the emissions will accumulate, and the concentrations increase.

---

[3] The two counting points in at Sysslomansgatan/Luthagsesplanaden and Götgatan/ Luthagsesplanaden has been excluded due to too construction work during the counting week.

Aldrin and Haff (2005) investigated what meteorological variables affect the concentrations of nitrogen dioxide. The study uses observations from four different locations in Oslo. The authors conclude that the variables with the most impact are wind speed and wind direction. The authors also find an effect of temperature and difference in temperature between high and low air. The concentration level is found to decrease with higher temperature. The study did not find a significant effect from relative humidity and an unclear pattern for precipitation. In a similar study for Rome, Sayegh et al. (2016) draw the same conclusion as Aldrin and Haff that wind speed is the most important factor. Sayegh et al. (2016) also find a significant impact of temperature. The conclusion from the two studies is that the model needs to control for wind and temperature.

5.3 Estimation strategy

The ideal model for this analysis would be a difference in difference model using another similar city with the same traffic pattern as control. A critical assumption of the difference in difference approaches is a common trend between the treatment and control group. That would, in this case, require that a city with the same trend in traffic volume but that did not implement low emission zones could be found. It also requires that the trends in the urban background concentrations are the same. Due to lack of data, the traffic trend in Uppsala is not known, it will also be impossible to fully know how well the control city matches the trend of Uppsala. The more the trend differs, the more significant the bias generated by the model.

The thesis will use two different identification strategies to overcome the problems with common trend and insufficient control group. The first strategy is to find a control group within Uppsala using changes in traffic pattern over 24 h. The second strategy uses other cities of similar size as the control.

5.3.1 Identification using controls within Uppsala

The first strategy uses the variation in effect from the low emission zone over the day. For instance, the traffic from heavy vehicles should be significantly lower during the night compared to the day, making the effect of the low emission zone small or zero. During the day when the trucks and buses start trafficking the street, the effect from the low emission zone should be the largest. If the low emission zone has an impact on the air quality, the difference in concentration levels between night and day should be smaller after the implementation. The difference in the difference between day and night hours will, therefore, be the effect of the low emission zone. Hence the difference in difference approach will give an unbiased result. The results will, however, only be unbiased under some assumptions.

Assumption 1: The low emission zone has a marginal effect on the nitrogen dioxide emissions between 22 in the evening and 6 in the morning. Hence, there is no spillover between treatment and control group.

The biggest polluters that the low emission zones affect are the heavy trucks that in 2011 accounted for 46 % of the total traffic emissions of nitrogen dioxide (Uppsala municipality, 2014). Given the regulations for undisturbed night rest between 22.00-06.00 (Naturvårdsverket, 2018), trucks are not allowed to enter and deliver goods in the city during these hours. Given that trucks are not allowed to enter the central part of the city (regardless of how clean they are) the effect of the low emission zone is expected to be small during these hours. Hence, for trucks, assumption 1 is likely to hold.

The other category that is affected by the low emission zones is heavy buses, which account for 16 % of the traffic nitrogen dioxide emissions in 2011 (Uppsala municipality, 2014). There is no similar ban on buses after 22.00 as there is for trucks, making the argument for assumption 1 weaker. However, it is important to note that only the buses that were too old to meet the requirements are affected. Given that the traffic volume goes down during the night, there is an excess of buses in the operator's fleet. What buses the operator in 2012-2013 chooses to run is not known. However, it is not obvious why the operator would park the new buses and run the ones older than 8 years at night.

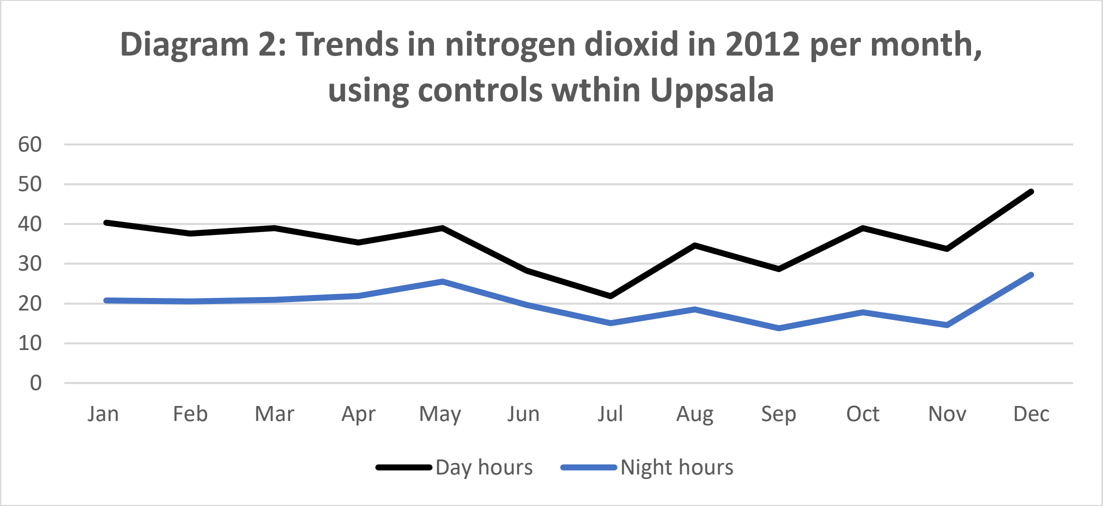
The overall conclusion is that assumption 1 holds for heavy trucks, but this is less certain for buses. Most likely, there have been heavy vehicles older than eight years entering the area covering the low emission zone. Especially buses are likely to have violated the assumption at some points. However, the number of vehicles that violated the assumption is most likely small. The emissions from these vehicles are, therefore, also likely to be small in relation to the total emissions. Hence, assumption 1 is assumed to be a reasonable approximation, and the violations are not large enough to have any significant effect on the results.

Assumption 2: Without the low emission zone the difference between night and day hours are the same. Hence the two groups have a common trend.

Assumption 2 is a strong assumption. The biggest argument against assumption 2 is the existence of changes in traffic volume due to other policies implemented at the time. Just as the low emission zones, these policies are likely to have a more substantial effect during the day than during the night. The more substantial effect is likely because the traffic volume is larger during the day, and the same percentage change in traffic volume leads to a more substantial decrease in nitrogen dioxide concentration in absolute terms. Hence, the common trend assumption will not hold, and the estimated effect will include not only the low emission zone but also the effects of other policies.

The second argument against assumption 2 is changes in the regional pollution background. Even if traffic is the primary source of nitrogen dioxide on the street, changes from other sources have a potential effect on the overall emissions concentration. The changes in the regional background are, however, likely to be similar for day and night periods implying that assumption 2 is likely to hold.

Diagram 2 contains the average concentration of nitrogen dioxide for day hours (06.00-22.00) and night hours (22.00-06.00) for the year 2012. Observe that the 24th period starts and ends at 22.00. The diagram shows that the day (black line) and night (blue line) trends are similar. However, the trends are not perfectly correlated. The differences are, on the other hand, not large enough for assumption 2 to be an unreasonable approximation. However, there is reason to interpret the result with some caution.



Another problem with using the night hours as control is that it will not control for the natural rate of renewal of the heavy vehicle fleet. Hence, some vehicles would have been replaced without the low emission zone. The estimated effect will, therefore, include both the natural improvement and the extra effect from the low emission zone.

5.3.2 Identification using controls outside Uppsala

The second identification strategy is to find control cities outside Uppsala. Using similar cities as control is a strategy used in previous literature. The strategy presented below is perhaps closest to the strategies used by Wolff (2014). This strategy assumes that it is possible to find a control city that would have the same trend as Uppsala without the low emission zone. If such a city can be found, the differences in difference approach will generate unbiased estimates. Basically, this strategy demands the same assumption as that within Uppsala strategy. Assumption 1 that there is no spillover effect between the treatment and control group is likely to be fulfilled when the two groups are geographically separated. To further decrease the risk of spillovers all cities that implemented a low emission zone before 2014 will be excluded.

