Going Fast or Going Green? Evidence from Environmental Speed Limits in Norway

BY Ingrid Kristine Folgerø, Torfinn Harding and Benjamin S. Westby

DISCUSSION PAPER

Institutt for samfunnsøkonomi
Department of Economics

SAM 17/2019

ISSN: 0804-6824

October 2019

This series consists of papers with limited circulation, intended to stimulate discussion.

Going Fast or Going Green?
Evidence from Environmental Speed Limits in Norway

Ingrid Kristine Folgerø, Torfinn Harding and Benjamin S. Westby*

3 October 2019

Abstract

This paper studies the impact of speed limits on local air pollution using a series of date-specific speed limit reductions in Oslo over the 2004-2011 period. We find that lowering the speed limit from 80 to 60 km/h reduces travel speed by 5.8 km/h. However, we find no evidence of reduced air pollution as measured next to the treated roads. Our estimates suggest an annual time loss of the speed limit reductions of 55 USD per affected vehicle. Our findings imply that policy makers need to consider other actions than speed limit reductions to improve local air quality.

JEL classification: H23, Q53, Q58, R41

Keywords: temporary speed limit, air pollution, travel time, cost-benefit, regression discontinuity design

* NHH Norwegian School of Economics, Helleveien 30, 5045 Bergen, Norway, torfinnh@gmail.com. We would like to thank Rune Elvik for information about traffic and accidents, the Municipality of Oslo, the Norwegian Public Road Administration, the Norwegian Institute for Air Research and the Norwegian Meteorological Institute for access to data and generous information sharing. Lassi Ahlvik, Po Yin Wong and Jørgen Juel Andersen provided helpful comments. Harding holds the Equinor Chair in Economics at the NHH Norwegian School of Economics.

1. Introduction

Policy makers increasingly search for new ways to reduce air pollution, as projections suggest air pollution to be the top environmental cause of mortality worldwide by 2050 (OECD 2012). Transport is the only major sector in the EU where greenhouse gas emissions are still rising (European Commission 2017). As a new policy tool, cities like Amsterdam, Barcelona and Oslo have lowered speed limits to improve local air quality.[1] Speed limits have the desirable properties of being easy to enforce and difficult to circumvent, and their effects would be immediate.

Yet, the scientific evidence on the effect of lower speed limits on local air pollution is mixed. Engineering simulation models tend to find that reduced speed should improve air quality (EEA 2011a, UK Government 2017), while existing empirical studies offer mixed conclusions (van Benthem 2015, Bel and Rosell 2013, Dijkema, et al. 2008, Keuken, et al. 2010). The effect of speed limit reductions on local air quality is hard to predict, as it depends on the behavioural responses of drivers as well as on the technical relationship between speed and pollution for the affected vehicle fleet and roads. Ex-ante, there is considerable uncertainty about these aspects, calling for ex-post policy evaluation.

In this paper, we take advantage of speed limit reductions in Oslo to estimate the effect of speed on local pollution. In 2004, Oslo lowered the maximum speed limit from 80 km/h to 60 km/h on National Road 4 during the winter. The aim was to improve local air quality by reducing the level of Particulate Matter. Oslo later expanded the Environmental Speed Limit policy (ESL) to include additional roads, before national regulation halted the use of the policy in 2012-2015. In 2016, Oslo reintroduced the policy.

The date-specific introduction of the policy every year creates a series of natural experiments. High quality hourly data on the population of traffic and air pollution in the immediate vicinity of the highways allow us to utilize these experiments in a regression discontinuity design (RDD). We estimate the effect of the ESL on air quality in terms of Nitrogen Oxides (NO_2 and NO_X) and Particulate Matter ($PM_{2.5}$ and PM_{10}). We also estimate the effects on travel

[1] Reduced speed limits to reduce air pollution have been or are currently considered in Amsterdam, Rotterdam, Barcelona, Oslo, Texas, five cities in Wales, certain roads in England, as well as in Rennes and other cities in France.

speed and traffic volume, and we use the estimates to undertake a cost-benefit analysis of the policy.

This study adds to the existing literature by its use of real-world data, which allows for behavioural responses among drivers and other real-world aspects influencing the link between speed and air quality. The RDD, utilizing a series of natural experiment to isolate confounding factors, generates plausibly causal estimates.

The paper proceeds as follows. Section 2 presents a literature review, section 3 contains background information about the ESL-policy in Oslo and section 4 describes the data. Section 5 explains our empirical strategy. Section 6 presents the results and the cost–benefit analysis. Section 7 discusses threats to identification, robustness checks and external validity. The final section concludes. An online appendix provides supplementary material.

2. Literature review

Traffic is an important source of air pollution, as wear of brakes, tires and asphalt is a source of Particulate Matter, and exhaust fumes is a source of NO_2 and NO_X.[2] The relationship between average speed and vehicle emissions has been held to be U-shaped for stable speed (Bel and Rosell 2013). However, acceleration, decelerations and congestion make the relationship more complicated and recent work has put emphasis on the importance of traffic dynamics. For example, Makridis et al. (2019) emphasize the importance of modelling acceleration dynamics to accurately simulate fuel consumption and emissions. Jiang et al. (2018) integrate a macroscopic dynamic traffic assignment model with a microscopic emission model to capture the dynamics in speed and acceleration when predicting emissions. Lejria et al. (2018) combine a traffic microsimulation model with an emission model, and find that inclusion of the speed distribution increases emissions, in particular in combination with congestion.

[2] Other strategies than speed limit reductions to reduce traffic emissions include driving restrictions, congestion charging, stricter emission standards, expansions of public transport (OECD 2012). See Davis (2008) on driving restrictions in Mexico, Viard and Fu (2015) on driving restrictions in Beijing, Percoco (2015) on the London Congestions Charge and Chen and Whalley (2012) on public transport capacity in Taipei.

Recent empirical evidence has uncovered increasing emissions as speed decreases, related to congestion and acceleration. Gately et al. (2017) study emissions of carbon monoxide (CO), NO2, NOx, $PM_{2.5}$ and carbon dioxide (CO_2) from vehicles on 280,000 road segments in Massachusetts, using mobile phone and vehicle GPS data on speed. They find that $PM_{2.5}$ emission rates from heavy trucks increase markedly when speed falls below 55 km/h, while NO_X emission rates increase more smoothly as speed falls. They also find that congestion increases fuel consumption. Based on field experiments and modelling for Ann Arbor in Michigan, Zhang et al. (2011) find the highest emsisson rates of hydrocarbons (HC), CO and NOx from light duty vehicles to occur when traffic change from free-flow to congestion and from congestion to free-flow.

