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The Gothenburg congestion tax and air quality

A difference-in-difference analysis

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Abstract

Causing 300 premature deaths each year, the air quality is a major problem in Gothenburg. In 2013, the Gothenburg congestion tax was implemented with the goal to reduce congestion and improve the air quality in the city, as well as to finance investments in infrastructure. The aim with our study is to investigate if, and to what extent, the congestion tax has reduced air pollutants, with focus on nitrogen oxides (NO_X) and particulate matter (PM_{10}) concentrations. We analyse this by using a difference-in-difference approach where our control group is Malmö, a Swedish city without congestion tax. Since it is evident that meteorological conditions largely affect emission levels we control for wind speed and precipitation in our regressions. We find evidence that the implementation of the congestion tax was associated with reduced NO_X as well as PM_{10} levels in Gothenburg with up to 17-19 %. Hence, we draw the conclusion that the implementation of the congestion tax had a general positive effect on the air quality in Gothenburg.

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1. Introduction

Today, nine out of ten people living in cities breathe polluted air (United Nations, 2018). Each year air pollution causes around 400 000 premature deaths and is one of the single largest environmental health risks in Europe (EEA, 2018). To be able to tackle the climate change and protect the environment, United Nations have 17 Sustainable Development Goals which aim to be achieved by 2030. One of these goals is to “Make cities inclusive, safe, resilient and sustainable”. Included in this goal is the aim to reduce per capita environmental impact of cities, where improvements of air quality are of high priority (United Nations, 2018). Swedish cities are not exempted from air pollution problems. Only in Gothenburg, air pollution causes 300 premature deaths each year (Miljömedicinskt Centrum, 2018).

The Swedish government (Government Bill 2009/10:189) stated that introducing a congestion tax in Gothenburg would lead to a reduction in air pollution in terms of particles, hydrocarbons and nitrogen oxides. On account of this, we are interested in investigating if a congestion tax can be an efficient way to target the goal of reduced emissions in the city. The aim with our study is hence to investigate the environmental effects of the introduction of the congestion tax in Gothenburg, in terms of air quality. We do this by using a difference-in-difference approach based on hourly data from 2010-2017, where we analyse if the tax implementation resulted in reduced levels of nitrogen oxides (NO_X) and particulate matter (PM_{10})[1] in Gothenburg. We hypothesize the air quality to improve as a consequence of the Gothenburg congestion tax. According to the Swedish government (Government Bill 2009/10:189) the reason why a congestion tax would lead to better air quality is that people are assumed to change from using cars, to use public transport or bicycle. In addition, Santos (2005) discusses the importance of a good public transport system and concludes that the effectiveness of a congestion tax increases if there is a good substitute to car driving

One of the main goals with the Gothenburg congestion tax was to improve the air quality. Hysing et al. (2015) question whether the environmental values have been promoted or disregarded. The congestion tax was criticised for being suboptimal from an environmental point of view since it also included investments in new roads. He argues that the lack of clarity regarding the West Sweden Agreement (that includes the congestion tax) was the main reason for its success since it enabled different stakeholders to make their own interpretations

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[1] PM_{10} are coarse particles with a diameter between 2.5 and 10 micrometers.

about the deal. Environmental stakeholders referred to reduced traffic and proponents of more roads could point to the infrastructure investments. Because of this ambiguity regarding the environmental benefits of the Gothenburg congestion tax we find it interesting to investigate whether the tax led to better air quality in the city or not.

The European Commission (2018a) states that one of the main reasons for poor air quality within Europe is pollutants from transport. Because of this, the European Union has set restrictions of particulate matter, nitrogen oxides, unburnt hydrocarbons and carbon monoxide emissions. The concentration limits of NO_2 and PM_{10} are set to 40 $\mu g/m^3$ for both pollutants (European Commission, 2018b). This means that the average of hourly pollutant concentrations should not exceed this limit at an annual level. The emissions have environmental effects, where NO_X is one of the worst pollutants, leading to e.g. ozone layer depletion, acid rain, and worsen water quality and vegetation. In addition, two of the pollutants leading to most severe harms to human health in Europe are PM and NO_2. Together with NO_X emissions these cause respirational diseases and lung cancer. This in turn, can result in heart diseases and stroke, leading to premature deaths (EEA, 2018; Boningari & Smirniotis, 2016).

The transport sector is responsible for most of the NO_2 emissions and also a significant contributor to PM emissions. Also, according to Göteborg Stad (2018a), road traffic is the main contributor to Gothenburg's air pollution. Continuous measuring of air quality shows that the main problems in Gothenburg are NO_2 and PM_{10}. The levels of NO_2 exceed the yearly, daily and hourly limits set by the European Union and is hence the most severe pollutant in Gothenburg. Also, the levels of PM_{10} exceed the limits at some streets during some years but not to the same extent as NO_2 (Miljöförvaltningen, 2014).[2] Based on this, to capture the environmental effects of the congestion tax in Gothenburg, we have decided to investigate the effect of the congestion tax on emissions of PM_{10} and NO_X. The reason why we use NO_X instead of NO_2 is because trends in the level of ozone affect the relation between NO and NO_2 (Johansson et al., 2006). When only analysing NO_2, the emission levels will be greatly impacted by the level of ozone. Hence, to reduce the risk that ozone levels will bias our results we use NO_X levels, that is a composition of NO and NO_2.

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[2] It is worth to point out that the levels of pollutants in Gothenburg are still a severe problem to the environment and human health. Now, Gothenburg has tightened the limits of PM_{10} to not exceed 30 $\mu g/m^3$ at an annual level by year 2020. For NO_2 the levels should not exceed 20 $\mu g/m^3$ outside schools and residential areas. For this goal to be reached, road traffic has to be further reduced (Miljöförvaltningen, 2018).

Our results confirm a considerable and robust reduction in NO_X and PM_{10} levels associated with the implementation of the Gothenburg congestion tax in 2013. The effect is estimated to reduce NO_X emissions with up to 17 % and PM_{10} emissions with up to 19 %. These results are of great importance since the environmental effects from the Gothenburg congestion tax have not been examined to a large extent before. Previous studies use traffic data combined with emission models and hence they do not manage to connect the direct measures of emission levels to the congestion tax. Due to meteorological impacts, previous studies have not been able to find a causal relationship between the Gothenburg congestion tax and measured emission levels. To our knowledge we are the first to investigate the Gothenburg congestion tax by controlling for meteorological conditions. Our results contribute with an interesting and important environmental policy finding since the air quality was significantly improved as a consequence of the congestion tax implementation.

To investigate if the effect grows or fades as time passes, we perform an event study where we create several policy variables around the time of implementation. The results from this study suggest that the effect seems to be direct and fading over time. Further, since the congestion tax is only implemented in a specific zone and for specific hours of the day, we test for intertemporal and spatial substitution effects. More specifically, we investigate if the emissions seem to change also in adjacent areas or for uncharged hours. Our results show a decrease in emission levels in the adjacent area Mölndal, suggesting that there is a spill-over effect and hence an underestimation of our results. We find no evidence for any substitution effect into uncharged hours. Rather, we find evidence that the effect is largest during charged hours, which suggests that the improved air quality results from the congestion tax and is not only a general improvement. We also investigate how robust the results are by varying the time frame and the empirical specification.

The rest of this paper is structured as follows; section two provides background information about the Gothenburg congestion tax. It also gives an overview of previous studies about the effect of a congestion charge on air quality as well as the impact of meteorological conditions on emission levels. Section three outlines theories about road pricing and environmental externalities. This section also includes our hypotheses. In Section 4 the data and methodology is presented. The empirical results are presented in section 5 and discussed in section 6. Section 7 concludes the study.

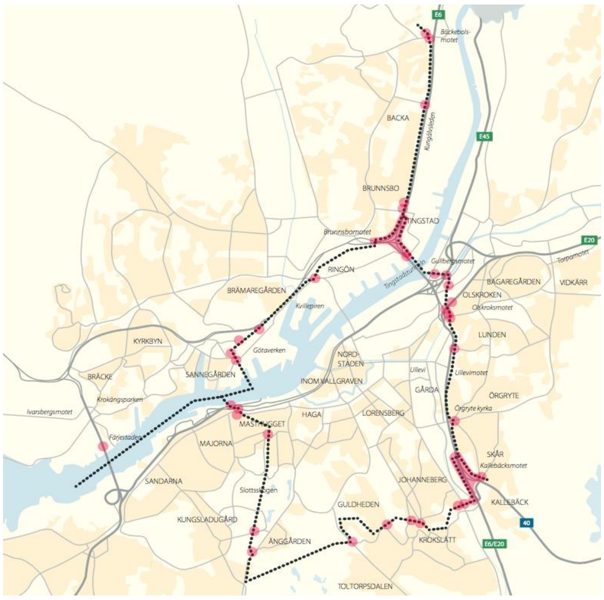
2. Background and Previous literature

2.1 Gothenburg congestion tax

On the 1st of January 2013, the congestion tax in Gothenburg was imposed. This tax is a part of the West Sweden Agreement, consisting of investments in public transport as well as infrastructure projects like building new roads and bridges. The stated purpose of the congestion tax was to reduce congestion, improve the air quality and to finance the construction of a railway tunnel system, the Western Link (Government Bill 2009/10:189). The program also included investments in public transport (e.g. new bus lanes as well as new commuter trains and platforms) to meet the increasing demand for public transport as a result of the increased cost of driving (GR, 2009).

All cars that enter or leave the charged zone on weekdays are charged between 06.00 and 18.30. The charge depends on the time of entering or leaving the charging zone, with higher price during highly congested hours as shown in figure 1, where we also see a price increase in 2015. During evenings/nights, on weekends and holidays it is free to travel into and out of the zone. The maximum amount charged per car and day is limited to 60 SEK. The cars are charged through an automatic number plate recognition system and people can choose to pay by automatic payment service, electronic billing or by invoice (Trafikverket, 2018). The charged area of Gothenburg is pictured in figure 1 where we can see the payment stations.

Figure 1. Map and pricing scheme of the charging zone in Gothenburg



Road pricing in Gothenburg

Time	*Charge 2013-2014*	*Charge 2015-*
06:00-06:29	8 SEK	9 SEK
06:30-06:59	13 SEK	16 SEK
07:00-07:59	18 SEK	22 SEK
08:00-08:29	13 SEK	16 SEK
08:30-14:59	8 SEK	9 SEK
15:00-15:29	13 SEK	16 SEK
15:30-16:59	18 SEK	22 SEK
17:00-17:59	13 SEK	16 SEK
18:00-18:29	8 SEK	9 SEK
18:30-05:59	0 SEK	0 SEK

Source: Trafikverket (2018)

2.2 Literature review

The environmental effect of the Gothenburg congestion tax has only been analysed in few studies. One of these is written by Börjesson and Kristofferson (2015), who perform an evaluation study of the Gothenburg congestion tax. By measuring traffic levels before (2012) and after (2013) tax implementation they show that the traffic volume is reduced due to the tax. Their results show a 12 % decrease in traffic volume during charged hours. As a consequence of this, they conclude that air pollution from traffic is reduced in the city centre of Gothenburg. Trafikverket (2014) shows that the measured levels of traffic volume in Gothenburg were lower after implementation of the congestion tax compared to the year prior to the policy implementation. Their modelled estimates indicate that the reduced traffic volume resulted in a reduction in exhaust as well as particle emissions. However, as a consequence of changing weather conditions, they do not find a clear relationship between the implementation of the congestion tax and measured levels of air pollutants.

Since meteorological aspects have been shown to have a large impact on emission levels[3], it is important to take these into account when analysing the relationship between the tax and air pollution. Trafikverket (2014) do not take this into account and hence they cannot identify to what extent the emission reduction depends on the reduction in traffic volume. Since Börjesson and Kristofferson (2015) use modelled, and not observed, values of air pollutants their result cannot with certainty be taken as the true effect. Therefore, none of these studies manage to directly connect the congestion tax to the observed levels of air pollutants.

Several empirical studies, performed in other cities than Gothenburg, find evidence that a congestion tax is associated with a reduction of air pollutants (Johansson et al., 2009; Gibson & Carnovale, 2015; Beevers & Carslaw, 2005; Daniel & Bekka, 2000). Johansson et al. (2009) investigate the effect from implementation of the Stockholm congestion tax on traffic flow and NO_X and PM_{10} levels. They analyse this by comparing the measured and modelled mean levels of road traffic, as well as comparing the mean of NO_X and PM_{10} levels before and after the policy implementation. They keep meteorological conditions as well as other emissions than from road traffic the same. The implementation of the Stockholm congestion tax substantially reduced traffic emissions of NO_X and PM_{10} in central Stockholm by 8.5 % and 13 % respectively. The reason for the reduction in traffic emissions was mainly explained

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[3] See section 2.3

by the decrease in traffic flows by 15 %. Further calculations show that a permanent system would imply up to 12 % and 7 % reductions of NO_X and PM_{10} respectively. Since there is a downward trend in traffic emissions due to cleaner cars and fuels they are not able to quantitatively ascertain how much of the reduction that is due to the congestion tax.