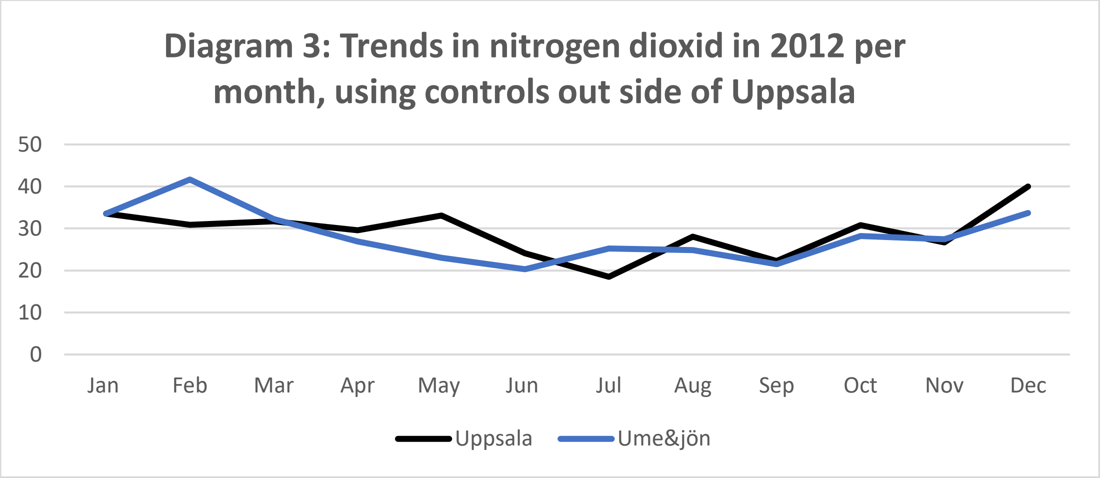
The critical assumption in this identification strategy will be assumption 2 and the common trend. The common trend assumption demands that the trend in the control and the treatment group should be identical without the low emission zone. The trend in Uppsala is, as discussed above, most likely downwards-sloping, meaning that the trend in the control city also needs to be falling. Note that requirements for monitoring the air quality increase when the quality is low. The cities that measure the pollution of nitrogen dioxide at street level will therefore not be random. Most likely the fact that data is available is an indication that the city has problems with high levels of nitrogen dioxide. It is therefore likely that the cities will implement other policies to improve the air quality. Hence, cities where data on street levels are available will, just as Uppsala, try to decrease the emissions of nitrogen dioxide. In an ideal situation, this policy would have the same effect as the ones in Uppsala. However, the effect can be both larger and smaller than in Uppsala, creating bias in the model.

In contrast to the within Uppsala strategy, it is not possible to predict the direction of the bias. The lack of predictability is a strong disadvantage of using control cities outside Uppsala. The more similar the control cities are to Uppsala, the more likely it is that the common trend is a reasonable approximation. In other words, by choosing control cities that are as close as possible to Uppsala, the bias can be minimised. The choice of control cities will, therefore, be based on three criteria.

1. *The municipality has at least 100,000 inhabitants*
2. *The city has not implemented a low emission zone before 2014*
3. *Data on nitrogen dioxide concentration on street levels are available for 2012 and 2013*

The first criterion will ensure that the cities are of similar size and therefore are affected by the same general trends. The municipality of Uppsala had 205,000 inhabitants in 2013 (SCB, 2019). Hence the included control cities must be at least half the size of Uppsala. The second criterion ensures that the low emission zone policy only affects Uppsala and not the control cities. The third criterion ensures that the concentration levels are comparable. Further, data for and one year before and after the implementation of the low emission zone should be available.

In the pollution database provided by SMHI, two cities match the criteria, Umeå and Jönköping. The control group will, therefore, be the two cities Umeå and Jönköping. Note that Umeå implemented the low emission zone policy 1 January 2014. The implementation could have influenced the concentration level at the end of 2013, but most likely, the effect is small. Diagram 3 shows the daily averages for Uppsala and the two control cities in 2012. The two groups follow a similar but not an identical trend in 2012, indicating that a common trend is not an unreasonable approximation for 2012.



In diagram A1 in the appendix, the trends for Uppsala, Umeå and Jönköping are presented separately for the 24 months from 1 January 2012 to 31 December 2013. Diagram A2 shows the trend for Umeå and Jönköping combined for the same period. What the diagram shows is that both trends and levels are similar for all the three cities in 2012. However, in the first month of 2013, the trend is increasing in Umeå and decreasing for Jönköping compared to Uppsala. Both the trends and levels seem to return to similar values in the second half of 2013. Hence, in the month just after the implementation of the low emission zone, a common trend for the two control cities is not a reasonable approximation. Diagram A2 shows that when the two cities are used as a control group the average value cancels out the differences and the trends are similar for the whole 24-month period.

Ideally, data for more cities would be available, making it possible to be both more restrictive in the choice of controls and include more cities. For example, Wolff's (2014) first screening for suitable cities generates a sample of 73 cities, making it possible to optimise the sample further. When only one city with and two without policy are available, the regression is very sensitive to short-term temporary effects. Whether the combined averages for Umeå and Jönköping cancelled out temporary effects or if other effects are in play is not known. This problem highlights the weaknesses with the difference in difference approaches and the common trend assumption. The questions about the trend in pollution levels in the first half of 2013 give reason to question the validity of the identification strategy. It cannot be excluded that another set of control cities, if available, would generate a different result.

Even if the identification strategy to find control cities outside Uppsala has shortcomings, the strategy will be included in the thesis. The main reason is to complement the within Uppsala strategy. The identification strategy using night hours as control group has not been found in previous studies of low emission zones and is therefore untested in the literature. The outside Uppsala strategy is an attempt to use techniques and strategy that have been tested and used in previous studies. This thesis believes that the outside Uppsala strategy presented above is the best possible approach using techniques from previous studies. Other estimation strategies are not possible since neither traffic data nor background pollution levels are known for Uppsala. The result from the outside Uppsala strategy should not be interpreted by itself but in combination with the within Uppsala strategy. If the two strategies generate similar results it will be possible to draw conclusions about the effect of low emission zones. The thesis will, therefore, include both strategies.

5.3.3 Difference in Difference estimations

Under the assumptions discussed above, it is possible to estimate the effect of low emission zones using a difference in difference approach. Equation 10 shows the expected concentration levels Y for the control group (con) in 2012. The yearly averages will be equal to the daily averages given that the observation is for the control group and a covariate X of weather and seasonal controls. Observe that in the identification strategy using control within Uppsala the control is the night hours between 22.00-06.00 For the identification outside Uppsala, the control will be values for Jönköping and Umeå. Equation 11 is the expected concentration levels for the year 2013 when the low emission zone was implemented. Given the control variables, the daily values are assumed to be the same if the time trend λ is added. Hence the difference between before and after the implementation of the low emission zone is captured by λ in the control group.

