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Environmental Speed Limits

Do temporary speed limits improve air quality?

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Master Thesis, Master of Science in Economics and Business Administration, Major in Economic Analysis

NORWEGIAN SCHOOL OF ECONOMICS

Abstract

In 2004, Oslo introduced a policy that involved a temporary reduction in the maximum speed limit of 20 km/h (80 – 60 km/h) during the winter. The aim of this policy was to improve local air quality in order to reduce the adverse health effects related to air pollution. This master´s thesis analyses the effectiveness of implementing environmental speed limits on the choice of speed and local air quality in Oslo. We use an ordinary least square regression (OLS) and a regression discontinuity design (RDD) to perform a pooled cross section analysis on four air pollutants, $PM_{2.5}$, PM_{10}, NO_2 and NO_X, for two selected roadways during the period 2006 – 2011. Our estimates are based on hourly data from multiple monitoring stations and independent data sources.

Our findings indicate a 5.8 km/h reduction in travel speed. However, there is no robust evidence of an improvement in air quality for any of the air pollutants. Our conservative cost–benefit calculation suggest that implementation of the environmental speed limits is associated with a net social loss of 4,120,000,000 NOK each environmental speed limit period. These findings suggest that the implementation and further expansions of the environmental speed limit policy is ill-advised and entails a loss to the society. The inefficiency of environmental speed limits suggest that other actions are necessary to improve local air quality in Oslo

Keywords: Oslo, Temporary Speed Limits, Environmental Economics, Air Pollution, Cost–Benefit, Regression Discontinuity Design

Preface

This master´s thesis was written as a part of our master´s degree in *Economic Analysis* at the Norwegian School of Economics (NHH). We found the policy of environmental speed limits interesting for several reasons. First, current research suggests that the negative health effects of air pollution are even more severe than first expected. Second, increased awareness among citizens about the adverse effects of poor local air quality has led to an increased demand for public policies that improves air quality. Lastly, the introduction and effects of environmental speed limits has been subject to much public debate since its first introduction in 2004. We hope that our thesis provides valuable input in the discussion about the efficiency of environmental speed limits on local air quality.

We would like to use this opportunity to thank our supervisor Torfinn Harding for enthusiastic guidance and discussion. We are grateful for your contribution and support during the entire process. We would also like to thank Rune Elvik for information about traffic and accidents. Last, but not least we would like to thank the Municipality of Oslo, more specifically the Norwegian Public Road Administration, the Norwegian Institute for Air Research and The Norwegian Meteorological Institute for access to data and for great information sharing. We appreciate your contribution and your positive response for our master´s thesis.

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1. Introduction

Recent research suggests that air pollution will be the top environmental cause of mortality worldwide by 2050, ahead of dirty water and lack of sanitation (OECD, 2012). Thus, several countries and cities worldwide have implemented actions to improve air quality. For example, in 2004, Oslo decided to implement an environmental speed limit policy on National Road 4. The environmental speed limit policy reduced the maximum speed limit from 80 km/h to 60 km/h during the winter (Det Kongelige Samferdselsdepartement, 2004). The aim of this policy was to improve local air quality by reducing the level of Particulate Matter. The environmental speed limit policy was extended to Ring Road 3 and European Route 18 in 2006 and 2007.

This master´s thesis estimates the effect of the environmental speed limits on drivers' choice of speed and air quality in Oslo. The motivation is based on contradicting findings in previous research about the effectiveness of speed management policies on air quality. Some papers estimate that a reduction in the maximum speed limit have no effect, or even a slightly deteriorating effect, on air quality (e.g. Bel & Bolancé, 2013; Bel, Bolancé, Guillén, & Rosell, 2015). Others find that a reduction in the maximum speed limit improves air quality (e.g. Dijkema, Zee, Brunekreef, & Strien, 2008; Keuken, Jonkers, Wilmink, & Wesseling, 2010). A pilot study on the introduction of the environmental speed limits concluded that the policy improved the air quality in Oslo (Hagen et al. 2005). Contradicting conclusions about the impact of a reduction in maximum speed limits on air pollution makes this master´s thesis an interesting contribution to existing literature and the evaluation of speed management as an environmental policy. Our analysis is also relevant to current environmental policies in Oslo, as the environmental speed limits were re-implemented in 2016.[1]

We use an ordinary least square regression (OLS) and a regression discontinuity design (RDD) to perform a pooled cross section analysis on four air pollutants, $PM_{2.5}$, PM_{10}, NO_2 and NO_X, for National Road 4 and Ring Road 3 during the period 2006 – 2011. Our estimates are based on hourly data from multiple monitoring stations and independent data sources. The Regression discontinuity design provides a transparent and credible

[1] Uncertainty about the legal basis ended the use of environmental speed limits in 2012. We present the history of environmental speed limits in section two

identification of how the implementation of a temporary reduction in maximum speed limit affects the local air quality. In our analysis, we control for possible cofounding factors by focusing on a narrow window of time before and after the implementation of the environmental speed limits.

Our findings indicate that reducing the maximum speed limit from 80 km/h to 60 km/h reduces travel speed by 5.8 km/h. We find no robust evidence of an improvement in air quality. The baseline estimates for air pollution are positive across all air pollutants, implying a deterioration in air quality. However, all estimates are also statistically insignificant leading to the conclusion that the introduction of environmental speed limits did not affect the air quality in Oslo. The baseline estimate for NO_2 is statistically significant and indicates an increase in the concentration of NO_2. However, this result is not robust to several robustness checks and should therefore be treated with caution. Overall, our findings are highly policy relevant and suggest no improvements in local air quality in Oslo. We calculate the loss for the society related to the estimated speed reduction to be approximately 4,120,000,000 NOK each environmental speed limit period. This is equivalent to 8% of the operating expenses for Oslo Municipality. In conclusion, our findings indicate that the implementation, extension and re-implementation of the environmental speed limit policy is ill-advised, as it has no effect on air quality and leads to a net social loss to society. The inefficiency of environmental speed limits suggest that other actions are necessary to improve local air quality in Oslo

This master´s thesis is divided into eight sections. In the first section, we present background information about the effects of traffic on air pollution and the history of the environmental speed limit in Oslo. Section three presents the data used in our analysis, while section four presents our empirical strategy. Section five presents our primary results. Section six supports our findings with several robustness checks in addition to testing the validity of our identifying assumption. Section seven quantifies the effect of some of our findings in a cost–benefit analysis. The final section concludes our findings.[2]

[2] Supplementary findings and information can be found in the Appendix

2. Background

2.1 Consequences of Air Pollution

Norwegian Institute for Air Research estimates that an adult breathe approximately 10,000 litres of air each day, which makes local air quality of great importance to human health. The air quality depends on the composition of particles and gases in the air, and some combinations have negative effects on human health and the environment (Låg & Refsnes, 2017). Recent research suggests that air pollution will be the top environmental cause of mortality worldwide by 2050, ahead of dirty water and lack of sanitation (OECD, 2012). Thus, the importance and focus on controlling the air quality has increased over the last decade, and legal restrictions and targets have been implemented worldwide. The European Environment Agency (2016) suggests that there has been a general decrease in concentration levels of Particulate Matter (PM) and Nitrogen Dioxide (NO_2) in Europe in the period 2000–2014 but claims that the improvements are still not good enough. Moreover, the number of premature deaths related to air pollution has not changed significantly over the last years. There are approximately 1,600 yearly premature deaths in Norway because of long-term exposure to $PM_{2.5}$, and about 170 premature deaths related to long-term exposure to NO_2 (The European Environment Agency, 2016).

In 2015, The average concentration levels of Particle Matter in Oslo were below the air quality standard required by Norwegian law, but above the air quality standard recommended by The Norwegian Institute of Public Health and the Norwegian Environmental Agency. This standard corresponds to the level of air pollution that is safe for everyone, also the most vulnerable groups (Folkehelseinstituttet, 2016). The concentration levels of Nitrogen Dioxides were above both the air quality standard required by Norwegian law and the air quality standard recommend by The Norwegian Institute of Public Health. None of the air pollutants complied with the number of permitted exceedances. This suggests that Oslo still have significant room for improvements in reducing the air pollution concentration. We list the current air quality standard regulations for both Norway and Europe in the Appendix.

In 2016, the European Environment Agency Executive Director, Hans Bruyninckx stated, "We need to tackle the root causes of air pollution, which calls for a fundamental and innovative transformation of our mobility, energy and food systems" (Guerreiro, 2016; The European Environment Agency, 2016). Traffic is related to about 94% of all exceedances above the legal criteria of NO_2 in Europe (The European Environment Agency, 2016). Thus, reducing traffic and its emission is of great importance to improve the local air quality. However, other sources of air pollution are also important. The share of traffic contribution to the general concentration levels of Particle Matter in Norway was only 5% for PM_{10} and 2% for $PM_{2.5}$ in 2015, while the contribution of household heating was 44% and 60% for PM_{10} and $PM_{2.5}$ respectively (SSB, 2016). Thus, even though traffic is an important contributor to concentration levels of Particle Matter, other sources of air pollution such as household heating may be of even larger importance.

2.1.1 Health Consequences

Health effects related to air pollution are tested in both clinical and population studies. A recent report from Institute of Public Health (2015) found that elevated concentrations of air pollution might cause irritation, acute and chronic inflammatory reactions and deterioration of certain types of allergies. The adverse health effects are also associated with deterioration and development of respiratory and cardiovascular diseases, increased mortality and premature deaths (Aasvang, Låg, & Schwarze, 2016). Moreover, recent research suggests the adverse health effects of air pollution are more serious than first expected, which is one of the reasons for the increased attention to improving air quality.

One contributor to the disadvantageous health effects of air pollution is Particulate Matter (PM). Particulate Matter exists in several sizes where the number defines the size of the particle in micrometre (µm) (Miljødirektoratet, 2014). $PM_{2.5}$ include particles with a diameter of 2.5 micrometres, while PM_{10} include particles with a diameter of 10 micrometres or less. These small particles tend to act like a gas and is therefore possible to inhale. The size of the particle decides its accessibility. PM_{10} access the upper respiratory, while smaller particles go deeper and remain longer before removal, and may even enter the Circulatory System and the Central Nervous System. Thus, it may affect the embryofoetal development and increase the risk of developing diabetes and obesity because of inference with metabolism (Folkehelseinstituttet, 2015). Norwegian Institute of Public Health (2015) suggest that the particle's attributes, the existence of respiratory diseases and the way one inhale the particles are important determinates of their adverse health effects. Furthermore, the current health condition and physical activity decides how particles are disposed of and how they exit the body. Continuous exposure increases the risk of adverse health effect, especially for the most vulnerable groups such as children and individuals with existing respiratory diseases, diabetes and obesity (Låg & Refsnes, 2017).

Another contributor to the unfavourable health effects is Nitrogen Oxides (NO_X). NO_X is the sum of Nitrogen Oxide (NO) and Nitrogen Dioxide (NO_2). NO has usually no direct adverse health effects, but when it reacts with ground-level ozone, it transforms into NO_2 which do have adverse health effects. The adverse health effects from NO_2 is hard to separate from Particle Matter but is associated with reduced lung function, deterioration in the status of respiratory diseases such as asthma and bronchitis as well as increased mortality and premature deaths (Låg & Refsnes, 2017).

2.2 Contribution of Traffic to Air Pollution

An important source of air pollution is traffic. Wear of brakes, tires and asphalt is a source of Particulate Matter, and exhaust fumes is a source of NO_2 and NO_X (Luftkvalitet.info, 2017). Because traffic is an important source of air pollution many countries and cities have introduced different policies to reduce traffic emissions (OECD, 2012). These strategies include driving restrictions, speed limit reductions, congestion charging and stricter emission standards. However, the effectiveness of such measures is rarely quantified.

The relationship between speed and vehicle emissions is often described by a U-shaped relationship, particularly at a constant speed (Bel & Rosell, 2013). However, acceleration and decelerations make the relationship more complicated because rapid acceleration and deceleration increases vehicle emissions. The complex relationship between real world traffic dynamics and vehicle emissions is an important reason to why papers often have contradicted conclusions about the effectiveness of different traffic management measures. Bel & Rosell (2013) analyse the effect of two separate policies implemented by the regional government of Catalonia (Spain) on concentrations of NO_X and PM_{10}. Bel & Rosell (2013) find evidence indicating that lowering the fixed speed limits to 80 km/h increase the level of NO_2 by 1.7–3.2% and PM_{10} by 5.3–5.9%. In contrast, the effect of introducing variable

Table 1. Summary of Previous Research on Speed Management Policies

Authors	Place and year	Policy	Pollution impact	NO	PM	Method
Dijkema et al. (2008)	Amsterdam (2004 – 2006)	Reduces speed limits from 100km/h to 80km/h	7.4% reduction in PM_{10} No improvement in NO_X	-	Better	Linear Regression
Bel & Rossel (2013)	Barcelona metropolitan area (2006-2010)	(1) Reduced speed limit of 120 km/h and 100 km/h to 80 km/h (2) Also variable speed system.	(1) Increase 1.7-3.2% for NO_X 5.3-5.9% for PM_{10} (2) Reduction 5.2-11.7% for NO_X 11.3-13.5% for PM_{10}	Worse Better	Worse Better	Difference-in-Difference
Bel et al. (2015)	Barcelona metropolitan area (2006-2010)	(1) Reduced speed (2) Also variable speed system.	(1) Increase in both NO_X and PM_{10} (2) Reduction in both NO_X and PM_{10}	Worse Better	Worse Better	Quintile Regression
Hagen et al. (2005)	Oslo National Road 4 (2004-2005)	Reduced speed limit of 80 km/h to 60 km	Reduction 35-40% for PM_{10} 12-13% for NO_X	Better	Better	Simple Differences
Keuken at al. (2010)	Amsterdam and Rotterdam metropolitan areas (2005-2006)	Reduced speed limit of 100 km/h to 80 km/h	Reduction 5-30% for NO_X 5-25% for PM_{10}	Better	Better	Modelling and linear regression
Benthem (2015)	Californa, Washington and Oregon (1984-1990)	Increased speed limit from 55 mph (89 km/h) to 65 mph (105 km/h)	Increase 8-15% in NO_2 No change in PM_{10}	Worse	-	Difference-in-Difference

Notes: Summary of previous research on the effects of changes in maximum speed limits on air quality. The columns labelled NO (nitrogen oxides) and PM (particle matter) indicates whether the speed management policy improved air quality or not. (-) indicates no change.

speed limits reduced the level of NO_2 by 7.7–17.1% and PM_{10} by 14.5–17.3%. Thus, the findings by Bel & Rosell (2013) suggest that lowering the fixed speed limit had a deteriorating effect on air quality. Dijkema et al. (2008) analyse the consequences of a similar reduction in the maximum speed limit in Netherland on NO_X, PM_1 and PM_{10}. Their findings suggest that the policy led to a decrease in PM_{10} of about 7.4%. However, they find no evidence for an improvement in the level of NO_2. Some of these results were disputed by Keuken et al. (2010) who looks at the effect of the same speed limit policy on a sample of roads with a strict reinforcement of the new speed limit. The findings of Keuken et al. (2010) suggest that a reduction in the maximum speed coupled with "strict enforcemet" led to a reduction of 5–30% for NO_X and 5–25% for PM_{10}. Finally, Bethem (2015) analyse the effects of a large-scale speed limit increase in the western United States on the concentrations of NO_2 and PM_{10}. Benthem (2015) findings suggests that an increase in the maximum speed limit is associated with an 15% increase in concentrations of NO_2. The study finds no statistically significant changes in the concentration of PM_{10}. All the studies presented above differ in their conclusion about the effectiveness of changes in the maximum speed limit on vehicle emissions. Consequently, we should be careful in generalising the effects given above, as the different studies are conducted in various regions, over different periods and using different methodologies. There are several reasons to why we should expect studies carried out at different locations and different years to differ. First, road quality affects the spread of air pollution. Newer roads typically have a smaller spread of Particle Matter compared to older roads, due to less wear and tear on the asphalt (Miljødirektoratet, 2016). Moreover, countries, municipalities and cities differ in their spending on new and existing road networks. Thus, road quality is also likely to differ across countries and cities. As a result, we would expect speed management policies to have less effect in areas with high quality roads. Second, effects are hard to distinguish from other confounding sources of emissions, such as industry, wood-burning, and residential heating (Låg & Refsnes, 2017). As a result, the effectiveness of speed management policies, on local air quality, is likely to differ from roadway to roadway, country to country, and methodology to methodology.

Speed is not the only factor assumed to impact air quality. The number of vehicles and vehicle attributes are also assumed to affect air quality. Davis (2008) analyse the effect of driving restrictions on air quality in Mexico. In 1989, Mexico City imposed driving restrictions on the basis of the last digit of the vehicle's number plate. These driving restrictions banned most drivers from using their vehicles one day of the week and were in place weekdays between 5:00 a.m. and 10:00 p.m. Davis (2008) find no evidence of improved air quality. Using additional evidence, Davis (2008) suggests that the restrictions led to an increase in the number of vehicles in circulation as well as a shift towards high-emission vehicles. Additionally, Davis (2008) find indications of intertemporal substitutions towards hours when the driving restrictions are not in place. Percoco (2015) analyse the effect of the London Congestions Charge on local air quality in London. Percoco (2005) find evidence of improvements in air quality within the charged area after the policy was implemented, and a deterioration in the surrounding areas. Moreover, he finds no change in the overall air quality at the aggregated level. This is consistent with the hypothesis that the introduction of the congestion charge led to a traffic substitution effect from the treated areas to surrounding untreated areas. Percoco (2015) supports this hypothesis with traffic data indicating an increase in the number of vehicles in the untreated surrounding areas.[3] Thus, policies may sometimes be ineffective or counterproductive because of unintended effects. This underlines the notion by Davis (2008) about the importance of conducting ex ante economic analysis of policies.

The city of Oslo has introduced several traffic related policies to improve local air quality. Norwegian law requires vehicles to be fitted with winter tires during the winter to assure sufficient grip on the road surface. Some winter tires use metal or ceramic studs to increase traction. Norwegian Public Road Administration (2012) suggests that the spread of road dust from studded tires is about one hundred times larger than studless winter tires. Because of the adverse effects on road surfaces and air quality, Norwegian law restricts the use of studded tires. Consequently, the use of studded tires is not permitted from the second Monday after Easter Sunday up to and including October 31st (Lovdata, 1990).[4] Furthermore, on November 1st, 2004, Oslo introduced a fee on the use of studded to create better incentives for choosing studless tires (Lovdata, 2004). Since the introduction of the studded tire fee, the share of studded tires in Oslo has declined from approximately 34% (2004) to about 15% (2011).[5] The share of studded tires has been stable around 15% since 2011. We will discuss these potentially cofounding factors later in our analysis. The city of Oslo has also introduced driving restrictions for diesel cars on selected days likely to experience elevated levels of pollution (Lovdata, 2016). However, this measure was introduced in 2016 and should therefore not be a threat to our analysis. Other measures implemented by the city of Oslo to improve air quality are sweeping, road washing and road dust treatment with magnesium chloride to reduce the spread of Particulate Matter. In general, public roads are swept and washed every other week during the winter in Oslo, and more frequent if the concentration of air pollution is high (The Norwegian Public Roads Administration, 2014). However, the effectiveness of these measures is disputed. Norman & Johansson (2006), suggest that the use of sweeping and washing have none or marginal effects on the concentration of Particulate Matter. This is also supported by Aldrin et al. (2008). The impact of salting have been evaluted to be more propitious especially on larger particles and during dry weather (Norman & Johansson, 2006; Aldrin, Haff, & Rosland, 2008; Aldrin, Steinbakk, & Rosland, 2010). However, the effects of salting are only

[3] We discuss potential traffic substitution effects in section six
[4] The fine for using studded tires in the period from the second Monday after Easter Sunday up to and including October 31st is 1000 NOK (ca. $ 113) (Lovdata, 1990)
[5] Illustration of the development of studded tires in the period 2001–2016 can be found in the Appendix

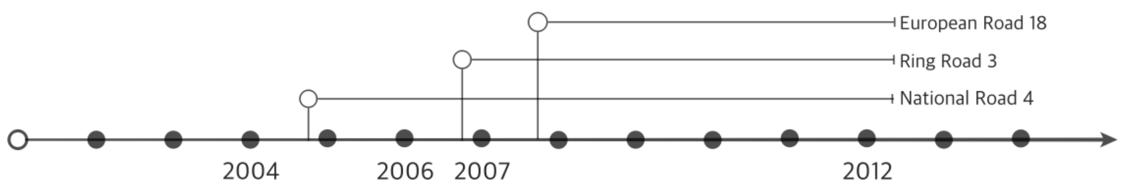
temporary and disappear within few days. The use of sweeping, washing and magnesium chloride should not be a major threat to our analysis becasuse of the their limited effect, regular periodicity and our long sample period

2.3 History of the Environmental Speed Limit Policy

High levels of air pollution led the city of Oslo to implement environmental speed limits on National Road 4 (Sinsen to Grorund) as a pilot project in 2004. The environmental speed limit policy temporary reduced the maximum speed limit from 80 km/h to 60 km/h, from November 1st 2004, to March 2005. Hagen et al. (2005) analysed the effect of this pilot project and found evidence suggesting a decrease in the levels of PM_{10} of about 35–40%, 12–13% for NO_X, and no change in $PM_{2.5}$. The report also suggested that the introduction of environmental speed limits reduced travel speed by approximately 10 km/h. Moreover, the report indicated that the implementation of environmental speed limits reduced the amount of traffic by 2.7%.[6] Their conclusion resulted in the implementation of environmental speed limits as a permanent policy during wintertime, i.e. from November 1st to the first Monday after Easter (Statens Vegvesen, 2005). The environmental speed limit policy was extended to Ring Road 3 (Ryen to Granfosstunnellen) in 2006 and European Route 18 (Hjortnes to Lysaker) in 2007. The latter only introduced the environmental speed limits during peak hours with a speed limit of 60 km/h between 06:00 a.m. and 22:00 p.m., and 80km/h otherwise (Statens vegvesen, 2012).

The authority of the police to impose fines for violations of the temporary speed limits was uncertain. In a letter from Oslo police district to the state attorneys in Oslo, Oslo police district specified that they would not enforce the environmental speed limits before the

Figure 1. Timeline of Environmental Speed Limits in Oslo



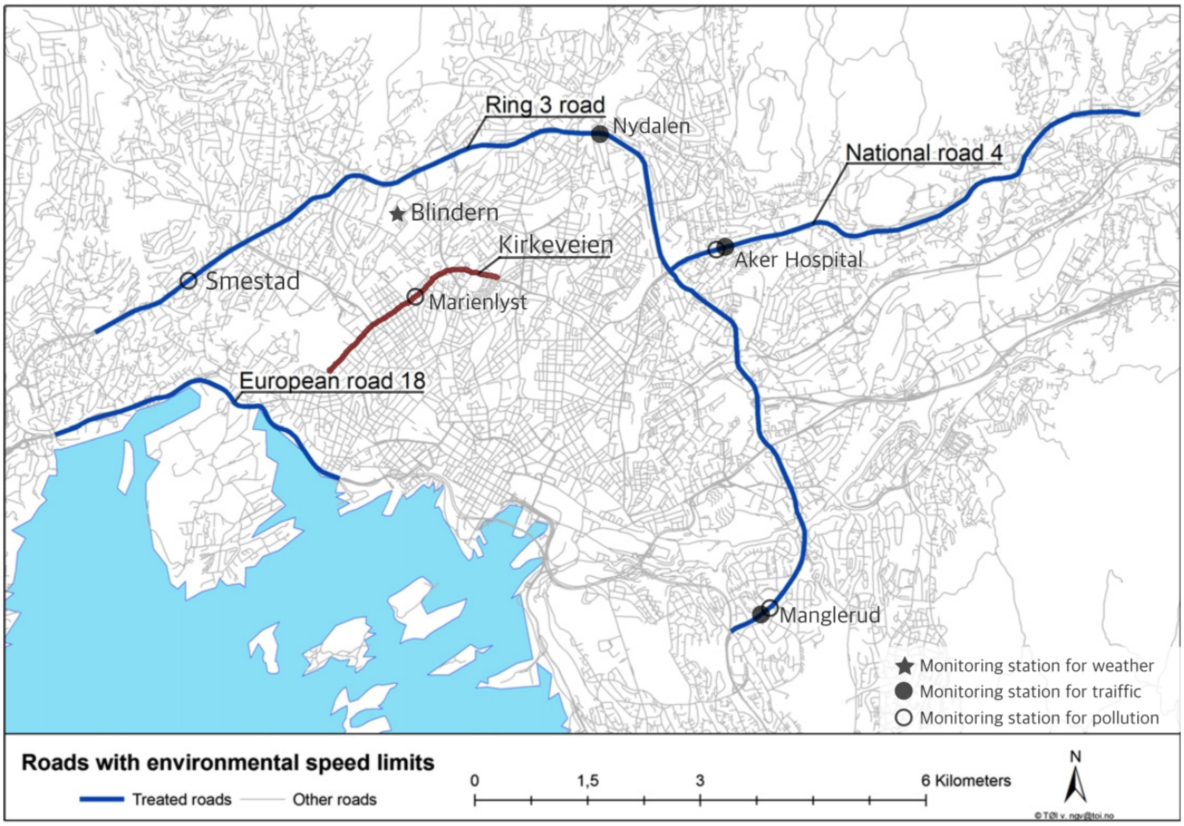
Notes: Timeline describing the development of environmental speed limits in Oslo for National Road 4, Ring Road 3 and European Route 18.

[6] We discuss this report in more detail in section six

authority to impose fines was clarified. The reason for this unwillingness to fine violators was the possibility that fines would have to be reversed and paid back if enforcement of environmental speed limits lacked legal basis (Hultgren, Berg, & Johansen, 2011). As a result, the environmental speed limit policy ended, on all three roads, in 2012 (Statens vegvesen, 2012). Moreover, the speed limit on the National Road 4 and Road Ring 3 was set to 70 km/h annually, and the speed limit for European Route 18 returned to 80 km/h.

The environmental speed limit was reintroduced on November 1st 2016 because of stricter air pollution regulations, and revised Road Legislation that gave a clearer legal basis for the enforcement of environmental speed limits. Violations of environmental speed limits are now punished in the same manner as violations of regular speed limits.

Figure 2. Map Over Monitoring Stations and Roadways in Oslo



Notes: Map showing the location of the Monitoting stations. The monitoring stations Smestad, Nydalen and Manglerud are all located roadside to Ring Road 3 while the location for Aker Hospital is roadside to National Road 4. European Road 18 have been excluded from our analysis. Marienlyst located roadside to Kirkeveien (A part of Ring Road 2) is used as a placebo station. The weather station is located at Blindern.
Source: Modified map from Elvik (2013)

3. Presentation of the Dataset

In this section, we present the data used in our analysis. Our empirical strategy requires high-frequency data on both air pollution and traffic. The dataset used in our analysis have been constructed by combining hourly data from several different data sources. Data on traffic has been collected from the Norwegian Public Road Administration, data on air pollution has been collected from the Norwegian Institute for Air Research, and weather data has been collected from the Norwegian Metrological Institute.

3.1 Data and Monitoring Stations

Our analysis will mainly focus on three monitoring stations for air pollution and three monitoring stations for traffic located at four different locations in Oslo. Table 2 shows a summary over the main characteristics for each monitoring station, including the percentage of missing observations for October and November during the years 2006–2011. The monitoring stations *Smestad*, *Manglerud* and *Nydalen* are all located roadside to Ring Road 3 while the location for *Aker Hospital* is roadside to National Road 4. To estimate the effect of implementing environmental speed limits on air quality in Oslo we match our air pollutant observations and traffic observations on each road, and then pool the roads together in our main analysis.[7] Kirkeveien has been included as a placebo location. We have excluded European Route 18 from our analysis because of many missing observations and because the policy differs slightly from the policy implemented on National Road 4 and Ring Road 3. Only focusing on roads with similar policies increases the interpretability of our results. Moreover, different policies complicate the simplicity of our research design by possibly biasing or limiting our sample and obscuring the cut-off in our regression discontinuity design. Furthermore, European Route 18 is also the roadway with the smallest reduction in travel speed. The reduction in travel speed from October to November on European Route 18 is only 4 km/h.[8] As a consequence, we argue that excluding European Route 18 does not significantly influence the statistical power of our analysis because the magnitude of the effect is likely to be smaller on European Route 18. Moreover, the number of missing

[7] The analysis is also done for each individual monitoring station for air pollution. The estimates are mostly similar to the full pooled sample. The empirical results for each individual station are presented in the Appendix

[8] The corresponding numbers for Ring Road 3 and National Road 4 is 6 km/h and 8 km/h., respectively These numbers have been calculated by averaging all observations in October and November over all the years 2006–2011 for each individual roadway

Table 2. Summary of Station Characteristics and Missing Data

Pollution monitoring site	Manglerud	Smestad	Aker Hospital	Kirkeveien
NO_2	4.38 %	8.15 %	26.48 %	11.29 %
NO_x	4.26 %	8.06 %	25.83 %	11.10 %
PM_{10}	3.39 %	8.62 %	20.15 %	3.04 %
$PM_{2.5}$	3.75 %	8.48 %	20.58 %	7.80 %
Road Location	Ring Road 3	Ring Road 3	National Road 4	Ring Road 2
Year of implementation	2006	2006	2004	-
Distance from Blindern (met. station)	7 km	3 km	4 km	1 km
Corresponding traffic monitoring site	Manglerud	Nydalen	Aker Hospital	-

Notes: This Table shows the key characteristics and the percent of missing observations for each monitoring station for air pollution. The percent of missing observations are from October and November. The sample includes the years 2006 – 2011. The distance is measured "as the crow flies". The Year of implementation indicates the first year that environmental speed limits were introduced for each roadway.

observations for October and November in the years 2006–2011 is over 40% for NO_2 and NO_X. The corresponding number of missing observations for PM_{10} and $PM_{2.5}$ on European Route 18 is 37%. This makes European Route 18 the roadway with the highest number of missing observations.[9] Thus, we argue that including European Route 18 would not significantly increase our sample size and thereby the statistical power.

Figure 2 illustrates the location of each monitoring station for both traffic and air pollution. For both *Manglerud* and *Aker Hospital*, the monitoring station for traffic and air pollution are located close to each other, less than 1 km apart. For the air pollution monitoring station located at *Smestad*, the nearest traffic monitoring station is located in *Nydalen*, 8 km to the north-east of the air pollution monitoring station. This distance may pose some problems for the validity of our fuzzy regression discontinuity approach when it comes to estimates obtained from the monitoring station located *Smestad*. However, we feel confident that *Nydalen* monitoring station still captures the traffic close to the air pollution monitoring station located at *Smestad* reasonably well, as it is located on the same road and has few major exits between the monitoring stations for air pollution and traffic[10].