Gibson and Carnovale (2015) perform a natural experiment and use regression models to evaluate driver responses to road pricing in Milan. They use the unanticipated court injunction that the road pricing was suspended for eight weeks. Since they can investigate the difference between when there is a charge and when the road pricing is suspended, this makes it possible for them to analyse the effect of road pricing on the traffic and air pollution. In their analysis they control for meteorological conditions. They find that Milan's road pricing reduced air pollution substantially by 6 to 17 %, measured by CO, PM_{10} and $PM_{2.5}$. They also find evidence of intertemporal substitution to uncharged hours as well as spatial substitution to uncharged roads. Beevers and Carslaw (2005) investigate the impact of the London congestion charge on emission levels. They state that due to unusual weather conditions in the year of implementation it is difficult to assess the ambient measurements alone. Therefore, they combine a traffic emission model and data on road traffic to analyse to what extent the traffic related emission levels are determined by the congestion charge. They find that the London congestion charge significantly reduced NO_X and PM_{10} levels by approximately 12 %, to a large extent dependent on higher vehicle speed.

Since there are only few studies performed on Gothenburg, our study contributes with important information for policymakers about the effect on air quality after implementing a congestion tax. Even though several studies have been performed in different cities there is a need for more evidence from more cities. Compared to earlier studies we use hourly data on emission levels and hence we have a substantial number of observations. This allows us to capture a higher degree of variation than previous researchers who compare mean levels before and after tax implementation. Also, since we perform a difference-in-difference analysis, we can compared to previous studies, get closer to capture the causal effect from the congestion tax per se and not from other factors changing at the same time. Our model specification allows us to control for the downward trend in emissions, e.g. the share of green vehicles and cleaner fuels. By accounting for different meteorological conditions in our analysis we aim to reduce the problems to quantify how much of the change in level of NO_X and PM_{10} emissions that depends on the congestion tax.

2.3 Meteorological conditions

Congestion charges are often implemented as a way to reduce congestion in cities. A successful charge hence means reduced overall traffic and also, if the charge fluctuates throughout the day, smoothed traffic flows. This in turn results in reduced emissions from traffic. However, except from traffic flows and degree of emissions, the air quality also depends on the assimilative capacity of the environment, which is the environments own capacity to clean the air. This capacity depends on meteorological conditions, such as wind speed and rain, and hence it varies over time with diurnal as well as seasonal variations (Coria et al., 2015; Jones et al. 2010, Mayer, 1999). Based on these dynamics, Coria et al. (2015) investigate how the assimilative variations, proxied by wind speed, affect air quality in Stockholm and thereby how the congestion tax should be set to optimally reduce the level of air pollution. Their results indicate that a differentiated charge is optimal, charging the highest prices in hours with lowest assimilative capacity like in mornings and springtime.

Mayer (1999) concludes that motor traffic is a very important part of emissions and hence air quality. However, he also shows that air quality is dependent on many different factors, one of which is meteorological conditions such as wind speed, temperature, humidity and atmospheric stability. He finds that the NO concentrations are higher in mornings than in evenings, which can partly be explained by higher atmosphere stability in mornings. In addition, Jones et al. (2010) find evidence that there is a relationship between wind speed and concentration of NO_X in the air. Increased wind speed is associated with reduced concentration of pollutants.

Rost et al. (2009) and Holst et al. (2008) analyse PM_{10} concentrations in Germany, and find that level of PM_{10} concentrations are negatively affected by precipitation. They conclude that precipitation is the main meteorological aspect influencing levels of PM_{10}. Rost et al. (2009) also find that the presence and not the amount of precipitation have a significant effect on PM_{10} levels. In their analysis they find no strong relationship between wind speed and PM_{10} levels, which they believe can be explained by surrounding buildings. In contrast to this, Holst et al. (2008) find a negative and significant relationship between near surface wind speed and PM_{10} concentrations.

3. Theory and Hypothesis

3.1 Theory

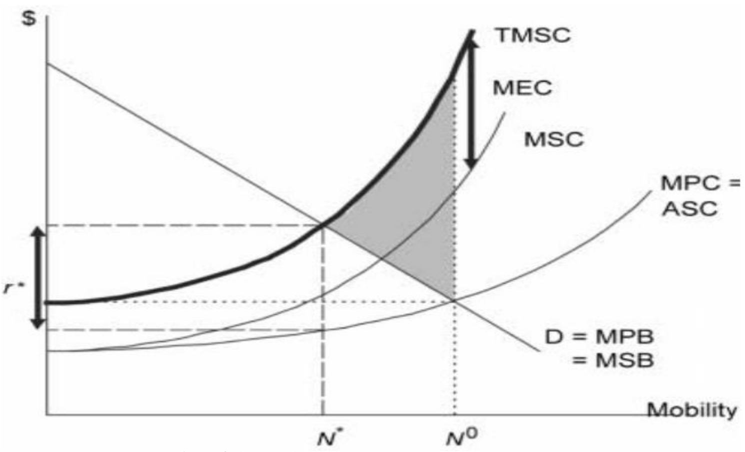
The main focus of early theories regarding urban road pricing was congestion. It is not until recently the environmental effects have raised more attention. Nowadays, road pricing often takes both environmental effects as well as congestion into account. One researcher taking environmental externalities into account is Verhoef (2000) who states that the marginal external cost pricing is straightforward. When there is high demand, resulting in congestion, prices should be high to reduce the excessive road use during peak hours. In the same way prices should be higher where the environmental externalities from traffic are large.

The last decades, road pricing has been considered to be an efficient way to reduce congestion and to collect revenues. Pigou (1920) introduced the idea of implementing a congestion charge to correct for externalities of driving. Pigou’s idea of imposing a tax that equates the marginal social cost and the marginal private cost, leading to an efficient distribution of vehicles on the roads, has been further developed by many researchers. Vickrey (1963) and Walters (1961) adds to Pigou’s theory that the price of driving should be higher in peak hours than in peak-off hours. Walters (1961) connects the tax to the elasticity of demand. If car drivers have a high elasticity they will respond a lot to increased road pricing. Further, Walters (1961) also discusses that increased price of driving will lead to an increase in its closest substitute, namely public transport. In addition, Vickrey (1963) suggests that a suitable pricing system is a more efficient and publicly accepted policy to reduce congestion in the city than direct bans of driving are. On the other hand, he also states that charging certain areas in a city might move the traffic flows to another area. However, this will still reduce congestion and it also increases the possibilities to introduce a better system of public transport.

Road traffic is associated with a variety of external costs like congestion, environmental effects, accidents and noise annoyance. These are divided into two types, namely “intra-sectoral externalities” and “inter-sectoral externalities”. The first concerns externalities that road users pose upon each other, like congestion, where the latter are posed upon society at large. The environmental externalities are part of the inter-sectoral externalities. From a welfare point of view both intra-sectoral and inter-sectoral externalities are Pareto-relevant (Verhoef, 2000).

Figure 2 shows the benchmark model of road transport externality regulation. This figure shows that due to the intra-sectoral and the environmental externalities, the market equilibrium N^0 exceeds the Pareto optimal level of traffic mobility, N*. The demand curve is equal to the marginal social and private benefits (D=MSB=MPB). By only taking the intra-sectoral externalities into account, MSC represents the marginal social cost curve. TMSC represents the total marginal social costs when also accounting for the inter-sectoral externalities e.g. environmental costs (MEC).

Figure 2. Graphical representation of the benchmark model of traffic externality regulation



Source: Verhoef (2000)

From figure 2 we see that when not accounting for the social or environmental externalities we end up at the market equilibrium N^0, where the demand curve intersects with the MPC curve. This is a higher level of traffic mobility compared to the Pareto efficient equilibrium at N*, the interaction between the total marginal social cost curve and the demand curve. At this point the social benefits are maximized and the deadweight loss (the shaded area) is avoided. To ensure this socially optimal level of mobility, the road price has to be set to r*, that equals the level of the marginal external cost. This means that a road price at r* will result in that drivers between N^0 and N* will not use the road anymore since the sum of the marginal private cost (MPC) plus the road price charge r* will exceed their benefits of road use (MPB). This means that the Pareto-efficient price will lead to a reduction in road mobility. This first-best benchmark policy is difficult to implement in reality because of a variety of barriers like political, social, institutional, psychological and technical. Another problem with this model is that it relies on strong assumptions like perfect information, homogenous road users and stable demand over time. Since these assumptions often do not hold in reality, we have to rely on second-best pricing when implementing policies (Verhoef, 2000).

3.2 Hypothesis

As we can see in figure 1, the Gothenburg congestion tax follows the peak and off-peak pricing Vickrey (1963) and Walters (1961) mention as the rational way of pricing. During hours when congestion is worst, prices are the highest. This would according to them lead to a smoothing of the traffic as well as a switch to public transport. Based on this we believe that the implementation of the congestion tax in Gothenburg will lead to improved air quality, through the channel of reduced traffic levels. Also, the fact that motorists do not bear the social marginal cost of driving in absence of a tax, results in that people drive too much. As Verhoef (2000) suggests, when motorists have to pay for this social marginal cost of driving, the demand will be reduced and hence they will drive less and the externalities will decrease.

Based on these theories and that previous literature finds evidence that congestion taxes lead to improved air quality (Gibson & Carnovale, 2015; Daniel & Bekka, 2000; Beevers & Carslaw, 2005; Johansson et al., 2009), we hypothesize that NO_X and PM_{10} levels will be reduced as a consequence of the Gothenburg congestion tax.

4. Data and Methodology

4.1 Data

To investigate the effect of the Gothenburg congestion tax on air quality we use data from SMHI[4] and Miljöförvaltningen, which report the hourly concentrations of pollutants. Data on air pollution is collected both for the charged zone of Gothenburg as well as for the control city, Malmö[5]. In Gothenburg there are three permanent stations measuring levels of NO, NO_2 and PM_{10}. Malmö also has three permanent stations, which all measure NO and NO_2 and two of them also measure PM_{10} (Göteborg Stad, 2018b; Malmö Stad, 2018). The data is collected for the period 2010-2017, which includes three years prior and five years after the implementation of the Gothenburg congestion tax in January 2013. Since the monitoring stations in Gothenburg and Malmö are in similar environments and the correlation between the emissions at the different stations in each city are high (between 0.6 and 0.9) we create city averages of NO_X respectively PM_{10}.

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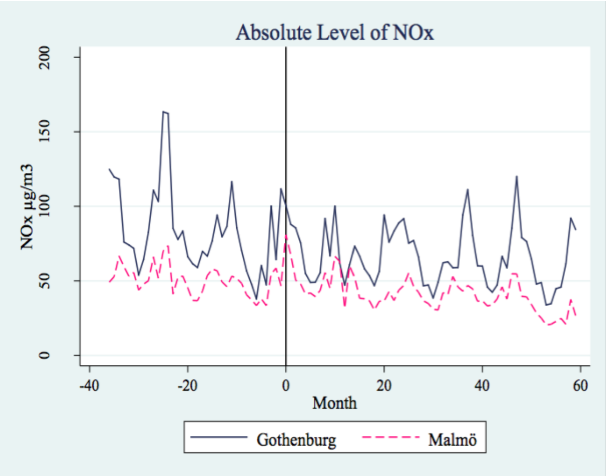
[4] The Swedish Meteorological and Hydrological Institute

[5] The reason why Malmö is chosen as the control city is because it is the largest Swedish city after Gothenburg, and that Malmö still not has introduced a congestion tax. In addition, Malmö also has equally many measuring stations as Gothenburg, placed in similar environments. Gothenburg and Malmö are also shown to follow parallel trends (see section 4.2).