Equation 12 and 13 shows the expected concentration levels for the treatment group (tre). The main difference from the control group is that in equation 13, the effect of the low emission zone is captured by the parameter δ. Hence for the treatment group, the difference before and after the implementation of the low emission zone will be both the time trend λ and the effect of the policy δ.

$$E[Y_{con}^{2012}] = E[\gamma_i | con, \boldsymbol{X}] \tag{10}$$
$$E[Y_{con}^{2013}] = E[\gamma_i | con, \boldsymbol{X}] + \lambda_{con} \tag{11}$$
$$E[Y_{tre}^{2012}] = E[\gamma_i | tre, \boldsymbol{X}] \tag{12}$$
$$E[Y_{tre}^{2013}] = E[\gamma_i | tre, \boldsymbol{X}] + \delta + \lambda_{tre} \tag{13}$$

The effect of the low emission zone can then be found by subtracting 2012 values for the two groups and then calculating the difference. Equation 14-16 shows the results.

$$DiD = \{E[Y_{tre}^{2013}] - E[Y_{tre}^{2012}]\} - \{E[Y_{con}^{2013}] - E[Y_{con}^{2012}]\} \tag{14}$$
$$\begin{aligned} DiD = \{&E[\gamma_i | tre, \boldsymbol{X}] + \delta + \lambda_{tre} + -E[\gamma_i | tre, \boldsymbol{X}]\} \\ -\{&E[\gamma_i | con, \boldsymbol{X}] + \lambda_{con} + -E[\gamma_i | con, \boldsymbol{X}]\} \end{aligned} \tag{15}$$
$$DiD = \delta + \lambda_{tre} - \lambda_{con} \tag{16}$$

Equation 16 shows the effect of the difference in difference estimation. If the common trend assumption holds will $\lambda_{tre} = \lambda_{con}$ and the terms will cancel out. The difference in difference estimator will then give the true effect of the low emission zone (δ). However, as discussed above when the night hours are used as control group λ_{tre} is likely to be smaller than λ_{con}. Hence the effect of lower traffic changes in traffic volume will be larger (a larger decrease) during the day than during the night. The difference between the two parameters will lead to a bias in the model. The bias will give an overestimation of the effect of the low emission zone. This is to say, the estimated effect of the difference in difference estimator would be larger than the true effect. When Jönköping and Umeå are used as controls, it is not possible to make any prediction about the direction of the bias. The effect of the time trend can be both larger and smaller compared to Uppsala.

From equation 15, it is possible to see what happens if assumption 1 does not hold. Hence there is a spillover between the control and the treatment group. Assumption 1 is, as discussed above, most likely only a problem in the within Uppsala strategy. If assumption 1 is violated, the low emission zone will affect both the day and the night hours. In equation 17 the policy effect on the control group is captured by the δ_{con} parameter. Subtracting all the terms and the result of the difference in difference estimator will be equation 18. As the equation shows a violation of assumption 1 will lead to an underestimation of the true effect. Where parts of the true effect get cancelled out by δ_{con} .

$$[Y_{con}^{2013}] = E[\gamma_i | con, \boldsymbol{X}] + \delta_{con} + \lambda_{con} \tag{17}$$

$$DiD = \delta_{tre} - \delta_{con} + \lambda_{tre} - \lambda_{con} \tag{18}$$

5.4 Model specification

In the regression model equation 19 will be used. The first term is the intercept. The second variable (treatment) is a dummy variable taking the value one if the observation is part of the treatment group and zero for the control group. This variable will catch the differences between the control and the treatment group. The third term (postLEZ) is a dummy variable taking the value one from the first of January 2013 when the low emission zone was implemented. Hence the dummy postLEZ takes the value one for 2013 and zero for 2012. This term will pick up the difference in nitrogen dioxide concentration that depends on the time trend. The next term (LEZ) is the variable of interest corresponding to the interaction between the treatment and postLEZ variables. This variable will take the value one only for the treatment group after the implementation of the low emission zone. Hence, β_3 will capture the effect of the low emission zone.

$$\begin{aligned}\ln(NO2) = \beta_0 &+ \beta_1 treatment + \beta_2 postLEZ + \beta_3 LEZ + \beta_4 wind \\ &+ \beta_5 wind^2 + \beta_6 temp + \beta_7 public\ holyday + \beta_8 spring \qquad (19) \\ &+ \beta_9 summer + \beta_{10} autumn + \boldsymbol{weekday\delta} + \varepsilon\end{aligned}$$

$$LEZ = tretment * postLEZ \tag{20}$$

Equation 19 also includes several control variables. Controls for meteorological conditions include wind speed (including also a quadratic term which allows the effect of wind speed to differ from wind speed) and temperature. Control for seasonality in the concentration levels, public holidays and weekdays are also added. The traffic volumes and therefore the concentration levels are expected to decrease during public holidays. To capture this effect a dummy variable for public holiday is included. The variables spring, summer and autumn are dummy variable taking the value one during each season. These variables will capture differences in nitrogen dioxide concentration due to seasonality over the year. The next term is a vector of dummies taking the value one for the different weekdays. This vector will capture seasonality within the week. The last term in equation 19 is the error term. The standard error is adjusted for heteroscedasticity using robust standard errors.

5.5 Data and descriptive statistics

Data for the concentration levels of nitrogen dioxide is available from the Swedish Meteorological and Hydrological Institute (SMHI) public database of air quality (SMHI, 2019a). From the database hourly data is collected for the three cities: Uppsala[4], Jönköping[5] and Umeå[6] The hourly data is recalculated to daily averages or averages for the day and night hours. All data is for street level.

The meteorological variable for wind and temperature is collected from SMHI's database meteorological observations (SMHI,2019b). Data for daily or hourly values were collected and recalculated in the same format as the nitrogen dioxide levels. Nitrogen dioxide levels and weather conditions are not measured in the same location. Therefore, the weather station closest to the air pollution reader is used. In Uppsala, the closest station is Uppsala Aut located approximately 1 km to the west of Kungsgatan 42. For Jönköping and Umeå, the weather observations come from the local airports located approximately 7 and 4 km from the nitrogen dioxide station.

Table 3 contains descriptive statistics for the daily average values between 2012 and 2013. The tables show that the nitrogen levels were the highest in Umeå and the lowest in Jönköping. Note that the difference between the largest and smallest observation is relatively large in all three cities. To make sure that outliers do not get disproportional weight in the regressions the logarithmic values are used. Table 3 also shows that Umeå, located in the north, has an average temperature lower than the two other cities.

---

[4] Station name: Uppsala Kungsgatan 42, station code: 20414

[5] Station name: Jönköping Kungsgatan, station code: 18650

[6] Station name: Umeå Västra Esplanaden, station code: 13532

Table 3: Descriptive statistic, averages daily values 2012-2013 for nitrogen dioxide and weather controls

Variables	Unit	Obvs.	Mean	Std. Dev.	Min	Max
Uppsala						
NO2	µg/m^3	731	28,38	13,44	5,78	76,46
wind	m/s	731	2,08	0,90	0,04	5,04
temp	Degrees C	731	6,78	8,25	-16,60	22,21
Jönköping						
NO2	µg/m3	701	24,31	11,78	4,55	77,88
wind	m/s	730	3,61	1,68	0,17	9,63
temp	Degrees C	731	5,99	7,62	-17,02	20,30
Umeå						
NO2	µg/m3	704	33,54	19,03	3,96	141,26
wind	m/s	727	2,99	1,57	0,08	9,50
temp	Degrees C	731	3,94	9,12	-24,54	20,20

6 Results

Table 4 contains the result for the full-time period of one year before and after the implementation of the low emission zones. Column 1 contains the results of a before and after regression where the dummy variable PostLEZ takes the value one for 2013 and zero for 2012. The regression shows a statistically significant decrease of 5 % (t-value -2,1; p-value 0,04) for the concentration of nitrogen dioxide. It is important to note that the before and after regression not only will capture the effect of the low emissions zone but all factors that are not controlled for. For example, the regression does not control for changes in traffic volume. Given that the traffic volume most likely has decreased over the period, the regression will be an overestimate of the effect of the low emission zone. The regression should instead be interpreted as the difference in average concentration levels between 2012 and 2013, given the control variables.

Column 2 shows the result for the difference in difference regression using the night hours as control. The variable of interest is the LEZ variable that captures the effect of the low emission zone. The estimated effect is -0,028, which represents a 3 % decrease in nitrogen dioxide levels. However, the variable is not statistically significantly different from zero (t-value -0,66; p-value 0,51). Hence it is not possible to reject the null hypothesis that the low emissions zone had no effect. Note that in column 2, the sum of PostLEZ and LEZ is the total change in concentration level. Hence, the model indicates that of the total decrease of 5 %, 3 % is due to the low emission zone and 2 % due to the time trend. However, the uncertainty is large, and none of the variables is significantly different from zero.

The third column contains the result for the difference in difference regression using Jönköping and Umeå as a control group. The estimated effect is similar to column 2 and indicates a decrease of 3 %, which is statistically insignificant with a t-value of -0,94 and p-value 0,35. The overall conclusion from table 4 is, therefore, that it is not possible to reject the null hypothesis that the low emissions zone had no effect.