The percentage of missing observations varies somewhat between the different monitoring stations. The worst performing monitoring station in terms of missing values is *Aker*

[9] The main reason for the poor data quality related to missing observations is that the monitoring station for European Route 18 was first operational in October 2008

[10] Ring Road 3 has six interchanges between *Smestad* and *Nydalen*

Hospital close to National Road 4. Using observations from October and November and the sample years 2006–2011, the percentage of missing observations ranges between 20% and 27% for both traffic observations and air pollution observations. The corresponding numbers for the monitoring stations *Smestad*, *Nydalen* and *Manglerud* roadside to Ring Road 3 are between zero and 2% missing observations for traffic and 3–8% for the different air pollutant observations. The percentage of missing observations for Kirkeveien is similar to those found for Smestad and Manglerud and ranges between 3–11%. None of the monitoring stations shows any signs of patterns in the missing values. Moreover, the missing values seem to be evenly distributed before and after November 1st.

3.1.1 Traffic Data

The Norwegian Public Road Administration monitors the traffic in Oslo and records hourly speed and the number of passing vehicles each hour for each lane.[11] Actual speed is measured in km/h and is based on all vehicles passing the monitoring station the last hour. In our analysis, we have treated observations with no passing vehicles and speed observations lower or equal to 0 as missing.

Table 3, Panel A summarises the descriptive statistics for traffic. Results for the full sample include all observations from the years 2006–2011. Column 6 and 8 reports the descriptive statistics for the months October and November in the sample period 2006–2011. The last column states a simple t-test for differences in means between October and November. From column 6 and 8 we observe that the average speed was below the posted speed limit before the implementation of the environmental speed limits, and approximately 8 km/h above the posted speed limit after the implementation. About 2,400 vehicles passes each monitoring station every hour, on average. This adds up to almost 58,000 vehicles every day. The simple test statistic reports a significant reduction in speed of 6.8 km/h from October to November and a significant decrease in the number of passing vehicles of nearly 80 vehicles each hour. We also note the large variation in the number of passing vehicles. This is expected as the amount of traffic varies over the course of the day and over the different days in the week. In general, traffic is much higher during the day compared to the night, with peaks during the morning and evening commute.[12]

[11] The dataset includes individual observations for each lane. Average hourly speed has been defined as the average speed across all lanes, and traffic counts have been aggregated by summing across all lanes

[12] Figures of the weekly pattern for traffic can be found in the Appendix

3.1.2 Air Pollution Data

The Norwegian Public Road Administration in collaboration with The Norwegian Institute for Air Research operates the automated monitoring stations for air pollution in Oslo.[13] The Norwegian Institute for Air Research validates all air pollution data by using both automatic and manual procedures. This control means that the data have been corrected for measurement errors and that the air pollution levels have been manually calibrated. The dataset includes hourly observations of the air pollutants NO_2, NO_X $PM_{2.5}$ and PM_{10}. All air pollutants are measured in $\mu g/m^3$.[14] The Norwegian Environment Agency, Norwegian Institute for Air Research, and the Norwegian Public Road Administration use these measures in their efforts to monitor and improve air quality in Oslo. In our analysis, we have treated entries with zero or negative concentrations as missing. Table 3, Panel B summarises the descriptive statistics for each of the individual air pollutants, NO_2, NO_X, PM_{10} and $PM_{2.5}$. The variance in hourly concentration levels is high across all air pollutants, and all air pollutants have hourly observations above the legal standards for air quality regulated by Norwegian law.[15] The simple t-test suggests that the air pollution levels in November are significantly higher in November compared to October. This is also what we expect, as air pollution concentration levels are highly seasonal and tend to increase during the winter.

3.1.3 Weather Data

Climatic factors are important determinants for the movement of air pollution and their chemical reactions in the air. Because of Oslo´s protected location at the end of the Oslofjord, surrounded by forested hills, the wind speed is often moderate and for the most part calm. Little wind in combination with little horizontal air during the winter, as the sun provides less warmth and the cool surface air is more likely to be trapped by the warmer air above, makes Oslo more likely to experience temperature inversions. As a result, Oslo is more likely to experience elevated concentrations of air pollution during the winter compared to the summer (Dannevig, 2009). Weather observations have been acquired from

[13] We have converted all data series that use 0-23 into hours based on the 1-24 standard, e.g. 01.11.2008 00:00 has been redefined as 31.10.2008 24:00. The reason for this is that the Traffic and weather data is measured from 1-24.
[14] Mg/m^3 is microgram (i.e. one millionth (1×10^{-6}) of a gram) per cubic metre of air. 1 $\mu g/m^3$ = 1 parts per billion (ppb) = 0.001 parts per million (ppm)
[15] The Appendix lists current Air Pollution Regulation for health effects

Table 3. Descriptive Statistics for Traffic, Air Pollution and Weather

	Full Sample					October		November		t-test
	Obs.	Mean	S.D.	Min.	Max.	Mean	S.D.	Mean	S.D.	(1) - (2)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Panel A: descriptive statistics for traffic										
Speed	149,068	72.0	8.7	14.8	121.5	74,6	8,6	67,8	7,9	-6.8***
Vehicles	149,067	2,399	1,791	12	6,778	2588	1896	2509	1848	-79.5***
Panel B: descriptive statistics for pollution										
NO_2	103,572	50.7	36.6	0.1	355	45,5	32,5	49,1	31,8	3.6***
NO_X	103,961	145.5	159.3	0.1	2,339.4	146	146	159	163	13***
PM_{10}	106,088	24.3	20.8	0.1	439.5	22,6	18,2	25,7	22,9	3.1***
$PM_{2.5}$	105,455	11.5	8.1	0.1	352.4	10,3	5,9	11,3	7,9	1.0***
Panel C: descriptive statistics for weather										
Temp.	157,743	6.9	8.8	-20.3	32.6	6,6	3,9	2,4	4,2	-4.3***
Rain	137,901	0.1	0.6	0	25.5	0,1	0,5	0,1	0,4	-0.0
Wind	157,611	2.6	1.7	0	12	2,4	1,7	2,7	2,0	0.3***

Notes: This table contains the descriptive statistics for the period 2006-2011 and includes observations from all monitoring stations (i.e. Blindern Manglerud, Smestad, Nydalen and Aker Hospital). Speed is measured in kilometres per hour (km/h), Vehicles measures the number of passing vehicles per hour across all lanes. NO_2, NO_X, PM_{10} and $PM_{2.5}$ is measured in parts per billion ($\mu g/m^3$), Temperature (Temp.) is measured in degrees Celsius, Precipitation (Rain) is measured in millimetres (mm) and wind seed is measured in meters per second (m/s). Column (10) state the difference in means between October and November. The asterisk indicates the p-value for the hypothesis that the means in October and November do not differ. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

the Norwegian Metrological Institute and their monitoring station located at *Blindern*. The monitoring station collects hourly weather observations and is located within 7 km from all off the monitoring stations for pollution. Moreover, the height difference between the weather monitoring station and the lowest and highest monitoring station for pollution is no more than 50 meters. Thus, we connect the same weather observations to all the monitoring stations for air pollution. Minute observations of precipitation have been aggregated up to hourly observations of precipitation.[16] Precipitation is measured in millimetres and includes both snow and rain, and has been included because of its ability to interact with existing air pollutants to create secondary ones and because of its ability to wash away particles from the air and minimise their formation (Viard & Fu, 2015). In our analysis, we have treated entries for precipitation with negative values as missing. To reduce the number of missing observations we have imputed hourly observations of precipitation with zero precipitation based on observations that record the total precipitation in the last 7 hours. Temperature is

[16] The aggregated values of precipitation are based on clock hours, i.e. observations for 01:00 are calculated as the sum of all precipitation in the timespan 00:01 – 01:00.

measured in Celsius Degree, two meters above the ground level. Wind speed is measured in m/s and is measured as the mean value for last 10 minutes, 10 m above ground level. Higher wind speeds may remove air particles; however, it may also import air particles from nearby areas. The wind direction has been simplified into a Northern, Southern, Eastern and Western wind and is based on the general wind direction the last 10 minutes.[17] Descriptive statistics for temperature, precipitation and wind speed are presented in Table 3, Panel C. We observe a small decrease in wind speed between October and November. Furthermore, the temperature is 4.3 degrees Celsius lower in November compared to October. All these differences are statistically significant at conventional significance level. We observe no significant change in precipitation between October and November.

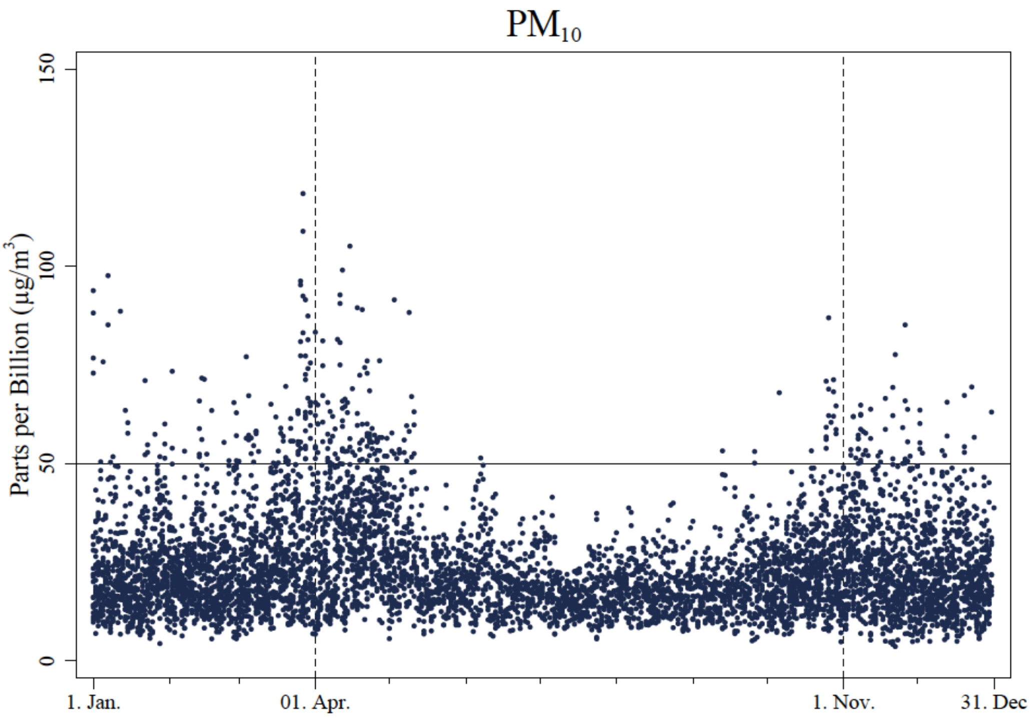
3.2 Graphical Presentation

Figure 3, 4 and 5 shows the yearly pattern for PM_{10}, $PM_{2.5}$ and NO_2 in Oslo. All figures contain individual observations from each individual monitoring and are constructed using observations from 2006–2011. Figure 3 and 4 have been constructed by averaging hourly observations across each hour of the day into the daily average concentration for each individual monitoring station for air pollution. Figure 5 shows hourly observations of NO_2. The horizontal line in figure 3 and 5 corresponds to the air quality standards required by Norwegian Law. Because Norwegian Law has no air quality standard for daily concentrations of $PM_{2.5}$ the horizontal line in figure 4 corresponds to the air quality standards recommended by the Norwegian Institute of Public Health and the Norwegian Environmental Agency. This criterion reflects the level of air pollution that is safe for everyone, also the most vulnerable groups. We see that both PM_{10} and NO_2 have observations above the legal limit. We also note the high seasonality of the different air pollutants. All air pollutants show elevated concentrations during the winter and most of the exceedances are within the environmental speed limit period. This seasonality underlines the importance of including weather data in our empirical analysis to improve efficiency and to include time trends to control for this seasonality. We also note that the increase in air pollution concentrations for PM_{10} during the beginning of the winter coincides with the change from summer to winter tires.[18] Furthermore, we observe an increase in the

[17] Wind direction is measured in degrees, where North = 360, South = 180, East = 90 and West = 270. The simplified dummies for wind direction are defined as Northern = 315° - 45°, Eastern = 46° - 134°, Southern = 135° - 224° and Western = 226° - 314°

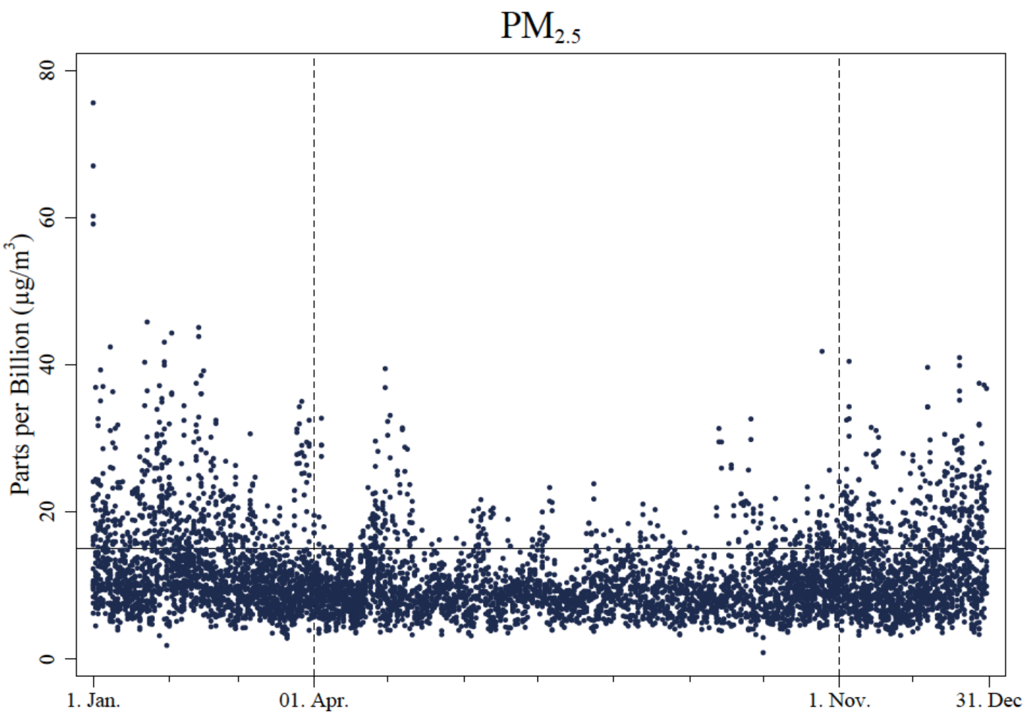
[18] As noted previously we will discuss the use of studded tires as a potential cofounding factor later in our analysis.

Figure 3. Yearly pattern for PM_{10}



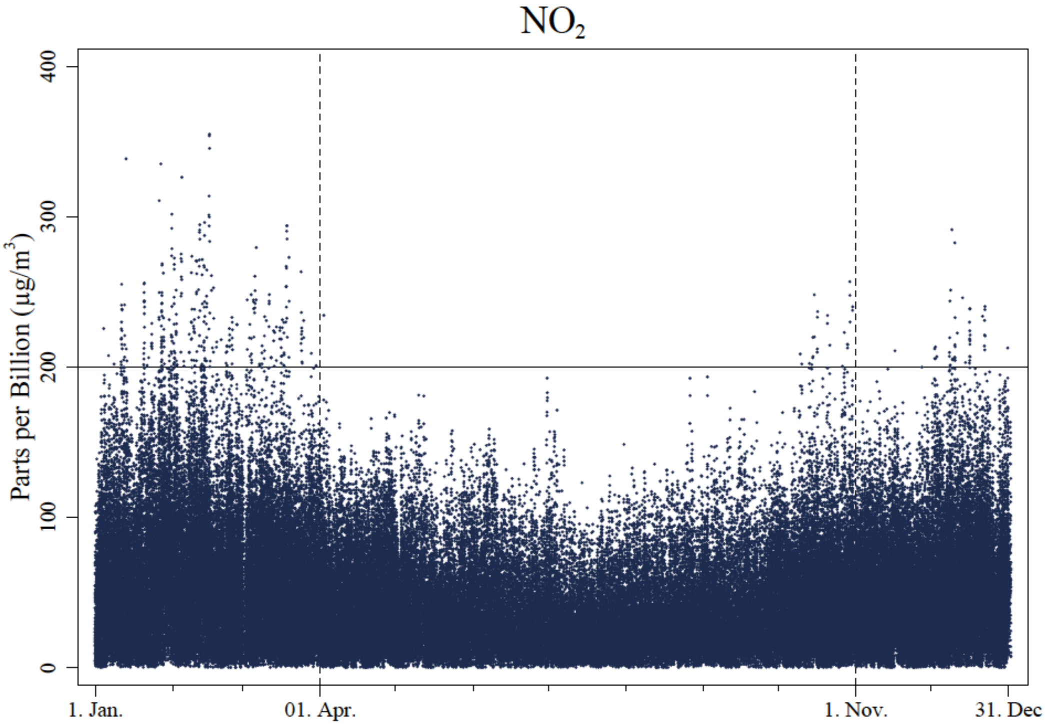
Notes: The figure illustrates the yearly pattern for the daily average concentrations of PM_{10} for each individual monitoring station (Manglerud, Smestad and Aker Hospital), in the period 2006-2011. The horizontal line corresponds to the air quality standards required by Norwegian Law. Most exceedances occur within the policy period.

Figure 4. Yearly Pattern for $PM_{2.5}$



Notes: The figure illustrates the yearly pattern for the daily average concentrations of $PM_{2.5}$ for each individual monitoring station (Manglerud, Smestad and Aker Hospital), in the period 2006-2011. The horizontal line shows the air quality standard recommended by the Norwegian Institute of Public Health and the Norwegian Environmental Agency.

Figure 5. Yearly Pattern NO_2



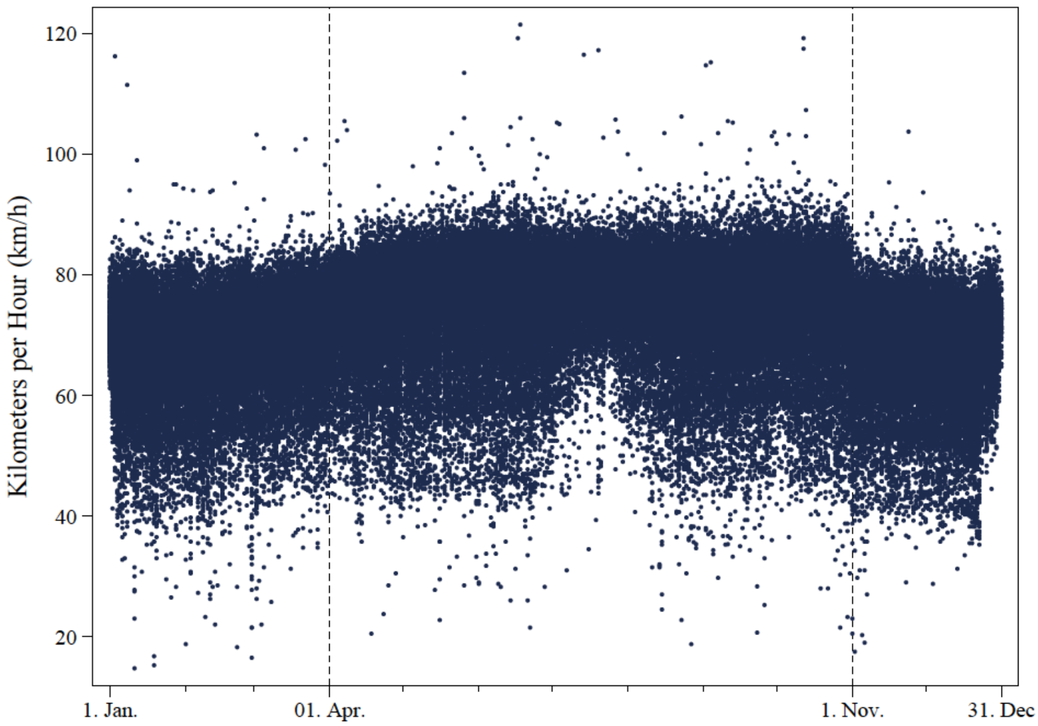
Notes: The figure illustrates the yearly pattern for hourly concentration observations of NO_2 for each individual monitoring station (Manglerud, Smestad and Aker Hospital), in the period 2006-2011. The horizontal line corresponds to the air quality standards required by Norwegian Law. Most exceedances above the legal criteria occur within the policy period.

concentrations of PM_{10} during the spring. A possible explanation for this is that Particle Matter is released when the snow melts and moisture from the road evaporate. The extreme concentrations of $PM_{2.5}$ and PM_{10} on January 1st, due to the use of fireworks on New-Year's eve, is outside of our estimation sample and should therefore not be a threat to our main analysis.

Figure 6 illustrates the yearly pattern for speed in the period 2006 – 2011. The figure has been constructed by using hourly observations of speed from the monitoring stations *Manglerud, Nydalen* and *Aker Hospital*. We observe a clear downwards shift in travel speed in the fall. This reduction in speed coincides with the implementation of the environmental speed limits on November 1st. We do not observe a corresponding shift upwards in the spring. This is also what we expect as the end date for the environmental speed limit period depends on Easter, which is a movable feast.[19] We also see some signs of seasonality;

[19] This is also the main reason to why we have chosen to focus on the implementation of environmental speed limits during the fall on November 1st. Focusing on November 1st is preferable because it provides a clean implementation without any interference from special circumstances such as festivals or holidays. Furthermore, focusing on November 1st is preferable

Figure 6. Yearly Pattern Speed



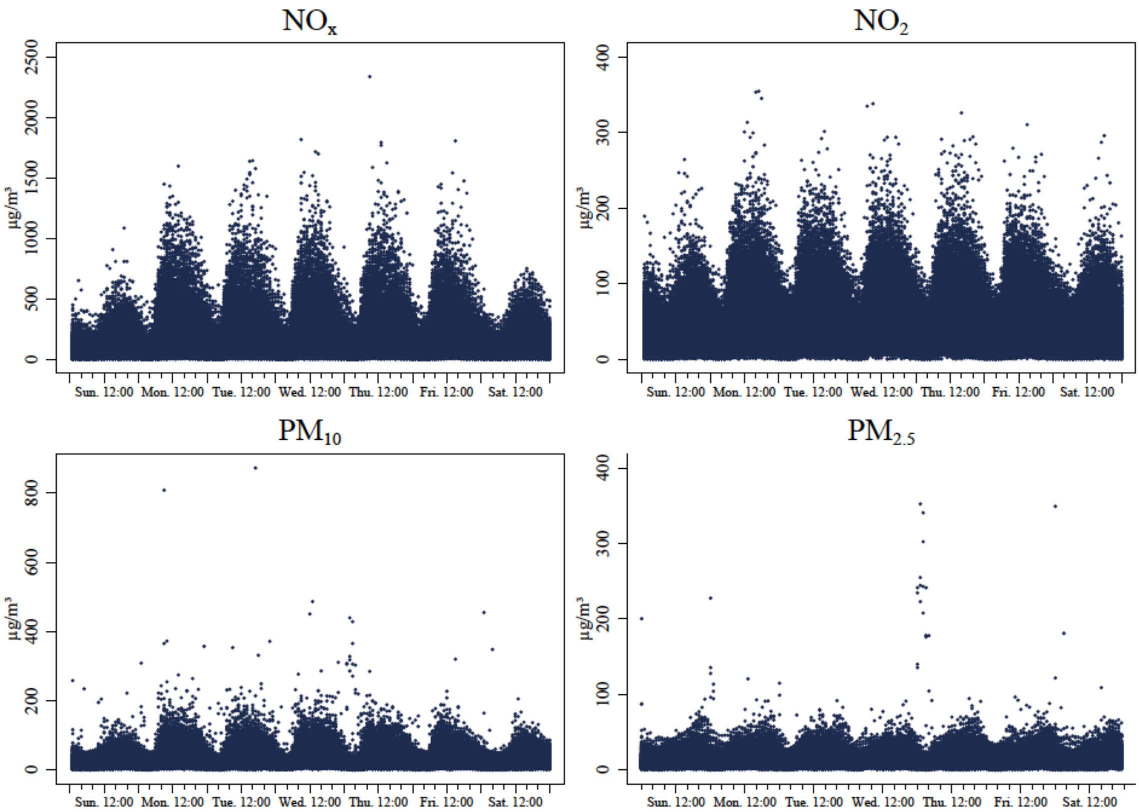
Notes: This figure illustrates the yearly pattern of speed using hourly observations from each individual monitoring station (Manglerud, Nydalen and Aker Hospital), in the period 2006-2011. There is visible downward shift in speed in the fall that coincides with the implementation of environmental speed limits on November 1st. There is no corresponding shift in the spring.

however, the seasonality is not as strong as with the different air pollutants. The seasonality is strongest during the summer with a reduction in speed variance due to the summer vacation in July. A similar reduction in the speed variance can be found during the Christmas season. However, these changes in traffic dynamics should not be a threat to our analysis because they are outside of our estimations sample.

Figure 7 illustrates the weekly pattern of the different air pollutants. The Figure has been constructed by using hourly observations from the monitoring stations *Manglerud, Smestad* and *Aker Hospital*, in the period 2006–2011. In general, the figure shows substantial variation in the concentration levels of air pollution across the different days of the week as well as variation over the different hours of the day. More specifically, we see that concentration levels are higher during the weekdays compared to weekends. This is especially apparent for NO_X, NO_2 and PM_{10}. Furthermore, the figure also shows that air pollution concentrations are low during the night and high during the day. Moreover,

because the date falls on the same day each year (with the only exceptions being leap years). Thus, climate and weather conditions are likely to be similar.

Figure 7. Weekly Pattern of Air Pollution



Notes: This figure illustrates the weekly pattern of the different pollutants by using hourly observations from the stations Mangerud, Smestad and Aker Hospital, in the period 2006 – 2011. We observe substantial variation in the level of pollution between the weekdays and the weekend as well as variation over the course of the day.

concentrations increase during the morning and decrease during the evening with peaks between the morning and evening commute. The rapid changes over the different hours of the day indicate that the air quality in Oslo responds quickly to changes in emissions. This observation is important for our empirical analysis because it means that it is possible to make inference about the changes in emission within a relatively narrow time window. The large variations also suggest that the main contributor to the measured concentrations is likely to be vehicle emissions. This reduces concerns about possible confounding factors unrelated to traffic and the magnitude of their possible impact. However, we should also be careful in ruling out the impact of possible confounding factors such as economic activity. $PM_{2.5}$ follows a slightly more stable pattern compared to the other pollutants. The stable concentrations of $PM_{2.5}$ may suggest that vehicle emissions are less important for the total concentrations of $PM_{2.5}$ compared to the other air pollutants.

4. Empirical Strategy

Determining the causal impact of environmental speed limits on local air quality requires the specification of an empirical strategy that deals with possible confounding factors such as changing vehicle fleet compositions, driving patterns and economic activity. The following section presents the empirical approaches used in our thesis.

4.1 Ordinary Least Squares

The results from the ordinary least squares (OLS) models serve a useful baseline for our primary estimation strategy. It also provides a sense of the relationship between speed and air pollution, even though they are subject to significant endogeneity concerns. To estimate the effect of speed and the environmental speed limit policy on air pollution, we estimate the following time series models (1.a) and (1.b) by using hourly observations.

$$y_t = \alpha_0 + \alpha_1 s_t + \alpha_2 Z_t + \varepsilon_t \quad (1.a)$$

$$y_t = \beta_0 + \beta_1 1(ESL_t) + \beta_2 Z_t + \varepsilon_t \quad (1.b)$$

Where y_t is the logarithm of the air pollutant at time t and s_t is the speed at time t. $1(ESL_t)$ is an indicator variable that equals 1 in the environmental speed limit period and 0 otherwise. Z_t is a set of control variables including current wind direction and traffic density (the number of passing vehicles);[20] current and 1-hour lags of precipitation, wind speed and temperature; in addition to station, year, month, day-of-the-week and hour fixed effects and a full set of interactions between the hour and day-of-the-week fixed effects and between station and wind direction. Because we use time-series data in our analysis, observations are unlikely to be independent. To address this issue, we cluster the standard errors. To determine the relevant time dimension for clustering, we have investigated the autocorrelation functions for the pollution observations for each individual station and for each individual pollutant. By following the procedure of Benthem (2015), we have recorded the first lag for which the autocorrelation function was insignificant and then calculated the

[20] Excluding passing vehicles may result in omitted variable bias. Thus, if speed is negatively correlated with passing vehicles, estimates will be downwards biased. We illustrate the two OLS models without passing vehicles in the Appendix.

average over all stations for each air pollutant. The results are 12, 33, 24 and 40 days for NO_X, NO_2, PM_{10} and $PM_{2.5}$, respectively. The median is slightly lower as the autocorrelation function for *Manglerud* is particularly persistent across pollutants compared to the other monitoring stations. Consequently, we conclude that the relevant time dimension for clustering is at the monthly level in the OLS analysis. Clustering assumes that model errors are uncorrelated across clusters but correlated within clusters (Cameron & Miller, 2014). To be conservative, we chose to not cluster at the station level in addition, as the locations of the stations are close to each other. Equation (1.a) and (1.b) is estimated using the complete hourly time series, with a time window ranging from 2006 to 2011.

4.1.1 Possible Threats to Identification

The main concern with estimating the equation (1.b) is that the exclusion of unobservable time varying factors may cause ε_t to be correlated with time and consequently also $1(ESL_t)$. In general, the exclusion of a relevant explanatory variable will bias the estimated treatment effect β_1 (Wooldridge, 2014). Based on the objective of the environmental speed limit we would expect β_1 to have a negative sign. In our case, there are several possible sources of omitted variable bias. One important source of bias is the use of studded tires. The use of studded tires implies a larger spread of air Particulate Matter because of more wear and tear on tires and asphalt. Thus, excluding this factor from the estimated model would bias the estimate of the treatment effect towards zero. Further, the level of air pollution is higher during the winter compared to the summer because of higher emissions from several air pollution sources such as fireplaces and because of temperature inversions leading to elevated concentrations air pollution (Låg & Refsnes, 2017). These unobservable confounding factors are also likely to bias the estimated treatment effect. High emissions due to the use of fireplaces would likely bias the estimated treatment effect downwards. Furthermore, weather conditions such as temperature inversions are also likely to bias the estimates, but the direction is likely to depend on the specific combination of weather conditions. Consequently, the estimated treatment effect of environmental speed limits from our simple OLS approach is likely to be biased by unobserved confounding factors such as the use of studded tires, wood-burning and special combinations weather conditions. To address these concerns of endogeneity we also employ a second approach.

4.2 Regression Discontinuity Design

Our second approach is based on a regression discontinuity design (RDD). In this approach, we attempt to estimate the causal relationship of the introduction of environmental speed limits by looking for discontinuities in air pollution levels. Our main hypothesis of the analysis is that environmental speed limits reduce the speed and as a result also the air pollution concentration.