Madireddy et al. (2011) find in a model analysis of speed reductions from 50 to 30 km/h in residential areas in Belgium reductions in CO_2 and NO_X emissions of about 25%. In contrast, Gonçalves et al. (2008), who provide a simulation analysis of the variable speed limits and emissions in Barcelona in 2004, reductions in NO_2, PM_{10} and Sulfur dioxide (SO_2). Keller et al. (2008), who simulate the reduction of speed limit from 120 km/h to 80 km/h on certain Swiss motorways, find reductions in NO_X of 4% and little changes for volatile organic compounds (VOC) and peak ozone levels. The UK Government (2017) finds in simulations reductions of NO_x from reducing speed limits from 112 to 96 km/h, but that high cost of increased journey times contributes to a negative net present value of the policy. However, the UK Government (2017) stresses that factors such as topography, acceleration, congestion and actual speed lead to high uncertainty in the simulation results and call for further monitoring in real-world conditions.

The literature that has investigated the effect of actual speed limit changes on real-world air pollution has reached mixed conclusions. van Benthem (2015), studying rural areas in western U.S. states, finds that higher speed limits are associated with a 15% increase in concentrations of NO_2 and no statistically significant change in the concentration of PM_{10}. Bel and Rosell (2013) study the effect of two separate policies implemented by the regional government of Catalonia (Spain) on concentrations of NO_X and PM_{10}. They find that lowering the fixed speed limits to 80 km/h increases the level of NO_2 by 2–3% and PM_{10} by 5–6%. In contrast, the introduction of variable speed limits reduces the level of NO_2 by 8–17% and PM_{10} by 14–17%. Dijkema et al. (2008) analyse the consequences of a similar reduction in the maximum speed limit in Amsterdam on NO_X, PM_1 and PM_{10}. Their findings suggest that the policy lead to a decrease in PM_{10} of about 7%. However, they find no evidence of an improvement in the level of NO_2. Some of these results were disputed by Keuken et al. (2010), who look at the effect of the same speed limit policy on a sample of roads with a strict enforcement of the new speed limit. The findings of Keuken et al. (2010) suggest that a reduction in the maximum speed coupled with "strict enforcemet" lead to a reduction of 5–30% for NO_X and 5–25% for PM_{10}. Table 1 in summarizes the previous research evaluating the impact of speed management policies on air quality using statistical methods and real-world data. The previous papers using statistical methods to unocver the effects of speed limits have relied on difference-in-difference estimators (Ashenfelter and Greenstone 2004, Bel and Rosell 2013; Benthem 2015) or simple difference regressions comparing before vs. after a speed limit change (Bel, et al. 2015; Hagen, et al. 2005; Keuken, et al. 2010). These identifiation strategies are prone to omitted variable bias, e.g., speed limits are not set randomly but depend on, for the researcher, unobserved characteristics.[3]

The studies reviewed above indicate a complex relationship between traffic dynamics and vehicle emissions. This paper adds to the litearture by providing plaubily causal estimates of the effect of speed on emissions based on natural experiments and real-world behaviour.

[3] Hussein et al. (2008), Kupiainen et al. (2011) and Gustafsson et al. (2008) exemplify the alternative approach of using mobile laboratories or a road simulator hall to measure particle matter concentrations across different conditions. Johansson et al. (2005) use both measurements and dispersion modelling to study the temporal and spatial distribution of PNC (total particle number concentrations) and PM_{10}.

Table 1. Summary of Previous Real-World Evaluations of 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 and 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
van Benthem (2015)	California, 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.

3. Background for the ESL-policy in Oslo

High levels of air pollution led the city of Oslo to implement an ESL on National Road 4 (Sinsen to Grorud) as a pilot project in 2004 (Norwegian Ministry of Transport and Communications 2004). From November 1st 2004 to March 2005, the policy temporary reduced the maximum speed limit from 80 km/h to 60 km/h. Local climatic factors, important for the movement of air pollutants and their chemical reactions in the air, determined the focus on the wintertime. Oslo is located at the end of the Oslofjord and surrounded by forested hills. The combination of little wind and little horizontal air during the winter, as the sun provides less heat and the cool surface air is more likely to be trapped by the warmer air above, makes Oslo likely to experience elevated concentrations of air pollution during the winter (Dannevig 2009). Hagen et al. (2005) evaluated the pilot project and suggested a decrease in the levels of PM_{10} of 35–40%, a decrease of NO_X of 12–13%, no change in $PM_{2.5}$, an approximately 10 km/h lower travel speed and a decline in the number of cars by 2.7%.

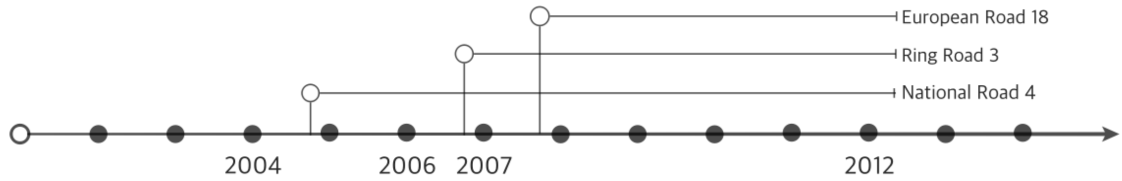
The ESL was permanently implemented on National Road 4 during wintertime (Statens Vegvesen, 2005). The policy was extended to Ring Road 3 (Ryen to Granfosstunnellen) in 2006 and European Route 18 (Hjortnes to Lysaker) in 2007. In the latter case, the ESL was active during daytime only, with a speed limit of 60 km/h between 06:00 a.m. and 22:00 p.m., and 80 km/h otherwise (Norwegian Public Roads Administration 2012).

The authority of the police to impose fines for violations of the temporary speed limits was for long unclear, leading the Oslo police district to ask for a clarification from the state attorney. Meanwhile the police would not enforce the ESL.[4] A lack of legal basis could imply paying back imposed fines (Hultgren, Berg and Johansen 2011). As a result, the ESL-policy ended on all three roads in 2012 (Norwegian Public Roads Administration 2012). The speed limit on the National Road 4 and Road Ring 3 was set to 70 km/h all year around, and the speed limit for European Route 18 returned to 80 km/h. On November 1st 2016, the municipality of Oslo reintroduced the ESL because stricter air pollution regulations and revised road legislation gave a clearer legal basis for enforcement. In the new regime, the police treats violations of the ESL in the same manner as violations of regular speed limits.

[4] According to an article in Aftenposten, the main newspaper in Oslo, 14.10.2011.

Figure 1 shows the time-line of the ESL in Oslo. In this paper, we use data covering the period 2001-2015.