For the control variables, table 4 shows that the postLEZ variable is not statistically significantly different from zero, indicating that there was no significant time trend between the two periods. The treatment variable shows (as expected) a large difference in concentration levels between the night and day period (column 2). In column 3, the treatment variable is significant and negative, indicating that the concentration level is lower in Uppsala than in the two control cities. The meteorological controls wind and temperature are (as expected) statistically significant and have a negative sign. The squared wind term has a positive sign indicating that the marginal effect of wind speed is decreasing. Table 4 further shows that, as expected, the nitrogen concentration is lower during public holidays.

For the dummies for season, the results indicate higher emissions concentration during the spring and the autumn compared to the winter period and no statistically significant difference for the summer. Finally, the model predicts that compared to Fridays, the concentration levels are lower on Saturdays, Sundays and Mondays. The seasonality pattern within a week indicates the highest concentrations on Fridays and the lowest value on Sundays. The weekly pattern is expected since the nitrogen dioxide accumulates during the week and decreases during the weekend when the traffic volume goes down.

Table 4: Results full sample one year before and after implementation

	OLS Before and after Treatment	DiD Control: night hours	DiD Control: Ume & Jön
	(1)	(2)	(3)
VARIABLES	lno2	lno2	lno2
Treatment		0,875***	-0,140***
		(0,0308)	(0,0227)
PostLEZ	-0,0494**	-0,0175	-0,0264
	(0,0235)	(0,0320)	(0,0177)
LEZ		-0,0279	-0,0283
		(0,0423)	(0,0300)
Wind	-0,499***	-0,518***	-0,244***
	(0,0508)	(0,0327)	(0,0168)
Wind^2	0,0494***	0,0512***	0,00826***
	(0,0113)	(0,00712)	(0,00222)
Temp	-0,0264***	-0,0288***	-0,0274***
	(0,00241)	(0,00226)	(0,00151)
Public holiday	-0,390***	-0,251***	-0,421***
	(0,0880)	(0,0641)	(0,0506)
Spring	0,209***	0,243***	0,116***
	(0,0410)	(0,0352)	(0,0226)
Summer	-0,0313	0,0605	-0,0349
	(0,0584)	(0,0531)	(0,0361)
Autumn	0,0949**	0,0971***	0,0580**
	(0,0423)	(0,0375)	(0,0252)
Saturday	-0,452***	-0,263***	-0,368***
	(0,0470)	(0,0402)	(0,0277)
Sunday	-0,365***	-0,176***	-0,453***
	(0,0474)	(0,0414)	(0,0287)
Monday	-0,0474	-0,115***	-0,0346
	(0,0467)	(0,0400)	(0,0270)
Tuesday	-0,0384	-0,0336	-0,0335
	(0,0460)	(0,0385)	(0,0267)
Wednesday	-0,00555	-0,00212	0,0226
	(0,0430)	(0,0355)	(0,0255)
Thursday	0,0118	0,0392	0,0273
	(0,0450)	(0,0368)	(0,0260)
Constant	4,291***	3,622***	4,148***
	(0,0626)	(0,0495)	(0,0399)
Observations	731	1,446	2,131
R-squared	0,604	0,613	0,626

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

6.1 Altering the time period

The regressions in table 4 show the results for a time window of one year before and one year after the implementation of the low emission zone. Hence, during two years. As discussed previously, there is a risk that the model contains a bias from changes in traffic volume due to other policies implemented to mitigate the effects of the low emissions zone. However, if the time window is shortened, there should arguably be fewer changes in traffic due to other policies, and therefore less bias. Another possible problem of using a wide time window around the implementation date is that the effect of the low emissions zones is not constant over time, but gradually changing. The estimated time effect will, therefore, be the average difference between 2012 and 2013, which is not necessarily representative of the immediate effect of the low emission zone.

In table 5 and column 1 and 2, the period is shortened to six months. In column 1, the night hours are used as controls, and the model indicates a decrease in concentration levels of 6 %. When using Umeå and Jönköping as control, the estimates indicate an effect of -0,2 %. Even if the differences between the approaches are relatively large, none of the coefficients are statistically different from zero (t-value -1,02; p-value 0,31 and t-value -0,05; p-value 0,962).

In column 3 and 4, the period is shortened further to two months before and after. With a total period of only four months, the time trend should only have a marginal effect on the results. On the other hand, the sample size is reduced to 238 and 360 observations, which gives less statistical power. The results from the regressions are that none of the two identification approaches yields results statistically significant from zero. In column 3, the estimated coefficient has an unexpected positive sign. The uncertainty and the standard errors are large in the regression, which can explain the positive sign.

A potential problem with the short time period is announcement effects. There is a risk that many of the affected vehicles were upgraded in the last months before the implementations of the low emission zone. If this is the case, will the regressions not catch the full effect of the policy. If there are announcement effects, the problem is likely to be the largest for the short period of two months before and after presented in column 3 and 4. The potential problem with announcement effects gives reason to interpret the result from column 3 and 4 with some additional caution.

The conclusion from table 5 is that results seem to be robust to the choice of time window. Independent of approaches and time window it is not possible to reject the null hypothesis that the low emissions zone had no effect.

Table 5: Robustness check time periods

VARIABLES	Six months Control: night hours (1) lno2	Six months Control: Ume & Jön (2) lno2	Two months Control: night hours (3) lno2	Two months Control: Ume & Jön (3) lno2
Treatment	0,900***	-0,156***	0,781***	-0,0361
	(0,0413)	(0,0296)	(0,0681)	(0,0448)
PostLEZ	-0,0795	-0,0972***	-0,112	0,0482
	(0,0548)	(0,0338)	(0,0951)	(0,0409)
LEZ	-0,0609	-0,00196	0,0208	-0,0418
	(0,0595)	(0,0414)	(0,112)	(0,0694)
Weather controls	X	X	X	X
Seasonality controls	X	X	X	X
Observations	724	1,060	238	360
R-squared	0,641	0,645	0,630	0,722

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

6.2 Wind direction

One factor not included in the analysis so far is the direction of the wind. The wind direction could potentially be one of the explanations for the variation in the estimated coefficient in table 5. Both Aldrin and Haff (2005) and Sayegh et al. (2016) discuss and argue for the need to control for the wind direction. Both the content of the incoming wind and the physical planning with blocking buildings and trees can affect the concentration levels. However, controlling for wind direction in this model has some problems. Firstly, there are no meaningful linear interpretations of direction. Just adding the wind direction in degrees as control is therefore not possible. The solution to this problem will be to transform the direction into four categorical variables: north, west, south and east. The problem with a categorical variable is that the difference between the categories becomes larger than the real differences. The actual difference between a direction of 45 and 46 degrees is practically zero. However, the directions will nonetheless get split into two different groups (north and west).

The second problem is how to make a meaningful definition of the average wind direction. The model needs the average wind direction per day or night and day hours. In this regression, the average wind direction is calculated by taking the average direction in degrees (full circle 360 degrees) from hourly values. If the wind direction changes significantly over the day, the results can be questionable. If the wind direction is east for half the day and west the other half, is it then meaningful to interpret the average direction as south? Due to the problems of interpreting average direction will the included variables in table 6 not be perfect controls. The problems associated with average wind direction gives further cause to interpret the results with caution.

Table 6 presents the results of a regression model including the variables West, South and East as variables for the wind direction (using north as the baseline). Furthermore, an interaction term between the wind direction and wind is included. The effect of different wind directions should depend on wind speed. If there is no wind, there should not be any effect. The interaction between speed and direction will capture this interaction effect.

For the identification strategy using Umeå and Jönköping, it is likely that the effect of wind direction differs between cities. To capture the city-specific effect of wind direction an interaction term with wind direction, wind speed and city is included. Hence the model will allow the effect of wind direction to differ between the three cities.