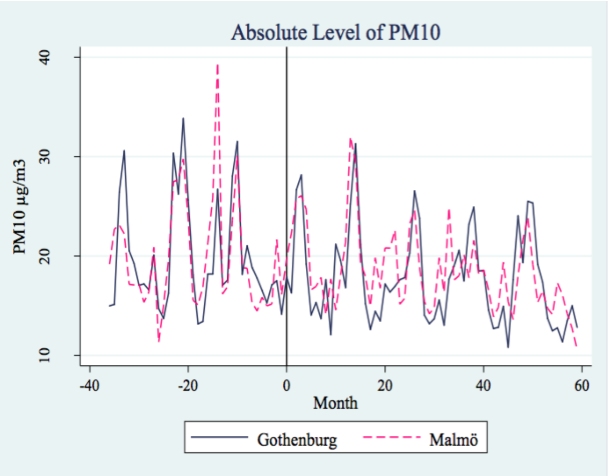
4.2 Parallel trends

Graph 1 and 2 show monthly averages of NO_X respectively PM_{10} emission levels in Gothenburg and Malmö, from 2010 to 2017. As the figures clearly show, there is seasonality in both the absolute NO_X and PM_{10} levels. This seasonality is well-known and has been shown in several studies and is mainly explained by the weather varying over the year (Holst et al., 2008; Mayer, 1999; Rost et al., 2009). These graphs show that the patterns of seasonality follow closely for Gothenburg and Malmö. In addition, there is a slight downward trend for both cities.

Graph 1. Absolute level of NO_X ($\mu g/m^3$)

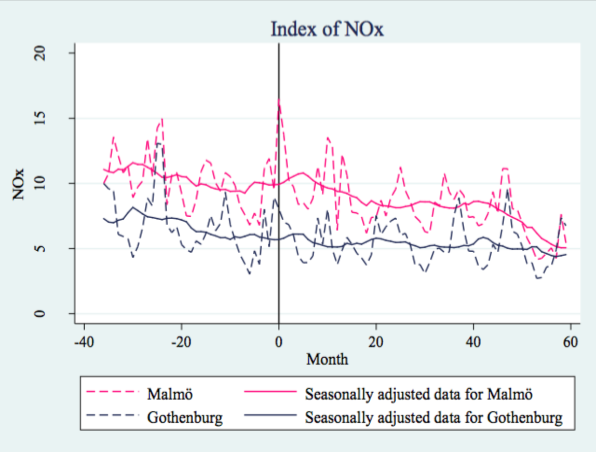


Graph 2. Absolute level of PM_{10} ($\mu g/m^3$)

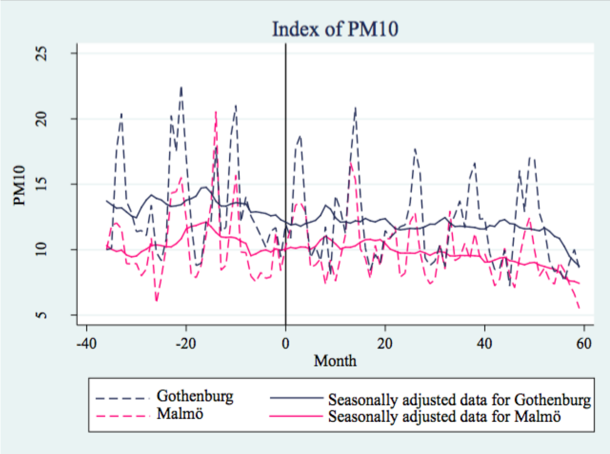


To adjust for the fact that Gothenburg has higher levels of NO_X in absolute terms and that the emissions are more volatile compared to Malmö, we create an index showing the relative levels of NO_X. This index is created by setting the initial emission level in 2010 to value 10. This is done also for PM_{10}. The indexed data is shown in graph 3 and 4. In order to further investigate if the cities follow parallel trends we create seasonally adjusted data, also presented in graph 3 and 4, for NO_X and PM_{10} respectively. This is done using moving averages with six months pre and six months post the observation, using the monthly averages. This smooths the curve, reducing the patterns of seasonality, and it becomes clearer that the cities follow the same trends regarding air quality, both for NO_X and PM_{10}.

Graph 3. Indexed and seasonally adjusted data of NO_X (µg/m^3)

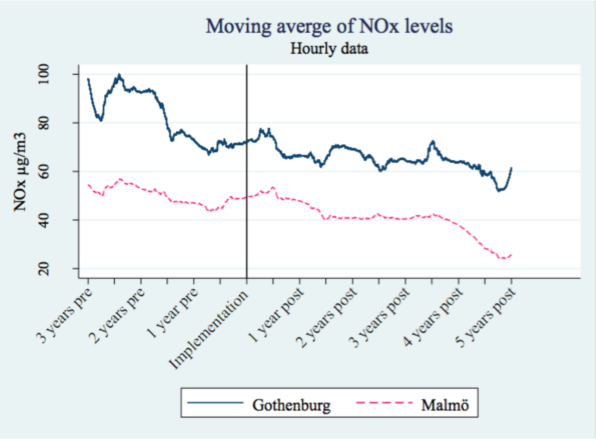


Graph 4. Indexed and seasonally adjusted data of PM_{10} (µg/m^3)

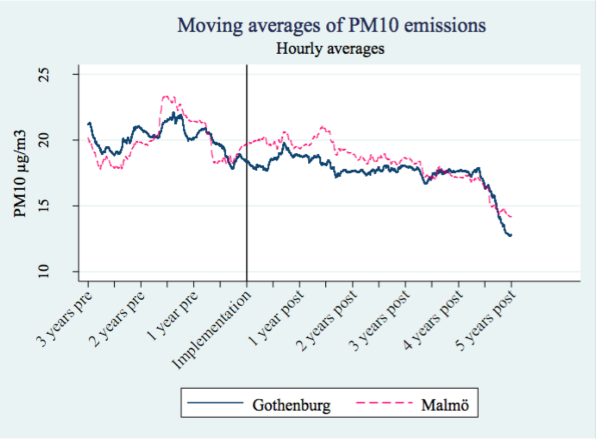


In order to allow for more variation we create similar graphs with moving averages but for hourly instead of monthly data, presented in graph 5 and 6 for NO_X and PM_{10} respectively. As we can see in graph 5, there is no clear immediate effect from the implementation of the Gothenburg congestion tax. However, one can see that the NO_X levels in Gothenburg gets closer to the NO_X levels in Malmö in the period after implementation compared to before. In this graph we see a sharp decline in Gothenburg in the beginning of 2011 (2 years before implementation). To make sure that this decline does not affect our results we are going to analyse this further in section 5.5.

Graph 5. Moving averages of hourly data (NO_X), using data of six months before/after the observation



Graph 6. Moving averages of hourly data (PM_{10}), using data of six months before/after the observation



In graph 6 we see the moving averages for PM_{10} levels. Here, it is clearer that something happens just before the implementation of the Gothenburg congestion tax. Before implementation PM_{10} levels in Gothenburg and Malmö follow each other closely. Around two months before implementation the levels in Malmö increase and stay above the level of Gothenburg until around three years after implementation, where they start to follow each other closely again. Since the graph is based on moving averages, events that occur up to six months after each observation is captured, and it is therefore not surprising that the effect seems to arise before implementation. Further, the graphical illustration suggests that the Gothenburg congestion tax had an effect on the air quality, although fading over time.

The above graphs indicate that the Gothenburg congestion tax had a positive effect on the air quality in Gothenburg. However, since we do not control for meteorological aspects in these graphs, it is difficult to state how large the effect is. To be able to draw any conclusions about the environmental impact, further analyses of the relationship between the congestion tax and emissions are needed. We investigate this by using a difference-in-difference approach, controlling for meteorological conditions, seasonality and the negative time trend. The method is explained in more detail in section 4.5.

4.3 Descriptive statistics

The emission data collected from SMHI and Miljöförvaltningen contains some negative values of NO_X and PM_{10}, and also some outliers of high values. To avoid that these observations drive or bias our results we exclude these extreme values from our dataset. We delete 160 observations due to negative values. The upper NO_X level is set to 700 and the upper PM_{10} level to 200, resulting in an exclusion of 153 additional observations[6]. This gives us a final dataset consisting of approximately 140 000 observations. We show some descriptive statistics of our final dataset in table 1, including number of observations, mean, standard deviation and max and min values.

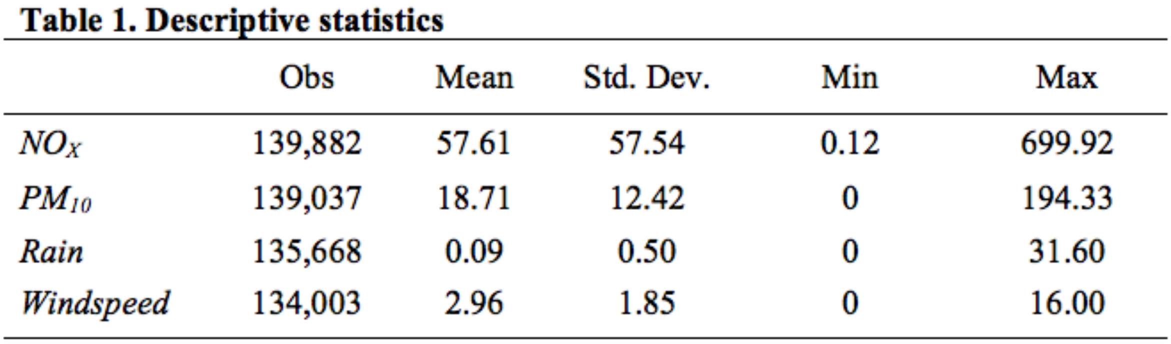


Table 1. Descriptive statistics

	Obs	Mean	Std. Dev.	Min	Max
NO_X	139,882	57.61	57.54	0.12	699.92
PM_{10}	139,037	18.71	12.42	0	194.33
Rain	135,668	0.09	0.50	0	31.60
Windspeed	134,003	2.96	1.85	0	16.00

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[6] Coefficient plots of NO_X respectively PM_{10} are presented in graph A1 and A2 in appendix. These graphs show some clear outliers that are excluded from the data set used for the analyses.

Table 2. Descriptive statistics for Gothenburg and Malmö separately

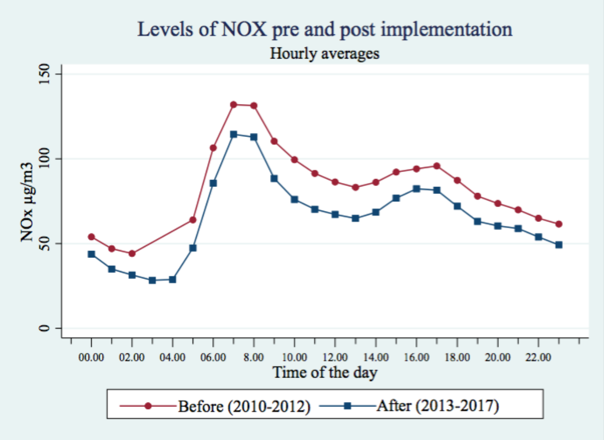
		All years		Before		After	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Gothenburg	NO_X	70.91	70.99	80.66	75.67	65.04	67.35
	PM_{10}	18.45	13.08	19.89	14.75	17.57	11.86
Malmö	NO_x	44.36	35.16	49.55	37.47	41.25	33.32
	PM_{10}	18.97	11.73	19.79	12.95	18.47	10.91

In table 2, we show the mean levels and standard deviations for Malmö and Gothenburg separately. In this table we also divide the period into before and after policy implementation. As we can see in this table, the mean values for NO_X are higher in Gothenburg than Malmö while the levels of PM_{10} are similar for the two cities. In the period before implementation Gothenburg has a mean NO_X level of 80.66 $\mu g/m^3$ while Malmö has a mean of 49.55 $\mu g/m^3$. In the period after implementation, the mean NO_X levels have decreased to 65.04 and 41.25 for Gothenburg and Malmö respectively. This shows a greater relative decline in mean level of NO_X in Gothenburg than Malmö, 19.37 % compared to 16.75 %. Similar patterns can be seen for PM_{10}, where Gothenburg stars at a mean of 19.89 $\mu g/m^3$ before implementation and decreases to a mean of 17.57 $\mu g/m^3$ after implementation, corresponding to a 11,66 % decline. The same values in Malmö are 19.79 $\mu g/m^3$ before implementation and 18.47 $\mu g/m^3$ after implementation, giving a 6.67 % decline. The standard deviations for both NO_X and PM_{10} are larger in Gothenburg suggesting that the levels fluctuate more in Gothenburg.