Based on a few assumptions RDD can be analysed like a randomised experiment (Lemieux & Milligan, 2008). RDD can be sharp or fuzzy, depending on the probability of receiving the treatment effect. The sharp RDD assumes that all subjects receive their assigned treatment condition and that the likelihood of receiving the treatment jumps from 0 to 1 after the cut-off point. In the setting of environmental speed limits, this is analogous to everyone complying with the new speed limits. In the fuzzy RDD, we no longer assume all subjects to receive the treatment condition. Thus, the likelihood of receiving the treatment at the cut-off point may be less than 1. This corresponds to the view that not all drivers will be able or willing to change their behaviour because of the new speed limit. There may be several reasons for this, some drivers may drive slower than the speed limit, e.g. because of traffic and congestion, while other drivers may drive above the speed limit. Thus, compliance to the new maximum speed limits is likely to be imperfect.

4.2.1 Sharp Regression Discontinuity

In our sharp RDD, the treatment is a deterministic function of the assignment variable time (X) and the date of introduction of the environmental speed limit policy (c). Using a sharp RD approach, we can find the treatment effect by estimating two separate regressions on each side of the cut-off date November 1st (c). Transforming X into $X - c$ allows us to estimate the intercepts at the cut-off point directly (Lee & Lemieux, 2010). The regression model for the control group is given by the regression on the left-hand side of the cut-off date ($c - h \leq X < c$).

$$Y_l = \alpha_l + f_l(X - c) + \varepsilon_l \tag{2}$$

While the regression model for the treatment group is given by the regression on the right-hand side of the cut-off date ($c \leq X \leq c + h$).

$$Y_r = \alpha_r + f_r(X - c) + \varepsilon_r \quad (3)$$

Where h is the window-width on both sides of the cut-off, and $f(\cdot)$ are unknown functional forms. The estimated treatment effect is given by the difference in intercepts $\alpha_r - \alpha_l$. Using this fact, we see that the treatment effect can be estimated directly by rearranging equation (2) and (3) into the pooled regression (4). The treatment effect is now given by τ, where D is an indicator variable equal to 1 for observations on the right side (treatment group) and 0 otherwise (control group) (Lee & Lemieux, 2010).

$$Y = \alpha_l + \tau D + f_l(X - c) + D[f_r(X - c) - f_l(X - c)] + \varepsilon \quad (4)$$

The main specification for our regression discontinuity based model is given by equation (5) and is estimated by using ordinary least squares:

$$y_t = \gamma_0 + \tau 1(ESL_t) + \gamma_1 f(X - c) + \gamma_2 1(ESL_t) \times f(X - c) + \gamma_3 Z_t + \varepsilon_t \quad (5)$$

Where τ is the estimated treatment effect of implementing environmental speed limits, and $1(ESL_t)$ is an indicator variable that equals 1 in the environmental speed limit period and 0 otherwise. Z_t is a set of control variables including current wind direction and traffic density (number of passing vehicles);[21] current and 1-hour lags of precipitation, wind speed and temperature; in addition to, station fixed effects, year, day of the week and hour fixed effects and a full set of interactions between hour and day of the week fixed effects; and between station and wind direction.[22] The interaction between the $1(ESL_t)$ indicator variable and the polynomial time trend, $f(\cdot)$, allow the time trend to differ on either side of the cut-off date.

To implement the RDD, we need to specify the order of polynomial time trend in $f(\cdot)$ and the width of the window on the two sides of the cut-off date, bandwidth. The primary concern when choosing the order of the polynomial trend and bandwidth is the trade-off between precision and bias (Lee & Lemieux, 2010). We choose to use a simple linear time

[21] A potential concern with including traffic density as a control variable is the potential bias associated with endogenous variables and traffic substitution effects (Angrist & Pischke, 2009). We examine the possibility of traffic substitution effect more closely in section six. We also explore the sensitivity of our result to the inclusion of control variables in section six and the appendix. Our baseline results are not significantly altered by the inclusion of control variables. These results suggest that the possibility of traffic density being an endogenous variable and the possibility of traffic substitutions effect should not be a major concern.

[22] Even though (Davis, 2008) and (Chen & Whalley, 2012) include current and 1-hour lags of quartics in the different weather variables we choose not to include quartics of these variables as the model residuals when using smaller bandwidths than 30 days behave better without quatrics of these control variables. Moreover, the papers do not provide any arguments for why they prefer quartics over simple linear variables. We explore the sensitivity of our results to the inclusion of covariates in section six. We also conduct a parallel RD analysis on our baseline covariates in section six.

trend in our analysis because simple specifications are in general preferred over more complex specification (Lee & Lemieux, 2010). The choice of functional form is also based on a close examination of the data, which does not exhibit any strong visible nonlinear trends.[23]

Our choice of bandwidth is based on the "leave-one-out" cross-validation procedure proposed by (Lemieux & Milligan, 2008) and (Ludwig & Miller, 2007) aimed specifically at estimating the regression function at the boundary; a visual examination of the data; and inspecting the estimates for a wide range of bandwidths. A broad bandwidth will potentially offer greater precision than a narrow bandwidth because it uses a larger range of data. However, the risk of bias may also be higher with a wide bandwidth because it is harder to ensure the right functional form over a broad range of data. On the other hand, a narrower bandwidth offers less risk of biased estimates at the expense of lower precision because of a smaller range of data. The "leave-one-out" cross-validation procedure suggest that optimal bandwidth is approximately 15 days for traffic and 40 days for most air pollutants, based on the minimization of the cross-validation criterion. Figure 12 and 13 illustrate this in section 6. As a consequence, we choose a bandwidth of 15 days before and after the cut-off date for traffic. However, because of concerns about shifting traffic due to a school holiday, we have chosen a bandwidth of 20 days for air pollution.[24] Since the choice of bandwidth restricts the possibility to cluster at the monthly level, we choose to cluster by year in the RDD specification.[25] In our main analysis equation (5) is estimated using the entire pooled cross-section dataset using observations from the period 2006-2011.

A graphical presentation of the data is used to visualise trends and other discontinuities that may violate the regression discontinuity approach. Unexpected and unexplainable jumps in the treatment variable would question the causal interpretation of jumps at the cut-off date. The graphical presentation is also affected by a trade-off in precision and bias. If the bin, the interval size, is too narrow, the precision will be weak, and the plot will be too noisy. As a

[23] Selecting the right functional form is one of the greatest challenges when using the parametric estimation approach. There are several data-driven strategies to choose the most appropriate functional form. One approach is to use the Akaike information criterion (AIC). However, in our case the AIC tend to select very flexible time trends with 9 or more polynomials. Another approach is to use the F-test approach suggested by (Lee & Lemieux, 2010). Applied to our data this method also tends to select very flexible time trends with 5 or more polynomials. We examine the sensitivity of our results to different order of polynomials in section six

[24] The Fall Holiday is a school holiday that takes place in week 40 every year. In our sample, the latest date on which week 41 starts is October 11th, 2010. This corresponds to a maximum bandwidth of 21 days

[25] We explore the sensitivity of our results to the time dimension of the clustering in section six

result, visualising the relationship between the outcome and assignment variable may be hard. On the other hand, the precision may also be small if the bins are too broad, because a potential jump at the cut-off may be hard to see (Jacob, Zhu, & Somers, 2012). We have chosen daily bins based on comparing different bin-sizes and visual examination of the data.

4.2.2 Possible Threats to Identification

Because RDD is a nonexperimental approach, it must meet several conditions to provide unbiased estimates (Jacob, Zhu, & Somers, 2012). Our primary identifying assumption is that absent of the change in speed, because of the environmental speed limit policy, the air quality in Oslo would not change discontinuously on November 1st. This is equivalent to the assumption that optimising agents do not have precise over the assignment variable (Lee & Lemieux, 2010). This is often referred to as the "no-manipulation" assumption. We find this to be a reasonable assumption since there are no other major reasons to expect a large discontinuous change in economic activity or travel activity on November 1st. However, days before and after November 1st are likely to differ in ways that could affect air quality, such as seasonal variation in the demand for travel or climate conditions. Our polynomial trend should capture any such differences that change smoothly around the cut-off date. Thus, only discontinuous changes in air quality driven by unobservable factors could pose a threat to our identification strategy. One possibility is that public officials wanted and could strategically choose an implementation date with unusual high or low concentrations of air pollution. However, we believe that this is unlikely. We also believe that it is unlikely that drivers strategically move driving from the days after the implementation of environmental speed limits to the days before the implementation.[26]

Another possible threat to our identification assumption is the ban on the use of studded tires up to and including October 31st. Studded tires are known to have a higher impact on the amount and spread of Particle Matter compared to studless tires, this could potentially bias our results if there is a large discontinuity in the use of studded tires on November 1st. In this case, the estimated treatment effect of implementing environmental speed limits would be biased towards zero. Another possible threat is the studded tire fee, which may lead individuals to substitute to other means of transportation such as public transportation. The implementation of environmental speed limits could also lead to a substitution effect away

[26] Table A.26 in the appendix indicate that the estimated time loss from a 5.7 km/h reduction in travel speed is only 40 seconds for a travel distance of ten-kilometres. Thus, the incentive to strategically move driving is very small.

from roadways with environmental speed limits to other roadways. Fewer vehicles on the road is likely to reduce the amount of air pollution. In this case, we would estimate a larger effect than the true causal effect of speed on pollution concentrations.

In conclusion, while we cannot completely rule out discontinuities in these confounding factors we argue that these discontinuities are very unlikely and that our regression discontinuity approach is less sensitive to confounding factors likely to bias our OLS estimates. Furthermore, to test the robustness of our identifying assumption, we examine whether there is any evidence of discontinuities appearing in places where they should not be in section 6. More specifically, we test whether there are any discontinuities in weather variables and the number of vehicles for the sample period. Moreover, we also conduct a placebo test by using observations from a time-period and a location without any temporary reduction in the maximum speed limit. Since unbiased estimates require using the correct functional form in the estimated model, we also report the sensitivity of our estimates to different choices of polynomials and bandwidths in section 6.

4.2.3 Fuzzy Regression Discontinuity

In our sharp regression discontinuity approach, we defined the indicator variable $1(ESL_t)$ as the treatment variable. However, the main objective of the implementation of environmental speed limit policy was to improve air quality by reducing travel speed. Thus, we now define speed as the treatment variable and estimate how responsive different air pollutants are to a given change in speed. Because our treatment is continuous and because compliance to the reduction in maximum speed limits is likely to be imperfect we estimate the effect of a given change in speed on air pollution by applying a two-stages least square estimation (2SLS) (Lee & Lemieux, 2010). Thus, in the Fuzzy regression discontinuity approach we use the implementation of environmental speed limits as an instrument for speed. To estimate the effect of a given change in speed on air quality we estimate the following specifications:

1st stage equation:

$$s_t = \gamma_0 + \tau_R 1(ESL_t) + \gamma_1 f(X-c) + \gamma_2 1(ESL_t) \times f(X-c) + \gamma_1 Z_t + \varepsilon_t \quad (6)$$

2nd stage equation:

$$y_t = \alpha_0 + \tau_F \hat{s}_t + \alpha_1 f(X-c) + \alpha_2 1(ESL_t) \times f(X-c) + \alpha_3 Z_t + u_t \quad (7)$$

Where τ_F is the coefficient of interest and yields the estimated treatment effect of the change in speed, given by the implantation of environmental speed limits, on air pollution. τ_R captures the effect of environmental speed limits on speed (s_t). $\hat{s}_t$ is the fitted values from the 1st stage estimation of equation (6) where we use $1(ESL_t)$ as an instrument for speed. The variables included in equation (6) and (7) are similar to the variables included in our sharp regression discontinuity approach. $1(ESL_t)$ is an indicator variable and is defined as in our sharp RDD approach. Furthermore, to be consistent with our Sharp RDD approach we also use the same control variables as previously, include a linear time trend and cluster the standard errors from equation (7) as before. Furthermore, we use a bandwidth of 20 days in the estimation of both equation (6) and (7).[27]

Note that our sharp regression discontinuity approach is the reduced form impact of environmental speed limits on air quality (Lee & Lemieux, 2010). Furthermore, by substituting equation (6) and (7) into equation (5) we see that the instrumental variable estimation is simply the reduced-form impact of environmental speed limits on air quality divided by the first stage impact of environmental speed limits on speed, i.e. $\tau = \tau_F \tau_R \Leftrightarrow \tau_F = \tau/\tau_R$ (Lee & Lemieux, 2010). Thus, our sharp regression discontinuity estimates can be interpreted as the "intent-to-treat" effect (Lee & Lemieux, 2010).

From the estimation of the 1st stage equation, we obtain an F-statistic of 1367.5. The rule of thumb suggests that an instrument is relevant if the F-statistic exceeds a value of 10 (Staiger & Stock, 1997). Thus, our instrument is highly relevant. Unfortunately, there is no possible way of testing the exogeneity condition because the true error term is unobserved (Lee & Lemieux, 2010). This is often referred to as the exclusion restriction. Our previous concerns about threats to identification mentioned under the sharp regression discontinuity also apply to this setting. However, we still argue that these concerns are unwarranted and that the effect of crossing the cut-off date is solely through the impact of environmental speed limits on speed. With these assumptions, it follows that the instrument is exogenous and relevant, and the 2SLS procedure will make valid estimates of the treatment effect of a given change in speed.

[27] Similar to the sharp regression discontinuity design, the functional forms in both equations need to be correctly specified for the model to provide unbiased estimates (Jacob R. , Zhu, Somers, & Bloom, 2012). Based on our previous discussion we find no good reason to include different functional forms in the two equations. We therefore choose to include a linear time trend in both specifications

5. Empirical Results

5.1 Traffic as Dependent Variable

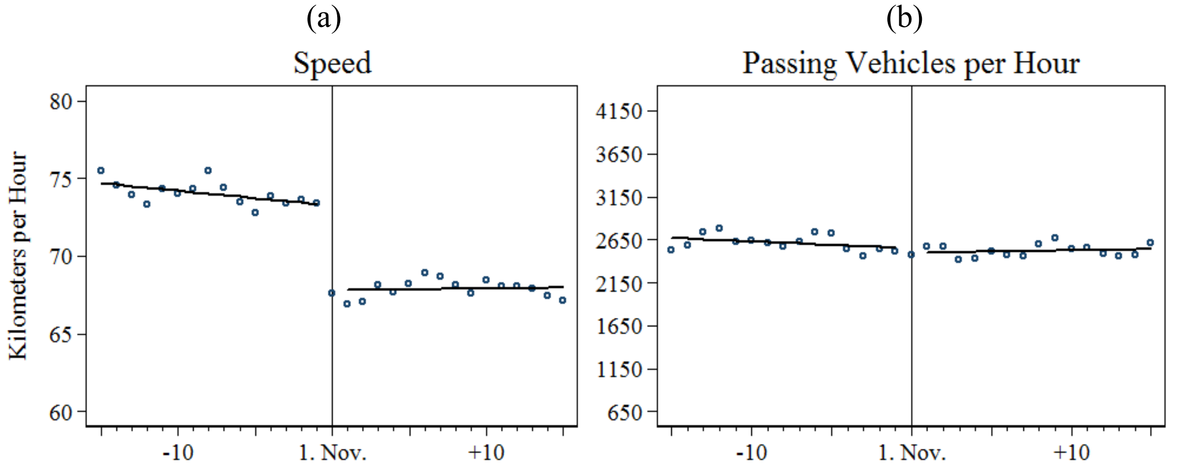
The purpose of the environmental speed limit policy was to improve local air quality by reducing travel speed. We start by looking at the effect of environmental speed limits on speed using a regression discontinuity design. A virtue of the RD design is that it provides a very transparent way of graphically identify the treatment effect. Thus, we start with a graphical depiction, before turning to a more detailed regression-based analysis.

Figure 8 shows the effect of lowering the maximum speed limit with 20 km/h on speed and traffic density. The figures are constructed by using unrestricted daily means and by plotting a linear regression on each side of the cut-off date.[28] From the figure, we see a clear discontinuity at the cut-off date, which indicates that the environmental speed limit did influence the choice of speed. However, the reduction in travel speed is much lower than the reduction in the maximum speed limit. This imperfect compliance to the reduction in the maximum speed limit is in line with our previous expectations and underlines the correctness of also employing a fuzzy regression discontinuity design. There are no indications of jumps at other points than the cut-off date on November 1st, which strengthens the argument that the jump at the cut-off date may be given a causal interpretation, and that the RDD is a valid approach for the situation.

Table 5, Panel A reports the results from estimating the discontinuity on November 1st.[29] Column (1) report the results from fitting equation (5) on speed. The point estimate for the effect of environmental speed limits (ESL) on speed indicates that a 20km/h reduction in the maximum speed limit results in a 5.8 km/h decrease in travel speed. Thus, a 1 km/h reduction in the maximum speed limit is associated with a 0.3 km/h reduction in travel speed. Table A.18 in the appendix reports the estimates from estimating equation (5) for each individual measuring station. We observe that the effect on travel speed is quite stable across the different measuring stations. The estimate ranges from 4.8 km/h for *Smestad* to 6.4 km/h for *Aker Hospital*. The small difference between the individual monitoring stations

[28] The daily means have been constructed by averaging across all stations and years (2006-2011). Thus, each bin contains a maximum of $6 \times 3 \times 24 = 432$ observations.
[29] We look more closely at the possibility of traffic substitutions effects in section six

Figure 8. Graphical Evidence of the Effect of Environmental Speed Limits on Traffic



Notes: The figure shows the effect of lowering the posted speed limit with 20 km/h on travel speed and traffic density (number of passing vehicles). We see a clear discontinuity at the cut-off (November 1st) for speed, but no visible discontinuity for Traffic Density. These findings indicate that the environmental speed limit did influence the choice of speed, but the choice of roadway (i.e. no traffic substitution effects).

and the full sample is reassuring and indicates that the estimated treatment effect is representative for roads with speed limit changes between 80 km/h and 60 km/h.

The estimates are considerably below 20 km/h. However, this might not be surprising as it is not only the posted speed limits that constraints a driver´s speed. Other factors such as congestion, weather and individual preferences are also important aspects. Moreover, we should expect a small effect during times of congestion, incidents or poor weather conditions. The modest effect could also be because of weak incentives to comply the new speed limits as the police would not ticket exceedances. We find similarities between our findings and the findings of Benthem (2015). The findings of Benthem (2015) indicate that a 1 km/h increase in maximum speed limit is associated with a 0.3-0.4 km/h increase in travel speed. However, our results are somewhat lower than the evaluation rapport by Hagen et al. (2005), where they estimate that the introduction of environmental speed limit on National Road 4 led to a decrease in travel speed of about 8-10 km/h. The different results could suggest that compliance differs between the various years. However, our estimate for *Aker Hospital* is not very different from the findings of Hagen et al. (2005).

5.2 Air Pollution as Dependent Variable

In the following section, we estimate the relationship between speed and air pollution and analyse the effect of the environmental speed limit on air quality. We start with a simple OLS model and proceed to the RDD approach later in this section.

5.2.1 Ordinary Least Squares

We estimate the effect of speed on air pollution by fitting equation (1.a) on NO_2, NO_X, PM_{10} and $PM_{2.5}$, Table 4, Panel A presents the results from this estimation. The results indicate that an increase in speed is negatively related to concentrations of NO_2, NO_X and $PM_{2.5}$. We also see that an increase in speed is positively related to the concentration of PM_{10}. Thus, a decrease in speed of 6 km/h is associated with a decrease in the concentration of PM_{10} of about 3.9%, ceteris paribus. All point estimates for speed are statistically insignificant using a 5% significance level, except for PM_{10}. We also note that the estimate for PM_{10} is statistically significant even at the 0.1% significance level. The positive sign and high statistical significance of PM_{10} is what we would expect based on the rationale behind the implementation of environmental speed limits, as the main objective of the environmental speed limit was to increase local air quality by reducing concentrations of Particle Matter. One possible explanation for the high statistical significance of PM_{10} and statistical insignificance of $PM_{2.5}$ is that traffic is the main contributor of large air particles, mainly captured by PM_{10}, while burning of wood in fireplaces is one of the main sources of fine air particles, captured by $PM_{2.5}$.

Table 4, Panel B reports the OLS estimates of the effect of environmental speed limits on air quality. We estimate the effect of implementing environmental speed limits by fitting equation (1.b) on NO_2, NO_X, PM_{10} and $PM_{2.5}$. The point estimate of the effect of implementing environmental speed limits indicate a statistically significant reduction in concentrations of NO_2, NO_X and PM_{10}, thus suggesting an improvement in air quality. More specifically, we estimate a reduction of 13.46% for NO_2, 20.91% for NO_X and 12.92% for PM_{10}. Comparing, the sign and statistical significance for the different point estimates in Table 4, Panel A with the sign and statistical significance in Table 4, Panel B we see that most point estimates are inconsistent. For example, the negative point estimates for the effect of speed on NO_2 and NO_X suggest that a reduction in speed is associated with a deterioration

Table 4. Effect of Speed and Environmental Speed limits on Air Pollution: Ordinary Least Squares (logs)

	(1)	(2)	(3)	(4)
	Panel A: Effect of Speed on Air Pollution (OLS)			
	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(α_1) Speed	-0.0026	-0.0022	0.0065***	-0.0001
	(0.0015)	(0.0016)	(0.0013)	(0.0010)
Observations	84636	84946	86391	85938
R^2	0.5025	0.5828	0.4124	0.3427
	Panel B: Effect of Environmental Speed Limit on Air Pollution (OLS)			
	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(β_1) ESL	-0.1346*	-0.2091**	-0.1292*	-0.1121
	(0.0665)	(0.0783)	(0.0553)	(0.0682)
Observations	84636	84946	86391	85938
R^2	0.5032	0.5840	0.4122	0.3441

Notes: Panel A displays the estimated effect of speed on concentration of air pollution by estimating equation (1.a) on NO_X, NO_2, PM_{10} and $PM_{2.5}$. Panel B displays the estimated effect of environmental speed limits on air pollution by estimating equation (1.b) on NO_X, NO_2, PM_{10} and $PM_{2.5}$. All pollutants are measured in logs. All models include control variables for current traffic density (number of vehicles) and wind direction; current and 1-hour lags of weather (precipitation, temperature and wind speed); in addition to, station, year, month, day of the week and hour fixed effects and a full set of interactions between hour and day of the weekday fixed effects; and between station and wind direction. The models are estimated by using hourly observation from a pooled sample of the monitoring stations Manglerud, Smestad, Nydalen and Aker Hospital. Sample years are 2006 – 2011. Standard errors in parentheses are clustered at the monthly level.
$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

in air quality. More specifically a reduction in speed of 6 km/h is associated with a 1.2% increase in concentrations of both NO_2 and NO_X, ceteris paribus. The inconsistency in statistical significance is also perplexing. Comparing the statistical significance in Table 4, Panel A and Panel B, we see that the point estimates for the effect of speed on concentrations of NO_2 and NO_X is statistically insignificant in Panel A, while the effect of environmental speed limits on concentrations of NO_2 and NO_X is statistically significant in Panel B. These inconsistencies strengthen our concerns about possible problems with omitted variables and endogeneity. The adjusted coefficient of determination, R-squared, ranges between 34% and 58% and indicate that our model explains a great portion of the variation. However, there is still a substantial portion of unexplained variation.

The results for each individual station can be found in Table A.15 and A.16 in the appendix. The most noteworthy difference across the different monitoring stations is the results for *Smestad* which suggest a statistically significant effect of speed on concentrations of NO_2, NO_X and $PM_{2.5}$, but not PM_{10}. Moreover, the estimated effect suggests a negative relationship between an increase in speed and concentrations of NO_2, NO_X and $PM_{2.5}$. Aker

Hospital also indicates a statistical significant effect of speed on the concentration of NO_2, also here with a negative relationship. Furthermore, comparing the results in Table 4, Panel A. with the results in Table A.15 in the appendix we see that the point estimate for PM_{10} is statistically insignificant across all stations. Table A.16 in the appendix displays the point estimates for the effect of implementing environmental speed limits on air quality. We see that all point estimates are statistically insignificant at conventional significance levels across all air pollutants and stations. This is contrary to the results in Table 4, Panel B where the point estimates for NO_2, NO_X and PM_{10} are statistically significant.

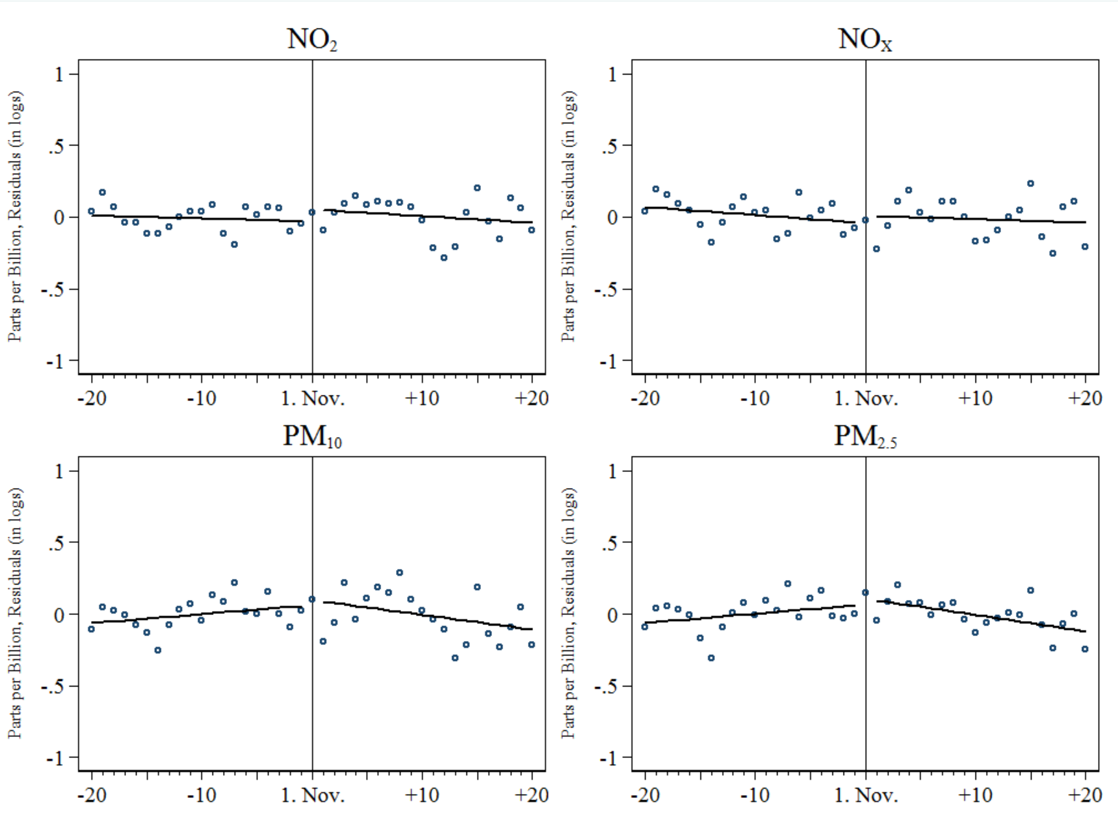
The variation in sign and statistical significance across each station and between the different panels underline our previous concerns about omitted variable bias from unobserved confounding factors in the simple OLS approach. Consequently, we treat the significant estimated effects with great caution and address the concerns by proceeding to a regression discontinuity design approach.

5.2.2 Sharp Regression Discontinuity

Figure 9 plots the residuals from estimating equation (5) using only the control variables along with a 1st order polynomial trend and a $1(ESL_t)$ intercept. The residuals have been averaged over all monitoring stations and years into daily bins.[30] Figure 9 provides no indications of a discontinuity at the cut-off date for any of the pollutants NO_2, NO_X, PM_{10} and $PM_{2.5}$. The lack of discontinuities at the cut-off date suggests that the implementation of environmental speed limits did not have any impact on air pollution concentrations. Furthermore, there is no indication of jumps at other points than the cut-off date, November 1st. This strengthens the argument that RDD is a valid approach for the situation. We observe a substantial variation and some cyclical patterns in the residuals. These observations are common to all of the air pollutants. Furthermore, we also note that the linear time trend fits the data reasonably well without overfitting.[31] All of the estimated time trends are very

[30] This "residualizing" approach is similar to the approach used by Davis (2008) and Chen & Whalley (2012). By "residualizing" the dependent variable we net out the variation in pollution concentrations that can be predicted using predetermined characteristics. Thus, making the remaining question whether our treatment variable can explain the remaining variation. The advantage of using the "residualizing" approach is that it can be used as an additional diagnostic check on whether the assumed order of the polynomial is justified. Because the "residualizing" approach sometimes can raise standard errors, all of the coefficients in the regression discontinuity tables are estimated by directly estimating equation (5) with the control variables included (Lee & Lemieux, 2010).
[31] Higher order polynomial models with small bandwidths are often imprecisely estimated because they "overfit" the data (Lee & Lemieux, 2010).

Figure 9. Graphical Evidence of the Effect of Environmental Speed limits on Air Pollution



Notes: The figure shows the effect of lowering the posted speed limit with 20 km/h on four pollutants. We do not see a discontinuity at the cut-off at any air pollutants. The lack of a clear discontinuity at the cut-off suggests that the environmental speed limit did not influence air pollution concentrations levels.

similar and almost horizontal indicating that the seasonal differences in air pollution concentrations between October and November are small.

To more formally test for discontinuities, we estimate equation (5) using a 20-day symmetric window around the cut-off date. Table 5, Panel A, columns (2) through (5) shows the results from fitting equation (5) on NO_2, NO_X, PM_{10} and $PM_{2.5}$. The results suggest that the implementation of the environmental speed limits has led to an increase in air pollution concentrations. The magnitude of the point estimates for each individual air pollutant ranges from 3.78 % to 11.75%. However, only NO_2 is statistically significant at the 5% level. Thus, we find no evidence for any improvements in air quality after the implementation of the environmental speed limit. Furthermore, the results for NO_2 even suggest a deterioration in air quality of 11.75%. These results are consistent with the graphical evidence indicated by figure 9 and the results for each individual station. The results for each individual station can be found in Table A.18, Panel A.I, B.I and C.I in the Appendix. Comparing the regression discontinuity results for each individual station with the results in Table 5, Panel A we see that all of estimates in Table A.18 are statistically insignificant. This suggest that the statistically significant baseline result for NO_2 should be interpreted with caution.

Our findings are quite different from the results of Hagen et al. (2005), both in terms of sign and magnitude. Hagen et al. (2005) suggest that the implementation of environmental speed limits improved air quality by reducing concentrations of both PM_{10} and NO_2. However, as discussed in section two, we should be careful when comparing findings from different locations and time periods. Hagen et al. (2005) only analyses the effect of implementing environmental speed limits on National Road 4 by using a sample of observations from the years 2004 and 2005. This thesis analyses the effect of implementing environmental speed limits over several years and for several roadways to increase the sample size and to generalise the effect. The paper by Hagen et al. (2005) also differs from ours in the methodology employed. These differences could explain our contradicting results. We provide a more detailed comment on the findings of Hagen et al. (2005) in section six. Furthermore, there could be several other reasons for our lack of evidence of an improvement in air quality. One potential concern is that our regression discontinuity models are misspecified or that there are possible unobservable confounding factors biasing our results. We therefore explore the sensitivity of our results to alternative specifications and evaluate the validity of our identifying assumption in section six.