As shown in table 6, the changes in the estimated effect are small compared to those in table 4 and 5. In none of the models or periods are the results statistically significantly different from zero. Thus, the result that it is not possible to reject the null hypothesis that the low emissions zone had no effect is therefore robust for inclusion of wind direction. The estimated effect from the wind directions can be found in table A.1 in the appendix.

Table 6: Robustness check, wind direction

	One-year Control: night hours (1)	One-year Control: Ume & Jön (2)	Six months Control: night hours (3)	Six months Control: Ume & Jön (4)	Two months Control: night hours (5)	Two months Control: Ume & Jön (6)
VARIABLES	lno2	lno2	lno2	lno2	lno2	lno2
Treatment	0,879***	0,0730*	0,899***	0,0683	0,803***	0,120
	(0,0279)	(0,0430)	(0,0389)	(0,0588)	(0,0666)	(0,0878)
PostLEZ	-0,0168	-0,0261	-0,0909*	-0,100***	-0,0572	0,0589
	(0,0293)	(0,0171)	(0,0503)	(0,0332)	(0,0845)	(0,0401)
LEZ	-0,0331	-0,0272	-0,0597	-0,00139	-0,0108	-0,0695
	(0,0386)	(0,0289)	(0,0563)	(0,0402)	(0,102)	(0,0688)
Weather controls	X	X	X	X	X	X
Wind direction	X	X	X	X	X	X
Wind*Direction	X		X		X	
Wind*Direction*City		X		X		X
Seasonality controls	X	X	X	X	X	X
Observations	1,446	2,131	724	1,060	238	360
R-squared	0,681	0,633	0,693	0,652	0,710	0,729

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

6.3 Discussion

The conclusion from table 4-6 is that it is not possible to reject the null hypothesis that the low emissions did not have any effect on the nitrogen dioxide levels. Hence, the low emission zone has failed to deliver on the policy target of lowering the nitrogen dioxide concentration. The main problem in the regressions has been to distinguish the effect of the low emission zones from other policies and trends. The difference in difference model should in an ideal state be able to solve this problem and estimate the true policy effect. However, the problem with fulfilling the common trend assumption, especially for the outside Uppsala strategy, raises questions about the reliability of the models.

There are three main arguments why the result should be considered reliable and a good indication of the true effect. Firstly, both identification strategies lead to the same conclusion. Hence, whether the control group is found within or outside Uppsala does not affect the result. The fact that both strategies yield the same result gives the result credibility. It is unlikely that both strategies would be affected by the same source of bias. Secondly, the results are robust for different periods. Arguably, the problem with common assumption should be smaller if the period is shortened. Thirdly, the within Uppsala identification strategy is likely to overestimate rather than underestimate the effect. Even though the model is likely to overestimate the effect the result is not significantly different from zero. The overall conclusion is, therefore, that the results are robust and should be considered reliable.

An additional reason to trust the result is that the finding is in line with previous literature. Several European studies have, as discussed in section 2, found the same results. The only Swedish study that has calculated the effect for nitrogen dioxide concentration (Rapaport, 2002) finds a decrease at street level of 1.5 %. The effect found by Rapaport (2002) is rather small, and further ads to the belief that the effect of low emission zones in Sweden is likely to be small.

The result that the low emission zone did not decrease the levels of nitrogen dioxide is to some extent, counterintuitive. The pollution level should decrease if the oldest and dirties vehicles no longer can enter the zones. Hence, the expected result differs from the empirical results. In the economic theory discussed in section 4, the policy under certain assumptions gave the optimal emission levels in a second-best world. The question is, therefore, why the theoretical model and the expected results differ from the estimated effect?

One possible explanation would be that the policy does not create any shift from old to newer vehicles. Hence, the enforcement of the policy is not strong enough for the vehicle owners to replace their vehicles. The evidence from the literature does, on the other hand, show that age distribution in both Stockholm and Gothenburg did change after implementation of the policy. The studies indicate that the low emission zone influences the age distribution of the vehicle fleet. Further, both studies reported that the compliance with regulations was high, and up to 97 % of the controlled vehicles were in compliance (City of Stockholm, 2001; City of Gothenburg, 2006). There are no apparent reasons why the effect should be different in Uppsala.

A second possible explanation as to why the result is insignificant could be that the decrease in emissions from the affected vehicles is too small to have an impact on the total pollution level. If not enough of the transportation within the zones is affected or the improvement in emissions levels from new vehicles is low, the effect of the policy will be small. Hence, the policy can successfully prohibit older vehicles from entering the zones, but the change in emissions from the affected vehicles is not large enough to give a statistically significant impact.

6.3.1 The number of affected vehicles

The entering requirements do not only impact the maximum allowed emissions within the zone but also how many vehicles are affected by the policy. If the requirements are low compared to the existing fleet, the number of affected vehicles will be small. The fewer the vehicles affected, the smaller the expected effect. Malina and Scheffler (2015) showed the importance of the entering requirements in German cities where the effect increased three times with stricter regulations. In the theoretical model, low entering requirements would correspond to a lower than optimal z parameter. Note that in the model, all vehicles are assumed to be the same. Hence, if the entering requirements are lower than the existing vehicle, the effect in the model will be zero.

The number of affected vehicles is, as discussed in section 2, not known. Statistics from Trafikanalys (2014) showed that 85 % of the transport kilometres in Sweden are made by trucks eight years old or newer. As showed in table 2 only vehicles older than eight years were affected by the policy. Joakim Viberg[7] spokesperson at the Swedish Association for Road Transport Companies estimates that large operators typically replace their vehicles after 5-8 years. Hence, the larger operators replace their vehicles before they no longer meet the requirements.

It is important to note that the statistics from Trafikanalys (2014) and a shift in the age distribution do not necessarily conflict. It is possible that the group of larger operators that Viberg refers to represent the vast majority of transport kilometres. Hence, the operators responsible for the larger part of the emissions are not affected by the policy. The affected vehicles may be relatively numerous, but their emissions may be low due to a limited number of kilometres driven. The policy may, therefore, affect the age distribution without significant effect on the pollution level.

---

[7] Telephone interview 2019-04-04, Joakim Viberg. joakim.viberg@akeri.se Branschföreträdare, Sveriges åkeriföretag

In summary, it is likely that one of the most prominent explanations for the lack of effect is that too few of the transports are affected to make a significant difference. However, since the age distribution within the zone before the implementation is not known, is it not possible to fully know how many vehicles or transport kilometres were affected. It is therefore not possible to know if the target group was large enough to affect the nitrogen dioxide levels. A recommendation for cities planning for low emission zones is, therefore, to make a simple ex-ante analysis of how many vehicles will be affected and what the maximum potential decrease in total emissions is. If the number is low, other policy options should be considered.

6.3.2 Improvement in emissions levels from new vehicles

A second potential difference between the theoretical model and the real conditions, is the decrease in emissions from new vehicles compared to older ones. Beevers et al. (2012) and Carslaw & Rhys-Tyler (2013) and Velders et al. (2011) found that the differences between the Euro classes were low, and the emissions higher than expected. A fundamental condition for the low emission zone using the Euro class system as entering requirements is that there should be a clear difference in emissions between the levels. Without a difference a shift to newer vehicles would have little effect on the pollution level. Hence, one possible explanation for the insignificant effect of the low emission zone could be that new vehicles do not decrease the emissions enough to make an impact on the total emissions.

In the theoretical model, the transition from emissions standard to emissions is captured by the alfa parameter. The weaker the connection between emissions and the Euro standard, the lower the alfa parameter. Equation 9 showed that if the alfa parameter is low, the low emission zone will give less social welfare and other policy options such as road tolls, become relatively more attractive. Hence, if alfa is small, policies aiming for traffic volume are preferable to policies such as the low emission zone that aims to decrease the emission per kilometre.

Given the indication that the Euro class system connection is weak, the system can be questioned, but also the decision to base the low emission zone system on it. In the end, it is the real emissions in real driving that will affect the pollution levels and public health. Preferably the entering requirement should be best on actual emission levels where an increase of the standard led to an equal improvement in affected vehicle emissions. Hence, an alfa parameter of close to one. The Euro class system has the benefit of being cross-European and relatively simple to use. However, the fundamental mechanism in the low emission zone is that the emission decreases when drivers upgrade their vehicles to meet the standards. If this connection is weak the simplicity argument is inadequate.