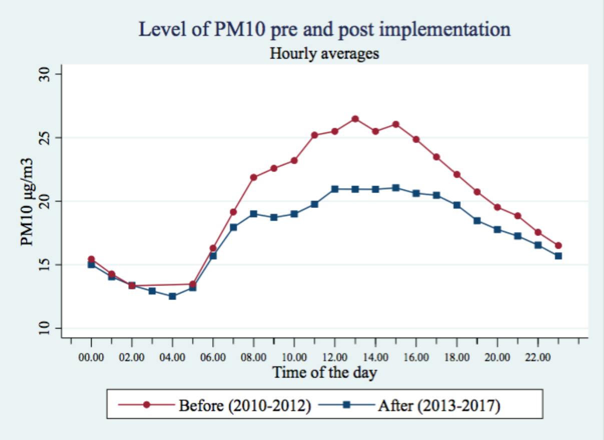
That Gothenburg has a higher initial level of NO_X emissions than Malmö and that they have similar levels of PM_{10} emissions can also be seen in graph 1 and 2 presented in the previous section. As stated before, it is difficult to distinguish how large effect the congestion tax has on the emission levels in Gothenburg by only looking at the graphs. It is however clear that both cities experience a downward trend in emission levels, which also this comparison of mean values shows. Since Malmö also shows a clear decline in emission levels, the percentage changes regarding emission levels in Gothenburg cannot be assumed to be directly connected to the congestion tax. Therefore, to be able to quantify how much of the effect that is connected to the congestion tax, further analysis is needed. This analysis follows the model presented in the methodology section below.

Graph 7 and 8 show the hourly averages of NO_X respectively PM_{10} emissions in Gothenburg before and after the policy implementation separately. In these graphs we see that the hourly averages are lower after the policy implementation. However, since we have a downward trend in emission levels, we cannot draw any conclusion that this effect follows from the policy implementation without further analysis. Because of the downward trend we need a good and suitable counterfactual to be able to find a causal effect of the Gothenburg congestion tax on NO_X and PM_{10} levels. We also see in Graph 7 that NO_X seems to be directly connected to the traffic volume, with peaks in the most trafficked hours in the morning and afternoon.

Graph 7. Hourly averages of NO_X ($\mu g/m^3$) in Gothenburg



Graph 8. Hourly averages of PM_{10} ($\mu g/m^3$) in Gothenburg



For PM_{10} on the other hand, the pattern is not directly connected to the traffic volume. The reason why PM_{10} levels adjust more slowly is that they to a larger extent are affected by other sources, such as road dust and industries, but mainly since the particles are floating in the air for a longer time than gas emissions. This results in a slower reduction of particle emissions, and that PM_{10} does not follow the traffic flow as clear as NO_X emissions do. The PM_{10} levels instead increase with the morning traffic, stay at a high level during the day and slowly decline after the afternoon traffic peak. The lower peak in the afternoon for NO_X might follow from the diurnal wind pattern. Higher wind speed, i.e. higher assimilative capacity, in the afternoon results in a dispersion of NO_X emissions (Coria et al., 2015; Miljöförvaltningen, 2013). We can also see in graph 8 that the largest reduction in PM_{10} levels seems to be during the charged hours of the day. For NO_X it rather seems to be a general reduction for all hours of the day. We analyse this further in section 5.3, where we investigate if there is any intertemporal substitution effect from charged to uncharged hours.

4.5 Methodology

To estimate the effect of the implementation of the congestion tax, we use a difference-in-difference approach. By doing this we estimate the effect of introducing a congestion tax in Gothenburg and compare this with Malmö where there is no congestion tax implemented.

The proposed econometric model will be the following:

$$Air_{it} = \phi + \delta Got_t + \alpha After_i + \beta(Got_t * After_i) + \gamma X_{it} + \rho T_i + \pi(T_i * Got_t) + \varepsilon_{it} \quad (1)$$

In this specification *i* is the subscript for city and *t* is the subscript for the time period. *Air* is the measure of air quality; NO_X and PM_{10}[7]. *Gothenburg* is a dummy variable equal to one if the observation is within the charged area in Gothenburg, and zero if it is in Malmö. *After* is a dummy variable equal to one if the air quality is measured after the congestion tax policy was implemented, and zero before. *X* is a vector of control variables and *T* is a linear time trend that we include to control for the negative trend in emissions. The interaction between the linear time trend and Gothenburg allows for separate time trends in the cities. Since empirical evaluations show that meteorology affects the assimilative capacity of the environment, it is evident that the level of air pollution depends on more factors than only traffic flow. On account of this, we control for different meteorological conditions affecting the pollution concentrations. The meteorological conditions that have the largest impact on NO_X and PM_{10} concentrations, and hence those we control for, are wind speed and precipitation. Wind speed is measured in m/s and precipitation is included as a dummy variable equal to one if it is raining[8]. When using a difference-in-difference model we automatically control for individual fixed effects that are constant in each city over time, like area, population[9], shipping and industry. As shown in section 4.2, Gothenburg and Malmö follow parallel trends before the tax implementation in Gothenburg. This implies that Malmö serves as a counterfactual to Gothenburg, meaning that in absence of the congestion tax they would follow the same trend even in the period after implementation. Because of this our difference-in-difference approach allows us to control for time fixed effects, i.e. things that vary over time but not across cities, like the share of green vehicles, fuel prices and Swedish laws and

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[7] NO_X and PM_{10} levels are measured in $\mu g/m^3$ air

[8] This follows from the conclusion, by Rost et al. (2009), that it is the presence and not the amount of rain that affects PM_{10} concentrations.

[9] Population data from SCB shows that the population growth in both Gothenburg and Malmö is approximately 6 % in the period after policy implementation. Since we only have yearly population data we cannot include it as a control variable in our regressions. However, since the population growth is approximately the same for both cities it should not bias our estimates.

regulations. Hence, we can distinguish how much of the reduction in emissions that is due to the congestion tax. The effects from our model specification will be interpreted as follows:

$\phi \; is \; the \; effect \; for \; the \; control \; group \; before \; treatment$
$\phi + \alpha \; is \; the \; effect \; for \; the \; control \; group \; after \; treatment$
$\phi + \delta \; is \; the \; effect \; for \; the \; treatment \; group \; before \; treatment$
$\phi + \delta + \alpha + \beta \; is \; the \; effect \; for \; the \; treatment \; group \; after \; treatment$

Hence, the parameter β shows the difference-in-difference estimate of the effect of the Gothenburg congestion tax on air quality, and is thus the key parameter of interest. The difference-in-difference estimate is calculated from the following equations (2 and 3). As mentioned before, and as we can see in these equations, the individual fixed effects i.e. things that are constant for each city over time, will cancel out and are hence controlled for in our regressions.

$$\hat{\beta}^{DID} = (\bar{Y}^{Gothenburg,after} - \bar{Y}^{Gothenburg,before}) - (\bar{Y}^{Malmö,after} - \bar{Y}^{Malmö,before}) \qquad (2)$$

$$\hat{\beta}^{DID} = [(\phi + \delta + \alpha + \beta) - (\phi + \delta)] - [(\phi + \alpha) - (\phi)] \qquad (3)$$

One limitation with the difference-in-difference approach is that it relies on the strong assumption about parallel trends, and hence it is important to find a good counterfactual. However, if the parallel trend assumption is fulfilled, this approach is a good way to study policy interventions that are not implemented everywhere. As shown in graph 3 and 4 this seems to be the case in our study. One advantage of the difference-in-difference specification is that there is no need to control for all confounding variables, since the approach allows us to control for unobserved but fixed omitted variables. On the other hand, the difference-in-difference approach do not control for shocks that occur in the period after implementation for one city but not the other. This would cause endogeneity problems if not controlling for these shocks. However, since our treatment and control cities are located in the same country and hence to a large extent are affected by the same laws, regulations and unforeseen factors, this should not be a crucial problem in our case.

Two additional model specifications are performed to test the robustness of our results. We do this by using a logarithmic specification, and by including another specification of monthly dummies, ranging from 1 to 96[10] instead of January to December. Due to the decline

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[10] 1 represents January in 2010 and 96 represents December in 2017. These are included as 96 dummy variables.

in 2011 that we saw in graph 5, we perform an additional analysis where we exclude the period after this decline. We also check the robustness by only including one respectively two years before and after the implementation of the Gothenburg congestion tax. This is further discussed in section 5.5. Additionally, based on the hourly observations we calculate daily averages for NO_X and PM_{10}[11]. Based on these averages we run regressions where we change the dependent variable to be a dummy variable equal to one if the air quality standard concentration limits of NO_X and PM_{10} are exceeded. As mentioned in section 1, the European Union has set these limits to 40 $\mu g/m^3$ for both pollutants (European Commission, 2018b). This model specification allows us to analyse whether the Gothenburg congestion tax was successful in lowering the number of days the pollution threshold limits are exceeded.

To investigate the duration of the effect, we perform an event study where the examined period is divided into shorter time periods. We include 6 months before the implementation to investigate if people started to adjust in advance and divide the year of implementation into two half-year periods to see if the effect comes directly or if it is delayed. For the rest of the time we have yearly periods apart from that we combine the years that are more than three years after implementation. We do this to see when the effect arises, if it grows or fades over time, for how long it lasts and if the price increase in 2015 results in an additional effect. The model used to perform the event study is the following:

$$Air_{it} = \phi + \delta Got_t + \alpha After_i + \sum_{\tau=1}^{5} \beta_{-\tau} (Got_{t-\tau} * After_i) + \sum_{\tau=0}^{1} \beta_{+\tau} (Got_{t+\tau} * After_i) + \gamma X_{it} + \rho T_{it} + \varepsilon_{it} \quad (4)$$

where the sums represent the five lagged periods and the two lead periods, respectively. In this model, $\beta - \tau$ shows the post-treatment effects and $\beta + \tau$ shows the pre-treatment effects. As stated above, this is of interest when analysing how the effect changes over time.

Finally, since there is a possibility that the Gothenburg congestion tax results in substitution effects, we perform additional analyses to examine this. To investigate if there is any spatial substitution we replace Gothenburg with the adjacent city Mölndal[12] in the regression analysis. The intertemporal substitution effect is studied by dividing the day into uncharged and charged hours.

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[11] The daily averages are calculated by adding all 24 hourly observations per day and divide by 24. This is done for all variables in our data set.

[12] Mölndal is used since it is the only adjacent area with measured emission levels for the whole time period.

5. Empirical results

5.1 Empirical results on levels of emissions

In the first column of table 3 and 4 we show simple difference-in-difference estimates of the effect from the Gothenburg congestion tax on levels of NO_X and PM_{10} emissions respectively. As we can see, the difference-in-difference estimate is negative and highly significant for both NO_X and PM_{10}. We develop this simple regression model to use the specification in equation (1), where both monthly dummies[13] and a linear time trend are included to control for the seasonality and the downward trend in emissions, respectively. Possible trend differences between Gothenburg and Malmö are captured by the interaction term between the trend variable and Gothenburg. Further, to control for meteorological conditions, wind speed and precipitation[14] are included in both the NO_X regressions and PM_{10} regressions. The results from these regressions are presented in column 2 in table 3 and 4 for NO_X and PM_{10} respectively.

The coefficient for the variable *Gothenburg* in column 2 in table 3 shows that on average, Gothenburg has approximately 26 $\mu g/m^3$ higher NO_X level than Malmö. The key coefficient in this regression is the one for the interaction between *Gothenburg* and *after*, showing the treatment effect of the congestion tax. The highly significant negative coefficient indicates that the congestion tax led to a reduction in NO_X levels by 5.28 $\mu g/m^3$ in Gothenburg compared to not having a congestion tax.

The negative coefficient on the trend variable in column 2 in table 3 shows that the levels of NO_X pollutants are decreasing over time for Malmö. As the interaction between the time trend and Gothenburg is positive and smaller in magnitude than the time trend itself, it shows that the trend is negative in Gothenburg as well, but not as large as in Malmö. The coefficient for *after* is positive, indicating that the level of pollutants increases in Malmö in the time after treatment. However, this is in absence of the negative time trend. As we can see in the simple regression in column 1 in table 3, the variable *after* is negative since we do not control for the negative time trend.