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.

4. Data

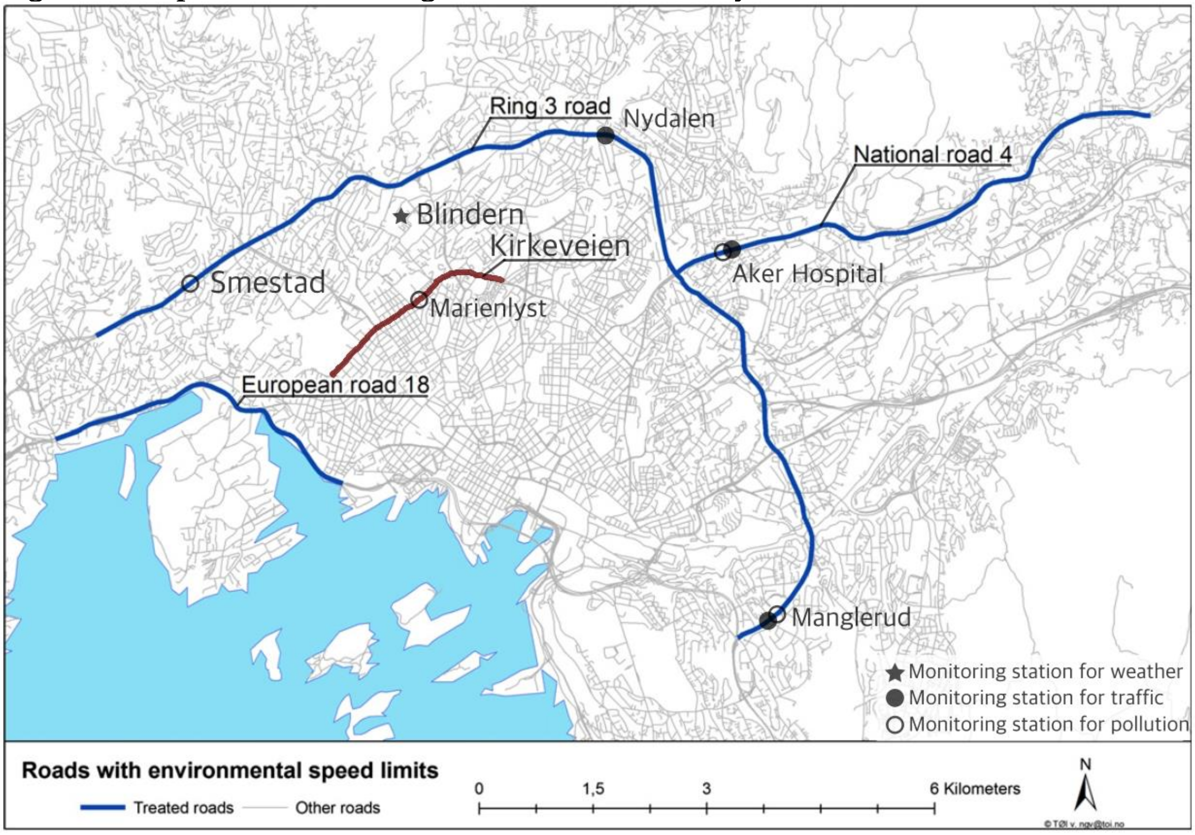
4.1 Monitoring stations and sample

We combine hourly data from separate sources for traffic, air pollution and weather. We focus on three monitoring stations for air pollution and three monitoring stations for traffic, located at four different locations in Oslo. 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.[5] We match our air pollutant observations and traffic observations on each road and pool the roads together. In our main analyses, we use this pooled dataset for the period 2006-2011. As a placebo location for air pollutants, we use *Kirkeveien*. The monitoring station for weather is located at *Blindern,* i.e. within 7 km from all of the monitoring stations for air pollution. The height difference between the weather monitoring station and the lowest and highest monitoring station for air pollution is no more than 50 meters. We link the same weather observations to all the monitoring stations for air pollution. Figure 2 shows the location of each monitoring station for traffic (solid circle), air pollution (hollow circle) and weather (star).[6]

[5] We have excluded European Route 18 from our analysis because of many missing observations and because the policy there differs slightly from the policy implemented on National Road 4 and Ring Road 3. The differences would complicate the interpretation of the results and obscure the clean cut-off in the regression discontinuity design.

[6] 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 northeast of the air pollution monitoring station. This

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 is 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. For reference, the distance between Manglerud and Smestad along the treated road in the map is about 13 km. Source: Modified map from Elvik (2013). Table A.5 in the online appendix presents a summary of the main characteristics for each monitoring station.

4.1.1 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.[7] Actual speed 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 2, 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 report the descriptive

distance may pose some problems for the validity of our 2SLS-regressions, where we scale the effects on pollution with the effects on speed. However, the two monitoring stations are located on the same road and there are few major exits between the monitoring stations (Ring Road 3 has six interchanges between *Nydalen* and *Smestad*).

[7] 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

Table 2. 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 speed 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. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

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 approximately 5 km/h 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.

4.2 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. The monitoring stations are located close to the roads with the purpose of measuring pollution related to traffic. The Norwegian Institute for Air Research validates all air pollution data by automatic as well as manual procedures, i.e. they correct measurement errors and manually calibrate the levels of air pollution. The dataset includes hourly observations for NO_2, NO_X, $PM_{2.5}$ and PM_{10}

measured in μg/m^3.[8] In our analysis, we have treated entries with zero or negative concentrations as missing. Table 2, 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 maximum observations with worse air quality than what is legal according to Norwegian law.[9] The simple t-test suggests that the air pollution levels are significantly higher in November compared to October, reflecting that air pollution is seasonal and tend to increase during the winter.

4.3 Weather data

Data on temperature, precipitation, wind speed and wind direction are from the Norwegian Metrological Institute. *Temperature* is measured in Celsius Degree, two meters above the ground level. *Precipitation* is measured in millimetres and includes both snow and rain. It is 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 and Fu 2015). We set entries with negative values of precipitation as missing. Minute-observations of precipitation are aggregated to hourly observations. To reduce the number of missing observations, we have imputed values based on observations that record the total precipitation in the last 7 hours. *Wind speed* is measured in metre per second (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. *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.[10] Descriptive statistics for temperature, precipitation and wind speed are presented in Table 2, 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.