5.2.3 Fuzzy Regression Discontinuity

The estimates from our sharp regression discontinuity approach presented above are based on a simple indicator variable for the implementation of the environmental speed limits. In this section, we augment the previous analysis by considering the direct effect of a given change in speed on local air quality. This is consistent with the idea that the effect of speed on air quality is only partly determined by whether the assignment variable, time, crosses the cut-off date. In this fuzzy regression discontinuity approach, we use the implementation of environmental speed limits as an instrument for speed. Table 5, Panel B shows the estimates from fitting equation (6) on speed and equation (7) on concentrations of NO_2, NO_X, PM_{10} and $PM_{2.5}$. The 1^{st} step regresses speed on the instrument and test the relevance of the instrument. The results in Table 5, Panel B are analogous to the reduced form results for air quality and yield the intent-to-treat effect, i.e. the effect of assignment to treatment. In our case, the effect of crossing the cut-off date. The point estimate for the effect of

Table 5. Effect of Environmental Speed Limits on Air Quality: Regression Discontinuity (logs)

	(1)	(2)	(3)	(4)	(5)
	Panel A: Sharp Regression Discontinuity Approach				
	Speed	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(τ) ESL	-5.7762***	0.1175*	0.1053	0.0442	0.0378
	(0.7968)	(0.0357)	(0.0435)	(0.0874)	(0.1270)
Observations	10462	12371	12420	12482	12555
R^2	0.7730	0.5343	0.6302	0.5381	0.4783
	Panel B: Fuzzy Regression Discontinuity Approach				
	Speed	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(τ_1) 1st step	-5.8169***				
	(0.7113)				
(τ_2) 2nd step		-0.0189	-0.0170*	-0.0071	-0.0061
		(0.0129)	(0.0074)	(0.0181)	(0.0146)
F-stat. instr.	1367.5***				
Observations	13802	12371	12420	12482	12555
R^2	0.7776	0.5269	0.6244	0.5309	0.4702

Notes: This table displays the primary results for the effect of the environmental speed limit (ESL) on NO_X, NO_2, PM_{10} and $PM_{2.5}$ and travel speed. Panel A displays the results form estimating equation (5) on each air pollutant and travel speed. Panel B, 1st step displays the results from estimation equation (6) on travel speed while Panel B, 2nd step displays the results from estimating equation (7) on each air pollutant. All pollutants are measured in logs. All models include control variables for current traffic density (number of passing vehicles) and wind direction; current and 1-hour lags of weather (precipitation, temperature and wind speed), in addition to, station fixed effects, year, day of the week and hour fixed effects and a full set of interactions between hour and day of the weekday fixed effects; and station and wind direction. The models are estimated by using hourly observation from a pooled sample of the monitoring stations Manglerud, Smestad, Nydalen and Aker Hospital. Sample years are 2006 – 2011. F-statistic measures the relevance for the instrument in the fuzzy approach. Panel A, columns (2) through (5) and Panel B have been estimated by using a bandwidth of ±20 days. Panel A, column (1) have been estimated by using a bandwidth of ±15 days. Standard errors in parentheses are clustered by year. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

environmental speed limits on speed indicates a 20km/h reduction in the maximum speed limit results in a 5.8 km/h decrease in travel speed. The result is statistically significant at all conventional significance levels. Moreover, the result is very similar to our previous estimate in the sharp regression discontinuity design. This is expected, as the only difference is the bandwidth of the estimation. The high F-statistic indicates that the indicator variable for the environmental speed limit period is a highly relevant instrument for speed.

The, 2SLS, 2nd stage results are presented in columns (2) through (5). The instrumental variable estimates for the effect of a given reduction in speed on pollution concentrations are negative across all air pollutants. However, only NO_X is statistically significant at a 5% level, all other estimates are statistically insignificant at conventional significance levels. The point estimate for NO_X indicates that the implementation of environmental speed limits has reduced the concentration level of NO_X by 1.89%. The statistically insignificant result for PM_{10} is reassuring as it provides support for our previous findings using the sharp regression discontinuity design. The lack of significant results for PM_{10} is also supported by previous research (e.g. Bel & Bolancé, 2013; Benthem, 2015). The results for each individual station can be found in Table A.18, Panel A.II, B.II and C.II in the appendix. The estimates from each individual station are quite similar to our baseline results and statistically insignificant across all air pollutants and stations. This suggest that our statistically significant result for NO_X in Table 5, Panel B should be interpreted with caution. The differences between the results for the sharp and fuzzy regression discontinuity designs can be attributed to the slightly different interpretations of the results. The results of the sharp regression discontinuity design should be interpreted as the effect of only just crossing the cut-off date. While the results for the fuzzy regression discontinuity should be interpreted as the effect of both crossing the cut-off date and receiving the treatment of lower travel speed, i.e. dates and hours with lower speeds due to the reduction in the maximum speed limit that would not otherwise have lower speeds.[32]

In conclusion, we find no robust evidence of a reduction in concentration levels across the different air pollutants. This suggests that the implementation of environmental speed limits have not improved local air quality in Oslo. We find some weak evidence of an effect on Nitrogen Oxides (NO_2 and NO_X). However, the results for the Nitrogen Oxides are not robust across specifications and should therefore be interpreted with caution. To further evaluate the robustness of our results and the validity of our identifying assumption we present several robustness tests in section six. Because the fuzzy regression discontinuity approach is only a scaled version of the sharp regression discontinuity approach we choose to focus on the sharp approach in the robustness section for simplicity reasons.[33]

[32] This interpretation is similar to the average treatment effect ”for the subpopulation affected by the instrument”, i.e. the Local Average Treatment effect (Lee & Lemieux, 2010)

[33] The second stage estimate is numerically identical to the ratio of the reduced form coefficients, in our case $\tau_F = \tau/\tau_R$, provided that they are estimated using the same bandwidth and the same order of polynomials (Lee & Lemieux, 2010). E.g. $-0.017 \approx 0.1053 / -5.8169$ for NOx

6. Threats to Validity and Robustness Analysis

In this section, we first examine potential threats to the validity of our identifying assumption by looking for discontinuities where we would not expect them. More specifically, we test for discontinuities in weather and traffic density. We also conduct placebo tests by using a location that did not implement environmental speed limits and by looking at periods without environmental speed limits. Second, we examine the robustness of our results to alternative specifications. We end this section with an augmented replication of the study conducted by Hagen et al. (2005).

6.1 Threats to Validity

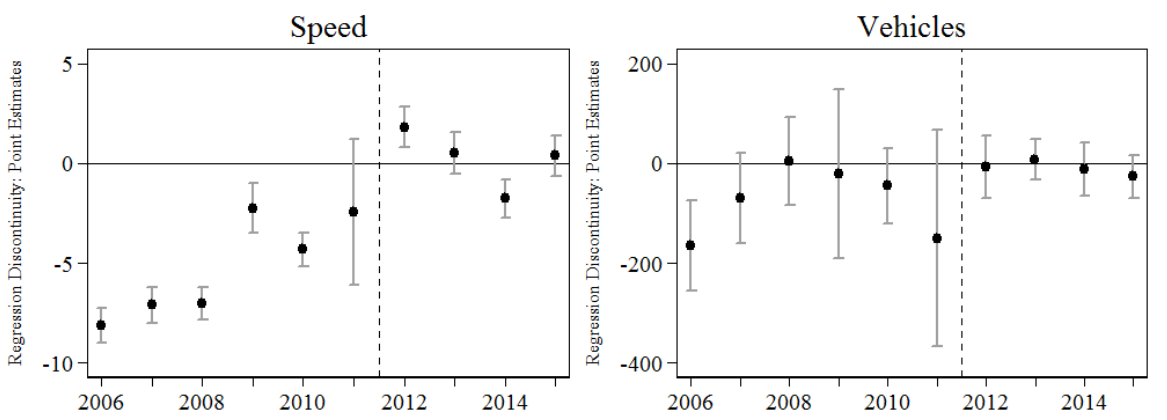
6.1.1 Traffic Substitution and Weather Effects

One concern is the possibility of traffic substitution effects. Our findings in section 5 suggest that the implementation of the environmental speed limits has no effect on air quality. Moreover, most of our estimates have a positive sign. If the implementation of environmental speed limits also caused a substitution of traffic towards roads without environmental speed limits, our strategy would yield a downward biased estimate of the causal effect of speed on air quality. Moreover, this would also threaten the causal interpretation of speed because the estimated effect could simply be a result of changes traffic density and not a change in speed.

The plot on the right-hand side of Figure 8 shows the number of passing vehicles during the period 2006–2011, as well as a linear trend with an intercept centred on the cut-off date, November 1st.[34] We observe little or no effect on the cut-off date from the figure. This observation indicates that drivers did not substitute away from roadways with the environmental speed limits to other roadways. To further test for the possibility of discontinuities in traffic density we estimate equation (5) on the number of passing vehicles for the sample period 2006–2011. Table 5, Column (1) reports the estimated treatment effect of the environmental speed limits on traffic density. The point estimate for traffic density has a negative sign, suggesting that people may have been substituting away from roads with

[34] To better illustrate the noise in the underlying data the scale of the y-axis in Figure 8 (b) have been set to equal the 25th and 75th percentile for the hourly observations of the number of passing vehicle

Figure 10. Yearly Estimates of the Treatment Effect on Traffic



Notes: This figure illustrates the point estimates of lowering the posted speed limit with 20 km/h on speed and traffic density (number of passing vehicles) for each separate year using equation (5) and the same control variables as previously. The whiskers illustrate the upper and lower 95% confidence intervals for the point estimates. All point estimates for speed are statistically significant, except the point estimate for 2011, 2013 and 2015. All point estimates for traffic density (number of passing vehicles) are close to zero and statistically insignificant using a 5% significance level, with the only expectation being the point estimate for 2006. Because of the inability to cluster by year standard errors have been clustered by week.

environmental speed limits. However, the point estimate is small and statistically insignificant at a 5% significance level. Thus, this result suggests the roads with the environmental speed limits and other roads are poor substitutes and that traffic substitution is not a major concern. Additionally, this result supports the claim that including traffic as a control variable should not bias our estimates.[35]

To increase confidence in our conclusion that the implementation of environmental speed limits did not cause any traffic substitution towards roads without environmental speed limits we also illustrate the estimated treatment effect on traffic density for each separate year using equation (5) in figure 10. All point estimates are close to zero and statistically insignificant using a 5% significance level, with the only expectation being the point estimate for 2006. We also note the high uncertainty in the point estimates for both speed and traffic in 2011. The large uncertainty in the point estimates for 2011 is due to few observations because of missing weather observations. The point estimate for the year 2006 indicate that the implementation of environmental speed limits in 2006 reduced the number of passing vehicles per hour, by 165 vehicles. The negative and statistically significant point estimate for 2006 coincides with the implementation of environmental speed limits on Ring Road 3 for the first time. Thus, a possible explanation is that the statistically significant point

[35]We have also estimated the effect environmental speed limits on speed without using traffic as a control variable. The results are unchanged by the inclusion of traffic as a control variable supporting the conclusion that the inclusion of traffic as a control variable does not bias our results. Table 11 shows the results without control variable.

Table 6. Traffic Substitution and Weather Effects:
Regression Discontinuity (logs)

	(1)	(2)	(3)	(4)	(5)
	Traffic Density	Wind Speed	Precipitation	Temperature	Wind Direction
(τ) ESL	-48.9083	-0.3130	-0.0739	-0.4761	0.1722
	(20.4302)	(0.7336)	(0.0748)	(0.5821)	(0.1668)
Observations	10462	5903	4917	5904	5903
R^2	0.9322	0.0702	0.0550	0.3628	0.0600

Notes: This table displays the main results for the effect of environmental speed limits on wind speed, precipitation, temperature and wind direction in addition to traffic density. The results in columns (2) through (5) include control variables for station fixed effects, the day of the week and hour fixed effects and a full set of interactions between the hour and day of the weekday fixed effects. The results in column (1) include control variables for current and 1-hour lags of weather (precipitation, temperature, wind speed and wind direction), in addition to, station fixed effects, year, day of the week and hour fixed effects and a full set of interactions between hour and day of the weekday fixed effects; and station and wind direction. The models are estimated by using hourly observation from a pooled sample of the monitoring stations Manglerud, Smestad, Nydalen. Sample years are 2006 – 2011. All models have been estimated by using a bandwidth of ±20 days. Standard errors in parentheses are clustered by year.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

estimate for 2006 was a one-off effect. One possible explanation is that drivers substituted away from using Ring Road 3 on November 1st as a precaution to potential adverse traffic effects from the implementation of environmental speed limits. However, the statistically significant result for 2006 is small relative to the average number of passing vehicles each hour. Thus, the statistically significant results for 2006 does not alter our conclusion that environmental speed limits, in general, did not lead to a substitution of traffic away from roads with environmental speed limits.[36].

Another possible concern is that our lack of significant results is due to unusual weather conditions. Table 5, columns (2) through (5) reports the results of fitting equation (5) on the weather control variables. Thus, using our previous weather covariates as dependent variables. All point estimates reported in the table are statistically insignificant at a 5% level. The absence of discontinuities in the weather control variables supports the assumption that the weather variables change smoothly over the cut-off date, November 1st.

6.1.2 Studded tires

Another concern is the coincidence between the implementation of environmental speed limits on November 1st and the end date for the restrictions on the use of studded tires. The

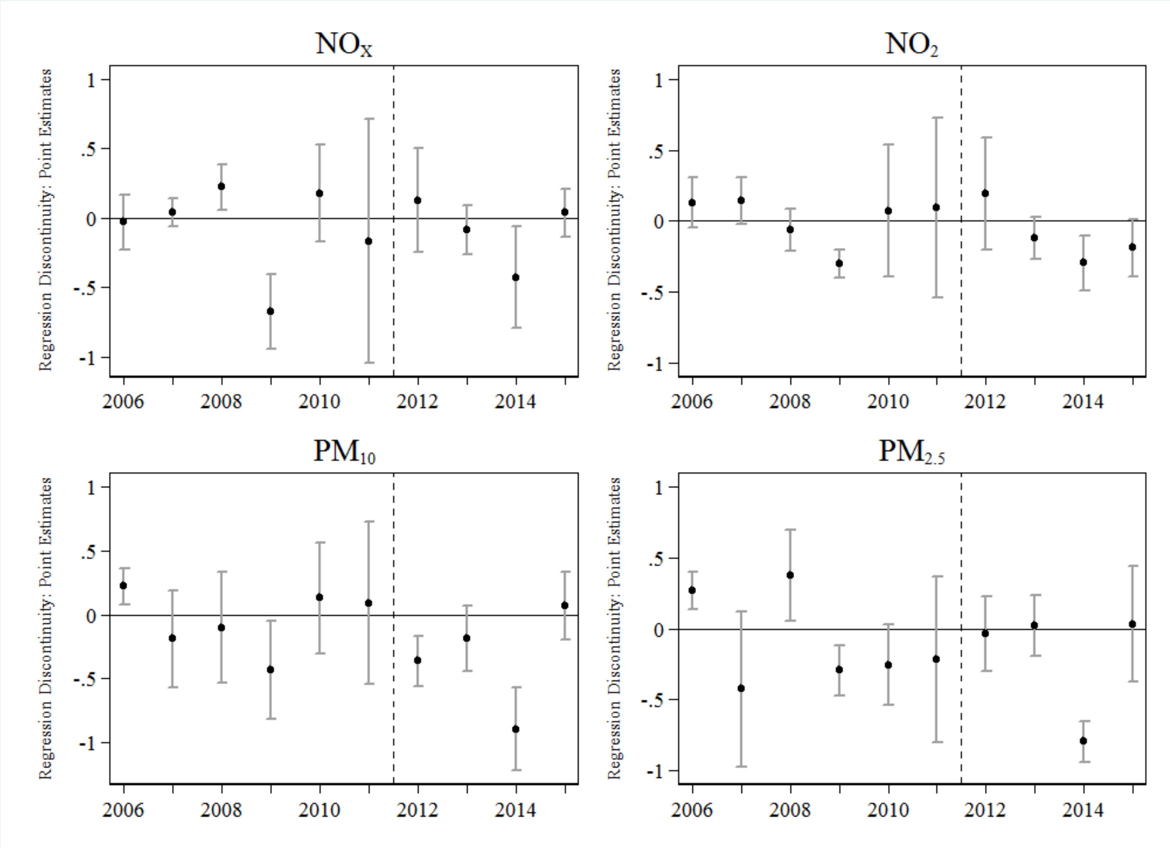
[36] Excluding 2006 from our sample hardly change the estimated treatment effects of environmental speed limit on any of the pollutants: NO_x, NO_2, PM_{10} or $PM_{2.5}$

use of studded tires is not permitted up to and including October 31st.[37] As put forward in section 2, the use of studded tires has a significant impact on the amount and spread of Particulate Matter, and could potentially bias our estimates of the effect of environmental speed limits. This concern is primarily connected to the estimates for the air pollutants PM_{10} and $PM_{2.5}$, and will be especially prominent if a lot of drivers change to studded tires on November 1st. However, we argue that that the change from summer tires to winter tires is most likely continuous over the cut-off date, November 1st. If the change from summer tires to studded winter tires is a continuous function of time, we also know that the continuity assumption required for RD estimates to be consistent is also satisfied (Lee & Lemieux, 2010).

An important determinant for the choice and timing of changing from summer tires to winter tires is temperature. Figure A.3 in the Appendix illustrates the minimum and maximum hourly temperature as well as the daily mean of the hourly temperature for each day in October and November, using observations from the sample period 2006–2011. We see that the average daily temperature decreases gradually and that the average daily temperature is higher than zero degrees Celsius for most of November. Assuming that drivers base their choice of date for the switch on either minimum temperature or average daily temperature and that preferences for temperature are evenly distributed we argue that there should not be any discontinuity in the use of studded tires on November 1st. Another concern is that the restriction on the use of studded tires leads to a heaping of drivers wanting to change to studded tires and that we for that reason should expect a discontinuity in the number of drivers changing to studded tires on November 1st. However, we believe that this scenario is unlikely as the law permits the use of studded tires due to unusual weather or driving conditions, e.g. sudden snowfall.[38] Furthermore, in the absence of unusual weather or driving conditions, we argue that drivers are likely to delay the changing of tires to the closest weekend after November 1st. We also expect drivers to delay the change of summer tires to studded tires for as long as possible as drivers with vehicles using studded tires have to pay a daily, monthly or yearly fee to the municipality of Oslo.[39] Especially

[37] Norwegian Law: Regulatory Act of 25 January 1990 no. 92, §1-4 Use of Vehicles. Infringements in the use of studded tires are fine with 1000 NOK, approximately $ 115 (10.05.2017), Regulatory Act of 17 September 1993 no. 855, §1 and §2.
[38]. Requirements for tire traction and grips outweigh the date
[39] Norwegian Law: Regulatory Act of 7 May 1999 no. 437. (Lovdata, 2017)You can choose between daily, monthly or seasonal stickers. For light vehicles, the prices are NOK 35, 450 and 1400 respectively. Prices are double for weighing more than 3.5 tonnes. If you are caught with studded tires in Oslo without having paid the fee, the penalty is NOK 750 (Oslo Kommune, 2017)

Figure 11. Yearly Estimates of the Treatment Effect on Air Quality



Notes: This figure illustrates the point estimate from estimating equation (5) on each of the air pollutants NO_X, NO_2, PM_{10} and $PM_{2.5}$ for each separate year using the same specifications as in Table 5, Panel A. The vertical dashed line indicates the end of the environmental speed limit policy. The whiskers illustrate the upper and lower 95% confidence intervals for the point estimates. We see no clear indication of a decreasing bias over the years for any air pollutant. Looking at the statistical significance of the yearly estimates we see no clear trends and that most of the point estimates are statistically insignificant. Standard errors have been clustered by week because of the inability to cluster by year.

drivers paying a daily fee would have incentives to delay the use of studded tires. If there is a discontinuity in the use of studded tires the estimated effect of environmental speed limits would be biased downwards compared to the true causal effect of environmental speed limits. Particularly PM_{10} and $PM_{2.5}$ would be biased downwards, and towards zero. The share of vehicles using studded tires have decreased from about 24% in 2006 to about 15% in 2015. A decrease in the share of vehicles using studded tires would imply a reduction in bias over the years. To test the postulate that a decrease in the share of studded tires would imply a decreasing bias over the years, we estimate the effect of implementing environmental speed limits by fitting equation (5) on each of the four air pollutions for each separate year. Figure 11 shows the point estimate from estimating equation (5) on each of the air pollutants NO_X, NO_2, PM_{10} and $PM_{2.5}$ for each separate year. Figure 11 gives no clear indication of a decreasing bias over the years for PM_{10} or $PM_{2.5}$. The same is true for NO_X

and NO_2. Looking at the statistical significance of the yearly estimates we see no clear trends and that most of the point estimates are statistically insignificant. Furthermore, the sign of the point estimates displays a no particular pattern and sporadically changes from positive to negative. The erratic movement of the point estimates over the different years and lack of any clear trends may suggest that looking at a larger sample of years is preferable over looking at a single year. Also here we note the high uncertainty in the point estimate for all the air pollutants in 2011 due to missing weather observations.[40] To further test the possibility of discontinuities in the use of studded tires we estimate equation (5) on each of the four air pollutions using a placebo period, i.e. a period without the environmental speed limit policy but with the studded tire ban. Table 7, Panel A shows that the estimated treatment effect of "environmental speed limits" using a sample of observations from 2012–2015. The point estimates in the table indicate no discontinuities on November 1st in the years without environmental speed limits. These results are reassuring as they support the validity of our methodology. Furthermore, we also note that all point estimates are negative. The negative point estimates for PM_{10} and $PM_{2.5}$ also supports the conclusion that the coincidence between the implementation of environmental speed limits on November 1st and the end date for the restrictions on the use of studded tires should not be a large concern.

An alternative way of investigating the validity of our methodology and identifying assumption is to look for discontinuities in locations that did not implement environmental speed limits. One road that did not implement environmental speed limits is Kirkeveien. The monitoring station for Kirkeveien is located on *Marienlyst* roadside to Ring Road 2. Kirkeveien was chosen as a placebo because it has good access to data for all of the analysed air pollutants and because the monitoring station is located close to a Ring Road. Selecting a monitoring station close to a highly trafficked road is preferable as road traffic is more likely to be the main contributor to the measured air pollution concentrations. Thus, minimising the bias from other sources of air pollution. A potential concern is the risk of contamination from other roadways where the environmental speed limits have been implemented since *Marienlyst* is located in the middle of the three other monitoring stations located at *Manglerud*, *Smestad* and *Aker Hospital*. However, we argue that this concern is limited as

[40] Excluding 2011 from the sample decreases the point estimates for PM_{10} and $PM_{2.5}$ to 4% and 4.4% respectively. However, both PM_{10} and $PM_{2.5}$ are statistically insignificant using a 5% significance level. The point estimates for NO_2 and NO_x increases slightly to 11.8% and 12.5% respectively, and both are statistically significant using a 5% significance level. In the robustness analysis, we see that 5 out of the 18 point estimates are statistically significant for NO_2 and NO_x. All of the point estimates for PM_{10} and $PM_{2.5}$ are statistically insignificant using a 5% significance level in the robustness analysis for PM_{10} and $PM_{2.5}$

Table 7. Effect of Environmental Speed Limits on Air Quality Validity Tests
Regression Discontinuity (logs)

	(1)	(2)	(3)	(4)	(5)
		Panel A: Time Period Placebo (2012-2015)			
	Speed	NO_X	NO_2	PM_{10}	$PM_{2.5}$
(τ) ESL	-0.2688	-0.0374	-0.0626	-0.2787	-0.1790
	(0.5846)	(0.0609)	(0.0772)	(0.1435)	(0.1767)
Observations	2543	14073	14069	14801	14809
R^2	0.7662	0.6804	0.6395	0.5121	0.3916
		Panel B: Marienlyst Placebo (2006-2011)			
		NO_X	NO_2	PM_{10}	$PM_{2.5}$
(τ) ESL		0.0023	0.0288	-0.0075	0.0792
		(0.1054)	(0.1163)	(0.1101)	(0.1256)
Observations		4202	4186	4792	4777
R^2		0.7241	0.6405	0.5617	0.5757
		Panel C: Maximum Compliance (2007-2008)			
		NO_X	NO_2	PM_{10}	$PM_{2.5}$
(τ) ESL		0.1332	0.0634	-0.1900	0.0123
		(0.0966)	(0.0852)	(0.0419)	(0.3294)
Observations		5229	5222	5108	5229
R^2		0.6586	0.5835	0.5733	0.4783

Notes: This table displays the main results for the effect of environmental speed limits on NO_X, NO_2, PM_{10} and $PM_{2.5}$ using different samples. All air pollutants are measured in logs. All models include control variables for current traffic density (number of passing vehicles) and wind direction; current and 1-hour lags of weather (precipitation, temperature and wind speed); in addition to, traffic density, school holiday fixed effects, station fixed effects, day of the week and hour fixed effects and a full set of interactions between hour and day of the weekday fixed effects; and station and wind direction. The models in Panel A and C are estimated by using hourly observation from the monitoring stations Manglerud, Smestad, Aker Hospital. Panel B uses hourly observations from the monitoring station located at Marienlyst. Column (2) through (5) in Panel A, B and C has been estimated using a bandwidth of ±20 days. Column (1) has been estimated using a bandwidth of ±15 days. Thus, all bandwidths are consistent with the choice of bandwidth in Table 5, Panel A. Standard errors in parentheses are clustered by year.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

our previous findings suggest that the implementation of environmental speed limits has no effect on concentration levels of air pollution. Table 7, Panel B shows the estimated treatment effect of "environmental speed limits" on the placebo location, *Marienlyst*, using the same sample years as in our baseline model, i.e. 2006-2011. All point estimates are statistically insignificant using a 5% significance level. These results are reassuring, as any discontinuities would question the validity of our approach. We also note the negative sign of PM_{10}. Both the negative sign and the statistical insignificance of PM_{10} supports the argument that there are no discontinuities in the use of studded tires on the cut-off date, November 1st. Looking at the magnitude of the point estimate for NO_X, NO_2 and $PM_{2.5}$ we see that the point estimate for $PM_{2.5}$ is higher compared to our baseline results, while the point estimates for NO_X and NO_2 are smaller than in our baseline results. However, the differences in magnitude are relatively small. Similar sign and magnitude of the point estimate for NO_2 between the placebo location and our baseline results suggest that our statistically significant estimate for NO_2 in Table 5, Panel A should be interpreted with caution.

6.1.3 Intertemporal Variance in Compliance

The causal interpretation of speed on air quality hinges on the assumption that there is a discontinuity in speed. Thus, another concern is temporal variance in the compliance of the environmental speed limits. Because the Police did not strictly enforce the environmental speed limit, there could be temporal variation in the compliance to the environmental speed limits as drivers adapt to the laissez-faire attitude of the police.[41,42] Figure 10 above shows the point estimate of lowering the posted speed limit with 20 km/h on travel speed for each separate year using equation (5). We see that the point estimate decreases over the years suggesting decreasing compliance to environmental speed limits over the years. One possible explanation for this reduction in compliance could be that driver´s perceived risk of punishment decreased over the years leading to a change in the choice of speed. Thus, one possible explanation for our lack of evidence of an improvement in PM_{10} and $PM_{2.5}$ is that the decrease in speed, and thus the effect on PM_{10} and $PM_{2.5}$, is too small to be estimated with precision. To further explore this possibility, we estimate equation (5) on sub-sample of years with the greatest estimated changes in speed, consisting of the years 2007–2008.[43] Table 7, Panel C reports the results from this estimation. We see that the estimates for NO_X, NO_2, and $PM_{2.5}$ are similar to our baseline estimates. Looking at PM_{10} the results are somewhat different from our previous results as the sign of PM_{10} is now negative. The negative sign for PM_{10} is more in line with what we would expect based on the rationale behind the implementation of environmental speed limits. However, all estimates are statistically insignificant. Thus, even when we try to maximize the effect of implementing environmental speed limits we find no indication of an improvement in air quality.

[41]. For example, in 2008 NRK (The Norwegian Broadcasting corporation) posted an article with a statement from the police saying that they would not prioritise resources to enforce the environmental speed limits (Jenssen & Nakken, 2008).

[42] Classical behavioural theory specifies the importance of risk and severity of punishment in changing unwanted behaviour. The importance of risk of punishment in moderating travel speed is also supported by several studies (Fildes & Lee, 1993).

[43] To remove any possible concerns about results being driven by a one-off traffic substitution effect in 2006, we have also excluded 2006 from our sample period, c.f. the discussion in section 6.1.1 and the introduction of environmental speed limits on Ring Road 3.

Table 8. Effect of Environmental Speed Limits on Air Quality Trimmed Sample Regression Discontinuity (logs)

	(1)	(2)	(3)	(4)
	NO_X	NO_2	PM_{10}	$PM_{2.5}$
(τ) ESL	0.0670	0.0944*	-0.0032	0.0256
	(0.0333)	(0.0323)	(0.0597)	(0.0975)
Observations	11265	11248	10984	11574
R^2	0.5818	0.5343	0.4789	0.4490

Notes: This table displays the main results for the effect of environmental speed limits on NO_X, NO_2, PM_{10} and $PM_{2.5}$ by using a trimmed sample. The trimmed sample have been constructed by excluding outliers, defined as observations above the 95th percentile and below the 5th percentile for each separate pollutant. All pollutants are measured in logs. All models include control variables for current traffic density (number of vehicles) and wind speed; current and 1-hour lags of weather (precipitation, temperature and wind speed), in addition to, station fixed effects, year, day of the week and hour fixed effects and a full set of interactions between hour and day of the weekday fixed effects; and station and wind direction. The models are estimated by using hourly observation from a pooled sample of the monitoring stations Manglerud, Smestad, and Aker Hospital. Sample years are 2006–2011. Standard errors in parentheses are clustered by year. All columns have been estimated by using a bandwidth of ±20 days.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Furthermore, NO_2 is now statistically insignificant supporting the claim that the statistically significant point estimate for NO_2 in our baseline results should be interpreted with caution. We also see that the estimates for the years after 2011 are close to zero and statistically insignificant. This observation is also supported by Table 7, Panel A, which shows the estimated treatment effect of the "environmental speed limits" using a placebo period without environmental speed limits, i.e. 2012–2015. The point estimates in Table 7, Panel A indicate that there are no discontinuities on November 1st in the period without environmental speed limits. These results are encouraging as they support the validity of our methodology and add credibility to our results.

6.2 Robustness Analysis

Since the RD design is associated with a high degree of freedom in the choice of specification, we examine the robustness of our results along four dimensions: monitoring station reporting, bandwidth selection, polynomial order specification and the inclusion of covariates. We first examine whether our results are sensitive to reporting bias by excluding outliers. We exclude outliers by only including values that lie below the 95th percentile and above the 5th percentile for each separate air pollutant. Table 8 present the results from estimating our baseline specification with the trimmed sample. We find no evidence for substantial changes in magnitude, sign or statistical significance when we exclude potential outliers. The magnitude of the estimates for NO_X, NO_2 and $PM_{2.5}$ is lower compared to our baseline results. However, the sign is still the same for most air pollutants. Looking at PM_{10}, we see that point estimate is now negative. A negative sign for PM_{10} is more in line with the expected effects of the environmental speed limits. We also see that the precision for NO_2, PM_{10} and $PM_{2.5}$ is a little higher compared to our baseline estimates. However, all estimates have the same statistical significance as in our baseline results. Thus, excluding outliers does not significantly alter the conclusions from our baseline results.