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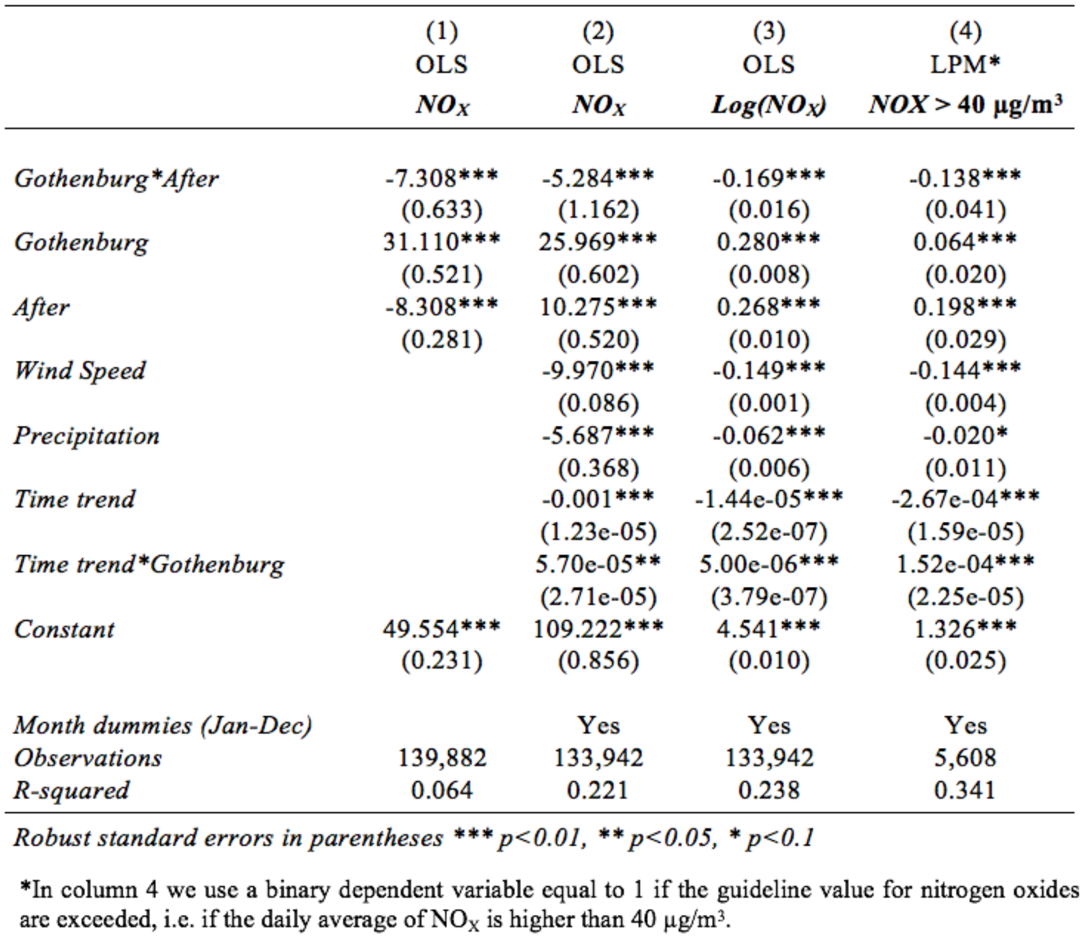
[13] One dummy is created for each month of the year, January to December, resulting in twelve monthly dummies. To avoid the dummy variable trap, December is excluded.

[14] Wind speed and precipitation are included since they are the meteorological conditions shown to have the largest effect on NO_X and PM_{10}. However, since Mayer (1999) shows that also humidity and temperature have an effect on air quality, we have performed the regressions including these weather conditions as well. When doing this we get similar results both regarding magnitude and significance level.

Table 3: Regression output for NO_X



	(1) OLS ***NO_X***	(2) OLS ***NO_X***	(3) OLS ***$Log(NO_X)$***	(4) LPM* ***$NOX > 40$ µg/m^3***
*Gothenburg*After*	-7.308***	-5.284***	-0.169***	-0.138***
	(0.633)	(1.162)	(0.016)	(0.041)
Gothenburg	31.110***	25.969***	0.280***	0.064***
	(0.521)	(0.602)	(0.008)	(0.020)
After	-8.308***	10.275***	0.268***	0.198***
	(0.281)	(0.520)	(0.010)	(0.029)
Wind Speed		-9.970***	-0.149***	-0.144***
		(0.086)	(0.001)	(0.004)
Precipitation		-5.687***	-0.062***	-0.020*
		(0.368)	(0.006)	(0.011)
Time trend		-0.001***	-1.44e-05***	-2.67e-04***
		(1.23e-05)	(2.52e-07)	(1.59e-05)
*Time trend*Gothenburg*		5.70e-05**	5.00e-06***	1.52e-04***
		(2.71e-05)	(3.79e-07)	(2.25e-05)
Constant	49.554***	109.222***	4.541***	1.326***
	(0.231)	(0.856)	(0.010)	(0.025)
Month dummies (Jan-Dec)		Yes	Yes	Yes
Observations	139,882	133,942	133,942	5,608
R-squared	0.064	0.221	0.238	0.341

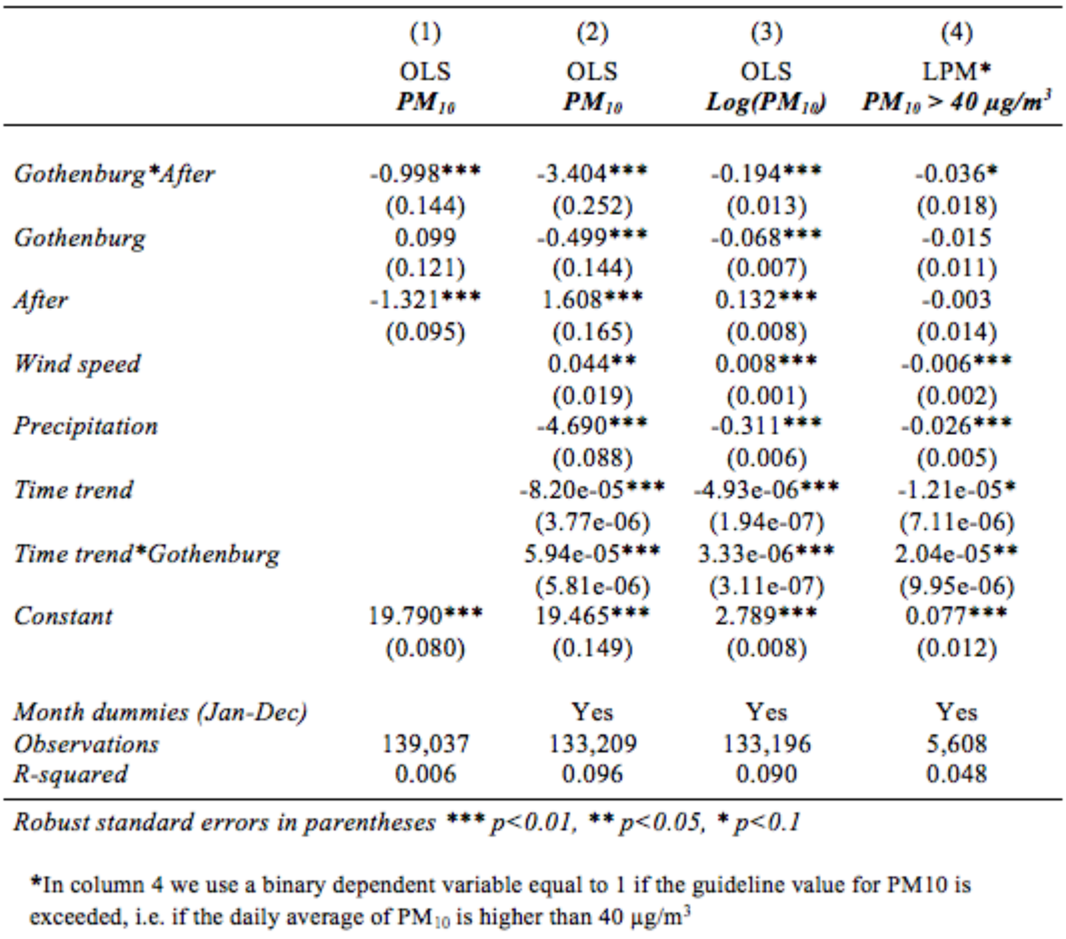
*Robust standard errors in parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$*

*In column 4 we use a binary dependent variable equal to 1 if the guideline value for nitrogen oxides are exceeded, i.e. if the daily average of NO_X is higher than 40 µg/m^3.

Previous studies have shown that increased wind speed is associated with reduced concentrations of NO_X. This result can also be seen in column 2-4 in table 3, showing that wind speed has a great negative impact on levels of NO_X emissions. From column 2 we see that increased wind speed with 1 m/s is associated with approximately 10 µg/m^3 lower levels of NO_X, significant at the 1 % level. As we can see from column 2-4 in table 3 also precipitation has a negative and highly significant effect on NO_X levels. Presence of rain is associated with a reduction in NO_X levels by approximately 6 µg/m^3, compared to when not raining. This result is shown in column 2 and is significant at the 1 % level.

In order to examine if it is possible to interpret the results in causal terms, and to test if the results are robust, we also run regressions using other specifications and approaches. In column 3 in table 3 we use the same model specification as in regression 2, but use the logarithmic values of NO_X emissions. Also in this regression output we can see that the treatment effect is highly significant, suggesting that the implementation of the Gothenburg congestion tax was associated with a reduction in NO_X levels by approximately 17 %, compared to the case of no congestion tax. In the last column of table 3, we use a Linear Probability Model (LPM) specification, where the dependent variable is a dummy variable equal to one if the NO_X level exceeds 40 µg/m^3. The results show that the implementation of the Gothenburg congestion tax was associated with a highly significant decrease, of 13.8 percentage points, in the probability of exceeding the recommended emission limits, compared to no tax implementation.

Table 4: Regression output for PM_{10}



	(1) OLS *PM_{10}*	(2) OLS *PM_{10}*	(3) OLS *Log(PM_{10})*	(4) LPM* *PM_{10} > 40 µg/m^3*
*Gothenburg*After*	-0.998***	-3.404***	-0.194***	-0.036*
	(0.144)	(0.252)	(0.013)	(0.018)
Gothenburg	0.099	-0.499***	-0.068***	-0.015
	(0.121)	(0.144)	(0.007)	(0.011)
After	-1.321***	1.608***	0.132***	-0.003
	(0.095)	(0.165)	(0.008)	(0.014)
Wind speed		0.044**	0.008***	-0.006***
		(0.019)	(0.001)	(0.002)
Precipitation		-4.690***	-0.311***	-0.026***
		(0.088)	(0.006)	(0.005)
Time trend		-8.20e-05***	-4.93e-06***	-1.21e-05*
		(3.77e-06)	(1.94e-07)	(7.11e-06)
*Time trend*Gothenburg*		5.94e-05***	3.33e-06***	2.04e-05**
		(5.81e-06)	(3.11e-07)	(9.95e-06)
Constant	19.790***	19.465***	2.789***	0.077***
	(0.080)	(0.149)	(0.008)	(0.012)
Month dummies (Jan-Dec)		Yes	Yes	Yes
Observations	139,037	133,209	133,196	5,608
R-squared	0.006	0.096	0.090	0.048

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

*In column 4 we use a binary dependent variable equal to 1 if the guideline value for PM10 is exceeded, i.e. if the daily average of PM_{10} is higher than 40 µg/m^3

When repeating the regressions from table 3 for PM_{10} we find similar results, presented in table 4. From table 4, column 2, we see that for PM_{10} the level is somewhat lower in Gothenburg compared to Malmö, on average 0.50 µg/m^3 lower. The implementation of the congestion tax is associated with a reduction in PM_{10} levels by 3.40 µg/m^3 significant at the 1 % level. The logarithmic specification in column 3 suggests that PM_{10} levels decrease by approximately 19 % as a consequence of the congestion tax. In column 4 the LPM is presented, where the dependent dummy variable is equal to one if the PM_{10} level exceeds 40 μg/m^3. The results show that the probability to exceed the recommended average level of PM_{10} decreases with 3.6 percentage points, significant at the 10 % level.

It is evident from previous studies that presence of precipitation has a great negative impact on PM_{10} concentration. We find similar evidence, since precipitation has a substantial and highly significant negative effect on PM_{10} levels[15], as seen in column 2-3 in table 4. Wind speed seems to have a small positive significant effect on the concentration of PM_{10}. This is in line with the result presented by Rost el al. (2009), which shows no strong relationship between wind speed and PM_{10} levels.

5.2 Event Study

In order to investigate how the effect from the congestion tax developed over time and if the price increase in 2015 had an effect on emissions, we perform an event study. We do this by dividing the time into different treatment periods according to the description in section 4.5. The results from the event study of NO_X are presented in table 5, column 1, showing a highly significant decrease of 5.71 μg/m^3 in level of NO_X pollutants in the first six months post the tax implementation. Except from this the result shows positive and significant or insignificant effects in the post periods, suggesting a short-term policy effect. The period of six months pre implementation shows no significant effect, suggesting that there is no evidence that people adjust to the congestion tax before it came into effect.