6.3.4 The importance of data collection and evaluations

The main challenges in evaluating the effect of the low emission zone in Uppsala has been to disentangle the effect of the policy from other factors. The lack of key control variables has made it hard to use the econometric techniques used in previous literature. The evaluation of the low emission zone (and any other policy) would have been significantly simplified if the municipality of Uppsala had measured and collected data on traffic volume and background levels of nitrogen dioxide. Hence, if the municipality had a plan for how to evaluate the policy. The fact that none of this data was collected indicates that there was no plan in Uppsala how to evaluate the policy. A recommendation for cities that implement low emission zones in the future is, therefore, to develop a plan and collect the data needed for an evaluation. With a plan for evaluation, policy evaluation can be simplified, and cities can learn from each other.

6.3.5 The future for low emission zones in Sweden

The result of the analysis shows that the low emissions zone in Uppsala had no significant effect on nitrogen dioxide concentration. The lack of a positive effect raises the question of whether the policy should be removed not just in Uppsala but in all Swedish cities? The answer is that the decision about removing the policy should depend on a broader set of parameters than only the average nitrogen dioxide level.

This thesis only evaluates the effect on nitrogen dioxide. The policy could, however, have an impact on other traffic-generated emissions such as PM10. Further, Cyrys et al. (2014) argue that the impact can be more significant for particles such as black smoke and elemental carbon than the border PM10 levels indicate. In order to rule out the effectiveness of the low emission zone in Sweden further research on a broader spectrum of particles is needed.

A second perspective that has not been taken into consideration in this thesis is if the low emission zone has an effect on the number of days and hours with high levels of pollution. This thesis and the broader literature focuses on average differences in the period before and after implementation. As shown in diagram 1 in section 2, high daily values were the most critical of the environmental quality standards. In other words, decreasing the number of days with high values is an important policy goal. The main problem with empirically answering this question is that it will be even harder to distinguish the effect of the low emission zone and short-term temporary variations. Future research, therefore, needs to develop new econometric models and techniques to evaluate the effect for short periods.

The conclusion is, therefore, that further research is necessary before the total effect of the low emission zone can be determined. What the thesis shows, however, is that a low emission zone is hard to motivate if the policy goal is to lower the average concentration of nitrogen dioxide. The main policy goal for several Swedish cities has been to lower the nitrogen dioxide levels. The results show that low emission zones do not reach this target. Until there is clear evidence that the effect is substantial for other particles, the argument for implementing low emission zones in Sweden under the current regulation is weak.

The Swedish government decided in 2018 that from 2020 it will be possible for the municipalities to extend entering requirements for low emission zones. The new regulation opens for the possibility to include cars and lighter vehicles than 3.5 tonnes. The municipalities will also get the opportunity to impose a stricter entering requirement (Swedish government, 2018). The evidence from German literature indicates that both these changes can have a positive effect on the pollution levels (see, e.g. Holman et al., 2015; Malina and Scheffler, 2015). Whether the new regulations will increase the effect of the policy enough to have a significant impact on air pollution is beyond the scope of this thesis. However, it shows that the Swedish government see low emission zones as a policy option, even in the future.

7 Conclusions

The first conclusion is that in a theoretical model, the low emission zone can be an optimal policy in a second-best world, given that the first best emissions tax is not possible. The theoretical model further shows that low traffic elasticity and cost of compliance increase social welfare from low emission zones. A third important factor for the low emission zones is how strong the connection is between the emissions standard used as an entering requirement and the real emissions. If the connection is weak, social welfare will decrease, and other policy options will be relatively better.

The main conclusion from the thesis is that it is not possible to reject the null hypothesis that the effect of low emission zones in Uppsala had no effect. Hence, the low emission zone has failed to deliver on the policy target of lowering the nitrogen dioxide concentration. The results are robust to alternative identification strategies, different periods and model specifications. Given that it is not possible to find any statistically significant results for nitrogen dioxide, it is hard to motivate the policy based on this pollution. It is possible that low emission zones have a positive impact on other pollution. However, until this potential effect is proven, the argument for low emission zones in Sweden will be weak.

The thesis discusses two possible explanations for the lack of results. The first possible explanation is that too few transport kilometres were affected by the policy. Data from Trafikanalys (2014) indicates that only a limited number of total transport kilometres within the zone are affected by the policy. In other words, the entering requirements of the emission zone are too lax. The other possible explanation is the indication in the literature that the differences in emissions between the different Euro classes are lower than expected. Hence, the expected improvement in emissions levels from newer vehicles may be lower than the Euro class system indicates.

Finally, is it important to note that this thesis has only focused on the average concentrations of nitrogen dioxide. Further research for how other particles are affected by the Swedish regulation is essential before the total effect of the low emission zone in Sweden can be determined. Another priority for future research is to develop new econometric models and techniques to evaluate the effect on days and hours with high values. It is not only the average values but also the number of days and hours with high values that impact public health. Solving the problem of disentangling the effect of the low emission zone for other factors is therefore essential in order to get a complete picture of the effect from low emission zones.

Sources:

Aldrin, M., & Haff, I. H. (2005). Generalised additive modelling of air pollution, traffic volume and meteorology. *Atmospheric Environment*, *39*(11), 2145-2155.

De Borger, B., & Proost, S. (2013). Traffic externalities in cities: the economics of speed bumps, low emission zones and city bypasses. *Journal of Urban Economics*, *76*, 53-70.

Beevers, S. D., Westmoreland, E., de Jong, M. C., Williams, M. L., & Carslaw, D. C. (2012). Trends in NOx and NO2 emissions from road traffic in Great Britain. *Atmospheric Environment*, *54*, 107-116.

Boogaard, H., Janssen, N. A., Fischer, P. H., Kos, G. P., Weijers, E. P., Cassee, F. R., ... & Brunekreef, B. (2012). Impact of low emission zones and local traffic policies on ambient air pollution concentrations. *Science of the total environment*, *435*, 132-140.

Carslaw, D. C., & Beevers, S. D. (2002). The efficacy of low emission zones in central London as a means of reducing nitrogen dioxide concentrations. *Transportation Research Part D: Transport and Environment*, *7*(1), 49-64.

Carslaw, D. C., & Rhys-Tyler, G. (2013). New insights from comprehensive on-road measurements of NOx, NO2 and NH3 from vehicle emission remote sensing in London, UK. *Atmospheric Environment*, *81*, 339-347.

Chay, K. Y., & Greenstone, M. (2003). The impact of air pollution on infant mortality: evidence from geographic variation in pollution shocks induced by a recession. *The quarterly journal of economics*, 118(3), 1121–1167.

City of Gothenburg. (2006.) Utvärdering av miljözon i Göteborg, En rapport för Trafikkontoret i Göteborg stad. Trafikkontoret i Göteborg, May 2016

City of Stockholm. (2001). Stockholms miljözon - EFFEKTER PÅ LUFTKVALITET 2000. Miljöförvaltningen i Stockholm, April 2001.

City of Stockholm. (2008). Miljözon för tung trafik i Stockholm 1996–2007. City of Stockholm, Trafikkontoret, 2008-05-12

County Administrative Board of Skåne. (2009). Reviderat åtgärdsprogram för att klara miljökvalitetsnormen för kvävedioxid i Helsingborg. Länsstyrelsen i Skåne län, 2009-10-15

Cyrys, J., Peters, A., Soentgen, J., & Wichmann, H. E. (2014). Low emission zones reduce PM10 mass concentrations and diesel soot in German cities. *Journal of the Air & Waste Management Association*, *64*(4), 481-487.

Dockery, D. W., Pope, C. A., Xu, X., Spengler, J. D., Ware, J. H., Fay, M. E., ... & Speizer, F. E. (1993). An association between air pollution and mortality in six US cities. *New England journal of medicine*, 329(24), 1753-1759

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.