6.2.1 Choice of Functional Form and Bandwidth

Next, we examine if our results are sensitive to the choice of bandwidth and a range of orders to the polynomial trend. The selection of the bandwidth and order of polynomial in our main specification have been based on a visual examination of the data, the cross-validation procedure and preferences for a simple model. However, since these methods of choosing the optimal bandwidth and order of polynomials are imperfect and somewhat ambiguous, we follow the recommendations of Lee & Lemieux (2010) and explore the sensitivity of our results to different sets bandwidths and order of polynomials.

Table 9 reports the estimates of the effect of environmental speed limits on speed and traffic density using different combinations of order of the polynomial and bandwidths. For speed, we see that there is little change in the magnitude of the point estimates across the different combinations when the order of the polynomial is lower than five. Furthermore, we also see that all point estimates for speed are negative and that almost all are statistically significant using a 5% significance level. The only exceptions are the point estimates obtained when using a polynomial trend with five polynomials. Even though the optimal order of polynomial given by Akaike´s information criteria suggests a model with five polynomials, we believe that the inclusion of a linear trend is preferable to keep the model as simple as possible.[44] Estimators with third, fourth or higher order of polynomials are, in general, not recommended as they can be misleading (Gelman & Imbens, 2014). Furthermore, the precision of the estimates seems to decrease with the order of polynomials. Thus, also supporting our choice of a linear trend. Looking at traffic density, we see that all point estimates of the treatment effect are negative and that 5 out of the 18 point estimates are

[44] We calculate AIC as $AIC = N\ln(\hat{\sigma}^2) + 2p$ where N is the number of observations used in the regression, $\hat{\sigma}^2$ is the mean squared error of the regression, and p is the number of parameters in the regression model (Lee & Lemieux, 2010).

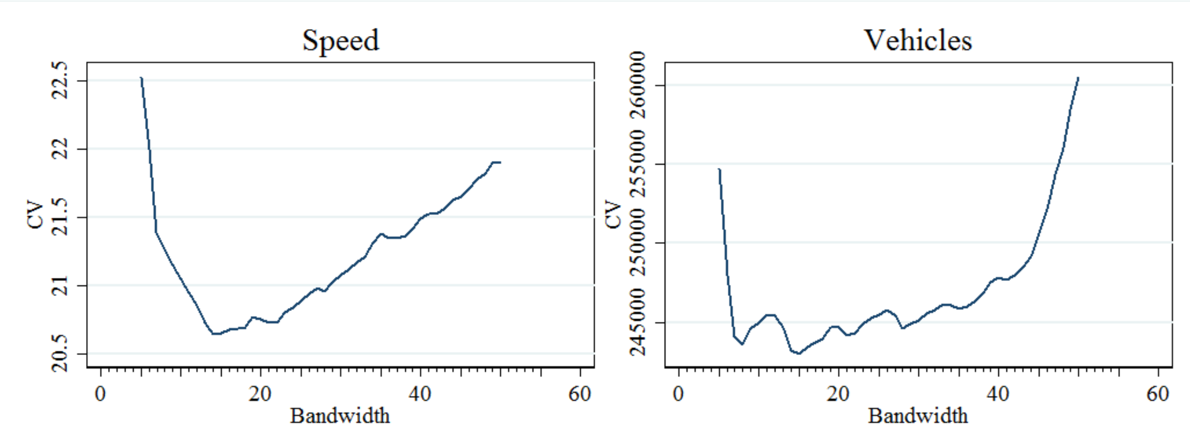
Table 9. Effect of Environmental Speed Limits on Traffic Robustness
Regression Discontinuity (logs)

	Speed		.	Traffic Density		
Bandwidth:	±20 days	±15 days	±10 days	±20 days	±15 days	±10 days
	(1)	(2)	(3)	(4)	(5)	(6)
The polynomial of Order:						
Zero	-6.2064***	-6.0621***	-5.8611***	-87.1466**	-81.9305**	-68.7667**
	(0.3232)	(0.3823)	(0.4980)	(14.9084)	(16.4387)	(16.1603)
One	-5.8169***	-5.7762***	-6.0153***	-59.0351*	-48.9083	-60.3373
	(0.7113)	(0.7968)	(0.6673)	(20.2178)	(20.4302)	(31.9665)
Two	-5.8492***	-6.0489***	-5.5154***	-40.9321	-51.3904	-20.3333
	(0.7812)	(0.6175)	(0.4871)	(30.5488)	(40.0859)	(31.4427)
Three	-6.0152***	-5.5537***	-5.7898*	-52.3849	-34.1852	-83.5387
	(0.5646)	(0.5994)	(1.4886)	(41.0842)	(41.9839)	(35.1438)
Four	-5.3925***	-5.8634**	-5.1282*	-41.5995	-61.3285	-136.0386
	(0.7173)	(1.1311)	(1.7678)	(45.8777)	(37.7532)	(100.0418)
Five	-5.8642**	-5.8213	-1.5999	-60.4394	-167.8746*	-113.5092
	(1.2472)	(2.3519)	(2.2316)	(56.8516)	(54.0268)	(138.8531)
Optimal order of the polynomial	5	5	3	1	0	0
Observations	13802	10462	7260	13802	10462	7260

Notes: This table displays the main results for the effect of implementing environment speed limits on NO_X, NO_2, PM_{10} and $PM_{2.5}$ using different combinations of bandwidth and order of polynomials. All pollutants are measured in logs. All models include control variables for current wind direction; current and 1-hour lags of weather (precipitation, temperature and wind speed), in addition to, station fixed effects, year, day of the week and hour fixed effects and a full set of interactions between hour and day of the weekday fixed effects; and station and wind direction. Model (1), (2) and (3) also an include a control variable for current traffic density. The models are estimated by using hourly observation from a pooled sample of the monitoring stations Manglerud, Nydalen and Aker Hospital. Sample years are 2006 – 2011. Standard errors in parentheses are clustered by year.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

statistically significant using a 5% significance level. These results suggest that our conclusion of no traffic substitution effect away from roads with environmental speed limits is not as robust as the results for speed. However, since most point estimates are statistically insignificant and the magnitudes are relatively small compared to the average number of passing vehicles, we still believe the validity of our conclusion that the number of passing vehicles can be included as a control variable. This is also supported by the results in Table 11, where the results indicate that our baseline results are robust to the exclusion of traffic density as a control variable. We also observe that most of the statistically significant point estimates can be found when using a zero-order time trend polynomial. A zero-order polynomial is equivalent to a simple mean comparison before and after the cut-off date (Lee & Lemieux, 2010). Since the simple nonparametric approach of comparing the difference in means just before and after the cut-off is usually biased in the neighbourhood of the cut-off, it is recommended that a local linear regression are used (Jacob, Zhu, & Somers, 2012).

Figure 12. Cross-Validation Function for Traffic



Notes: This figure plots values of the Cross-Validation Function for a range of bandwidths (5-55). The cross-Validation function has been calculated by applying the "leave-one-out" cross-validation procedure and assuming a polynomial order of one. The cross-validation function suggests that using a bandwidth of about 15 is optimal for both speed and traffic density. CV is a measure of Mean Squared Error, see Appendix for further explanation (Last Page).

Comparing the magnitude of the point estimates obtained from using a zero-order polynomial with specifications using higher orders of polynomials we see that the estimates from using a zero-order polynomial tend to be more negative. This is consistent with a decreasing trend over the cut-off. A decreasing trend suggest that the point estimates from a zero-order polynomial trend is negatively biased. In general, is seems that our baseline results for speed and traffic density are robust to the choice of bandwidth and order of the polynomial.

Figure 12 shows the Cross-Validation function from applying the "leave-one-out" cross-validation procedure suggested by (Imbens & Lemieux, 2008) to our traffic data. The main objective of the cross-validation criterion is to find the right balance between precision and bias (Jacob, Zhu, & Somers, 2012). From Figure 12 we observe that the optimal choice of bandwidth for traffic, suggested by the cross-validation procedure, is approximately 15 days for both speed and traffic density. The main difference between the two variables in Figure 12 is that larger bandwidths start getting penalized more quickly in the case of traffic density compared to speed, for bandwidths larger than 40 days. This is expected as larger bandwidths overlap with the Christmas season which is likely to have greater impact on traffic density than travel speed.

Table 10 illustrates the estimated treatment effect of implementing environmental speed limits on NO_X, NO_2, PM_{10} and $PM_{2.5}$ using different order of polynomials and bandwidths.

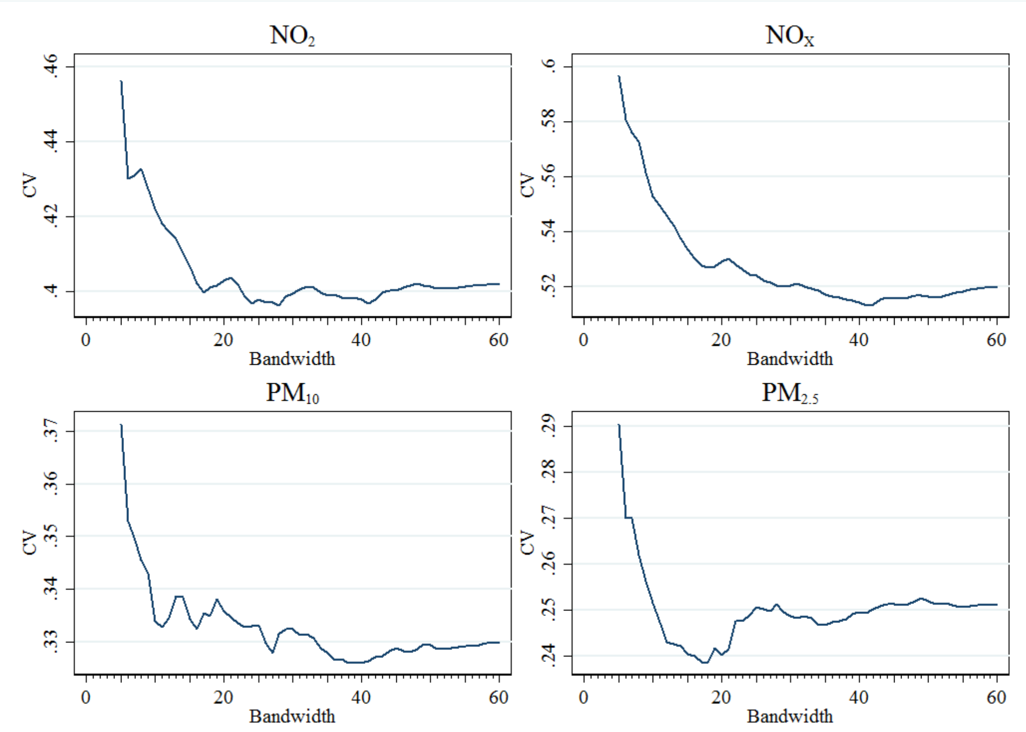
Table 10. Effect of Environmental Speed Limits on Air Quality Robustness Regression Discontinuity (logs)

	NO_x		NO_2		PM_{10}		$PM_{2.5}$	
Bandwidth:	±40 days	±20 days	±40 days	±20 days	±40 days	±20 days	±40 days	±20 days
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Polynomial of order:								
Zero	-0.0909	-0.0314	0.0238	0.0339	0.0298	0.0054	-0.0025	-0.0073
	(0.0395)	(0.0541)	(0.0524)	(0.0694)	(0.0502)	(0.0543)	(0.0454)	(0.0559)
One	0.0339	0.1053	0.0618	0.1175*	0.0355	0.0442	-0.0129	0.0378
	(0.0650)	(0.0435)	(0.0928)	(0.0357)	(0.0969)	(0.0874)	(0.1383)	(0.1270)
Two	0.1306	0.0853	0.1332	0.1121	-0.0248	0.0466	0.0058	0.0695
	(0.0747)	(0.0742)	(0.0546)	(0.0527)	(0.0457)	(0.0420)	(0.1179)	(0.1730)
Three	0.1141	0.1336	0.1289	0.1353*	0.2014	0.1357	0.1863	0.2915
	(0.0726)	(0.0909)	(0.0856)	(0.0490)	(0.1200)	(0.0653)	(0.1548)	(0.1184)
Four	0.1615*	0.1493	0.1303	0.0956	0.1542	0.1602	0.1830	0.3257
	(0.0614)	(0.1029)	(0.0667)	(0.0444)	(0.0666)	(0.1769)	(0.1878)	(0.1971)
Five	0.0085	0.0420	0.0311	0.1270	0.0639	-0.1258	0.1768	-0.0513
	(0.0900)	(0.1913)	(0.0348)	(0.1196)	(0.1282)	(0.3242)	(0.1806)	(0.1500)
Optimal order of polynomial	5	5	5	5	5	5	5	5
Observations	22211	12420	22124	12371	22605	12482	22362	12555

Notes: This table displays the main results for the effect of environment speed limits on NO_X, NO_2, PM_{10} and $PM_{2.5}$ using different combinations of bandwidth and number of polynomials. All pollutants are measured in logs. All models include control variables for current traffic density (number of passing vehicles) and wind direction; current and 1-hour lags of weather (precipitation, temperature and wind speed), in addition to, station fixed effects, year, day of the week and hour fixed effects and a full set of interactions between hour and day of the weekday fixed effects; and station and wind direction. The models are estimated by using hourly observation from a pooled sample of the monitoring stations Manglerud, Smestad and Aker Hospital. Sample years are 2006–2011. The optimal order of the polynomial is chosen using Akiake's Information Criterion (AIC). Standard errors in parentheses are clustered by year.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

We observe that only 3 out of the 48 point estimates are statistically significant using a 5% significance level, when looking at the point estimates across all air pollutants. We also note that all the statistically significant point estimates are positive and belong to NO_2 and NO_X. Only 8 of the 48 point estimates of the treatment effect are negative. $PM_{2.5}$ is the air pollutant with the most negative point estimates. Thus, the number of negative estimates is even lower than what one would expect due to chance alone. As in the case of speed, we see that the optimal order of polynomials given by Akaike's information criteria is a polynomial trend of order five. Also in the case of air pollution, our choice of a simple linear time trend has been based on our preferences for a simple model. Comparing the point estimates from a simple mean comparison with the point estimates from using a first order or higher polynomial trend we see that the point estimates from a simple mean comparison tend to be closer to zero.

Figure 13. Cross-Validation Function for Air Quality



Notes: This figure plots values of the Cross-Validation Function for a range of bandwidths (5-55). The cross-Validation function has been calculated by applying the "leave-one-out" cross-validation procedure and assuming a polynomial order of one. The cross-validation function for NO_x, NO_2 and PM_{10} suggest a bandwidth of about 40 is optimal, while the cross-validation function for $PM_{2.5}$ suggests that using a bandwidth of about 20 is optimal. CV is a measure of Mean Squared Error, see Appendix for further explanation (Last Page).

Figure 13 plots the values of the Cross-Validation function over a range of bandwidths. These values have been calculated by carrying out the "leave-one-out" cross-validation procedure and assuming a polynomial of order one. From figure 13 we observe that the optimal bandwidth suggested by the minimization of the Cross-Validation function differs somewhat across the different air pollutants. While the cross-validation function for NO_X, NO_2 and PM_{10} suggest that using a bandwidth of about 40 days is optimal. The cross-validation function for $PM_{2.5}$ suggests that using a bandwidth of about 20 days is optimal. Comparing the results from using the "optimal" bandwidth of 40 days and a 1st order polynomial with our baseline results we see that the magnitude and precision of the point estimate are lower for the pollutants NO_X, NO_2 and PM_{10}. The central purpose of the cross-validation criterion is to find the right balance between precision and bias (Jacob, Zhu, & Somers, 2012). Thus, the lower magnitudes may suggest that our baseline estimates are slightly upward biased. However, the point estimates are statistically insignificant at a 5% level across all air pollutants. The statistically insignificant point estimate for NO_2 underlines the point that the statistically significant baseline result for NO_2 should be interpreted with

Table 11. Effect of Environmental Speed Limits on Pollution Using No Control Variables: Regression Discontinuity (logs)

	(1)	.	(2)	(3)	(4)	(5)
	Panel A: Sharp Regression Discontinuity Approach					
	Speed		NO_2	NO_X	PM_{10}	$PM_{2.5}$
(τ) ESL	-5.4384***		0.1421	0.1742	0.1445	0.1761
	(0.5534)		(0.1166)	(0.1455)	(0.1825)	(0.2128)
Observations	12045		12371	12420	12482	12555
R^2	0.1167		0.5343	0.6302	0.5381	0.4783
	Panel B: Fuzzy Regression Discontinuity Approach					
	Speed		NO_2	NO_X	PM_{10}	$PM_{2.5}$
(τ_1) 1st step	-5.5558***					
	(0.2778)					
(τ_2) 2nd step			-0.0256	-0.0317	-0.0314	-0.0260
			(0.0219)	(0.0329)	(0.0217)	(0.0238)
F-stat. instr.	399.96***					
Observations	16125		15965	16015	16209	16327
R^2	0.1248		0.0043	0.0061	0.0075	0.0074

Notes: This table displays the primary results for the effect of the environmental speed limit (ESL) on NO_X, NO_2, PM_{10} and $PM_{2.5}$ and speed. Panel A displays the results form estimating equation (5). Panel B, 1st step displays the results from estimation equation (6) while Panel B, 2nd step displays the results from estimating equation (7). All pollutants are measured in logs. None of the models include control variables. The models are estimated by using hourly observation from a pooled sample of the monitoring stations Manglerud, Smestad and Aker Hospital. Sample years are 2006 – 2011. The F-statistic measures the relevance for the instrument in the fuzzy approach. Panel A, columns (2) through (5) and Panel B have been estimated by using a bandwidth of ±20 days. Panel A, column (1) have been estimated by using a bandwidth of ±15 days. Standard errors in parentheses are clustered by year.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

caution. Furthermore, we observe that using the optimal bandwidth suggested by the cross-validation function does not change the sign for any of the air pollutants. The robustness of the positive signs underpins our previous conclusion that the implementation of air quality did not improve local air quality in Oslo. Furthermore, the fact that the estimated treatment effect remains statistically insignificant in 45 out of 48 replications is reassuring as it suggests that the conclusion that environmental speed limits have no effect on air quality is robust to the choice of bandwidth and order of the polynomial.

Lastly, we examine how the sensitive our results are to the inclusion of control variables. The inclusion of baseline covariates should not affect the estimated discontinuity, no matter how correlated they are with the outcome if the “no-manipulation” assumption holds (Lee & Lemieux, 2010). Table 11, Panel A reports the effect of implementing environmental speed limits by estimating equation (5) using no control variables. Panel B reports the estimates from estimating equation (6) and (7) without control variables. The point estimate for speed is similar to our baseline estimate, but the precision is somewhat lower. However, the estimate is still statistically significant at the 5% level. Less precision is expected as the main reason for including control variables is to reduce sampling variability (Lee & Lemieux, 2010). When we examine the sensitivity of NO_X, NO_2, PM_{10} and $PM_{2.5}$ to the exclusion of control variables we see that the precision of the point estimates is lower compared to our baseline estimates. However, as discussed above, this is expected. The greatest differences in magnitude can be found for PM_{10} and $PM_{2.5}$. We also note that the magnitude of the point estimates in general are higher compared to our baseline estimates. Comparing the results in Table 11, Panel A, columns (2) through (5) to our baseline results in Table 5, Panel A, columns (2) trough (5), we see that the magnitude of PM_{10} increases from 4.4% to 17.4% and that the magnitude of $PM_{2.5}$ increases from 3.4% to 14.5%. These changes in magnitude indicate that the inclusion of control variables is important. One possible reason for this is that the control variables improves the ability of the model to describe the hourly and daily trends in the data. However, all air pollutants have the same sign as in our baseline results and are still statistically insignificant at the 5% level.

Significant changes in the estimated treatment effect or increases in the standard errors may be an indication of a misspecified functional form (Lee & Lemieux, 2010). Even though a 1^{st} order polynomial may not fully capture the trends in the data, we believe that a linear approximation is sufficient as the results are relatively incentive to different choices of bandwidth and order of polynomials. Moreover, the changes are also relatively modest, even in the case of PM_{10} and $PM_{2.5}$. The insensitivity of our results to the inclusion of covariates is reassuring and increase the confidence our results and the validity of the "no-manipulation" assumption.

6.2.2 Clustering of Standard Errors

We cluster our standard errors to mitigate the problem that our observations are unlikely to be independent across time. However, few clusters mean less independent information in the sample since data are assumed to be independent across clusters but not within. Few clusters are likely to lead to biased standard errors and misleading inference. Thus, few clusters may over-estimate the precision of our point estimates (Angrist & Pischke, 2009). Since too few

Table 12. Effect of Environmental Speed Limits on Air Quality S.E. Robustness Regression Discontinuity (logs)

	(1)	(2)	(3)	(4)	(5)
	Speed	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(τ) ESL	-5.7762***	0.1175	0.1053	0.0442	0.0378
	(0.5026)	(0.0686)	(0.0569)	(0.0911)	(0.0986)
Observations	10462	12371	12420	12482	12555
R^2	0.7730	0.5343	0.6302	0.5381	0.4783

Notes: This table displays the results from estimating equation (5) on NO_X, NO_2, PM_{10} and $PM_{2.5}$, speed and vehicles. All models include control variables for current wind direction; current and 1-hour lags of weather (precipitation, temperature and wind speed), in addition to, station fixed effects, year, day of the week and hour fixed effects and a full set of interactions between hour and day of the weekday fixed effects; and station and wind direction. Columns (2) through (5) also include a control variable for current traffic density (number of passing vehicles). The models are estimated by using hourly observation from a pooled sample of the monitoring stations Manglerud, Smestad, Nydalen and Aker Hospital. Sample years are 2006 – 2011. Columns (2) through (5) have been estimated by using a bandwidth of ±20 days. Column (1) have been estimated by using a bandwidth of ±15 days. Standard errors in parentheses are clustered by week.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

clusters may lead to biased standard errors we also examined how sensitive our results are to our choice of time dimension used to account for serial correlation.

In our main analysis, we cluster the standard errors at yearly level in the regression discontinuity approach. Table 11 reports the results for our main specification with standard errors clustered at the weekly level.[45] By clustering at the weekly level we increase the number of clusters from 6 to 40 for the different air pollutants and from 6 to 29 for speed.[46] We see that clustering by week produces slightly larger standards errors for speed, NO_2, NO_X and PM_{10} and a slightly smaller standard error for $PM_{2.5}$. Few clusters tend to underestimate the serial correlation of a random shock. An underestimation of the serial correlation is associated with an over-estimation of the precision (Angrist & Pischke, 2009). This may explain why our standard errors tend to increase with few clusters.

In conclusion, the choice of clustering does not seem to impact our results. We also note that NO_2 is statistically insignificant using weekly clusters. This result underlines our previous concerns that the statistically significant results for NO_2, in our baseline results, should be interpreted with caution.

[45] Clustering at the week level is less conservative compared to our main specification. However, Davis (2008) also use clustering within week-of-sample as a robustness test. Moreover, when the dataset is aggregated over all stations into a weekly time series and models are estimated with multiple lags the model that minimizes the AIC statistic is the model with only 1–lag (i.e. one-week-lag), this method is consistent with the methodology employed by Chen & Whalley (2012) to select the appropriate time dimension of clustering. The weekly clustering is based on the week of the year.

[46] The differences in the number of clusters for speed and the air pollutants is because of the different bandwidths used in the estimation. The bandwidth is ±20 days across all pollutants while the bandwidth is ±15 days for speed.

6.2.3 Comment on Hagen et al. (2005)

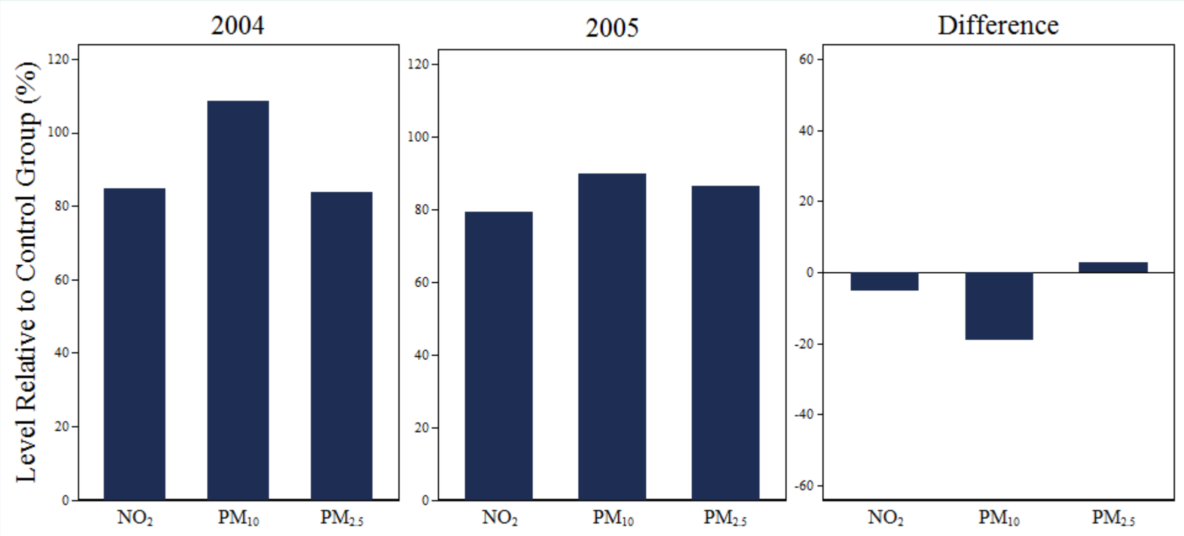
Our results differ from those found by Hagen et al. (2005). To examine these differences further we try to replicate their findings using our larger dataset. Hagen et al. (2005) employ several different methodologies to analysis the effect of implementing environmental speed limits on National Road 4 in 2004. However, their main methodology is to compare the relative difference between a treatment group (*Aker Hospital*) and a control group (*Mangelrud, Løren and Kirkeveien*), before and after the implementation of the environmental speed limits. An important concern is the limited sample of observations used by Hagen et al. (2005), as they only use observations from the period 2004–2005. Moreover, Hagen et al. (2005) only consider the implementation of environmental speed limits on National Road 4. These concerns may limit the external validity of their results to other periods and locations. To address these concerns, we replicate their results by using the implementation of the environmental speed limits on Ring Road 3 in 2006, and by using an extended pooled sample with observations from the years 2001–2012 (November through January) with both National Road 4 and Ring Road 3 as treatment roads. Moreover, we also try to augment the methodology of Hagen et al. (2005) by formally running a difference-in-difference regression.

Figure 14 is a replication of figure 3 in Hagen et al. (2005). The figure has been constructed by estimating the average air pollution concentrations at the treatment road National Road 4 for January through Mars in 2004 and 2005 relative to the air pollution concentrations at the control stations *Manglerud* and *Kirkeveien* during the same period.[47] The figure is very similar to the one found in Hagen et al. (2005), and shows a decrease in the air pollution levels at National Road 4 relative to the control stations *Manglerud* and *Kirkeveien*. The figure shows a reduction in the relative pollution levels of 5% for NO_2, 19% for PM_{10}, and an increase of 3% for $PM_{2.5}$. These results are almost identical to the results of Hagen et al. (2005) where they report a reduction in the relative pollution levels of 5% for NO_2, 19% for PM_{10} and no change in $PM_{2.5}$.[48] Figure A.7 and A.9 in the appendix replicates figure 3 using the implementation of environmental speed limits on Ring Road 3 in 2006 and by using the extended pooled sample (National Road 4 and Ring Road 3, November through Mars, 2001–

[47] Since we not have been able to obtain data from the monitoring station located at Løren we only use Manglerud and Kirkeveien as controls.

[48] Hagen et al. (2005) also considers $PM_{10\text{-}2.5}$. $PM_{10\text{-}2.5}$ is defined as the difference between PM_{10} and $PM_{2.5}$ and is supposed to capture heavy Particulate Matter better. We have chosen to exclude NO_x and $PM_{10\text{-}2.5}$ in our replication to keep the comparison as simple as possible. Thus, we only compare the results for pollutants that appear in both papers.

Figure 14. Avg. Air Quality on National Road 4 Relative to Manglerud and Kirkeveien



Notes: The figure shows the average pollution levels on National Road 4 (treatment road) relative to Manglerud and Kirkeveien (control roads) during the same period. Sample years are 2004 (pre-policy) and 2005 (post-policy). The difference describes the change in relative pollution levels before (January through Mars, 2004) and after the implementation of environmental speed limits (January through Mars, 2005) for National Road 4.

2012).[49] The results are very similar to those found using National Road 4. Thus, all the replications of figure 3 in Hagen et al. (2005) suggest a decrease in PM_{10} and a small increase in $PM_{2.5}$. The results for NO_2 are more uncertain, as the figure for Ring Road 3 indicates a decrease in NO_2 while the figure for the extended pooled sample indicate an increase in NO_2.[50]

The results presented above are based on a simple first difference comparison between the relative air pollution levels of the treatment roadways and the control roadways. Furthermore, the comparisons do not control for confounding factors such as weather. To formally analyze the statistical significance of these results we perform a difference-in-difference estimation. The difference-in-difference is estimated by using the following specification:

$$y_{it} = \beta_0 + \delta_0 1(t \geq t_{ESL}) + \beta_1 1(i \in T) + \delta_1 1(t \geq t_{ESL}) \times 1(i \in T) + \gamma Z_{it} \qquad (8)$$

[49] The control station for both Ring Road 3 and our extended pooled sample is Kirkeveien.

[50] Figure A.7 in the appendix compare the months November, December, January, February and Mars, before and after the implementation of environmental speed limits while Figure A.9 compare the months January, February and Mars before and after the implementation of environmental speed limits.

Where $1(i \in T)$ is an indicator variable equal to 1 for treatment stations and 0 otherwise, $1(t \geq t_{ESL})$ is an indicator variable equal to 1 in the environmental speed limit period and 0 otherwise. Z_{it} is a set of control variable similar to those in our previous analysis. δ_1 give the treatment effect of implementing environmental speed limits. Table 13 reports the estimated treatment effect of implementing environmental speed limits on National Road 4 for concentrations levels of NO_2, PM_{10} and $PM_{2.5}$ using the difference-in-difference approach.[51] We see that the sign of the point estimates is negative across all air pollutants. However, all point estimates are also statistically insignificant at a 5% level. These results are reassuring, and supports the conclusion that implementing environmental speeds does not improve air quality.