However, when including several treatment variables it might be the case that these variables are strongly correlated with the interaction between Gothenburg and the time trend. Therefore, we want to examine if the results from the event study change when excluding this interaction term. This result is presented in table 5, column 2. As we can see, the results change but the largest effect is still in the 6 months post the implementation in 2013 with a reduction in NO_X levels by 10.56 μg/m^3. In this regression we can also see a great negative significant effect on NO_X emissions of 9.84 μg/m^3 after the price increase in 2015 (3 years post). Another finding from this regression is that there is a highly significant decrease of 4.41 μg/m^3 for the six months pre implementation, suggesting that people changed their behaviour even before implementation. The coefficient plot in graph 9 represents the event

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[15] Since Rost et al. (2009) conclude that it is the presence, and not the amount, of precipitation that affects PM_{10} levels, we use a dummy variable indicating if it is raining or not. However, we also performed an analysis using level of precipitation instead. Since the key coefficient does not change when using levels of precipitations, we decide to continue to use the dummy variable in the following regressions.

study from column 1, and suggests that the effect becomes positive already one year post implementation. Graph 10 represents the coefficients from column 2, and shows a negative effect for all years. Even though the results from these two regressions differ, we can see from the coefficient plots that there is a direct effect that diminishes over time.

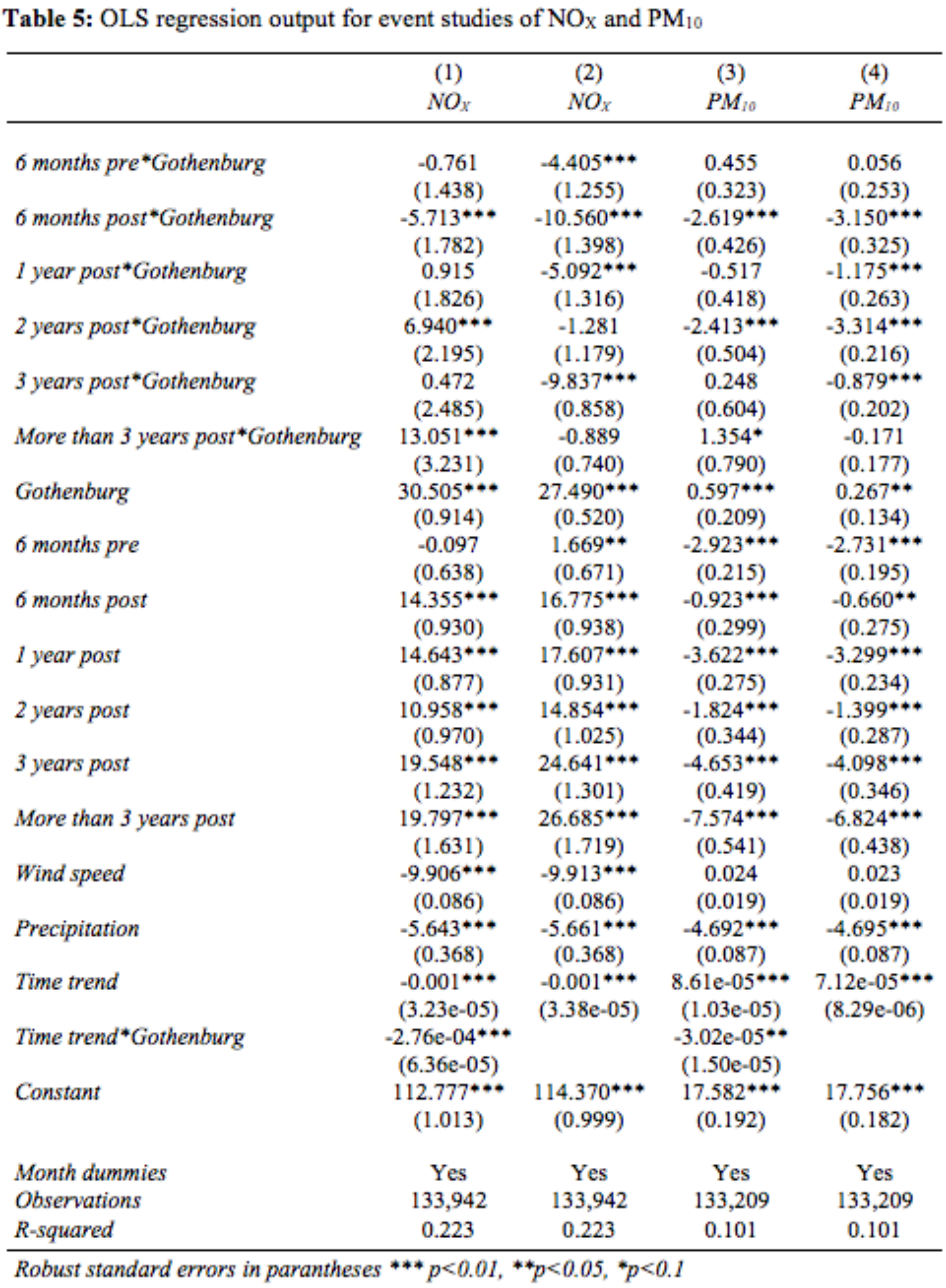


Table 5: OLS regression output for event studies of NO_X and PM_{10}

	(1) *NO_X*	(2) *NO_X*	(3) *PM_{10}*	(4) *PM_{10}*
*6 months pre*Gothenburg*	-0.761	-4.405***	0.455	0.056
	(1.438)	(1.255)	(0.323)	(0.253)
*6 months post*Gothenburg*	-5.713***	-10.560***	-2.619***	-3.150***
	(1.782)	(1.398)	(0.426)	(0.325)
*1 year post*Gothenburg*	0.915	-5.092***	-0.517	-1.175***
	(1.826)	(1.316)	(0.418)	(0.263)
*2 years post*Gothenburg*	6.940***	-1.281	-2.413***	-3.314***
	(2.195)	(1.179)	(0.504)	(0.216)
*3 years post*Gothenburg*	0.472	-9.837***	0.248	-0.879***
	(2.485)	(0.858)	(0.604)	(0.202)
*More than 3 years post*Gothenburg*	13.051***	-0.889	1.354*	-0.171
	(3.231)	(0.740)	(0.790)	(0.177)
Gothenburg	30.505***	27.490***	0.597***	0.267**
	(0.914)	(0.520)	(0.209)	(0.134)
6 months pre	-0.097	1.669**	-2.923***	-2.731***
	(0.638)	(0.671)	(0.215)	(0.195)
6 months post	14.355***	16.775***	-0.923***	-0.660**
	(0.930)	(0.938)	(0.299)	(0.275)
1 year post	14.643***	17.607***	-3.622***	-3.299***
	(0.877)	(0.931)	(0.275)	(0.234)
2 years post	10.958***	14.854***	-1.824***	-1.399***
	(0.970)	(1.025)	(0.344)	(0.287)
3 years post	19.548***	24.641***	-4.653***	-4.098***
	(1.232)	(1.301)	(0.419)	(0.346)
More than 3 years post	19.797***	26.685***	-7.574***	-6.824***
	(1.631)	(1.719)	(0.541)	(0.438)
Wind speed	-9.906***	-9.913***	0.024	0.023
	(0.086)	(0.086)	(0.019)	(0.019)
Precipitation	-5.643***	-5.661***	-4.692***	-4.695***
	(0.368)	(0.368)	(0.087)	(0.087)
Time trend	-0.001***	-0.001***	8.61e-05***	7.12e-05***
	(3.23e-05)	(3.38e-05)	(1.03e-05)	(8.29e-06)
*Time trend*Gothenburg*	-2.76e-04***		-3.02e-05**	
	(6.36e-05)		(1.50e-05)	
Constant	112.777***	114.370***	17.582***	17.756***
	(1.013)	(0.999)	(0.192)	(0.182)
Month dummies	Yes	Yes	Yes	Yes
Observations	133,942	133,942	133,209	133,209
R-squared	0.223	0.223	0.101	0.101

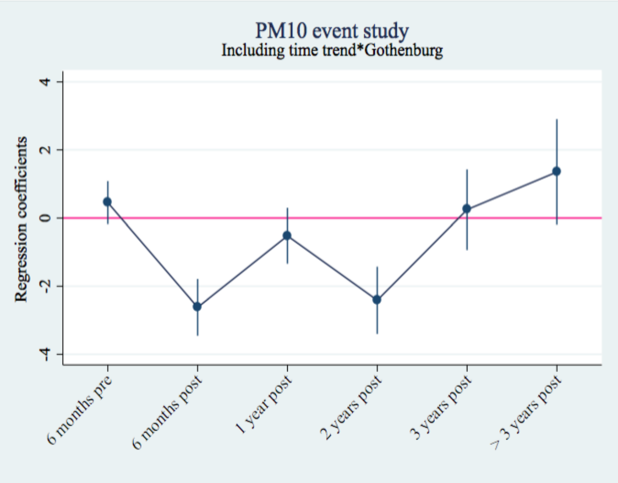
*Robust standard errors in parantheses *** $p<0.01$, **$p<0.05$, *$p<0.1$*

The same analysis is performed for PM_{10}, presented in column 3 and 4 in table 5. It is evident that also for PM_{10} levels, there is a substantial and highly significant treatment effect in the period directly after implementation. However, we are not able to see the exact same patterns for PM_{10} as for NO_X. It does not seem to be a substantial decrease in 2015 for PM_{10}, rather a decrease of similar magnitude in 2014 (2 years post) as in the first six months of 2013, as we can see in column 3 and 4. In the case of PM_{10} there is no evidence of an adjustment effect in the 6 months pre implementation since there is no negative and significant effect. The coefficient plots for the event studies of PM_{10} are presented in graph 11 and 12. The two graphs follow the same pattern but in graph 11 the effect is negative until 3 years post implementation, while in graph 12 the effect remains negative even after 3 years post implementation.

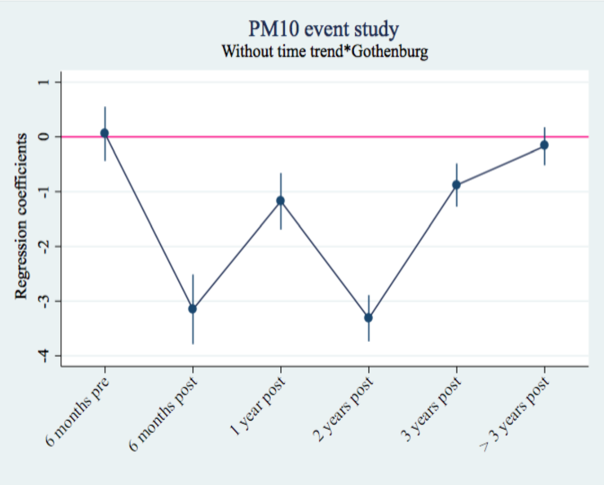
Graph 9. Coefficient plot for event study 1, NO_X

Graph 10. Coefficient plot for event study 2, NO_X

Graph 11. Coefficient plot for event study 1, PM_{10}



Graph 12. Coefficient plot for event study 2,PM_{10}



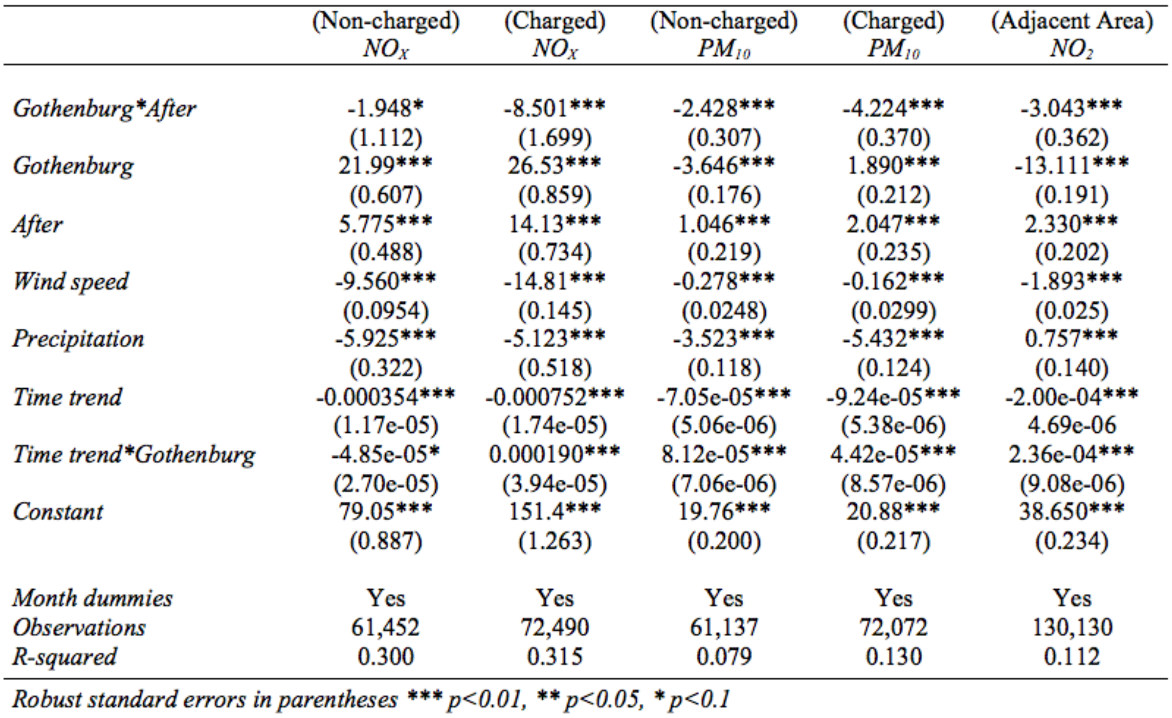
Since the results are mixed in the event study it is difficult to draw any general conclusion regarding the persistence and development of the effect over time. What we can tell is that there is a substantial decrease in the first period after implementation in the case for both NO_X and PM_{10}, regardless of which specification (with or without the interaction between the trend and Gothenburg) that is used.