[8] Mg/m^3 is microgram (i.e. one millionth (1×10^{-6}) of a gram) per cubic metre of air. 1 μg/m^3 = 1 parts per billion (ppb) = 0.001 parts per million (ppm).
[9] Table A.1 in the online appendix lists current Air Pollution Regulations.
[10] 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°

5. Empirical Strategy

The key identifying assumption in our regression discontinuity design (RDD) is that all characteristics relevant for speed and air pollution, other than the policy change, are continuous across the threshold, i.e. from October 31st to November 1st. As long as agents do not have precise control to sort themselves around the threshold date (e.g., move driving from the ESL-period to the earlier non-ESL-period), the variation in the treatment is as good as random and the RDD mimics a locally randomized experiment (Hahn et al. 2001; Lee and Lemieux 2010). Several similar applications, with time as the running variable, have used RDD (Hausman and Rapson 2018).

We estimate the effect of introducing the ESL on speed and traffic as well as on the four air quality outcomes NO_2, NO_X, PM_{10} and $PM_{2.5}$ by the following econometric model:[11]

$$y_t = \gamma_0 + \tau 1(ESL_t) + \gamma_1 f(X_t - c) + \gamma_2 1(ESL_t) \times f(X_t - c) + \gamma_3 Z_t + \varepsilon_t \tag{1}$$

Where y is a placeholder for speed, number of passing vehicles or one of the four air-quality outcomes. $1(ESL_t)$ is an indicator variable that equals 1 in the environmental speed limit period and 0 otherwise. When y is speed or traffic, $\tau 1$ expresses the compliance with the ESL. When y is one of the air quality outcomes, $\tau 1$ is the intention to treat (ITT) effect of implementing environmental speed limits (the reduced form effect of the policy). Z_t is a set of control variables (temperature, current and 1-hour lags of precipitation, wind speed and wind direction). We include a large set of fixed effects: station, year, day of the week and hour, in addition to interactions between the hour and day of the week fixed effects and between station and wind direction fixed effects. The assignment variable is time (X) and the date of introduction of the environmental speed limit policy is c. $f(\cdot)$ is a polynomial in time, and the interaction with $1(ESL_t)$ allows it to differ on either side of the cut-off date.

To estimate the effect of a reduction in speed on the air quality outcomes, we scale the effect on the air quality outcomes with the effect on speed. We do this by standard two stage least squares estimation (2SLS), where the first stage is equation (1) with speed as the dependent variable y and $1(ESL_t)$ as the instrument. The second stage is as follows:

[11] We follow the approach laid out in Lee and Lemieux (2010) and Dahl et al. (2016).

$$y_t = \alpha_0 + \tau_2 \hat{s}_t + \alpha_1 f(X_t - c) + \alpha_2 1(ESL_t) \times f(X_t - c) + \alpha_3 Z_t + u_t \quad (2)$$

$\hat{s}_t$ is the fitted values from the 1st stage. τ_2 is the coefficient of interest and gives an unbiased estimate of the effect of speed, s, on pollution, y, given that the relevance criteria and exclusion restriction hold. We use the same control variables in (2) as in (1). In both, we cluster the standard errors by year (we provide a robustness check to this choice in the online appendix).

6. Empirical Results

6.1 The first stage: The effects on speed and traffic volume

The purpose of the environmental speed limit policy was to improve local air quality by reducing travel speed. Figure 3 presents the effect of lowering the maximum speed limit with 20 km/h on speed and the number of passing vehicles, by showing unrestricted daily means together with a linear regression on each side of the cut-off date for the 2006–2011 period.[12] As explained in section 7.2, we use simple linear trends on each side of the cut-off and find the optimal bandwidth to be approximately 15 days for speed and traffic volume.

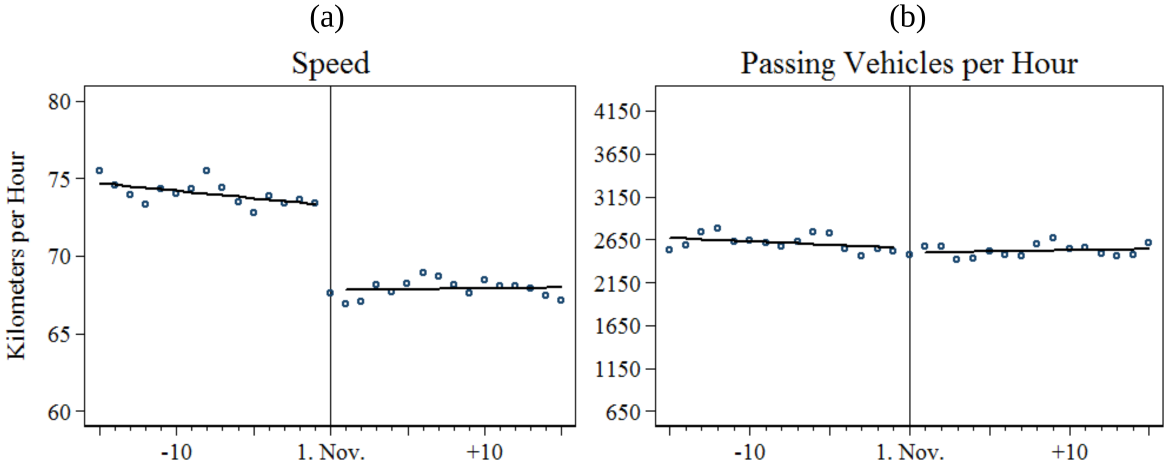
In the left-hand panel of Figure 3, there is a clear discontinuity in speed at the cut-off date, which indicates that the environmental speed limit did influence the choice of speed. However, the reduction in travel speed is much lower than the reduction in the maximum speed limit, in line with imperfect compliance to the new speed limit. There are no indications of jumps at other points than the cut-off date, providing support for a valid RDD and a causal interpretation of the jump at the cut-off date.

The right-hand panel of Figure 3 presents the number of passing vehicles, for which we observe little or no change at the cut-off date. This observation indicates that drivers did not substitute away from roads with the ESL to other roads. We confirm this finding in regressions in the online appendix and treat the number of vehicles as a control variable in the rest of the paper.[13]

[12] For the graphical presentation of the data, we have chosen daily bins based on comparing different bin-sizes and visual examination of the data. We average across all stations and years (2006-2011) to construct the daily means. Thus, each bin contains a maximum of $6\ (years) \times 3\ (stations) \times 24\ (hours) = 432$ observations.

[13] We show in the online appendix that our results are robust to the exclusion of control variables, and the issue of endogenous controls (Angrist and Pischke 2009) should therefore not be a big concern for our estimates.