We explore the sensitivity of these results by also estimating the effect of implementing environmental speed limits on Ring Road 3. Table A.22 in the appendix shows the results from estimating the effect of implementing environmental speed limits on Ring Road 3. The estimates suggest that the implementation of speed limits on Ring Road 3 led to a statistically significant reduction in the concentration of PM_{10} (-26.74%). The estimated effects on NO_2 and $PM_{2.5}$ are statistically insignificant at a 5% level. The statistically significant point estimate for PM_{10} contradict our previous findings from our regression discontinuity approach and the difference-in-difference results for National Road 4. Both the results for National Road 4 and Ring Road 3 has been estimated by comparing the months January through February the year before the implementation of environmental speed limits with the same months the year after the implementation. Thus, to further explore the sensitivity of the difference-in-difference results across periods and locations we estimate the effect of environmental speed limits by using an extended pooled sample (National Road 4 and Ring Road 3, November through Mars, 2001–2012).[52] Table A.20 in the appendix shows the estimated treatment effect of implementing environmental speed limits for our extended pooled sample. We see that all point estimates are statistically insignificant across all air pollutants. Thus, neither the estimates for National Road 4 nor the estimates for our extended pooled sample provide evidence of an improvement in air quality for any of the air

[51]Similar tables for the corresponding level-level models can be found in the Appendix. Using table A.19 in the appendix, we can calculate the results from the simple differences method employed by Hagen et al. (2005) by using the following formula: $\frac{\beta_0+\beta_1}{\beta_0} - \frac{\beta_0+\delta_0+\beta_1+\delta_1}{\beta_0+\delta_0}$.

[52] In the replication with the extended sample period (2001-2012) we define *Aker Hospital*, *Manglerud* and *Smestad* as the treatment group and Kirkeveien is as the control group. The years 2005 and 2006 have been dropped from the sample to deal with the problem of Ring Road 3 crossing over from control to treatment. The model for the extended sample period also include controls for year and station fixed effects in addition to a full set of interactions between year and station fixed effects. Furthermore, the sample also includes November and December in addition to January, February and Mars.

Table 13. Effect of Environmental speed limits on Air Quality, National Road 4: Difference-in-Difference (logs)

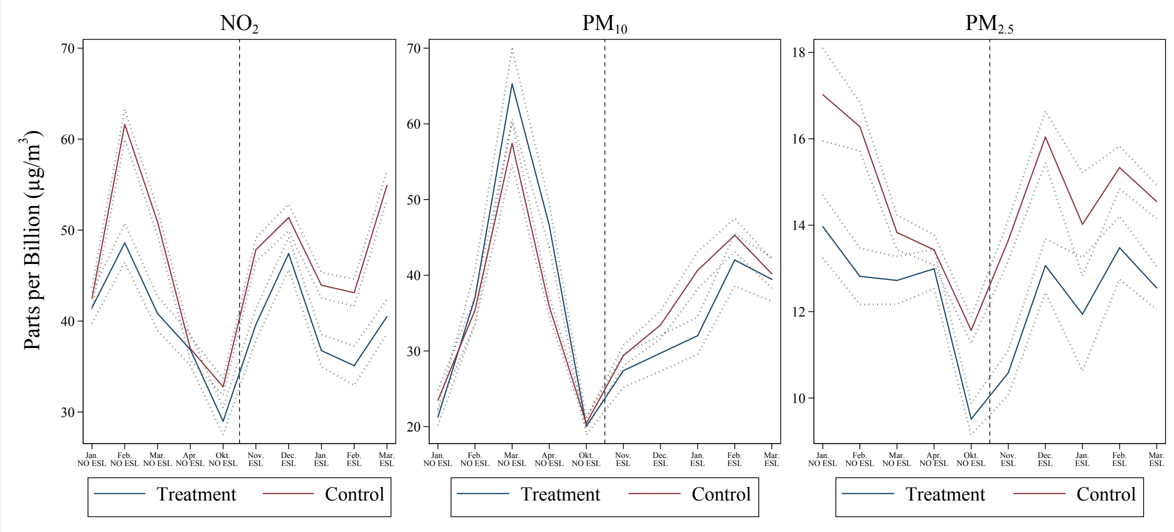
	(1)	(2)	(3)	(4)	(5)	(6)
	NO_2	PM_{10}	$PM_{2.5}$	NO_2	PM_{10}	$PM_{2.5}$
(δ_0) Period	-0.0556	-0.0418	-0.0143	-0.1191	0.1033	-0.0781
	(0.0836)	(0.1173)	(0.0772)	(0.1328)	(0.1998)	(0.0700)
(β_1) Treatment	-0.3345***	-0.0030	-0.1583**	-0.2516	-0.0278	-0.1873**
	(0.0608)	(0.0689)	(0.0485)	(0.1031)	(0.0469)	(0.0369)
(δ_1) Period×Treatment	-0.0500	-0.1560	-0.0180	-0.1314	-0.1328	0.0143
	(0.1339)	(0.0878)	(0.0567)	(0.1179)	(0.0521)	(0.0391)
(β_0) Constant	4.0469***	3.4822***	2.7360***	3.7530***	3.2695***	2.5500***
	(0.1300)	(0.1662)	(0.1276)	(0.1005)	(0.1921)	(0.0351)
Observations	10106	10119	10093	12478	12491	12439
R^2	0.5212	0.4193	0.3986	0.0461	0.0047	0.0192
Controls	YES	YES	YES	NO	NO	NO

Notes: This table displays the main results for the effect of implementing environmental speed limits on National Road 4 for the pollutants NO_2, PM_{10} and $PM_{2.5}$ measured in logs. The estimates are obtained by using a difference-in-difference methodology, comparing Aker Hospital (treatment road) with Manglerud and Kirkeveien (control roads). Columns (1) through (3) is estimated with control variables. Control variables include current wind direction; current and 1-hour-lags of weather (precipitation, temperature and wind speed); in addition to day-of-the-week and hour fixed effects and a full set of interactions between hour and day-of-the-week fixed effects. Columns (4) through (5) is estimated without any control variables. Sample uses hourly observations for January, February and Mars and the years 2004 and 2005. Standard errors in parentheses are clustered by week.

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.0$

pollutants. This suggests that our statistically significant results for Ring Road 3 is not robust to changes in sample periods or changes in location. Thus, the main difference between our results and the replication results is the consistency of positive estimates in the regression discontinuity approach and negative estimates in the difference-in-difference approach. There are several possible reasons for the consistency of positive estimates in the regression discontinuity approach and negative estimates in the difference-in-difference approach. One possible explanation is different sample periods. The sample period for Ring Road 3 and National Road 4 focus on January through Mars, while our RDD approach focus on a narrow window of time around November 1st. In addition to using different sample periods, our findings differ in terms of methodology. An important concern when using the difference-in-difference methodology is unobservable time varying factors. The estimates from the difference-in-difference method are unbiased if the true treatment effect of the average change in air pollution levels, absent of the policy change, are the same for treatment and control (Angrist & Krueger, 1999). This is often referred to as the "parallel trend" assumption.

Figure 15. Monthly Average Air Pollution Concentrations for the National Road 4 (treatment) and Manglerud and Kirkeveien (control)



Notes: The figure shows the average monthly pollution concentrations for the months October through April in the sample years 2004-2005 and a 95% confidence interval around the monthly means. The treatment road (blue) is defined as Aker Hospital while the control road (red) consist of Manglerud and Kirkeveien. The vertical line indicates the implementation of environmental speed limits on November 1st, 2004. Thus, NO ESL is pre-policy (2004) while ESL is post-policy (2005).

Figure 15 is a replication of figure 2 in Hagen et al. (2005), and shows the monthly average concentration levels for NO_2, PM_{10} and $PM_{2.5}$ during the period 2004–2005 for National Road 4 and the control stations *Manglerud* and *Kirkeveien*. Similar figures for Ring Road 3 and the extended pooled sample can be found in the Appendix. A visual inspection of Figure 15 indicates that the trends for the treatment and control roads are seemingly parallel in the pre-policy period. However, since it is impossible to test the parallel trend assumption, it is still possible that the consistency of the negative estimates is driven by unobservable time-varying factors.[53] One possible time-varying confounding factor is the use of studded tires. The share of drivers using studded tires decreased sharply from 34 to 14% between the years 2001 and 2012.[54] Since the relative importance of traffic on air pollution concentrations is greater on larger roads and because studded tires generate more PM_{10} compared to studless tires, this decrease would arguably have a greater impact on larger road, such as Ring Road

[53] All these estimates are based on the log-level specification. Looking at the level-level specification we see that the estimated treatment effect for Ring Road 3 in table A.23 is statistically insignificant across all pollutants. Table A.19 shows the estimated treatment effect for National Road 4 by using a level-level specification. We see that only PM_{10} is statistically significant at a 5% significance level. The magnitude and sign of the point estimate suggest a reduction of 11 Parts per Billion (µg/m³) in the concentrations of PM_{10}. Table A.21 shows the estimated treatment effect for the extended pooled sample by using a level-level specification. We see that only PM_{10} is statistically significant. The magnitude and sign of the point estimate suggest a reduction of 12 Parts per Billion (µg/m³) in the concentrations of PM_{10}. We have chosen to focus on the log-level models because the R^2 suggest that they explain a greater portion of the variation and because the interpretation of the estimated treatment effect is consistent with our previous analysis. The differences in the statistical significance of the point estimates between the log-level and the level-level specification suggests that our difference-in-difference results should be interpreted with caution.

[54] Figure A.4 in the appendix shows the decrease in the share of studded tires between 2001 and 2016.

3, compared to the smaller roads, such as *Kirkeveien*. This would bias a negative estimate upwards compared to the true causal effect of environmental speed limits, i.e. more negative estimates. Another possible confounding factor is traffic substitution from treatment roads to control roads and differences in population growth and economic activity. Traffic substitution from treatment roads to control roads would also bias the estimated treatment effect upwards as the traffic on the treatment roads decrease while the traffic on the control roads increase. However, as discussed previously, there is no evidence suggesting that traffic substitution should be a major concern. Another possible confounding time-varying factor is differences in population or traffic growth between the control and treatment roads. If population or traffic grows more quickly in the control areas, this will create an upward bias in the estimated effect of environmental speed limits. Increased population growth is likely to increase the ait pollution concentrations through higher frequencies of wood burning, more traffic and higher economic activity.

In conclusion, the advantage of using the RDD approach is that the identification assumptions are more relaxed compared to the difference-in-difference approach. The difference-in-difference requires that confounding unobservable time-varying factors have an identical impact on treatment and control groups, while the RDD approach only requires unobservable factors to be continuous over time. We find our results to be robust to several specifications tests, while similar tests have not been conducted to the difference-in-difference approach. However, we note that the statistical significance of PM_{10} for Ring Road 3 is sensitive to the inclusion of control variables and the choice between a level-level model and a log-level model. Furthermore, the statistically insignificant result from the replication using National Road 4 and the extended pooled sample is reassuring and support our previous conclusion. However, the constancy of the negative estimates and the statistically significant point estimate for PM_{10} in our replication using Ring Road 3 suggest that more research is desired to estimate the precise effect of implementing environmental speed limits.

7. Cost – Benefit Analysis

In the following section, we quantify some of the monetary effects of implementing environmental speed limits based on our findings in section five and six. Because our analysis indicates no changes in air quality, we first assume that the implementation of environmental speed limits has no impact on health outcomes. Thus, we start by quantify the costs directly associated with a reduction in speed and then end this section by quantifying the social cost of two major and growing diseases related to air pollution and traffic emissions. This cost can also be seen as the potential benefit (or the alternative cost) of implementing a (not) successful environmental policy. All calculations are based on conservative estimates of the costs and benefits that are possible to quantify. All numbers are adjusted for inflation, i.e. all estimates are reported in 2017 NOK. It is important to mention that this analysis is not complete as none cost-benefit analysis, but based on previous literature and assumptions.

The choice of speed includes private costs and benefits, as well as social costs and benefits. In our calculation, we estimate the private cost of travel time by computing the value of time based on the average salary in Norway and the time loss associated with the implementation of environmental speed limits for a ten-kilometre distance, adjusted for average vehicle occupancy. We assume the average monthly salary before tax, measured in 2017 NOK, to be 42,400 NOK (SSB, 2016), and we assume the average working hours to be 40 hours per week. Thus, we estimate the average hourly salary, after tax to 199 NOK.[55] To estimate the number of affected vehicles each period we use the average number of passing vehicles per hour from Table 2. Thus, 9,166,000 vehicles use National Road 4 or Ring Road 3 each environmental speed limit period.[56] We assume on average 1.5 persons per vehicle. This estimate is based on a previous research published by Elvik et al. (2010). To be conservative, we assume that each vehicle use National Road 4 or Ring Road 3 once a day, every day in the environmental speed limit period. Table 3 report the average speed before the implementation to 74.6 km/h. The estimated average speed after the implementation is assumed to be 68.8 km/h, based on the estimated 5.8 km/h speed reduction in section 5.1. As a consequence, each vehicle loses 40 seconds every day in the environmental speed limit

[55] Hourly salary after tax: 40,300 NOK x 1.052 x 0.75 tax / (40 hours x 4 weeks) = 198.7NOK

[56] Passing vehicles environmental speed limit period: 2399 vehicles hourly x 24 hours x 159,2 days = 9,166,099 vehicles

period for a ten-kilometre drive, which is 1.79 hours (1 Hour and 47 minutes) for the entire environmental speed limit period. The private cost related to the estimated speed reduction is then 356 NOK[57] per person, implying a private cost of 533 NOK per vehicle and total cost of 4,888 MNOK[58] in each environmental speed limit period. If we chose to be less conservative, and assume each vehicle to take a round-trip each day in the environmental speed limit period, the total private cost will double. The total private cost will then increase to 9,776 MNOK each environmental speed limit period. We illustrate our calculations in more detail in the Appendix.

A speed reduction from 80 km/h to 60 km/h is also associated with a reduction in fuel consumption. Research suggests that the most efficient speed in terms of fuel consumption, is between 50 – 90 km/h, as the fuel consumption curve is relatively flat within this window (Strand, Næss, Tennøy, & Steinsland, 2009). Strand et al. (2009) suggest a 22% fuel consumption reduction for private vehicles when the speed reduces from 90 km/h to 70 km/h. The decrease is somewhat smaller for larger vehicles. We assume this effect to be linear as the fuel consumption curve is relatively flat. Thus, in our private benefit calculation, we use a 5% reduction to calculate the change in fuel costs related to the 5.8 km/h speed reduction. The average fuel consumption for the current vehicles fleet is assumed to be 0.074 l/km (Tempo, 2017). The average fuel price in the period 2006 – 2011, measured in 2017 NOK, was 13.8 NOK/l (Norsk Petroleumsinstitutt, 2009)[59]. We assume, as we did above, a ten-kilometre drive each day in the environmental speed limit period, which adds up to 1600 km for each vehicle. Thus, the total private benefit related to a reduction in fuel consumption is 759 MNOK each environmental speed limit period.[60] This implies a benefit of 83 NOK per vehicle. The total private benefit doubles, to 1,518 MNOK, if we assume a 20 km drive each day in the environmental speed limit period.

Social benefits are usually excluded in private cost-benefit evaluations. However, it is important to also consider social benefits associated with a reduction in travel speed. Because of the lack of evidence of an improvement in air quality we have only calculated the

[57] Total time loss each environmental speed limit period: 199 NOK x 1.79 hours = 355 NOK
[58] Total time loss cost: -1.79 hours x 199 NOK x 1.5 passengers x 9,166,099 Vehicles = 4,888,100,859 NOK
[59] Average cost based on both diesel and gasoline
[60] Total fuel benefit: (1600 km x 0.074 l/km x 13.8 NOK x 9,166,099 vehicles) x 0.05 = 758,952,997 NOK

social benefits related to a reduction in accidents and noise pollution.[61] Higher speed is usually associated with an increased risk of accidents, but the rate depends on the initial speed and road type (European Comission, 2017). The Norwegian Public Road Administration records the number of injury accidents. These records include fatal, serious and slight injuries. Using these records, we calculate that the average number of injury accidents on National Road 4 and Ring Road 3 to be on average 39 injury accidents each year, during the period 2002–2015.[62] This implies a likelihood of being involved in an accident of 0.00019%.[63] We also calculate that 95% of these accidents included only slight injuries, 4.8% of the accidents included serious injuries and only 0.2% were fatal accidents. Figure A.5 in the appendix illustrate the development in the number of accidents during the period 2002–2015 for National Road 4 and Ring Road 3. Even though the of likelihood of an accident is small, a study by Elvik (2013) suggests that the implementation of environmental speed limits reduced the number of accidents by 25%. This is a conservative estimate as it constitutes the lower bound of the estimates by Elvik (2013). We assume this reduction to be equal for all environmental speed limit roadways and across all accident types. We value the cost of a fatal accident to be approximately 35.4 MNOK; the cost of an accident involving a serious injury to be 12.4 MNOK; and the cost of an accident involving a slight injury to be 0.7 MNOK. All valuations are measured in 2017 MNOK. These estimates are conservative and recommended by the Institute of Transport Economics in Norway (Elvik, Veisten, & Flügel, 2010).[64] Thus, the social benefit from a reduction in the number of accidents is estimated to be 5.7 MNOK each environmental speed limit period, implying a social benefit of 0.6 NOK per vehicle.[65] This estimate is very conservative as it only includes reported injury accidents and not purely materialistic accidents. The social benefit related to accidents is approximately equal to the value of saving one life every fifth year, if the value a statistical life is 30.5 MNOK.[66]

[61] Because out crash records do not distinguish single vehicle accidents from accidents that also involve other parties, we assume that all accidents also have an external effect (e.g. all accidents are assumed to also include other vehicles or cyclists). Thus, we consider all costs related to accidents to be social costs.

[62] These estimates are based on data obtained from Norwegian Public Road Administration. This estimate is very conservative as it only includes accidents with reported injuries. From Figure A.5 in the appendix we see that the number of accidents vary greatly across the different years. To mitigate the problem of statistical variance biasing our estimated number of accidents per year we choose to look at an extended time period of 13 years.

[63] Yearly number of vehicles is 57,576 x 365 = 21 024 000. Likelihood of accident: 39/21 024 000 = 0.0000019 = 0.00019%

[64] The costs include medical, material, administrative costs and costs of lost output in addition to valuations of statistical lives and injuries.

[65] Total Risk Benefit: 39 accidents x 25% x 160/365 x (95% x 0.7 + 4.8% x 12.4 + 0.2% x 35.4) = 5,739,000 MNOK

[66] We value a statistical life to 30.5 MNOK, measured in 2017 NOK. This estimate is based on a previous study of Elvik et al. (2010) on the valuation of statistical life related to traffic accidents.

Table 14. Cost – Benefit Analysis for the Environmental Speed Limits Period

. .	Conservative Calculation Results		Less Conservative Calculation Result	
Cost (-) / Benefits (+):	Per Vehicle (NOK)	All Drivers (MNOK)	Per Vehicle (NOK)	All Drivers (MNOK)
Travel time	- 533	- 4,888	- 1,067	- 9,776
Fuel	83	759	166	1,518
Total Private Cost	- 450	- 4129	- 901	- 8,258
Accidents	0.6	5.7	0.6	5.7
Noise	0.3	3	0.3	3
Total Social Benefits	0.9	8.7	0.9	8.7
Net Result	- 449 NOK	- 4,120 MNOK	- 900 NOK	- 8,249 MNOK
% of OPEX		8%		16%

Notes: This Table illustrate the private and social costs and benefits related to the estimated effect of implementing environmental speed limit in section 5.1. The first two columns assume one trip each day within the environmental speed limit period. The last two columns, the "less conservative calculation", assume a 20 km drive each day within the environmental speed limit period. All estimates are based on conservative on assumptions and valuations. All numbers are presented in current (2017) NOK or MNOK. To simplify, we classify Travel time and fuel costs as private costs. Furthermore, we classify benefits related to accidents and noise as social costs.

The last social benefit we relate to lower travel speed is the value of a reduction in noise pollution. The value depends on the initial speed as speeds above 30 – 40 km/h is dominated by rolling noise while speeds below 30 – 40 km/h is dominated by engine noise (Kable, 2011; Amundsen & Klæboe, 2005; Jongens, 2008). There are about 392,400 citizens in Oslo exposed to at least 55 dB from the 1310 kilometres of public roads (Bymiljøetaten, 2013). Thus, we assume there are about 300 vulnerable citizens per km.[67] The length of Ring Road 3 and National Road 4 is approximately 29 km. Thus, we assume there are 8,687 vulnerable citizens close to the environmental speed limit roadways that are exposed to at least 55 dB.[68] Meland et al. (2005) estimate the reduction in traffic noise related to the implementation of environmental speed limits is 2 dB. We assume that this result is generalisable to all environmental speed limit roadways. The value of one dB reduction in noise is most often based on either hedonic pricing methods or contingent valuation. The estimated value of a 1 dB reduction in noise pollution depends on the method employed and varies from 20 NOK to 900 NOK (Navrud, 2002; Navrud, 2004; Boer & Schroten, 2007). In our calculation, we value a one dB reduction to 383 NOK, measured in 2017 NOK. This estimate is calculated by Magnussen et al. (2010), and is also part of a report published by Samstad et al. (2010). Thus, the social benefit related to a 2 dB noise reduction within the environmental speed limit period is 3 MNOK[69], this corresponds to 0.3 NOK for each vehicle.

[67] Number of citizens per km: 392,400 citizens / (170 km + 1140 km) = 299.54
[68] Number of citizens close to the environmental speed limit roadways: 299.54 citizens x 29 km = 8,687
[69] Social Benefit Noise: 8,687 citizens x 335 NOK x 1.142 x 2 dB x 160/365 = 2,913,653 NOK

Our cost-benefit calculation indicates a conservative loss to society of 4,120 MNOK each environmental speed limit period, which is 8 % of the operating expenses (OPEX) in Oslo in 2016, measured in 2017 NOK (Oslo Kommune, 2017).[70] Our cost–benefit calculation is based on conservative estimates, and is likely to be underestimated. For example, our less conservative calculation assumes a round-trip every day in the environmental speed limit period. In this case, the loss to Society would be 8,249 MNOK every environmental speed limit period. This less conservative estimate, but also a more realistic estimate, constitutes 16% of the operating expenses in Oslo. To make this social loss more interesting we now proceed to calculate the potential social benefit of implementing a successful environmental policy. As we know from section two, Chronic Obstructive Pulmonary Disease (COPD) and asthma is two major and growing diseases related to air pollution and traffic emissions. Thus, we end this section by calculate the cost from these to disease that can be attributed to air pollution.

Many believe smoking is the reason to COPD, which is partly correct. Smoking can be related to approximately 2 of 3 cases of COPD. However, there are also other sources of importance, such as air pollution and working related causes. Norway recorded about 200,000 COPD patients in 2014 (Nielsen, 2014).[71] Further, there are about 20,000 new instances every year and approximately 1,400 patients die each year because of COPD. We assume air pollution are related to about 15% of all cases, and assume the disease could have been excluded without the exposure (Leira, 2011; American Thoracic Society , 2002). We also assume the instances are equally distributed across Norway. As a consequence, there are about 3,788 patients with existing COPD because of local air pollution in Oslo. This estimate is based on a conservative estimate of recorded patients and that 12.5% of the population in Norway live in Oslo (Oslo Kommune, 2017; SSB, 2016).[72] Further, Oslo has about 378 new instances every year and approximately 26 patients die every year because of the local air pollution. The annual cost of COPD, measured in 2017 NOK, is assumed to be 8,000 NOK for each patient (Nielsen, 2014). Further, if the patient has an existing disease the COPD may be deteriorated and cost additionally 4,000 NOK. If the condition deteriorates it will cost additionally 700 NOK. The value of statistical life is valued, as above, to 30.5 MNOK (Elvik, Veisten, & Flügel, 2010). Thus, we calculate the social cost of

[70] Society loss 4,120 MNOK / (OPEX 53,000 MNOK x 1.0015) = 8.4%

[71] This estimate is conservative only base on reported instances. The real estimate is assumed to be approximately 370,000 patients (Nielsen, 2014).

[72] COPD patients in Oslo: 200,000 patients x 0,15 x 0,125 = 3,788 patients

COPD in Oslo within the environmental speed limit period to be 369 MNOK[73], this implies a social cost of 40 NOK per vehicle.[74] We illustrate our calculation and the differences between the conservative estimate and the other situations in the Appendix.

Asthma is another health effect that is related to air pollution and work related situations. Previous calculations estimated the annual cost of asthma to be 2,262 MNOK, measured in 2017 NOK (Arbeidstilsynet, 2008). This expense includes among other, medicines, treatments, absence of work and financial support. We assume, as above, equal distribution in Norway and relate 12.5% of the cost to Oslo. The social cost of asthma is calculated to 125 MNOK for the environmental speed limit period, which is 14 NOK for each vehicle.

Consequently, the potential social benefit from reducing the incidence of COPD and Asthma is 494 MNOK each environmental speed limit period. Thus, even if we assume that the introduction of environmental speed limits did improve air quality, and in consequence also reduced health costs associated with COPD and Asthma, the loss for society would still be very high. More specifically, the loss to society would be 3,626 MNOK each environmental speed limit period. Thus, even a successful environmental speed limit policy would likely result in a loss to society.

[73] Social cost environmental speed limit, COPD: (7400 NOK x (3788 + 378 patients) + 26 deaths x 30.5 MNOK) x 160/365 = 369 MNOK

[74] This estimate is conservative as it assumes that none of the patients have pre-existing or additional disease. Including additional diseases would increase the cost per patient.

8. Conclusion

This master´s thesis analyses the effect of a temporary reduction in the maximum speed limit during the winter on the choice of speed and local air quality in Oslo. Our estimates are based on hourly observations of traffic and four air pollutants obtained from six different monitoring stations located roadside to two major roadways in Oslo. Using a regression discontinuity design we provide a transparent and credible identification of how the implementation of a temporary reduction in the maximum speed limit affects local air quality.

Our findings indicate that reducing the maximum speed limit from 80 km/h to 60 km/h reduces travel speed by 5.8 km/h. However, we find no robust evidence of improvements in air quality. Our results draw a quite different conclusion than the analysis of the pilot period 2004/2005 by Hagen et al. (2005). However, our augmented replication of Hagen et al. (2005) indicates that their findings are also statistically insignificant. Overall, our findings are highly policy relevant and suggest no improvements in local air quality in Oslo. We calculate the private costs of the environmental speed limit policy in Oslo to be 449 NOK per vehicle each environmental speed limit period. Moreover, the policy leads to a net social loss to society of approximately 4,120,000,000 NOK each environmental speed limit period, which is equivalent to 8% of the operating expenses for the municipality of Oslo. These calculations are based on conservative assumptions and valuations.

In conclusion, a temporary reduction in the maximum speed limit during the winter may seem like a reasonable approach for addressing the adverse effects of urban air pollution. However, this master´s thesis suggests that the implementation, extension and re-implementation of the environmental speed limit policy is ill-advised, as it has no effect on air quality and leads to a net loss to society. Thus, policymakers should focus on other actions to improve local air quality and consequently reduce the adverse health effects related to air pollution.

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Supplemental Appendix

LIST OF SUPPLEMENTARY FIGURES

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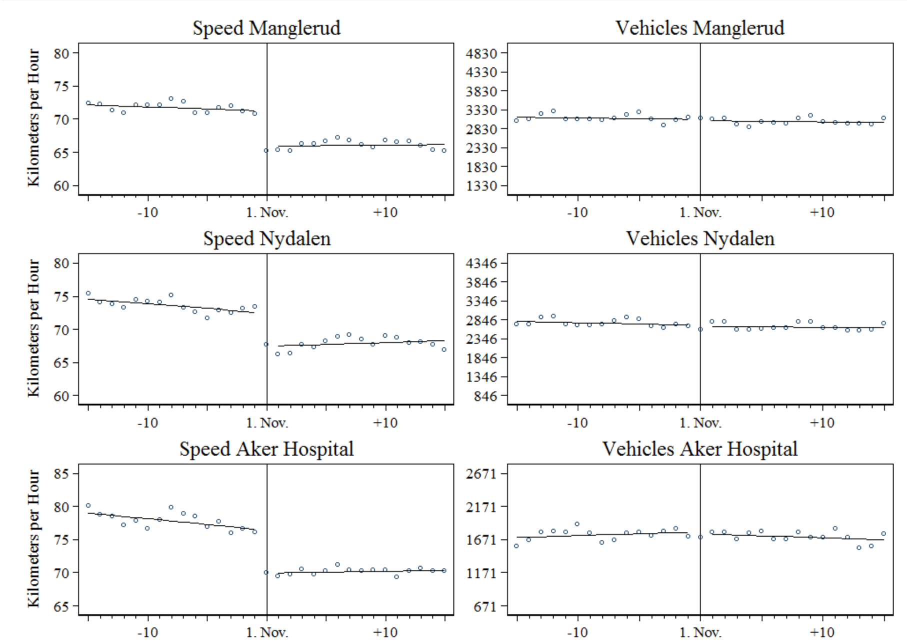
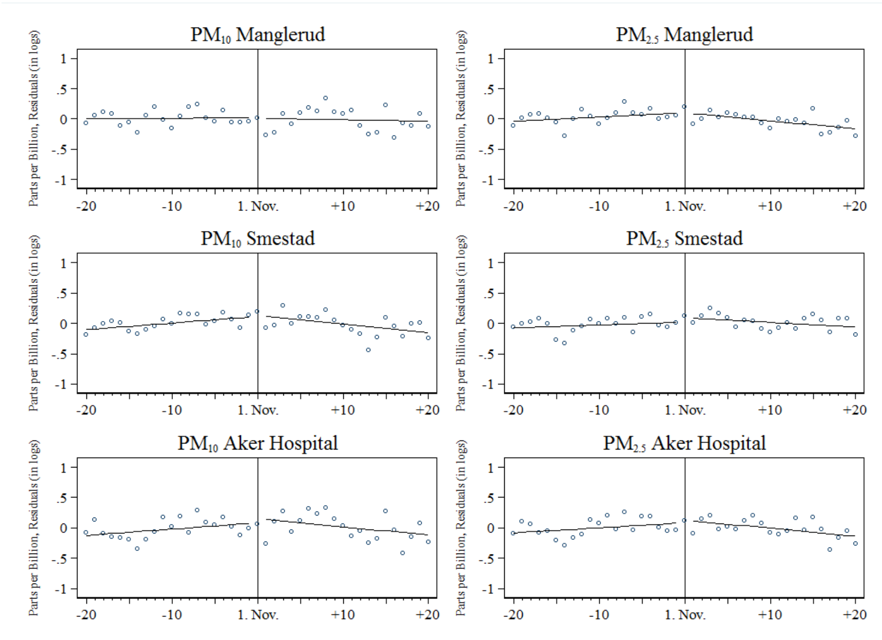
Figure A.1. Graphical Evidence of the Effect of Environmental Speed limits on Traffic for Each Individual Monitoring Stations



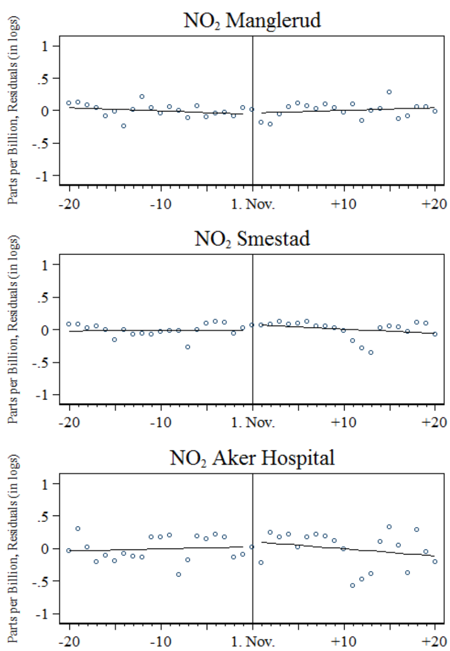
Notes: Visible discontinuity in speed at all stations. No visible jump in passing vehicles. We use a bandwidth of 15 days, and the sample period is 2006-2011.