European Parliament and Council Directive 2008/50/EC of 28 May 2018, on ambient air quality and cleaner air for Europe.

Fullerton, D., & West, S. E. (2002). Can taxes on cars and on gasoline mimic an unavailable tax on emissions?. *Journal of Environmental Economics and Management*, *43*(1), 135–157.

Gatu-och trafiknämnden. (2011). Ansökan om lokal trafikföreskrift om miljözon i innerstaden. Uppsala kommun, Gatu-och trafiknämnden, 2011-09-28. Diarienummer GTN-2010-0341 70

Gustafsson, M., Lindén, J., Tang, L., Forsberg, B., Orru, H., Sjöberg, K., & Åström, S. (2018). Quantification of population exposure to NO2, PM2. 5 and PM10 and estimated health impacts. *Swedish Environmental Research Institute*, No. C317 June 2018

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.

Kommunledningskontoret. (2009). Åtgärdsplan för att klara miljökvalitetsnormerna för kvävedioxid och partiklar i Uppsala 2009–2010. Uppsala kommun, Kommunledningskontoret, 2009-04-29. Diarienummer KSN-2009-0249

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.

Naturvårdverket. (2018). Riktvärden för buller från väg- och spårtrafik vid befintliga bostäder. naturvardsverket.se, 9 maj 2018. Contact person Henrik Larsson. https://www.naturvardsverket.se/Stod-i-miljoarbetet/Vagledningar/Buller/Buller-fran-vag--och-spartrafik-vid-befintliga-bostader/ [available 2019-04-11]

Naturvårdsverket. (2019). Luftguiden, Handbok om miljökvalitetsnormer för utomhusluft. Handbok 2019:1, Version 4, januari 2019

Panteliadis, P., Strak, M., Hoek, G., Weijers, E., van der Zee, S., & Dijkema, M. (2014). Implementation of a low emission zone and evaluation of effects on air quality by long-term monitoring. *Atmospheric environment*, *86*, 113-119.

Pigou, 1920. A.C. Pigou. The Economics of Welfare (fourth. ed. 1932), MacMillan, London (1920)

Pope III, C. A., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., & Thurston, G. D. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *Jama*, 287(9), 1132-1141.

Proost, S., 2011. Theory of external costs. In: de Palma, A., Lindsey, R., Quinet, E., Vickerman, R. (Eds.), A Handbook in Transport Economics. Edward Elgar (Chapter 14).

Rapaport, E. (2002). The Stockholm environmental zone, a method to curb air pollution from bus and truck traffic. Transportation *Research Part D: Transport and Environment*, 7(3), 213–224.

SMHI. (2019a). Datavärdskap för luftkvalitet. Smhi.se, Sveriges meteorologiska och hydrologiska institut. http://www.smhi.se/klimatdata/miljo/luftmiljodata [available 2019-04-27]

SMHI. (2019b). Ladda ner meteorologiska observationer. Smhi.se, Sveriges meteorologiska och hydrologiska institut. http://www.smhi.se/klimatdata/meteorologi/ladda-ner-meteorologiska-observationer#param=airtemperatureInstant,stations=all [available 2019-04-27]

Sayegh, A., Tate, J. E., & Ropkins, K. (2016). Understanding how roadside concentrations of NOx are influenced by the background levels, traffic density, and meteorological conditions using Boosted Regression Trees. *Atmospheric environment*, *127*, 163-175.

SCB. (2019). Folkmängden i Sveriges kommuner 1950–2018 enligt indelning 1 januari 2019. Statistiska centralbyrån, 2019-02-21. https://www.scb.se/hitta-statistik/statistik-efter-amne/befolkning/befolkningens-sammansattning/befolkningsstatistik/ [available 2019-04-29]

SFS 1998:1276. Trafikförordning

Sundblom, R. (2014). Trafik mätningar i Uppsala 2013. Uppsala kommun, kontoret för samhällsutveckling, maj 2014

Swedish government. (2018). Regeringen ger besked om miljözoner. regeringen.se, 2018-03-23 https://www.regeringen.se/pressmeddelanden/2018/03/regeringen-ger-besked-om-miljozoner/ [available 2019-05-13]

Trafikanalys. (2014). Swedish national and international road goods transport 2013. Trafikanalys, 2014-05-20. Statistik 2014:12

transportpolicy.net. (2019). EU: Heavy-duty: Emissions. International Council on Clean Transportation and DieselNet, 2018 https://www.transportpolicy.net/standard/eu-heavy-duty-emissions/ [available 2019-03-18]

Umeå municipality. (2012). Utredning av miljözon i centrala Umeå. Protokollsutdrag, Tekniska nämnden, 2012-12-13 §151. Diarier nr: TN0321/2008

Uppsala municipality (2014). Omprövning av Åtgärdsprogram för kvävedioxid och partiklar (pm10) i Uppsala. Uppsala kommun, april 2014.

Velders, G. J., Geilenkirchen, G. P., & de Lange, R. (2011). Higher than expected NOx emission from trucks may affect attainability of NO2 limit values in the Netherlands. *Atmospheric Environment*, *45*(18), 3025-3033.

Wolff, H., & Perry, L. (2010). Policy monitor: trends in clean air legislation in Europe: particulate matter and low emission zones. *Review of Environmental Economics and Policy*, 4(2), 293-308.

Wolff, H. (2014). Keep Your Clunker in the Suburb: Low-emission Zones and Adoption of Green Vehicles. *The Economic Journal*, *124*(578), F481-F512.

Appendix

A1 regressions

Table A.1: Robustness check wind direction ink Variables for wind direction and interaction terms

	One-year wind direction Control: night hours (1)	One-year wind direction Control: Ume & Jön (2)	Six months wind direction Control: night hours (3)	Six months wind direction Control: Ume & Jön (4)	Two months wind direction Control: night hours (5)	Two months wind direction Control: Ume & Jön (6)
VARIABLES	lno2	lno2	lno2	lno2	lno2	lno2
Treatment	0,879***	-0,148***	0,899***	-0,156***	0,803***	-0,0388
	(0,0279)	(0,0230)	(0,0389)	(0,0302)	(0,0666)	(0,0462)
PostLEZ	-0,0168	-0,0268	-0,0909*	-0,0952***	-0,0572	0,0498
	(0,0293)	(0,0177)	(0,0503)	(0,0342)	(0,0845)	(0,0414)
LEZ	-0,0331	-0,0294	-0,0597	0,00198	-0,0108	-0,0449
	(0,0386)	(0,0297)	(0,0563)	(0,0411)	(0,102)	(0,0688)
Wind	-0,535***	-0,267***	-0,491***	-0,224***	-0,313***	-0,149***
	(0,0397)	(0,0200)	(0,0578)	(0,0275)	(0,104)	(0,0426)
Wind^2	0,0393***	0,00968***	0,0333***	0,00334	-0,00271	-0,00579
	(0,00673)	(0,00230)	(0,00955)	(0,00329)	(0,0170)	(0,00498)
Temp	-0,0238***	-0,0263***	-0,0312***	-0,0287***	-0,0282***	-0,0398***
	(0,00222)	(0,00151)	(0,00174)	(0,00212)	(0,00842)	(0,00463)
West	-0,0195	0,0520	-0,0895	-0,0444	-0,149	-0,0522
	(0,0517)	(0,0579)	(0,0717)	(0,0810)	(0,157)	(0,0972)
South	-0,0869	0,0387	-0,142*	-0,0480	-0,297**	-0,142
	(0,0549)	(0,0540)	(0,0780)	(0,0791)	(0,141)	(0,0990)
East	-0,00661	0,113*	-0,0658	0,0342	-0,171	0,0265
	(0,0604)	0,0520	(0,0869)	(0,0870)	(0,149)	(0,124)
Wind*West	0,210***		0,195***		0,166***	
	(0,0250)		(0,0383)		(0,0620)	
Wind*South	0,124***		0,130***		0,119*	
	(0,0302)		(0,0406)		(0,0717)	
Wind*East	0,0566**		0,0791**		0,0622	
	(0,0258)		(0,0373)		(0,0579)	
Jön* West * Wind		-0,0199		-0,0123		-0,0126
		(0,0153)		(0,0219)		(0,0334)
Jön* South* Wind		-0,0163		0,00101		0,0418*
		(0,0145)		(0,0199)		(0,0238)
Jön* East* Wind		0,0175		0,0219		-0,0117