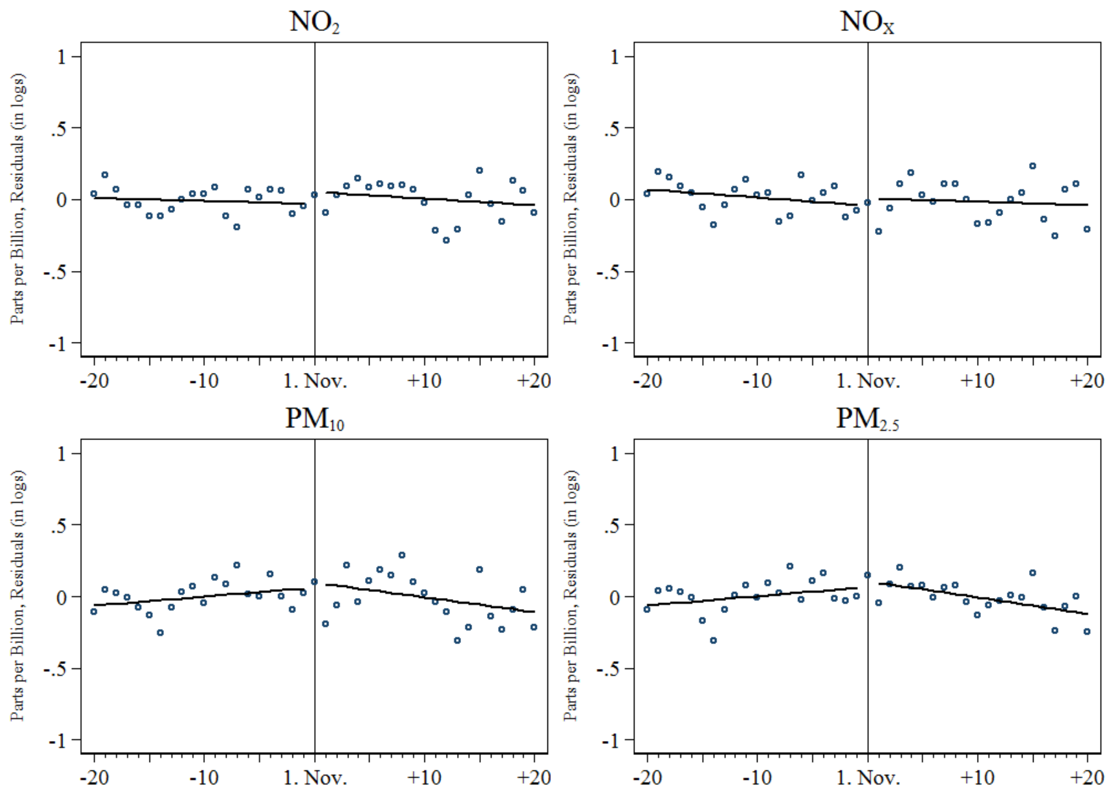
Figure 3. Graphical Evidence on the Effect of the ESL on Traffic



Notes: The figure shows the effect of lowering the posted speed limit with 20 km/h on travel speed and traffic volume (number of passing vehicles). We see a clear discontinuity at the cut-off (November 1st) for speed, but no visible discontinuity for Traffic Volume. These findings indicate that the environmental speed limit did influence the choice of speed, but not the choice of roadway (i.e. no traffic substitution effects). To illustrate the noise in the underlying data, the scale of the y-axis in Figure 3 (b) have been set to equal the 25th and 75th percentile for the hourly observations of the number of passing vehicle.

Table 3, Panel A, Column (1), reports our baseline estimate of the ESL on speed, which indicates a reduction of 5.8 km/h. Thus, a 1 km/h reduction in the maximum speed limit is associated with a 0.3 km/h reduction in travel speed. The estimates are considerably below 20 km/h. However, this might not be surprising as factors other than the posted speed limit may affect speed, such as congestion, weather and individual preferences. The modest effect could also be because of weak incentives to comply to the new speed limit, as the police would not ticket exceedances. Our finding of 0.3 km/h reduction in speed for a 1 km reduction in the speed limit is in line with Benthem (2015), who found that a 1 km/h increase in the maximum speed limit in the U.S. was associated with a 0.3-0.4 km/h increase in travel speed. Hagen et al. (2005) estimated that the pilot project on National Road 4 led to a decrease in travel speed of about 0.5 km/h per 1 km/h reduction in the speed limit.

Figure 4. Graphical Evidence on the Effect of the ESL 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.

6.2 The effects on air pollution

We first present Intention-to-Treat (ITT) estimates of the ESL on the four air pollutants. Figure 4 plots the residuals from estimating equation (1) excluding the ESL-dummy.[14] As we did for speed, we average over all monitoring stations and years into daily bins. We note that the linear time trends fit the data well. They are almost horizontal, indicating little variation between October and November in the air pollution, conditional on controls. The figure provides no indications of a discontinuity at the cut-off date, except for NO_2, which shows slightly higher levels in the ESL-period. There is also no indication of jumps at points away

[14] This "residualizing" approach is similar to the approach used by Chen and Whalley (2012) and Davis (2008). By "residualizing" the dependent variable, we net out the variation captured by our covariates. The resulting graph focuses on whether the treatment variable can explain the remaining variation. Another advantage of "residualizing" is that it provides an additional diagnostic check on whether the assumed order of the polynomial is justified. To get correct standard errors in the regressions, we include the control variables directly (Lee & Lemieux, 2010).

Table 3. Effect of Environmental Speed Limits on Air Quality: Regression Discontinuity

	(1)	(2)	(3)	(4)	(5)
	Panel A: First stage and intention to treat estimates				
	Speed	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(τ_1) 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: Scaling with speed using 2SLS			
	Speed	Speed	Speed	Speed
(τ_1) ESL (1st stage)	-5.8844***	-5.8994***	-5.9205***	-5.9360***
	(0.5547)	(0.5499)	(0.5607)	(0.5571)
	NO_2	NO_X	PM_{10}	$PM_{2.5}$
(τ_2) Speed (2nd stage)	-0.0200	-0.0178*	-0.0075	-0.0064
	(0.0135)	(0.0079)	(0.0183)	(0.0144)
F-stat. instr.	112.54	115.11	111.48	113.54
Observations	12371	12420	12482	12555
R^2	0.5319	0.6308	0.5335	0.4783

Notes: This table displays our baseline results. Panel A displays the results from estimating equation (1) on travel speed and the four air pollutants. Panel B, 1st stage displays the results from estimating equation (1) on travel speed, while Panel B, 2nd stage displays the results from estimating equation (2) on each air pollutant. All pollutants measured in logs. All models include control variables for current traffic volume (number of passing vehicles), 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, interactions between hour and weekday fixed effects and interactions between station and wind direction fixed effects. The data are hourly observations from a pooled sample of the monitoring stations Manglerud, Smestad, Nydalen and Aker Hospital. Sample years are 2006 – 2011. The F-statistics of about 110 indicate that our estimation should not suffer from weak instrument problems (Staiger and Stock 1997). Column (1) in Panel A based on a bandwidth of ±15 days, the remaining columns on a bandwidth of ±20 days. Standard errors in parentheses clustered by year. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

from the cutoff-date. The data show substantial variation and some cyclical patterns common to all the four air pollutants.