Figure A.2. Graphical Evidence of the Effect of Environmental Speed limits on Air Pollution for Each Individual Monitoring Stations



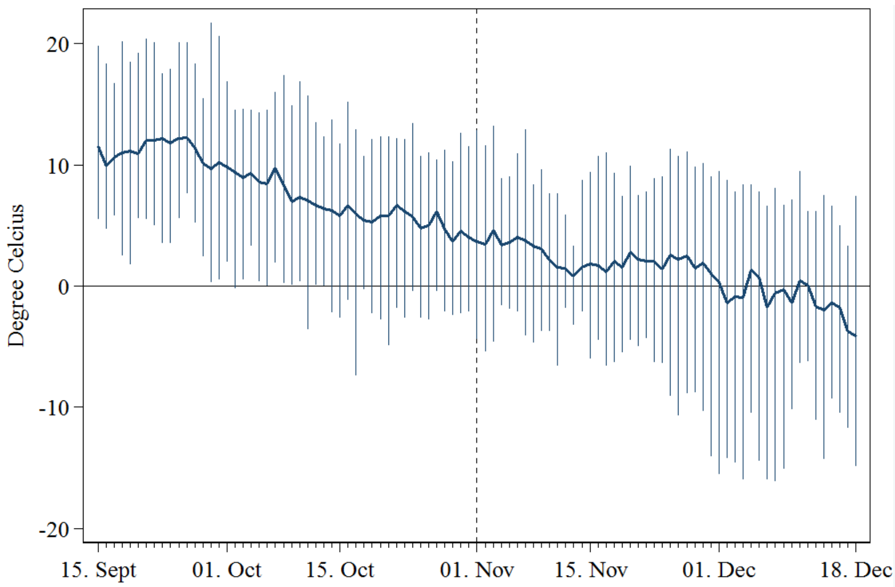
Notes: No visible discontinuity for PM_{10} or $PM_{2.5}$ at the individual air pollutant stations. We use bandwidth of 20 days, and the sample period is 2006 – 2011.

Figure A.2 – Continued



Notes: No visible discontinuity for NO_2 at the three individual air pollutant stations. We use bandwidth of 20 days, and the sample period is 2006 – 2011.

Figure A.3. Variation in Temperature Between September 15th and December 18th

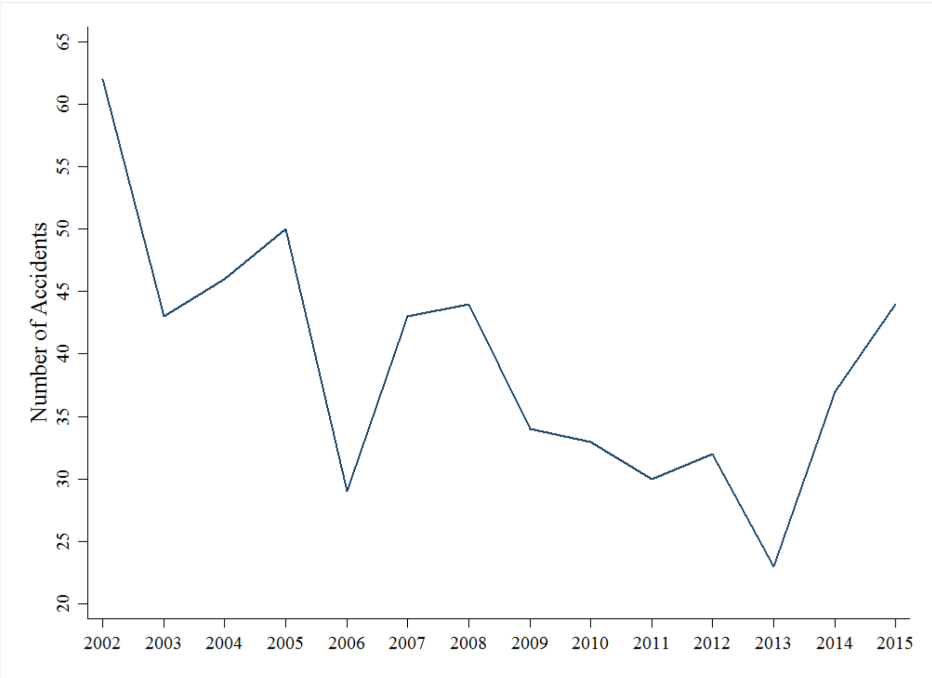


Notes: The figure shows the average daily temperature as well as the minimum and maximum temperatures for each individual day in October and November for the sample years 2006-2011. The hourly temperature varies between -15 and 20°C in the period 15th of September and 18th of December. The average temperature varies between -5 and 10°C.

Figure A.4. The Share of Drivers Using Studded Tires

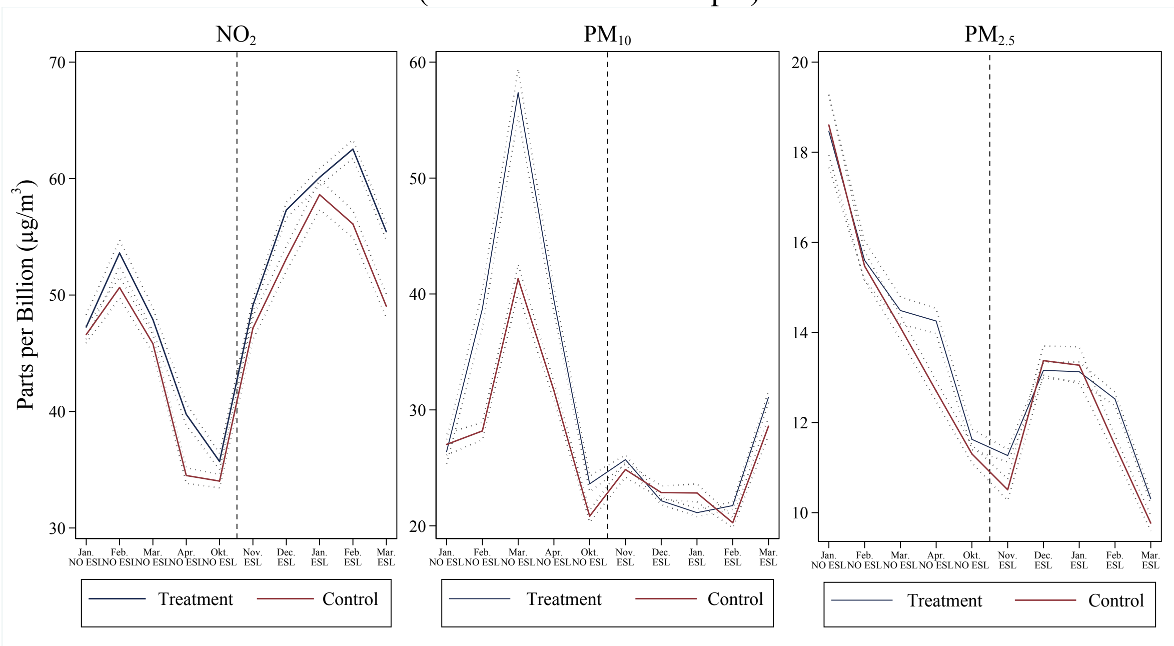
Notes: The figure shows the share (%) of drivers using studded tires for each separate year during the period 2001 to 2016. The share of studded tires has been relatively stable the last five years, about 15%. The fraction of studded tires has decreased greatly from 2004.

Figure A.5. The Number of Injury Accidents for National Road 4 and Ring Road 3



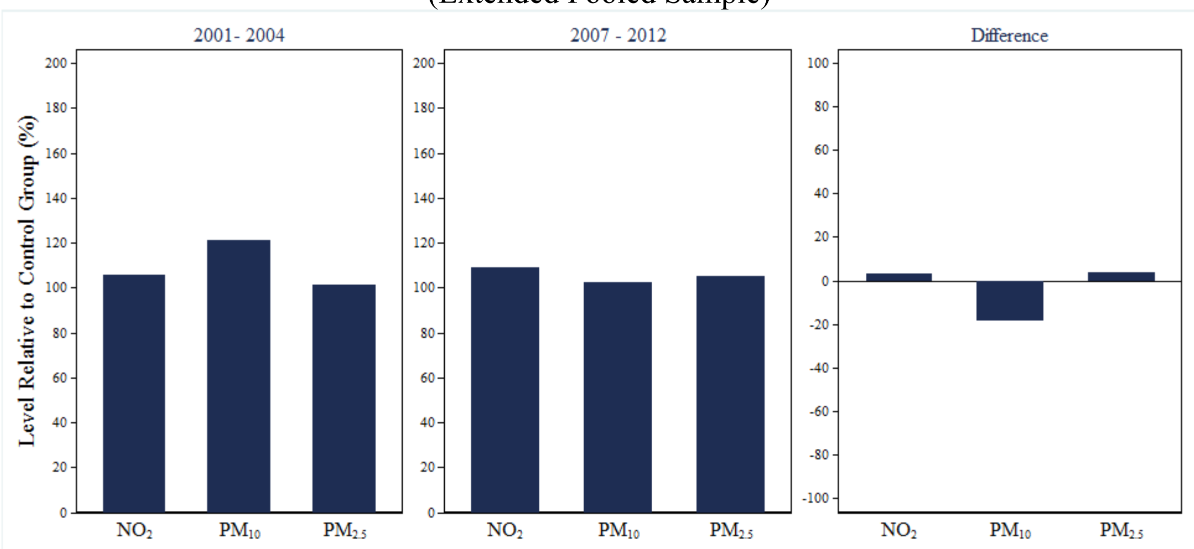
Notes: The figure describes the number of injury accidents for the National Road 4 and Ring Road 3 in the period 2002 to 2015. The number of injury accidents include slight, serious and fatal accidents. The average number of accidents in the period of 2002 – 2015 is about 39 accidents annually.

Figure A.6. Replicate of Figure 2 in Hagen et al. (2005) for All Stations (Extended Pooled Sample)



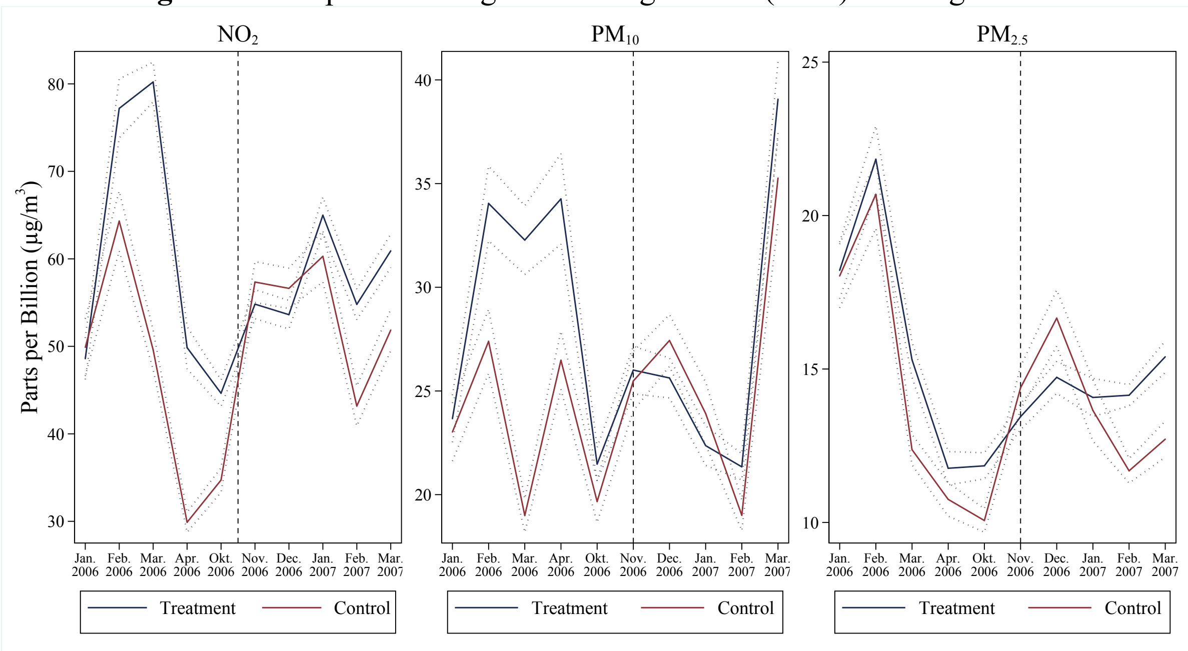
Notes: This figure illustrates the monthly average air pollution concentrations for the treatment roads (blue) National Road 4 and Ring Road 3 and the control road (red) Kirkeveien for the months October through Mars during the sample period 2001-2004 (before the implementation of environmental speed limit policy, NO ESL) and 2007-2012 (After the implementation of environmental speed limits, ESL). The monthly average air pollution levels for the treatment roads have been constructed by using observations from Manglereud, Smestad and Aker Hospital. The vertical line indicates the implementation of environmental speed limits while the dashed lines around the monthly means indicate the 95% confidence intervals of the monthly means.

Figure A.7. Replicate of Figure 3 in Hagen et al. (2005) for All Stations (Extended Pooled Sample)



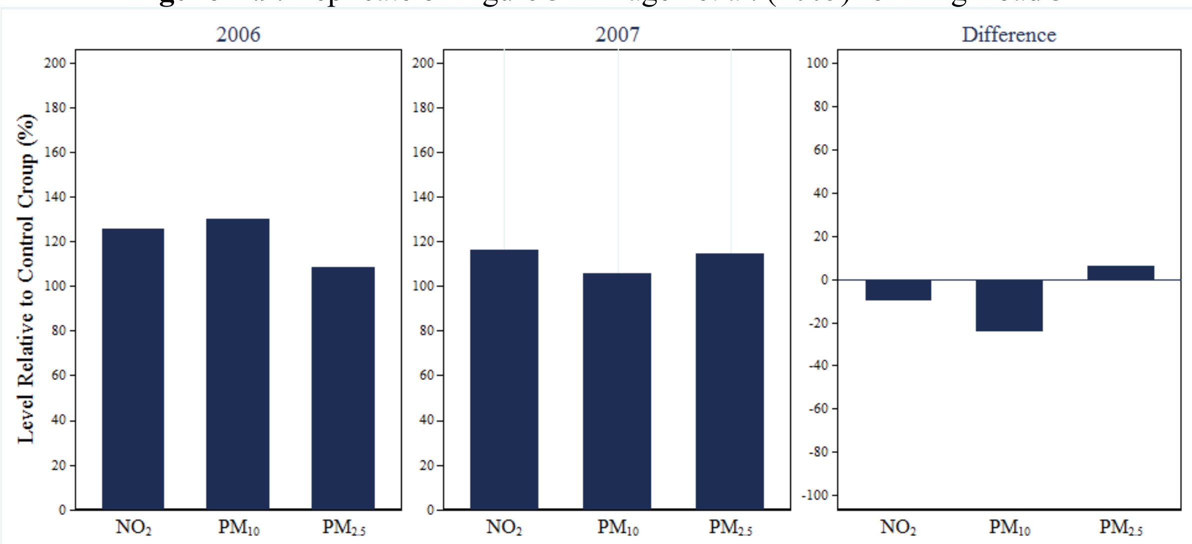
Notes: The figure shows the relative average pollution levels for the treatment roads relative to the control road during the same period. The figure has been constructed by estimating the average air pollution concentrations at the treatment stations Manglerud, Smestad and Aker Hospital for November through Mars in 2001-2004 (pre-policy) and 2007-2012 (post-policy) relative to the pollution concentrations at the control station Kirkeveien during the same period. We see some indications of a reduction in concentration levels of PM_{10}.

Figure A.8. Replicate of Figure 2 in Hagen et al. (2005) for Ring Road 3



Notes: The figure shows the average monthly pollution concentrations for the months October through April in the sample years 2006-2007 and a 95% confidence interval around the monthly means. The treatment road (blue) is defined as Manglerud and Smestad while the control road (red) consist Kirkeveien. The vertical line indicates the implementation of environmental speed limits on November 1st, 2006. Thus, NO ESL is pre-policy (2004) while ESL is post-policy (2005).

Figure A.9. Replicate of Figure 3 in Hagen et al. (2005) for Ring Road 3



Notes: The figure shows the average pollution levels on Ring Road 3 (treatment road) relative to Kirkeveien (control road) during the same period. The pollution concentrations of the treatment road include observations from the monitoring stations Manglerud and Smestad. Sample years are 2006 (pre-policy) and 2007 (post-policy). The difference describes the change in relative pollution levels before (January through Mars, 2006) and after the implementation of environmental speed limits (January through Mars, 2007) for Ring Road 3.

Figure A.10. Air Quality in Oslo by Monitoring Station, Raw Hourly Data 2000–2016

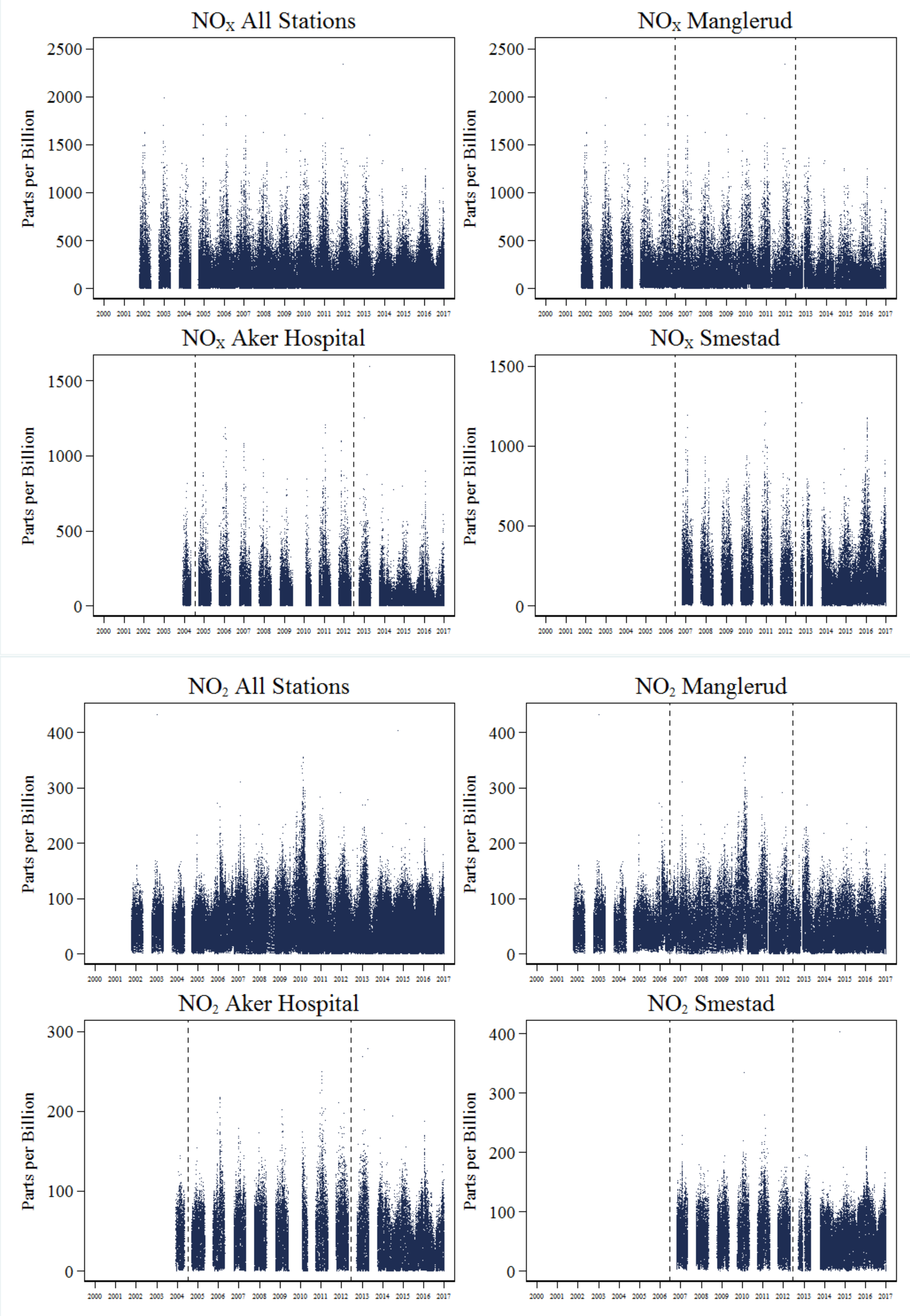
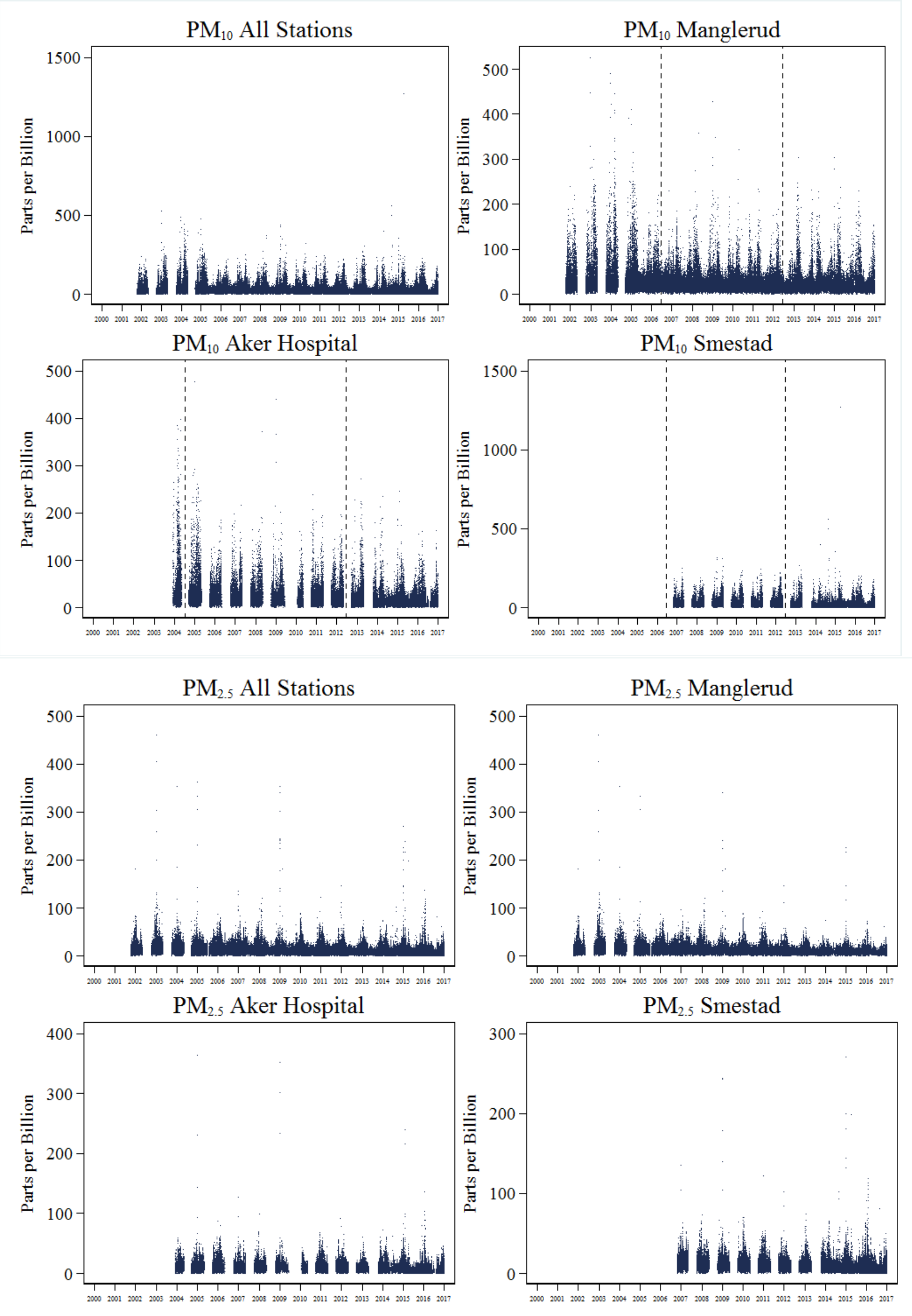
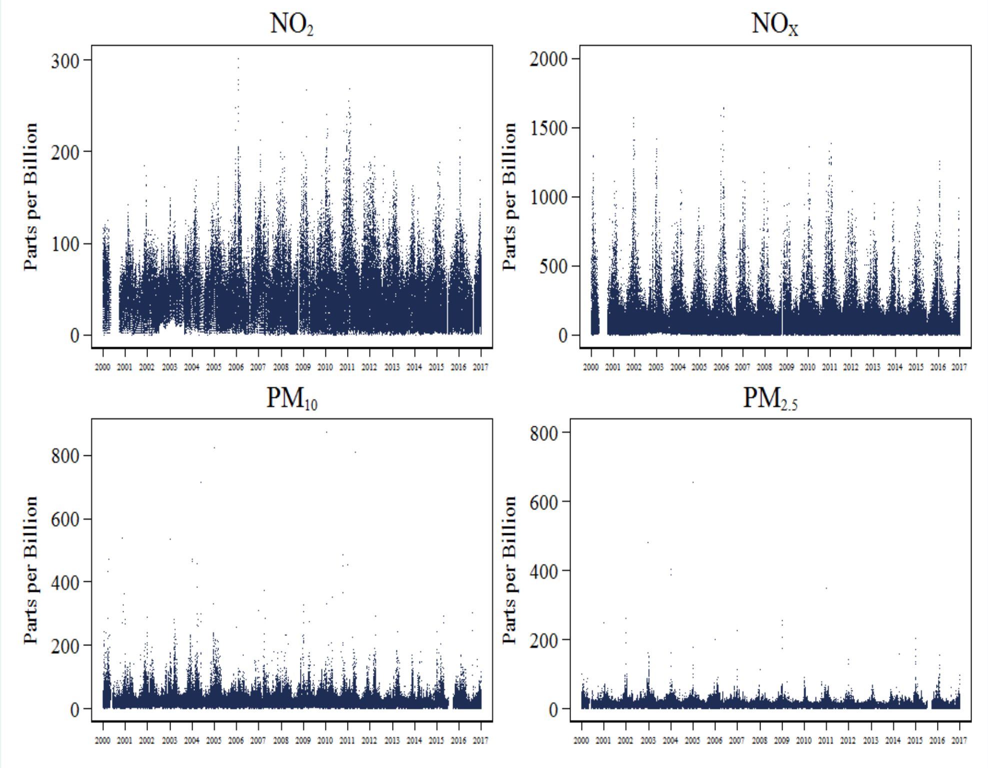


Figure A.10 – Continued



Notes: These figures illustrate periods with missing observations and the variation in our air pollution data for each individual monitoring station as well as our pooled sample. Smestad is the monitoring station with fewest observations. The vertical dashed lines indicate the implementation year and the end year for the environmental speed limits policy.

Figure A.11. Air Quality in Oslo for Marienlyst, Raw Hourly Data 2000–2016



Notes: This figure illustrates the periods with missing observations and the variation in our air pollution data from the monitoring station located at Marienlyst roadside to Kirkeveien (i.e. Ring Road 2).