		(0,0194)		(0,0252)		(0,0250)
Ume* North * Wind		0,0686***		0,0646**		0,0684***
		(0,0178)		(0,0317)		(0,0234)
Ume* West * Wind		0,0205		0,0343		0,0449
		(0,0179)		(0,0258)		(0,0401)
Ume* South * Wind		0,0298*		0,0352*		0,0643***
		(0,0155)		(0,0208)		(0,0248)
Ume* East* Wind		0,0343*		0,0779***		0,0555*
		(0,0194)		(0,0277)		(0,0331)
Upp* North * Wind		0,0300		0,0249		0,0262
		(0,0229)		(0,0360)		(0,0417)
Upp* West * Wind		-0,115***		-0,125***		-0,121**
		(0,0240)		(0,0319)		(0,0528)
Upp* South * Wind		-0,103***		-0,0836**		-0,0357
		(0,0250)		(0,0357)		(0,0456)
Upp* East* Wind		-0,0490		-0,0353		-0,00197
		(0,0309)		(0,0389)		(0,0403)
Seasonality controls	X	X	X	X	X	X
Observations	1,446	2,131	724	1,060	238	360
R-squared	0,681	0,633	0,693	0,652	0,710	0,729

A2 Tables

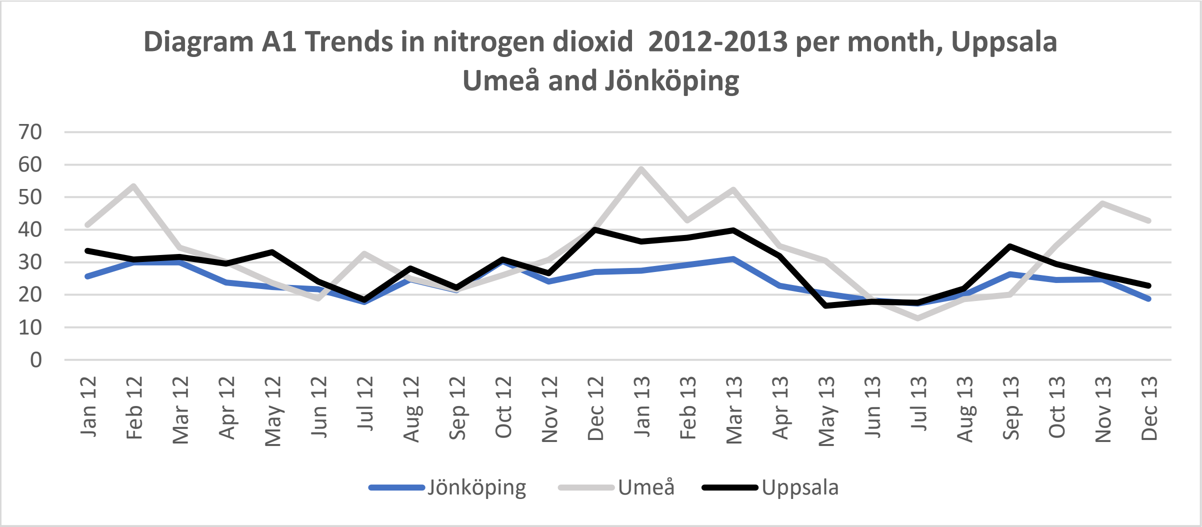


Diagram A1 Trends in nitrogen dioxid 2012-2013 per month, Uppsala Umeå and Jönköping

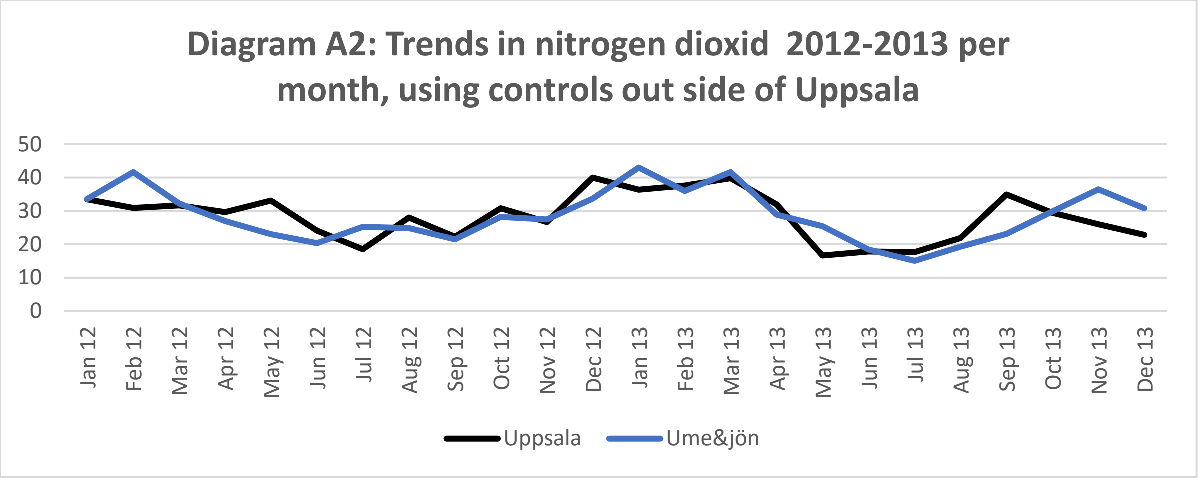


Diagram A2: Trends in nitrogen dioxid 2012-2013 per month, using controls out side of Uppsala

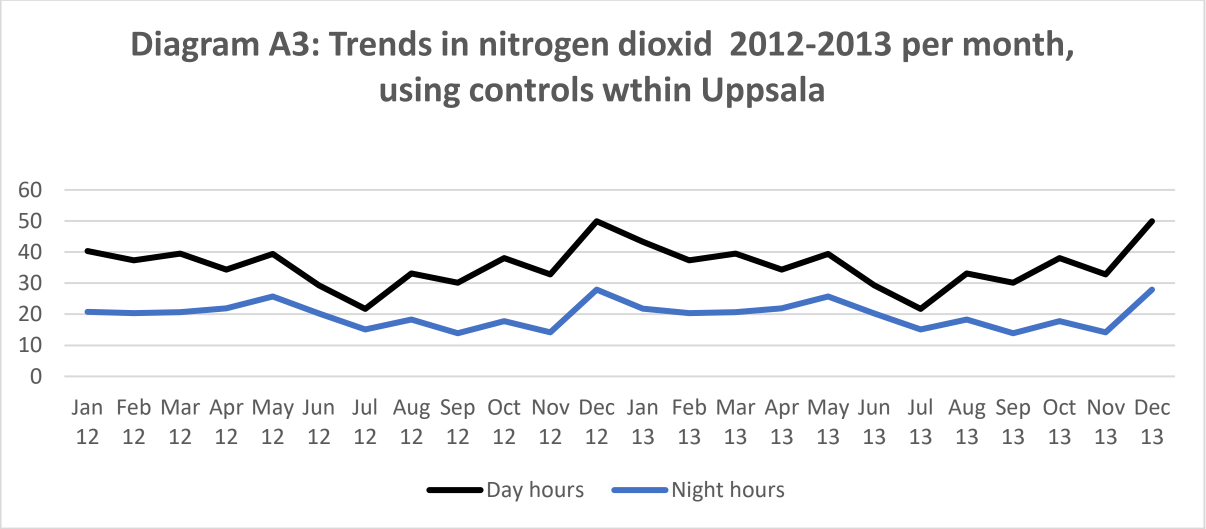


Diagram A3: Trends in nitrogen dioxid 2012-2013 per month, using controls wthin Uppsala