We obtain the ITT-estimates by estimating equation (1) with the four air pollutants as the dependent variable. We use a 20-day symmetric window around the cut-off date, as justified in section 7.2.

Table 3, Panel A, columns (2) through (5) present the ITT-coefficients. They all take an unexpected positive sign, but only for NO_2 is the coefficient statistically significant at the 5%-level. Thus, we find no evidence that the ESL-policy improves the air quality. The estimate for NO_2, suggests instead a deterioration of 11.75%. These results are consistent with the graphical evidence in Figure 4. Results for each individual station, presented in Table A.5 in the online appendix, show that all estimates are statistically insignificant.

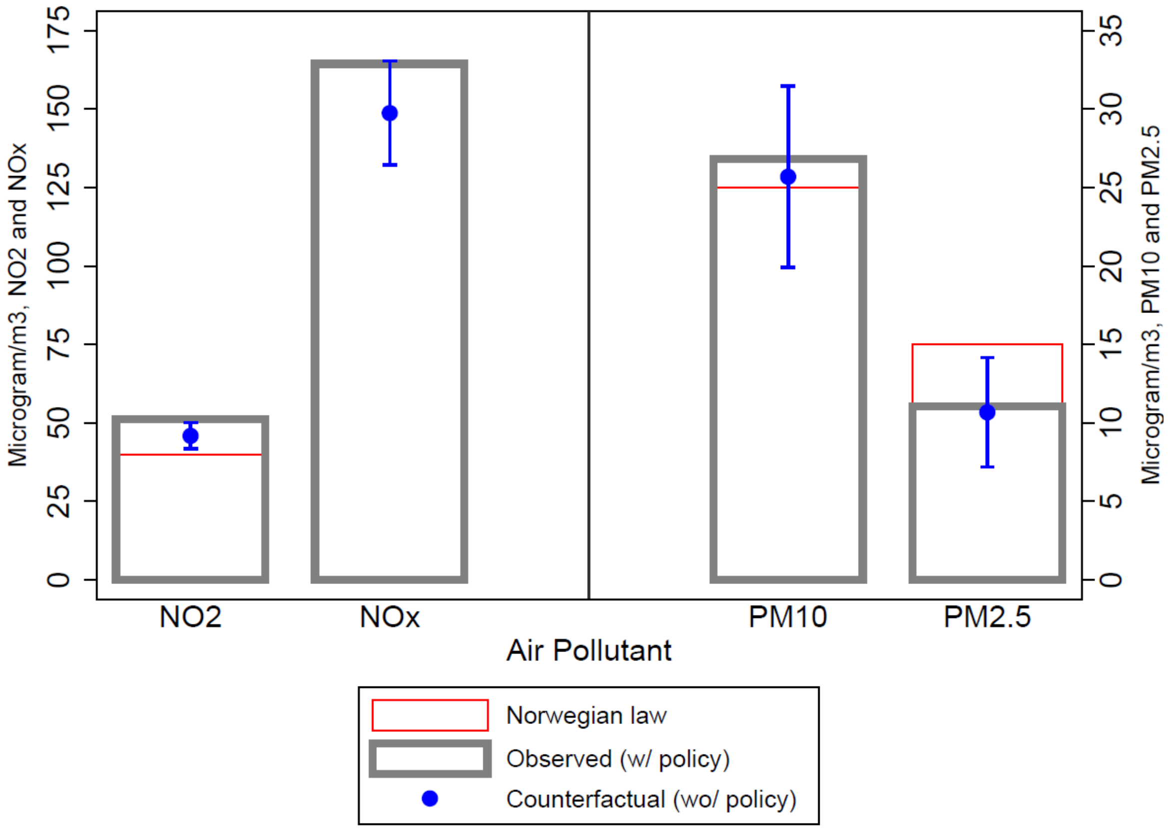
To estimate the effect of a 1 km/h-reduction in speed on the four air pollutants, we scale the jump in air pollution with the jump in speed. We do this by using the ESL-dummy as an instrument for speed in a 2SLS-estimation. Columns (2) through (5), Table 3, Panel B, present the results. As the scaled estimate is simply the ratio between the ITT-coefficient for the air pollutant and the first stage coefficient on speed, we find that all the second stage coefficients take a negative sign.[15] Higher speed is associated with lower level of air pollution. Only the estimate for NO_X is statistically significant, but this result is not robust to estimating for each station separately (results not presented to save space).[16]

We illustrate our estimates in Figure 5. The thin red bars show the Norwegian legal limits. For NO_X, the composite of NO and NO_2, there is no stated legal limit. The thick grey bars show the observed levels in our sample under treatment (the weeks in November). The blue circles show estimated counterfactual levels together with their 95% confidence bands. The counterfactual means of NO_2 and NO_X would have been the same or lower in absence of the policy than the observed levels with the policy, as the effect is borderline significant at the 95%-level. At the lower end of the confidence interval for NO_2, we can exclude that the air quality would have been within the legal limit without the policy.

For PM_{10}, we estimate insignificant coefficients, in line with the results of Bel et al. (2015) and Benthem (2015). Our findings differ from the results of Hagen et al. (2005). They had data only for one road and one season of the ESL, as they studied the pilot project. When we now use data for several roads and several seasons, we find their results not to be robust. Our estimated counterfactual mean of 26 µg/m3 is 1 µg/m3 below the observed mean and 1 µg/m3 above the legal limit. From the estimated 95% confidence interval, we cannot rule out that the counterfactual value would have been 20 µg/m3 or 32 µg/m3. These +/- 6 µg/m3 correspond to 25% of the standard deviation in the treated weeks in our sample.

[15] The second stage estimate is numerically identical to the ratio of the reduced form coefficients for pollution and speed, in our case $\tau_F = \tau / \tau_R$ (Lee & Lemieux, 2010). E.g., $-0.0178 = 0.1053 / -5.8994$ for NO_X.
[16] The results for each individual station are similar to the results for the pooled sample, with statistically insignificant coefficients across all air pollutants and stations.