Figure A.12. Traffic in Oslo by Monitoring Station, Raw Hourly Data 2000–2016

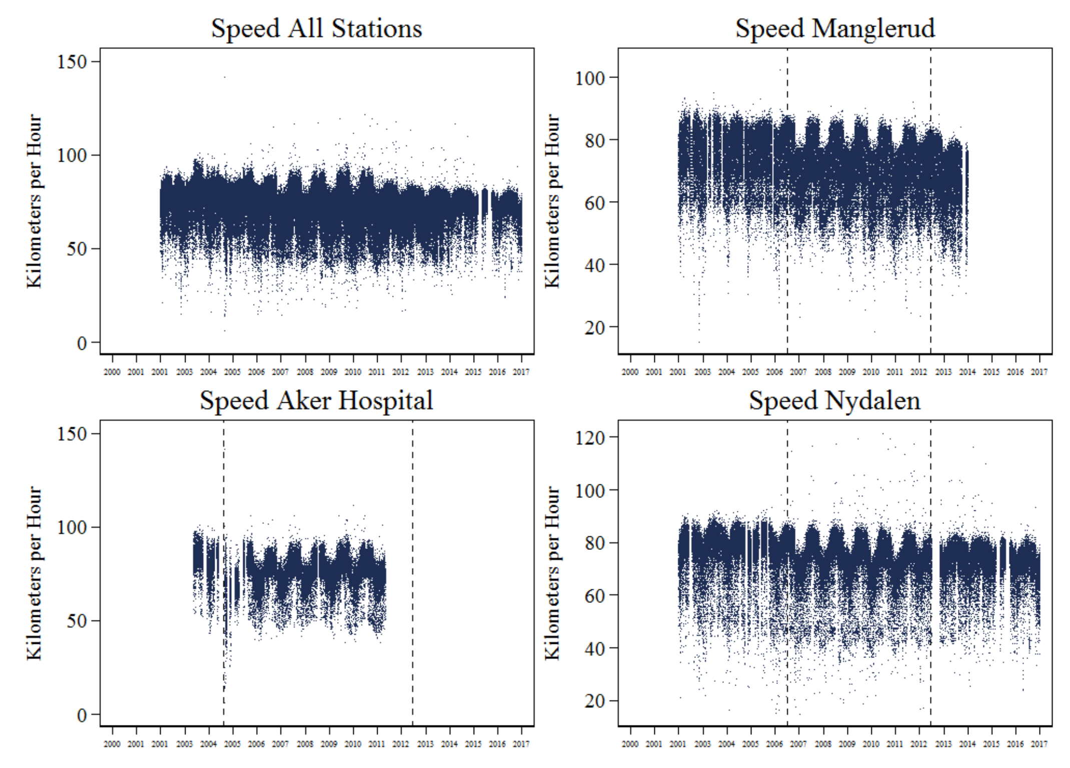
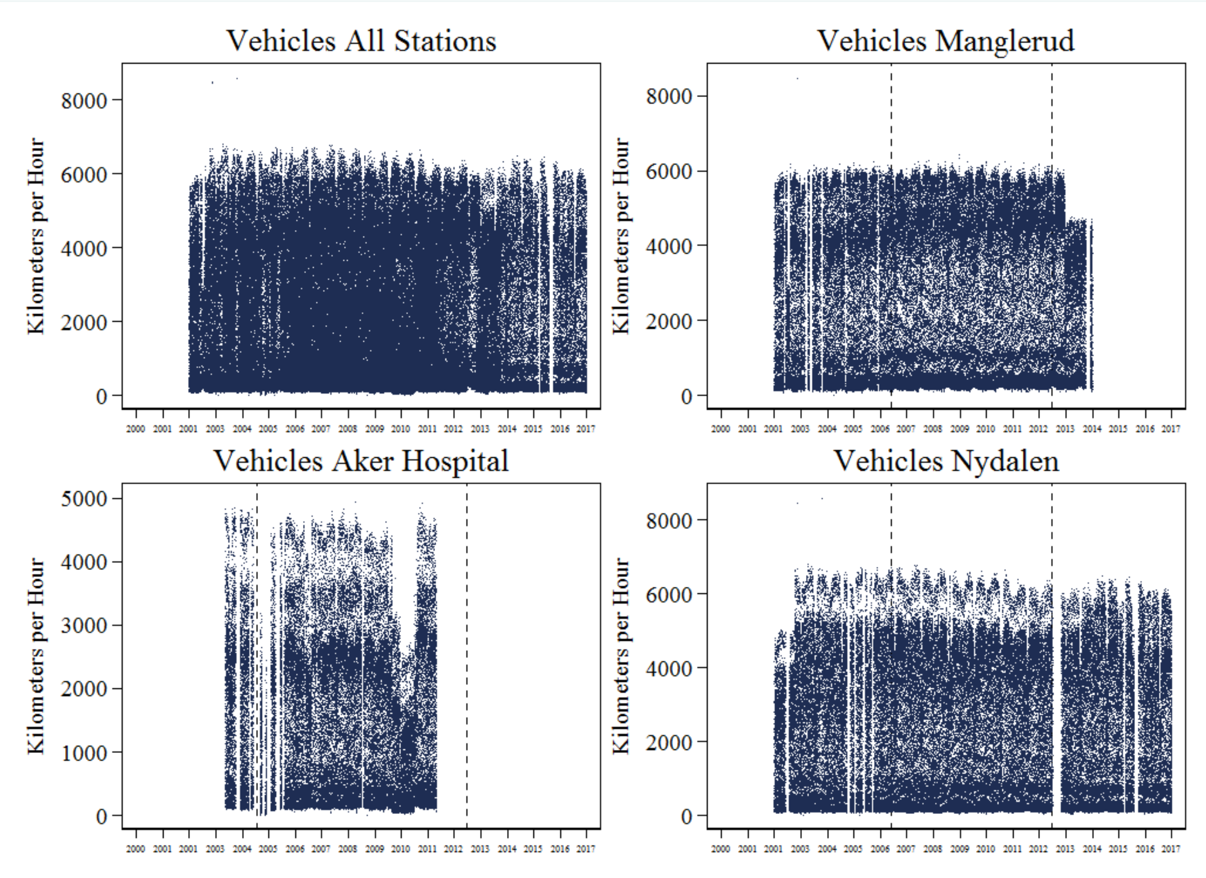
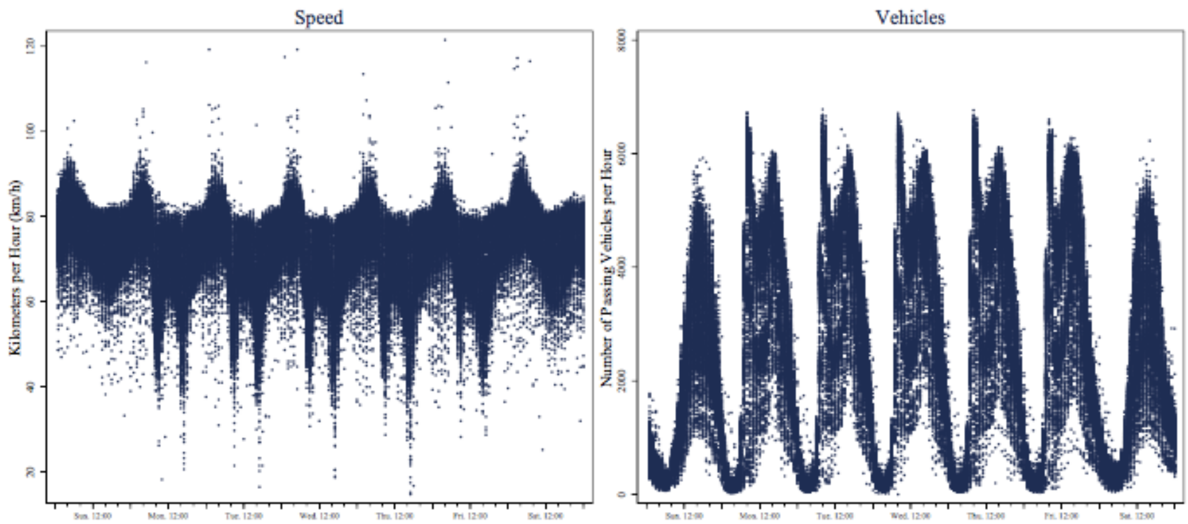


Figure A.11 – Continued



Notes: These figures illustrate periods with missing observations and the variation in our traffic data for each individual monitoring station as well as our pooled sample. Aker Hospital is the monitoring station with fewest observations. The vertical dashed lines indicate the implementation year and the end year for the environmental speed limits policy.

Figure A.13. Weekly Pattern of Speed and Traffic Density



Notes: This figure illustrates the weekly pattern of the travel speed and traffic density (number of passing vehicles) by using hourly observations from the monitoring stations Mangerud, Nydalen and Aker Hospital, and the period 2006 – 2011. We observe substantial variation in the level of pollution between the weekdays and the weekend as well as variation over the course of the day.

Table A.14. Current Regulatory Environment for Air Quality Standards

		(1)	(2)	(3)	(4)	(5)
		Recommened	Required by Law			
		Institute of Public Health	Norway		European Union	
	Averaging Period	Concentration	Concentration	Permitted Exceedances	Concentration	Permitted Exceedances
PM_{10}	Year	20μg/m³	25μg/m³		40μg/m³	
PM_{10}	Day	30μg/m³	50μg/m³	35 per year	50μg/m³	35 per year
$PM_{2.5}$	Year	8 μg/m³	15μg/m³		25μg/m³	
$PM_{2.5}$	Day	15μg/m³				
NO_2	Year	40μg/m³	40μg/m³		40μg/m³	
NO_2	Hour	100μg/m³	200μg/m³	18 per year	200μg/m³	18 per year

Notes: This table describes the current regulatory environment for air quality standards in Norway and the European Union. Column (1) describes the concentration levels recommended by the Norwegain Institutte of Public Health and the Norwegian Environmental Agency. This criterion reflects the level of air pollution that is safe for everyone, also the most vulnerable groups (Institute of Public Health, 2016). Columns (2) and (3) describes the concentration levels and the number of permitted exceedances per year required by Norwegian Law. Columns (4) and (5) describes the concentration levels and the number of exceedances that is legislated by the European Union (European Commission, 2016).

Table A.15. Effect of Speed on Air Pollution by Monitoring Station: Ordinary Least Squares (logs)

	(1)	(2)	(3)	(4)
	Panel A: Manglerud			
	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(α_1) Speed	-0.0022	0.0026	0.0048	-0.0012
	(0.0036)	(0.0036)	(0.0030)	(0.0022)
Observations	42,882	43,076	43,890	43,553
R^2	0.4682	0.5543	0.3383	0.3270
	Panel B: Smestad			
	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(α_1) Speed	-0.0099***	-0.0098**	0.0029	-0.0071***
	(0.0019)	(0.0028)	(0.0024)	(0.0018)
Observations	215,88	21,601	21,573	21,533
R^2	0.6708	0.7374	0.4702	0.4027
	Panel C: Aker Hospital			
	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(α_1) Speed	-0.0068*	-0.0066	0.0053	0.0015
	(0.0030)	(0.0034)	(0.0038)	(0.0028)
Observations	20,166	20,269	20,928	20,852
R^2	0.5284	0.5916	0.4166	0.3518

Notes: Panel A, B and C displays the estimated effect of speed on concentration of air pollution by estimating equation (1.a) on NO_X, NO_2, PM_{10} and $PM_{2.5}$ for each individual monitoring station for air pollution. All pollutants are measured in logs. All models include control variables for current traffic density (number of vehicles) and wind direction; current and 1-hour lags of weather (precipitation, temperature and wind speed); in addition to, station, year, month, day of the week and hour fixed effects and a full set of interactions between hour and day of the weekday fixed effects; and between station and wind direction. The models are estimated by using hourly observation from the monitoring stations Manglerud, Smestad and Aker Hospital. Sample years are 2006 – 2011. Standard errors in parentheses are clustered at the monthly level.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A.16. Effect on Environmental Speed Limit on Air Pollution by Monitoring Station: Ordinary Least Squares (logs)

	(1)	(2)	(3)	(4)
	Panel A: Manglerud			
	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(β_1) ESL	0.0723	-0.0300	0.0286	-0.0105
	(0.0828)	(0.0685)	(0.0660)	(0.0487)
Observations	42,882	43,076	43,890	43,553
R^2	0.4687	0.5543	0.3377	0.3269
	Panel B: Smestad			
	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(β_1) ESL	0.0906	-0.0193	0.0015	0.0245
	(0.0516)	(0.0521)	(0.0660)	(0.0545)
Observations	21,588	21,601	21,573	21,533
R^2	0.6684	0.7350	0.4699	0.4001
	Panel C: Aker Hospital			
	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(β_1) ESL	0.0548	0.0380	-0.0787	-0.0797
	(0.0529)	(0.0513)	(0.0786)	(0.0548)
Observations	20,166	20,269	20,928	20,852
R^2	0.5280	0.5912	0.4171	0.3536

Notes: Panel A, B and C displays the estimated effect of speed on concentration of air pollution by estimating equation (1.b) on NO_X, NO_2, PM_{10} and $PM_{2.5}$ for each individual monitoring station for air pollution. All pollutants are measured in logs. All models include control variables for current traffic density (number of vehicles) and wind direction; current and 1-hour lags of weather (precipitation, temperature and wind speed); in addition to, station, year, month, day of the week and hour fixed effects and a full set of interactions between hour and day of the weekday fixed effects; and between station and wind direction. The models are estimated by using hourly observation from the monitoring stations Manglerud, Smestad and Aker Hospital. Sample years are 2006 – 2011. Standard errors in parentheses are clustered at the monthly level. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Table A.17. Effect on Environmental Speed limit on Air Pollution Without Traffic Density as a Control Variable: Ordinary Least Squares (logs)

	(1)	(2)	(3)	(4)
	Panel A: Effect of Speed on Air Pollution			
	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(α_1) Speed	-0.0124^{***}	-0.0146^{***}	-0.0003	-0.0046^{***}
	(0.0016)	(0.0021)	(0.0016)	(0.0012)
Observations	84,636	84,946	86,391	85,938
R^2	0.4820	0.5627	0.3968	0.3330
	Panel B: Effect of Environmental Speed Limit on Air Pollution			
	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(β_1) ESL	-0.2374^{**}	-0.3270^{***}	-0.1859^{**}	-0.1660^{*}
	(0.0772)	(0.0943)	(0.0644)	(0.0761)
Observations	86747	87058	88600	88136
R^2	0.4803	0.5618	0.3993	0.3320

Notes: Panel A displays the estimated effect of speed on concentration of air pollution by estimating equation (1.a) on NO_X, NO_2, PM_{10} and $PM_{2.5}$. Panel B displays the estimated effect of environmental speed limits on air pollution by estimating equation (1.b) on NO_X, NO_2, PM_{10} and $PM_{2.5}$. All pollutants are measured in logs. All models include control variables for current wind direction; current and 1-hour lags of weather (precipitation, temperature and wind speed); in addition to, station, year, month, day of the week and hour fixed effects and a full set of interactions between hour and day of the weekday fixed effects; and between station and wind direction. The models are estimated by using hourly observation from a pooled sample of the monitoring stations Manglerud, Smestad, Nydalen and Aker Hospital. Sample years are 2006 – 2011. Standard errors in parentheses are clustered at the monthly level. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Table A.18. Effect of environmental speed limits on Air Quality by Monitoring Station Regression Discontinuity (logs)

	(1)	(2)	(3)	(4)	(5)
	Panel A: Manglerud				
	Panel A.I: Sharp Regression Discontinuity Approach				
	Speed	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(τ) ESL	-5.3898**	0.0692	0.1457	0.0187	-0.0308
	(0.9055)	(0.0880)	(0.0807)	(0.1027)	(0.0864)
Observations	3,582	3,599	3,601	3,610	3,655
R^2	0.9301	0.5789	0.6145	0.4776	0.4854
	Panel A.II: Fuzzy Regression Discontinuity Approach				
	Speed	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(τ_1) 1st step	-5.4322***				
	(0.1577)				
(τ_2) 2nd step		-0.0213	-0.0274	-0.0160	-0.0070
		(0.0169)	(0.0146)	(0.0168)	(0.0151)
F-stat. instr.	1186.88				
Observations	4,712	4,571	4,574	4,585	4,631
R^2	0.9260	0.5736	0.6144	0.4809	0.5012
	Panel B: Smestad				
	Panel B.I: Sharp Regression Discontinuity Approach				
	Speed	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(τ) ESL	-4.7945**	0.0818	0.0088	-0.0064	0.0054
	(0.9830)	(0.1008)	(0.0861)	(0.1334)	(0.1165)
Observations	3,772	3,861	3,869	3,790	3,889
R^2	0.8134	0.6429	0.7504	0.5976	0.4909
	Panel B.II: Fuzzy Regression Discontinuity Approach				
	Speed	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(τ_1) 1st step	-4.7107***				
	(0.2572)				
(τ_2) 2nd step		-0.0181	-0.0035	-0.0061	-0.0170
		(0.0170)	(0.0160)	(0.0235)	(0.0219)
F-stat. instr.	335.41				
Observations	4,902	4,679	4,687	4,618	4,645
R^2	0.8154	0.6584	0.7596	0.5992	0.4916
	Panel C: Aker Hospital				
	Panel C.I: Fuzzy Regression Discontinuity Approach				
	Speed	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(τ) ESL	-6.4013***	0.1338	0.1481	-0.0498	-0.1127
	(0.6986)	(0.2914)	(0.2221)	(0.2661)	(0.1266)
Observations	3,108	2,554	2,592	2,715	2,717
R^2	0.8663	0.4565	0.5440	0.5151	0.4417
	Panel C.II: Fuzzy Regression Discontinuity Approach				
	Speed	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(τ_1) 1st step	-6.6693***				
	(0.1924)				
(τ_2) 2nd step		-0.0093	-0.0102	0.0044	0.0043
		(0.0258)	(0.0241)	(0.0275)	(0.0180)
F-stat. instr.	1201.59				
Observations	4,188	3,121	3,159	3,279	3,279
R^2	0.8540	0.4614	0.5448	0.5126	0.4263

Notes: This table displays the primary results of the effect of the environmental speed limits (ESL) on NO_X, NO_2, PM_{10} and $PM_{2.5}$ and travel speed for each individual monitoring station. Panel A.I, B.I and C.I displays the results form estimating equation (5) on each air pollutant and travel speed. Panel A.II, B.II and C.II , 1st step displays the results from estimation equation (6) on travel speed while Panel A.II, B.II and C.II, 2nd step displays the results from estimating equation (7) on each air pollutant. All pollutants are measured in logs. The models are estimated by using hourly observation and the same specifications as in Table 5.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A.19. Effect of Environmental speed limits on Air Quality, National Road 4: Difference-in-Difference (levels)

	(1)	(2)	(3)	(4)	(5)	(6)
	NO_2	PM_{10}	$PM_{2.5}$	NO_2	PM_{10}	$PM_{2.5}$
(δ_0) Period	-2.9258	-3.4280	0.2339	-4.3647	2.9592	-1.0637
	(4.1658)	(5.8492)	(1.1786)	(5.8844)	(9.1816)	(0.9498)
(β_1) Treatment	-10.2793***	6.2890	-1.7421*	-7.8723	3.3516	-2.5613*
	(2.4542)	(3.3850)	(0.6525)	(3.2388)	(2.4419)	(0.6696)
(δ_1) Period×Treatment	0.4823	-10.6209*	-0.2845	-1.8722	-7.7109	0.5805
	(3.8309)	(4.0549)	(0.7300)	(3.8086)	(3.2413)	(0.6719)
(β_0) Constant	61.3293***	44.0449***	16.7563***	51.5421***	39.0416**	15.6805***
	(5.8278)	(6.4047)	(1.6286)	(4.8627)	(9.0694)	(0.8840)
Observations	10106	10119	10093	12478	12491	12439
R^2	0.4722	0.2759	0.1887	0.0296	0.0018	0.0073
Controls	YES	YES	YES	NO	NO	NO

Notes: This table displays the main results for the effect of implementing environmental speed limits on National Road 4 for the pollutants NO_2, PM_{10} and $PM_{2.5}$ measured in logs. The estimates are obtained by using a difference-in-difference methodology, comparing Aker Hospital (treatment road) with Manglerud and Kirkeveien (control roads). Control variables include current wind direction; current and 1-hour-lags of precipitation, temperature and wind speed; in addition to day-of-the-week and hour fixed effects and a full set of interactions between hour and day-of-the-week fixed effects. Sample uses hourly observations for January, February and Mars and the years 2004 and 2005. Standard errors in parentheses are clustered by week.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A.20. Effect of Environmental speed limits on Air Quality, All Stations: Difference-in-Difference (logs)

	(1)	(2)	(3)	(4)	(5)	(6)
	NO_2	PM_{10}	$PM_{2.5}$	NO_2	PM_{10}	$PM_{2.5}$
(δ_0) Period	0.4432***	0.0701	-0.1965***	-0.0016	-0.2562**	-0.3206***
	(0.0951)	(0.1403)	(0.0541)	(0.0672)	(0.0777)	(0.0596)
(β_1) Treatment	0.1081*	0.2409	0.1315	-0.0170	0.1305	-0.0197
	(0.0496)	(0.1323)	(0.0690)	(0.0571)	(0.0880)	(0.0198)
(δ_1) Period×Treatment	-0.1022	-0.2248	-0.1583*	0.0920	-0.1155	0.0590*
	(0.0601)	(0.1374)	(0.0720)	(0.0624)	(0.0901)	(0.0286)
(β_0) Constant	3.7769***	3.1397***	2.8588***	3.6975***	3.1444***	2.5566***
	(0.0699)	(0.1385)	(0.0542)	(0.0430)	(0.0574)	(0.0411)
Observations	72914	74017	73817	67289	68369	67948
R^2	0.5126	0.3990	0.4309	0.0021	0.0296	0.0362
Controls	YES	YES	YES	NO	NO	NO

Notes: This table displays the main results for the effect of implementing environmental speed limits on National Road 4 and Ring Road 3 for the pollutants NO_2, PM_{10} and $PM_{2.5}$ measured in logs. The estimates are obtained by using a difference-in-difference methodology, comparing Aker Hospital, Manglerud and Smestad (treatment roads) with Kirkeveien (control road). Control variables include current wind direction; current and 1-hour-lags of precipitation, temperature and wind speed; in addition to year, station, day-of-the-week and hour fixed effects and a full set of interactions between hour and day-of-the-week fixed effects and year and station fixed effects. The sample consists of hourly observations for November, December, January, February and Mars and the years 2001-2004 and 2007-2012. Standard errors in parentheses are clustered by month.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A.21. Effect of Environmental speed limits on Air Quality, All Stations: Difference-in-Difference (levels)

	(1)	(2)	(3)	(4)	(5)	(6)
	NO_2	PM_{10}	$PM_{2.5}$	NO_2	PM_{10}	$PM_{2.5}$
(δ_0) Period	27.1195***	1.9066	-2.2128*	7.6921**	-6.7524**	-3.9439***
	(4.7674)	(4.1220)	(0.9077)	(2.4192)	(2.0252)	(0.8199)
(β_1) Treatment	3.5513	7.9721	1.9024*	2.4316	6.4137*	0.1619
	(3.4554)	(4.7127)	(0.7182)	(1.5947)	(2.8945)	(0.4942)
(δ_1) Period×Treatment	-3.1355	-7.3809	-2.2708**	2.2044	-5.7980	0.4078
	(4.3370)	(4.7473)	(0.8044)	(2.1640)	(2.9329)	(0.5571)
(β_0) Constant	45.6274***	28.9612***	18.3420***	44.9100***	30.4616***	15.3510***
	(2.4815)	(3.9937)	(1.0448)	(1.5273)	(1.7033)	(0.6483)
Observations	72914	74017	73817	108066	109640	108973
R^2	0.4892	0.2423	0.2850	0.0192	0.0283	0.0244
Controls	YES	YES	YES	NO	NO	NO

Notes: This table displays the main results for the effect of implementing environmental speed limits on National Road 4 and Ring Road 3 for the pollutants NO_2, PM_{10} and $PM_{2.5}$ measured in levels. The estimates are obtained by using a difference-in-difference methodology, comparing Aker Hospital, Manglerud and Smestad (treatment roads) with Kirkeveien (control road). Control variables include current wind direction; current and 1-hour-lags of precipitation, temperature and wind speed; in addition to year, station, day-of-the-week and hour fixed effects and a full set of interactions between hour and day-of-the-week fixed effects and year and station fixed effects. The sample consists of hourly observations for November, December, January, February and Mars and the years 2001-2004 and 2007-2012. Standard errors in parentheses are clustered by month.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A.22. Effect of Environmental speed limits on Air Quality, Ring Road 3: Difference-in-Difference (logs)

	(1)	(2)	(3)	(4)	(5)	(6)
	NO_2	PM_{10}	$PM_{2.5}$	NO_2	PM_{10}	$PM_{2.5}$
(δ_0) Period	-0.0576	-0.0399	-0.2233*	-0.0289	0.0822	-0.2580
	(0.0882)	(0.0777)	(0.0976)	(0.1120)	(0.1370)	(0.1030)
(β_1) Treatment	0.3176***	0.2795**	0.1397*	0.3361	0.2526	0.1099
	(0.0789)	(0.0776)	(0.0510)	(0.1454)	(0.1081)	(0.0525)
(δ_1) Period×Treatment	-0.1798	-0.2674**	-0.0132	-0.1444	-0.2182	0.0304
	(0.0981)	(0.0949)	(0.0621)	(0.1515)	(0.1151)	(0.0639)
(β_0) Constant	4.1992***	3.6158***	3.2655***	3.7020***	2.9075***	2.5956***
	(0.1120)	(0.2165)	(0.2115)	(0.0742)	(0.0700)	(0.1015)
Observations	7635	7609	7627	10678	10652	10697
R^2	0.5319	0.4099	0.3911	0.0284	0.0122	0.0340
Controls	YES	YES	YES	NO	NO	NO

Notes: This table displays the main results for the effect of implementing environmental speed limits on National Ring Road 3 for the pollutants NO_2, PM_{10} and $PM_{2.5}$ measured in logs. The estimates are obtained by using a difference-in-difference methodology, comparing Manglerud and Smestad (treatment roads) with Kirkeveien (control road). Control variables include current wind direction; current and 1-hour-lags of precipitation, temperature and wind speed; in addition to day-of-the-week and hour fixed effects and a full set of interactions between hour and day-of-the-week fixed effects. The sample consists of hourly observations for January, February and Mars and the years 2006 and 2007. Standard errors in parentheses are clustered by week.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A.23. Effect of Environmental speed limits on Air Quality, Ring Road 3: Difference-in-Difference (levels)

	(1)	(2)	(3)	(4)	(5)	(6)
	NO_2	PM_{10}	$PM_{2.5}$	NO_2	PM_{10}	$PM_{2.5}$
(δ_0) Period	-5.9291	-2.1605	-4.1754	-2.2209	3.3831	-4.1983
	(7.0453)	(3.2656)	(2.0655)	(6.0253)	(4.7865)	(2.2401)
(β_1) Treatment	12.8230*	7.6281**	1.4962	14.0627	6.8927	1.4265
	(5.4375)	(2.5565)	(0.9211)	(8.5468)	(3.3894)	(0.7438)
(δ_1) Period×Treatment	-6.2057	-6.4140	0.2222	-5.6955	-5.4181	0.4167
	(5.8893)	(3.3837)	(1.1201)	(8.7312)	(3.6869)	(0.9908)
(β_0) Constant	75.9372***	48.9200***	31.5339***	54.2751***	22.9399***	16.9060***
	(7.5896)	(11.2357)	(6.8773)	(4.1876)	(2.0920)	(2.1838)
Observations	7635	7609	7627	10678	10652	10697
R^2	0.5319	0.4099	0.3911	0.0217	0.0099	0.0313
Controls	YES	YES	YES	NO	NO	NO

Notes: This table displays the main results for the effect of implementing environmental speed limits on National Ring Road 3 for the pollutants NO_2, PM_{10} and $PM_{2.5}$ measured in levels. The estimates are obtained by using a difference-in-difference methodology, comparing Manglerud and Smestad (treatment roads) with Kirkeveien (control road). Control variables include current wind direction; current and 1-hour-lags of precipitation, temperature and wind speed; in addition to day-of-the-week and hour fixed effects and a full set of interactions between hour and day-of-the-week fixed effects. The sample consists of hourly observations for January, February and Mars and the years 2006 and 2007. Standard errors in parentheses are clustered by week. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A.24. Cost-Benefit Calculation: Health Costs Related to Asthma

Population Norway	5,213,985	Source: SSB
Population Oslo	658,390	Source: Oslo Kommune
Share of Population, Oslo	12.6%	
Share of year, Environmental speed limit period	43.8%	
Numbers of vehicles, Environmental speed limit period	9,166,000	
Inflation (2005-2017)	19.5%	Source: SSB
Cost Norway (2005 NOK)	2,262,821,000	Source: Arbeidstilsynet
Cost Oslo (2017 NOK)	285,735,000	
Cost Oslo, Environmental speed limit period (2017 NOK)	125,254,000	
Cost each Vehicle, Environmental speed limit period (2017 NOK)	14	

Table A.25. Cost – Benefit Calculation: Health Costs Related to COPD

Population Norway	5,213,985	Source: SSB
Population Oslo	658,390	Source: Oslo Kommune
Share of Population, Oslo	12.6%	
Inflation (2014-2017)	7.5%	
Cost per patient (2017 NOK)	7,955	Source: LHL
Additional cost if another disease (2017 NOK)	3,978	Source: LHL
Additional cost if deterioration (2017 NOK)	699	Source: LHL
Value of Statistical Life (2017 NOK)	30,500,000	Source: TØI: Veisten, Flügel and Elvik

	All causes	Air pollution and relating causes, 15%	
New instances [B]	20,000	3,000	Source: Leira
Existing instances	200,000	30,000	Source: Leira
Deaths	1,400	210	Source: Leira
New instances, Oslo (12.6%)	2525,48	379	
Existing instances, Oslo	25254,77	3788	
Deaths, Oslo	176,78	26	

	Cost of COPD	+ Additional disease	+ Deterioration	+ Additional disease and deterioration
Cost new instances, Oslo	3,014,000	4,520,000	3,278,000	4,785,000
Cost existing instances, Oslo	30,135,000	45,203,000	32,782,000	47,850,000
Cost deaths, Oslo	808,784,000	808,784,000	808,784,000	808,784,000
Sum Cost per Year	841,933,000	858,507,000	844,845,000	861,419,000
Within ESL Period, (160/365)	43.8%	43.8%	43.8%	43.8%
Sum Treatment Period	369,066,000	376,332,000	370,343,000	377,608,000
Passing vehicles, ESL period	9,166,000	9,166,000	9,166,000	9,166,000
Sum Cost per Vehicle	40	41	40	41

Table A.26. Cost – Benefit Calculation: Value of Time

Inflation	1.052		Source: SSB
Average wage, after 25% tax	31,798		Source: SSB
Daily wage	1,590		Assume 20 days
Hourly wage	199[A]		Assume 8 hours

ESL Period	Start	End	Days
2005	01.11.05		
2006	01.11.06	17.04.06	
2007	01.11.07	09.04.07	159
2008	01.11.08	24.03.08	144
2009	01.11.09	13.04.09	163
2010	01.11.10	05.04.10	155
2011	01.11.11	25.04.11	175
2012		09.04.12	160
Average			*159.2[B]*

Distance for calculation	10 km/h
Speed $before_1$	74.6 km/h
Speed $after_2$	68.8 km/h

	Hours	Time (mm:ss)	Seconds
Distance / $time_1$	0.1340	08:03	483
Distance / $time_2$	0.1453	08:43	523
Difference	-0.0112	00:40	-40
Seconds lost ESL period	-6440.28	*(B x C)*	
Minutes lost ESL period	-107.34	*(B x C)*	
Hours lost ESL period	-1.79[D]	*(B x C)*	

Number of vehicles	57,576[E]	Table 3
Number of vehicles within ESL period	9,166,099[F]	*A x D*
Number of passengers in vehicles	1,5[G]	Source: TØI (2010)
Total loss ESL Period	-4 888,101,000	**A x D x F x G**

Appendix A.27. The Cross-Validation Function

As a guide to find the optimal balance between precision and bias we have followed the “leave-one-out” procedure proposed by Ludwig and Miller (2005) and Imbens and Lemieaux (2008) tailored for the regression discontinuity design (Jacob R. , Zhu, Somers, & Bloom, 2012). The cross-validation procedure has been carried out as follows:

For a given bandwidth, $5 \leq h \leq 60$, we have estimated equation XXX2 on each side of the cut-off date separately. Since we are mostly interested in the boundary properties of our model we have predicted the value of observation i one day outside of our estimation sample where our estimation sample is given by $h + i - 1 > i - 1 \geq 0$ for the right side and $-(h + i) < -i \leq 0$ for the left side. $1 \leq i \leq 15 = N$ is the number of predictions done for each bandwidth on each side and assignment variable have been centralized so that $(X - c) = 0$. The cross-validation criterion for each side has been defined as:

$$CV_Y(h) = \frac{1}{N}\sum_{i=1}^{N}\left(Y_i - \widehat{Y_i}\right)^2$$

Where $\widehat{Y_i}$ is the predicted value and Y_i is the actual realization. N is the number of predictions done for each bandwidth. We have restricted the number of predictions per bandwidth to 15 because the process is very time-consuming. The idea is to pick the bandwidth that produces the smallest mean square error.

$$h_{CV}^{optt} = \arg\min_{\text{h}} CV_Y(h)$$

Since we choose to use the same bandwidth on both sides of the cut-off we have averaged the cross-validation criterion over both sides. Our cross-validation criterion is therefor based on the average mean square error over both sides. The figure below is a visualization of the cross-validation procedure for the right side (The case for left side is analogous to the right side).