5.3 Intertemporal substitution

To analyse if there seems to be any intertemporal substitution effect within Gothenburg, i.e. if trips seems to be postponed to uncharged hours, we perform an additional analysis only including uncharged hours. This allows us to investigate if there is a displacement rather than a reduction in emissions. The regression model follows equation 1, and the result from this analysis is presented in table 6, column 1. The difference-in-difference estimate is negative but small (-1.95 $\mu g/m^3$) and only significant at the 10% level for uncharged hours. Since the emissions do not significantly increase for uncharged hours the result does not suggest that there is intertemporal substitution towards uncharged hours. However, it might be the case that people drive less in general, resulting in a reduction also for uncharged hours, but since some people might change to drive during uncharged hours the effect might be cancelled out. In column 2, we only include charged hours to investigate how large the effect was during charged time. From this result, we see that the effect on level of NO_X emissions in Gothenburg after policy implementation is larger than in the original model that includes both charged and uncharged hours, a decline of 8.50 instead of 5.28 $\mu g/m^3$.

The results from this analysis for PM_{10}, presented in column 3 and 4 in table 6, are similar to the results for NO_X with a larger effect among charged hours, 4.22 compared to 3.40 $\mu g/m^3$ in the original model including all hours of the day. However, there is a negative and highly significant effect also for uncharged hours, though smaller than in the original model. These results suggest that the main reduction in emissions takes place during charged hours, but also that people drive less in general. Further, since the main negative effect is shown to be connected to charged hours, it suggests that the congestion tax is effective in reducing traffic volumes and hence also successful in reducing NO_X and PM_{10} emissions.

Table 6: OLS regression output for NOX and PM10, for charged and non-charged hours/areas



	(Non-charged) NO_X	(Charged) NO_X	(Non-charged) PM_{10}	(Charged) PM_{10}	(Adjacent Area) NO_2
*Gothenburg*After*	-1.948*	-8.501***	-2.428***	-4.224***	-3.043***
	(1.112)	(1.699)	(0.307)	(0.370)	(0.362)
Gothenburg	21.99***	26.53***	-3.646***	1.890***	-13.111***
	(0.607)	(0.859)	(0.176)	(0.212)	(0.191)
After	5.775***	14.13***	1.046***	2.047***	2.330***
	(0.488)	(0.734)	(0.219)	(0.235)	(0.202)
Wind speed	-9.560***	-14.81***	-0.278***	-0.162***	-1.893***
	(0.0954)	(0.145)	(0.0248)	(0.0299)	(0.025)
Precipitation	-5.925***	-5.123***	-3.523***	-5.432***	0.757***
	(0.322)	(0.518)	(0.118)	(0.124)	(0.140)
Time trend	-0.000354***	-0.000752***	-7.05e-05***	-9.24e-05***	-2.00e-04***
	(1.17e-05)	(1.74e-05)	(5.06e-06)	(5.38e-06)	4.69e-06
*Time trend*Gothenburg*	-4.85e-05*	0.000190***	8.12e-05***	4.42e-05***	2.36e-04***
	(2.70e-05)	(3.94e-05)	(7.06e-06)	(8.57e-06)	(9.08e-06)
Constant	79.05***	151.4***	19.76***	20.88***	38.650***
	(0.887)	(1.263)	(0.200)	(0.217)	(0.234)
Month dummies	Yes	Yes	Yes	Yes	Yes
Observations	61,452	72,490	61,137	72,072	130,130
R-squared	0.300	0.315	0.079	0.130	0.112

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

5.4 Spatial substitution to adjacent areas

Our results yet presented indicate that the Gothenburg congestion tax is associated with a decline in NO_X emissions within the charging zone. This effect may be followed by a spatial substitution toward uncharged roads leading to increased emissions in adjacent areas. This would lead to an overestimation of the effect on emissions from the congestion tax. Such substitution effects might arise if people drive close to the zone and then switch to public transport. There is also a possibility that the policy results in a spill-over effect rather than a substitution effect, i.e. a reduction of emissions also in adjacent areas. To investigate if there is any substitution or spill-over effects to adjacent uncharged areas, we perform a study for Mölndal, which is a city located next to Gothenburg. PM_{10} is not measured in Mölndal, neither is NO. Due to the latter we cannot calculate NO_X levels, and the analysis is therefore performed using NO_2 instead of NO_X. However, since the correlation between NO_X and NO_2 is high (0.89 in Gothenburg and Malmö), this should serve as a good comparison to the study performed in Gothenburg with NO_X levels. The decline in NO_2 of 3.04 $\mu g/m^3$ in Mölndal in the period after implementation, showed in column 5 in table 6, is significant at the 1 % level and suggests that there is a spill-over effect. One possible explanation to this is that people reduce their travels by private vehicles through Mölndal into Gothenburg, using public transport instead. This result indicates that the policy effect is underestimated, but since we have to perform this analysis using NO_2 instead of NO_X we cannot conclude to what extent.

5.5 Sensitivity analysis

To investigate if our results are robust to different model specifications we have analysed the environmental effect of the Gothenburg congestion tax using a panel data approach. We have replicated table 3 and 4 using this approach, and the results are presented in table A3 and A4 in appendix. The magnitude and significance level are the same for all variables in these regressions as in the original ones, except from the LPM specification for PM_{10}, where the coefficients are significant at a lower level than in the original model in table 4.

To allow for a more flexible time trend than the linear one, we also run regressions where we include one dummy for each of the 96 months in the sample, instead of the ordinary January-December dummies as we use in table 3 and 4, column 2, for NO_X and PM_{10} respectively. To allow for city specific time trends, the linear time trend and its interaction with Gothenburg are included. The results from this specification are presented in column 1 and 3 in table A5 in appendix, for NO_X and PM_{10} respectively. To avoid the risk of over controlling and hence the risk that the interaction between the linear time trend and Gothenburg absorb a part of the treatment effect, we also run the regressions excluding the city specific linear time trends. These results are presented in table A5, column 2 and 4. The specification with city specific time trends included shows results very similar to the original regression outputs in table 3 and 4, column 2. The difference-in-difference coefficients from the specifications without the linear time trend is still highly significant, though smaller in magnitude than the regression output in table 3 and 4, column 2. Note that the variable *after* is excluded in these specifications due to perfect collinearity with the last 60 months.

Since the results are very similar regarding magnitude and significance in the panel data regressions as in the original ones, and since the results stay highly significant regardless of how we specify the seasonal variation, it suggests that our results are robust with respect to different model specifications.

To further check the robustness of our results and to investigate whether the substantial reduction in NO_X levels in the beginning of 2011 (see graph 5) seems to bias our results, we include different time periods in our original regression. First, we check whether the decline in 2011 affects our results by excluding the period until after this reduction, meaning that we only include the period after August 2011. This regression output is presented in table 7, column 1, where we can see that there still is a highly significant negative treatment effect of

4.80 $\mu g/m^3$. Since the effect is only slightly smaller than in the original regression including the whole time period, this does not seem to bias our results. For PM_{10} the results are similar, showed in column 4, with a highly significant coefficient of 3.11 $\mu g/m^3$, only slightly smaller than in the original model. We move on to only include two years before and two years after implementation, presented in column 2 for NO_X and 5 for PM_{10}. Finally, we only include one year before and one year after for both NO_X and PM_{10} presented in column 3 and 6 respectively. The results from these regressions also indicate that the results are robust since there still is a substantial and highly significant negative treatment effect.

Table 7: OLS regression output for different time periods, NO_X and PM_{10}

	(Month>20)	(2011-2014)	(2012-2013)	(Month>20)	(2011-2014)	(2012-2013)
	NO_X	*NO_X*	*NO_X*	*PM_{10}*	*PM_{10}*	*PM_{10}*
*Gothenburg*After*	-4.795***	-5.652***	-8.019***	-3.109***	-3.037***	-2.765***
	(1.188)	(1.778)	(2.966)	(0.261)	(0.376)	(0.566)
Gothenburg	17.67***	18.88***	12.15*	-1.985***	-0.632*	2.579*
	(0.913)	(1.667)	(6.755)	(0.224)	(0.374)	(1.409)
After	10.73***	14.73***	-34.24***	1.638***	2.545***	-4.339
	(0.532)	(0.904)	(12.01)	(0.173)	(0.261)	(2.735)
Wind speed	-9.726***	-9.601***	-10.22***	-0.009	0.0454	0.161***
	(0.097)	(0.123)	(0.181)	(0.020)	(0.029)	(0.039)
Precipitation	-4.698***	-4.971***	-5.895***	-4.709***	-4.943***	-4.602***
	(0.396)	(0.548)	(0.828)	(0.095)	(0.135)	(0.187)
Time trend	-0.001***	-0.001***	0.005***	-1.25e-04***	-1.81e-04***	0.001**
	(1.30e-05)	(4.48e-05)	(0.001)	(4.12e-06)	(1.37e-05)	(3.12e-04)
*Time trend*Gothenburg*	2.14e-04***	2.62e-04***	4.99e-04	8.39e-05***	3.20e-05*	-5.36e-05
	(2.94e-05)	(8.94e-05)	(3.09e-04)	(6.27e-06)	(1.85e-05)	(6.13e-05)
Constant	104.9***	111.6***	-27.93	22.24***	21.97***	-0.598
	(0.933)	(1.506)	(35.94)	(0.196)	(0.357)	(8.118)
Observations	104,823	64,062	33,913	104,089	63,910	33,847
R-squared	0.207	0.195	0.189	0.102	0.122	0.107

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

As discussed in section 4.2, it was a substantial decline in NO_X emissions in the beginning of 2011. In order to check that this decline does not bias our result we only include the period from September 2011 (month 20), when the levels had stabilized again. These results are presented in column 1 for NO_X and column 4 for PM_{10} levels. Two additional analyses with shorter time periods are also performed to check the robustness of the results (see column 2 and 3 for NO_X and 5 and 6 for PM_{10}.

6. Discussion

Our empirical results show that the Gothenburg congestion tax has a considerable and robust effect on the level of air pollutants within the city. These results go in line with the underlying theory and the results of previous studies.

Our results strengthen the results by Börjesson and Kristofferson (2015) and Trafikverket (2014), that the emission levels were significantly reduced as a consequence of the Gothenburg congestion tax. In contrast to their studies we establish the relationship between the congestion tax and the measured levels of emissions. Further, Beevers and Carslaw (2005) conclude that unusual weather conditions in London around the year of implementation complicates the evaluation of emission measurements alone. Since the weather conditions can be changing from year to year also in Gothenburg, we think it is of great importance to control for meteorological conditions when studying the effect of a congestion tax. Therefore, compared to previous studies about the Gothenburg congestion tax, our study contributes with a more comprehensive investigation of the effect. Our study is hence unique since we investigate the relationship between the congestion tax and emission levels by taking the negative trend in emissions and meteorological aspects into account. Hence, we get closer to establish the causal effect of the tax implementation on observed emission levels.

Compared to earlier studies we also investigate if the Gothenburg congestion tax successfully reduced the number of days the pollution concentrations exceed the concentrations limits set by the European Union. This analysis shows reduced number of days for both NO_X and PM_{10}, which are of importance for policy makers since it shows that a tax can be a good way to keep the concentrations within the air quality standards. However, the reduction in the number of days that the concentration limit of PM_{10} are exceeded is quite low compared to NO_X and is only significant at the 10% level. One possible explanation to this result is that the levels of PM_{10} often were within the limits already before implementation while NO_X levels were exceeded for yearly as well as daily and hourly levels at several times. Since the air quality in Gothenburg is still a severe problem, reduced road traffic as well as further environmental policies are needed to meet the new air quality standard, with lower emission limits, in Gothenburg by 2020.