Figure 5. Estimated Counterfactual Levels of Air Pollution



Notes: The figure presents the levels of the four air pollutants, as regulated by the Norwegian law (thin red) and as observed in our sample under treatment (thick grey). The blue circles indicate the estimated counterfactual level of air pollution, had the policy not been implemented. These estimates are our baseline reduced-form estimates presented in the upper panel of Table 3, and the 95% confidence intervals are based on standard errors clustered at the year-level. Note that clustering affects the standard errors as well as the critical t-values on which the confidence intervals are based. Figure A.8 in the online appendix includes also confidence intervals based on clustering on day or week. The level of clustering does not affect the conclusions of this study.

For $PM_{2.5}$, both the observed and the estimated counterfactual levels are below the legal limit, i.e. the legal limit is 15 µg/m3, the observed mean is 11 µg/m3 and the estimated counterfactual just below 11 µg/m3. The 95% confidence interval is +\- 3.5 µg/m3.

In conclusion, we find no evidence that the ESL-policy improves air quality in Oslo. If anything, there is some weak evidence that the ESL-policy increases the concentrations of Nitrogen Oxides (NO_2 and NO_X). The estimates for PM_{10} and $PM_{2.5}$ are uncertain. The expected effect of the policy is about zero, with about the same probability of worsening as improving air pollution in terms of PM_{10} and $PM_{2.5}$.

Table 4. Cost-Benefit Analysis for each Environmental Speed Limit Period

	Estimate based on estimation results	
Cost (-) / Benefits (+):	Per Vehicle (NOK)	All Drivers (MNOK)
Travel time	- 533	- 30.4
Fuel	83	4.7
Total Private Cost	- 445	- 25.7
Air quality	0	0
Accidents	0.6	5.7
Noise	0.3	3
Total Social Benefits	0.9	8.7
Net Result (NOK)	**- 444 NOK**	**-17.0 MNOK**
Net Result (USD)	**- 55 USD**	**-2.1 MUSD**

Notes: This table illustrates the private and social costs and benefits related to the estimated effect of the ESL-policy. All estimates based on conservative on assumptions and valuations, as described in the online appendix. Figures are in 2017 NOK or million NOK (MNOK). The exchange rate NOK to USD is about 8 NOK/USD. To simplify, we classify travel time and fuel costs as private costs. Furthermore, we classify benefits related to accidents and noise as social.

6.3 Cost-Benefit Analysis

Table 4 presents a simple cost benefit calculation of the ESL-policy, which indicates a time loss of about 30 MNOK each ESL-period (3.8 million USD). In addition comes potential saving in terms of fuel, noise and accidents of 4.7, 5.7 and 3 MNOK, respectively, adding up to a total social cost of 17 MNOK (2.1 million USD). We now explain how we have calculated these numbers. We present figures in local currency (NOK). The exchange rate between NOK and USD is about 8 NOK/USD. We provide more details in the online appendix.

The value of time is based on the average salary in Norway and the time loss associated with the implementation of the ESL for a ten-kilometre distance, adjusted for average vehicle occupancy. We stipulate an average hourly salary after tax of 199 NOK, 1.5 persons per vehicle, 40 seconds lost time for every vehicle and about 57 600 vehicles using National Road 4 or Ring Road 3 each day.[17] The average length of the ESL-periods is about 160 days. The

[17] We discuss these assumptions in online appendix C. In short, we arrive at these assumptions by the following: Our traffic data gives the mean number of cars per day. Data from Statistics Norway in combination with an assumed 25% tax rate give the after tax hourly wage. Research by Elvik et al. (2010) motivates 1.5 passengers per car. 40 seconds time-loss per vehicle is based on an assumed distance of 10 km travelled on the ESL-road. For reference, the distance between Manglerud and Smestad along the treated road in the map in Figure 2 is about 13 km.

private cost related to the estimated speed reduction is then 356 NOK per person, or 533 NOK per vehicle, and about 30 MNOK in total.

As alternatives, we use figures of "nationally representative travels", as recommended by the Directorate of Public Roads (2018) for new road projects. We then calculate the time costs to be between 26 and 40 million NOK.[18]

In terms of the levels of the four air pollutants, we cannot reject that the ESL-policy had zero effect. We therefore set the value of these potential benefits to zero.

The ESL-policy involves potential private benefits in terms of lower fuel consumption, which we calculate to 83 NOK per vehicle per ESL-period. Potential social benefits in terms of fewer accidents are set to 0.6 NOK and less noise to 0.3 NOK, per vehicle per ESL-period. Note that we regard the calculations of potential benefits in terms of fuel, accidents and noise as speculative, as we do not estimate the effect of the ESL-policy on these outcomes. We discuss details in the online appendix.

[18] The total value of time loss each environmental speed limit period: 199 NOK x 1.77 hours = 352 NOK. Total time loss cost: Total time loss cost: 1.77 hours x 199 NOK x 1.5 passengers x 57576 Vehicles = 30 419 992 NOK

7. Discussion regarding identification, specification and external validity

In this section, we provide an overview of checks we have undertaken regarding potential threats to identification and with respect to our specification choices. We also discuss robustness checks regarding maximum compliance and potential time-varying and non-linear effects. We conclude that none of the checks changes the conclusions of this study.

7.1 Potential threats to identification

Strategic driving shifts in driving around the cutoff could in principle be a threat to our identification. Our primary identifying assumption is that, absent of the ESL-policy, the air quality in Oslo would not change discontinuously on November 1st. I.e., all other relevant observable and unobservable characteristics are continuous across the cut-off of date. Drivers could in principle strategically move driving from the days after to the days before November 1st, or change their speed in advance to make up for the lost time after November 1st. However, work or other commitments typically determine the time of driving, and the incentives to shift the driving strategically to save time would be comparatively small. In line with this, Figure 3 reveals no suspicious bunching around the cutoff-date, neither in the number of passing vehicles nor in speed.

Strategic behaviour of public officials, i.e. choosing a time of implementation with unusual high or low concentrations of air pollution, is also not a threat in our setting. The policy is set to start on November 1st every year and our investigation of weather and pollution variables shows no discontinuities across the cutoff-date in years without the policy and at roads without the policy (see appendix Table A.2).