Johansson et al. (2009) who performed an analysis of the Stockholm congestion tax found that the percentage change in emission levels was lower than the traffic flow reduction. In contrast to this result we find a higher percentage reduction in emission levels than the 10-12 % reduction in traffic flow found by Börjesson and Kristofferson (2015) and Trafikverket (2014). A possible explanation to why the results differ is the use of different approaches, where we compared to them use measured instead of modelled levels of emissions. This suggests that the true effect of the Gothenburg congestion tax is larger than the modelled estimation found in earlier studies. Further, Johansson et al. (2009) mention that due to the downward trend in emissions they have problems to quantify how much of the reduction that arose from the congestion tax. We overcome this problem since we control for factors that vary over time in the cities, like the share of green vehicles, fuel prices, and Swedish laws and regulations.

Our results that the Gothenburg congestion tax has a substantial and highly significant negative effect on NO_X as well as PM_{10} levels are also in line with the results from several studies in other cities that have implemented congestion charges. For example, Beevers and Carslaw (2005) found that the London congestion charge reduced NO_X and PM_{10} levels by 12 % and Gibson and Carnovale (2015) found reductions of PM_{10} and $PM_{2.5}$ as a result of the Milan congestion charge. Therefore, our study adds to the literature showing that implementation of a congestion tax reduces air pollutants.

Verhoef (2000), Vickrey (1963) and Walters (1961) state that prices should be set high when the demand for driving is high and when environmental externalities are large. As we can see in figure 1, the Gothenburg congestion tax follows this differentiated road pricing with higher prices during peak-hours. Since our results show that the reduction in emission levels is largest during charged hours, this strengthens the idea that differentiated road pricing leads to lower environmental externalities. Further, since we find evidence that the Gothenburg congestion tax was successful in reducing emission levels, we conclude that the tax is set at a level that reduces the social cost of driving as discussed by Verhoef (2000). Since the inter-sectoral or environmental cost is reduced, it means that also the dead-weight loss is reduced and hence that the tax led to a more efficient allocation of traffic from a social point of view. This suggests that the Gothenburg congestion tax has been successful in reaching the environmental objectives with the policy.

The theory by Walters (1961) suggests that how responsive car drivers are to a congestion tax depends on the elasticity of demand. We find considerable and highly significant reductions in NO_X and PM_{10} emissions in all our regressions, with a decrease of up to 19 %. This suggests that drivers do adjust to the implementation of the tax. However, the results from the event studies show no robust or obvious reduction in emission levels due to the price increase in 2015. This makes it difficult to draw any conclusion about how price sensitive drivers are and hence if the price-increase has any effect on the emission levels. Since our main focus is the environmental effects of the implementation of the tax, we have only considered the emission levels per se and not the reduction in traffic volume. To be able to quantify the elasticity of demand and the effect on emissions of a price increase, further analysis is needed.

In contrast to Vickrey's (1963) theory and the findings by Gibson and Carnovale (2015), about traffic moving to uncharged areas as a result of a congestion charge, our results show that the emission levels rather decreased in the adjacent area Mölndal. However, this result is not unexpected in Gothenburg where the taxed area is very difficult to skirt, as seen in figure 1 showing a map of the charged zone. One reason for this result might be that people traveling from outside the charged zone change from going by car to public transport also in the area outside the zone when they travel to Gothenburg. This result suggests that there is a spill-over effect rather than a substitution effect to Mölndal and hence that our results are underestimated. Since the theory shows the risk of a substitution effect towards adjacent areas, our results suggest that a possible solution to this problem could be to cover the whole city and make it difficult to avoid the charging zone. Policy makers interested in reducing emissions by introducing a congestion tax should therefore consider the geography of the city and how the tax is best implemented to avoid substitution into other areas.

One limitation with our study is that we do not consider public transport in our analysis. Since the congestion tax was a part of the West Sweden Agreement it might be difficult to distinguish to what extent the improved air quality depends on the congestion tax and not on the investments in other infrastructure projects, such as public transport. However, previous studies (e.g. Santos (2005) and Vickrey (1963)) show that in order for a congestion tax to be successful, investments in public transport are necessary. If there is no good substitute for driving, people will continue to take the car. This argument is also strengthened by Walters (1961) who states that increased prices of driving will lead to a shift to its closest substitute, namely public transport. We do not consider the exclusion of public transport in our analysis as a severe problem since a congestion tax, according to above reasoning, should include investments in public transport. Because of this we still believe in our conclusion that the congestion tax had a positive effect on the air quality in Gothenburg. Our reasoning is that investments in public transport are one of the reasons why the Gothenburg congestion tax led to such a large reduction in emissions. In absence of these investments, we believe that the effect would have been smaller. Our suggestion for policy makers in other cities is hence to combine the congestion tax with investments in public transport.

7. Conclusion

Our difference-in-difference analysis has established the relationship between the Gothenburg congestion tax and air quality. We find evidence that the congestion tax has reduced NO_X as well as PM_{10} emissions with up to 17 % and 19 % respectively. Additionally, we show that the probability of exceeding the, of European Union, concentration limits are reduced for both pollutants. For NO_X the probability is reduced by approximately 14 percentage points and for PM_{10} by approximately 4 percentage points. Hence we draw the conclusion that the policy intervention successfully improved the air quality in Gothenburg. However, since new research by Miljömedicinskt Centrum (2018) show that the air quality is still a major problem in Gothenburg, new or improved environmental policy interventions are needed.

Further, we also find evidence for a spill-over effect toward adjacent areas, i.e. that emission levels were reduced also in nearby areas. This finding suggests that our results of the effect from the congestion tax is underestimated since the effect arises not only in the charging zone but also in adjacent areas. According to our results it seems like the effect diminishes over time. However, the results from our event studies, where we investigate when the effect arises and for how long it lasts, are not very robust and should hence be considered with caution. To be able to establish the persistence of the effect from the congestion tax, further research is needed.

Previous studies have had problems quantifying to what extent the reductions in emission levels depend on the implementation of a congestion tax, due to the downward trend (arising from e.g. share of green vehicles) and meteorological conditions. By using a difference-in-difference approach and by controlling for meteorological conditions we overcome this problem. Hence, this is a good method to use for studies of the effect from implementation of a congestion tax on air quality. However, one limitation with this approach is that it might not be applicable to all settings. The main reason for this is that the difference-in-difference approach requires a good counterfactual and hence relies on the parallel trend assumption.

Therefore, it might be difficult to perform a similar analysis for other cities implementing a congestion tax.

As stated by Miljömedicinskt centrum (2018), the polluted air in Gothenburg causes around 300 premature deaths each year. EEA (2018) and Boningari & Smirniotis (2016) also makes clear that bad air quality can have severe consequences on people's health. Based on this, we also suggest future researchers to analyse if the reduction in air pollutants, followed from the Gothenburg congestion tax, resulted in improved human health.

Since we find a robust substantial and significant effect on both NO_X and PM_{10} levels, we draw the conclusion that the implementation of the Gothenburg congestion tax had a general positive effect on the air quality in the city. To sum up, our results suggest that the congestion tax was successful in achieving the governmental objective of reducing the level of emissions from road traffic.

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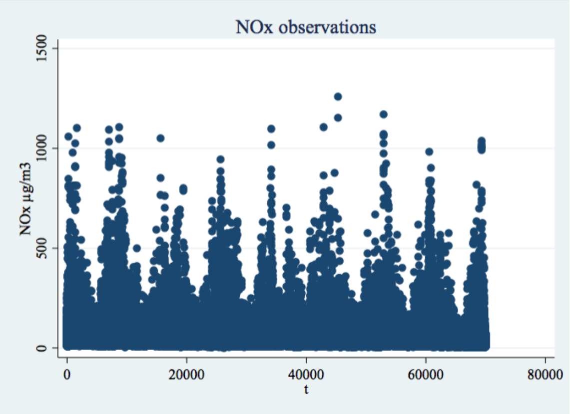
Appendix

Graph A1. Observation plot of NO_X over



Graph A2. Observation plot of PM_{10} over

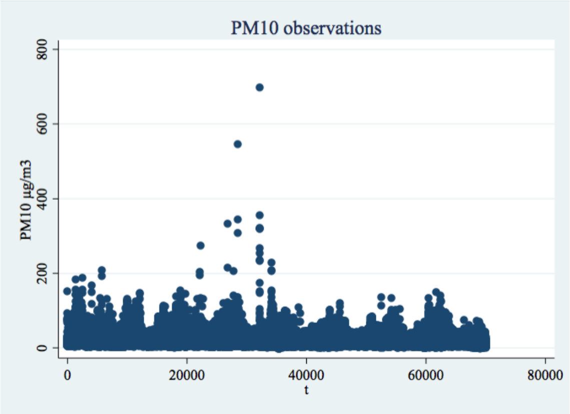


Table A3: Panel data regression output for NO_X

	(1) OLS *NO_X*	(2) OLS *NO_X*	(3) OLS *$Log(NO_X)$*	(4) LPM *$NO_X > 40\ \mu g/m^3$*
*Gothenburg*After*	-7.308***	-5.284***	-0.169***	-0.138***
	(1.59e-12)	(0.550)	(0.005)	(0.046)
Gothenburg	31.105***	25.969***	0.280***	0.064***
	(1.13e-12)	(2.808)	(0.022)	(0.004)
After	-8.308***	10.275***	0.268***	0.198***
	(1.22e-12)	(0.150)	(0.011)	0.001
Wind speed		-9.970**	-0.149***	-0.144***
		(4.927)	(0.038)	(0.008)
Precipitation		-5.687	-0.062	-0.020
		(3.673)	(0.054)	(0.033)
Time trend		0.001***	-1.44e-05***	-2.67e-04***
		(1.13e-05)	(1.92e-07)	(4.25e-07)
*Time trend*Gothenburg*		5.70e-05	5.00e-06***	1.52e-04***
		(4.76e-05)	(3.89e-07)	(9.58e-07)
Constant	49.554***	109.222***	4.541***	1.326***
	(7.56e-13)	(26.488)	(0.139)	(0.040)
Month dummies (Jan-Dec)		Yes	Yes	Yes
Observations	139,882	133,942	133,942	5,608

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

Table A4: Panel data regression output for PM$_{10}$

	(1) OLS *PM_{10}*	(2) OLS *PM_{10}*	(3) OLS *Log(PM_{10})*	(4) LPM *$PM_{10} > 40\ \mu g/m^3$*
*Gothenburg*After*	-0.998***	-3.404***	-0.194***	-0.036***
	(4.20e-14)	(0.251)	(0.0127)	(0.001)
Gothenburg	0.099***	-0.499	0.068***	-0.015***
	(3.19e-14)	(0.321)	(0.018)	(0.002)
After	-1.321***	1.608***	0.132***	-0.003***
	(3.38e-14)	(0.194)	(0.006)	(4.65e-04)
Wind speed		0.044	0.008	-0.006**
		(0.375)	(0.022)	(0.003)
Precipitation		-4.690***	-0.311***	-0.026***
		(0.660)	(0.032)	(0.002)
Time trend		-8.20e-05***	-4.93e-06***	-1.21e-05***
		(6.89e-06)	(2.59e-07)	(5.32e-07)
*Time trend*Gothenburg*		5.94e-05***	3.33e-06***	2.04e-05***
		(8.37e-06)	(4.46e-07)	(1.14e-06)
Constant	19.79***	19.465***	2.789***	0.077***
	(4.62e-15)	(0.453)	(0.028)	(0.003)
Month dummies (Jan-Dec)		Yes	Yes	
Observations	139,037	133,209	133,196	5,602

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

Table A5: Regression output using a more flexible time trend

	(1) OLS *NO_X*	(2) OLS *NO_X*	(3) OLS *PM_{10}*	(4) OLS *PM_{10}*
*Gothenburg*After*	-5.789***	-3.345***	-2.785***	-1.067***
	(1.171)	(0.594)	(0.252)	(0.136)
Gothenburg	25.882***	26.747***	-0.374***	0.240**
	(0.601)	(0.468)	(0.139)	(0.113)
Wind Speed	-9.743***	-9.738***	-0.002	0.005
	(0.086)	(0.086)	(0.019)	(0.019)
Precipitation	-5.891***	-5.878***	-4.129***	-4.124***
	(0.373)	(0.373)	(0.087)	(0.087)
Time trend	0.004***		9.08e-05***	
	(6.4e-04)		(1.54e-04)	
*Time trend*Gothenburg*	6.63e-05**		4.68e-05***	
	(2.73e-05)		(5.76e-06)	
Constant	96.768***	97.688***	17.133***	17.164***
	(2.069)	(2.078)	(0.325)	(0.319)
Observations	133,942	133,942	133,209	133,209
R-squared	0.234	0.233	0.151	0.151

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

In these regressions we allow for a more flexible time trend, by including 96 monthly dummies for each of the 96 months in our dataset. In column 1 and 3 the city specific linear time trends are included, and in column 2 and 4 they are excluded. The variable after is excluded from these specifications.