What about other policies changing at the same time? Two policies related to studded tires could bias our estimates for PM (the bias for NO_2 og NO_X should be negligible). First, during the summer and until October 31st, there is a ban on studded tires in Norway. As studded tires have a higher impact on the amount and spread of PM compared to studdless tires, a discontinuity in the use of studded tires on November 1st would bias our estimate of the effect of the ESL on PM towards zero.[19] Second, on November 1st, 2004, Oslo introduced a fee on

[19] Norwegian law requires vehicles to be fitted with winter tires during the winter to assure sufficient grip. Some winter tires use metal or ceramic studs to increase traction. Norwegian Public Road Administration (2012)

the use of studded tires to incentivize the use of studdless tires. The share of studded tires in Oslo declined from approximately 34% in 2004 to about 15% in 2011, and has since been stable at around 15% (see Figure A.5 in the online appendix). The fee could also lead individuals to substitute to other means of transportation, such as public transportation. Both of these responses to the studded tire fee could bias our estimate of the effect of the ESL on PM

We do not have micro data on the use of studded tires, but find no evidence of trends across the years in the discontinuity in PM_{10} and $PM_{2.5}$ on November 1st. The decline in the share of studded tires over time suggests that the bias caused by studded tires should decline over time (see Figure A.4 in the online appendix). Furthermore, in years and locations without the ESL-policy, we do not find a positive jump for PM_{10} and $PM_{2.5}$ at November 1st, in contrast to what we would expect if a discontinuity in the use of studded tires were important (see Figure A.4 and Table A.2 in the online appendix). Our conclusion is 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 big concern. One likely reason is that weather conditions, which we find to be continuous across the cutoff-date, influence the timing of the tire change. Another likely reason is that the convenient time for changing tires, i.e. free time for drivers to do it themselves or capacity of professional tire changers, is unlikely to occur at November 1st for everyone every year.

Other measures implemented by the city of Oslo to improve air quality are sweeping, road washing and road dust treatment with magnesium chloride (salt) to reduce the spread of PM. These efforts should not be a threat to our identification, as there is no reason why they should change discontinuously on the cut-off date November 1st. Instead, their use is likely to correlate with weather variables.[20] The share of diesel cars in Norway increased from 18.5%

suggests that the spread of road dust from studded tires is about one hundred times larger than from studdless winter tires. Because of the adverse effects on road surfaces and air quality, Norwegian law restricts the use of studded tires: the use of studded tires is illegal from the second Monday after Easter Sunday up to and including October 31st (Lovdata 1990), unless the weather requires the use of winter tires for safe driving. This exception applies also if one is travelling to a place where safety requires winter tires.

[20] 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 (Norwegian Public Roads Administration 2014). However, research debate the effectiveness of these measures, see Norman and Johansson (2006), Aldrin et al. (2008) and Kupiainen et al. (2011). The impact of salting has been evaluted to be propitious especially on larger particles and during dry weather (Norman and Johansson 2006, Aldrin, Haff and Rosland 2008, Aldrin, Steinbakk and Rosland 2010), but is temporary and disappears within few days.

in 2005 to 42% in 2012 (Statistics Norway, 2017).[21] As long as the share of diesel cars does not change discontinuously around November 1st, our RD design is robust to the changing share of diesel cars.

To investigate whether our identifying assumption of smooth variation in relevant characteristics around the cut-off is likely to hold, we test for discontinuities in weather variables (see Table A.4 in the online appendix). We also conduct placebo tests by using observations from years and locations without ESLs to investigate whether there are jumps in our outcomes around November 1st in absence of the ESL-policy (see Table A.2 in the online appendix). We do not find any indications of discontinuous changes around November 1st, other than those plausibly caused by the ESL-policy.

7.2 Specification checks

To estimate the jump at the cut-off, we need to specify the order of the polynomial time trend $f(\cdot)$ in equation (1) and the window of data to include on the two sides of the cut-off date (the bandwidth). The primary concern when choosing the order of the polynomial trend and bandwidth is the trade-off between precision and bias (Lee and Lemieux 2010). We use a simple linear time trend, in accordance with Figure 3 and Figure 4. Simple specifications are in general preferred over more complex specifications (Lee and Lemieux 2010, Gelman and Imbens 2014). A narrow bandwidth reduces bias at the expense of lower precision because of less data. We base our choice of bandwidth on the "leave-one-out" cross-validation procedure proposed by Lemieux and Milligan (2008) and Ludwig and Miller (2007). The procedure suggests the optimal bandwidth to be approximately 15 days for speed and traffic volume, and approximately 40 days for most air pollutants. Because of concerns about shifting traffic due to a school holiday, we have chosen a bandwidth of 20 days for air pollution.[22]

In the online appendix (Table B.1-B5), we vary our RD specification along four dimensions: bandwidth (number of days around the cut-off), the order of the polynomial trend, the inclusion of covariates and the role of outliers. We do also run a robustness check with alternative clustering.

---

[21] See Statistics Norway (2017), https://www.ssb.no/transport-og-reiseliv/artikler-og-publikasjoner/halvparten-koyrer-framleis-pa-diesel, for more on the composition of the car fleet in Norway.

[22] 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

As a final robustness check, we run our analysis for the years with the largest change in speed, to get an "upper bound" for the effect of the policy (see Table A.2 in the online appendix). We focus on the first stage estimates and the ITT-estimates. For completeness, we include a section with OLS-estimates in the online appendix (section D).

7.3 External validity

Although our RD design helps us to achieve high internal valitidy, local circumstances, such as the car fleet and road quality, may affect the relationship between speed and air pollution. For example, diesel cars have relatively high emissions of NO_X (ICCT 2017) and newer roads typically have less spread of PM than older roads, due to less wear and tear on the asphalt (Norwegian Directorate for the Environment 2016). The level of speed is also likely to matter, as the relationship between speed and emissions is U-shaped (Bel and Rosell 2013, van Benthem 2015). These are not concerns for our results for Oslo, as we have directly tested the policy on outcomes of interests, but they may affect the generalizability of our findings.

8. Conclusion

Authorities increasingly consider lowering speed limits in the hope of improving air quality, as road transport is an important contributor to air pollutants such as NO_X and $PM_{2.5}$. In this paper, we studied the environmental speed limit policy in Oslo, which the city has implemented to various degrees since 2004. The reduction of the maximum speed limit from 80 km/h to 60 km/h reduces travel speed by 5.8 km/h. However, we found no evidence that the policy improves air quality. We also calculated a net social loss from the policy. We conclude that policymakers should focus on other actions to improve local air quality and thereby reduce the adverse health effects of air pollution.

9. References

Aldrin, Magne, Gunnhildur Högnadóttir Steinbakk, and Pål Rosland. 2010. *Analyse av luftkvalitet og effekt av støvdemping basert på data fra 2001-2009 (Only in Norwegian).* Oslo: Norwegian Computer Center.

Aldrin, Magne, Ingrid Hobæk Haff, and Pål Rosland. 2008. "The effect of salting with magnesium chloride on the concentration of particular matter in a road tunnel." *Atmospheric Environment* 1762-1776.

Angrist, Joshua D., and Jörn-Steffen Pischke. 2009. *Mostly Harmless Econometrics: An Empiricist´s Companion.* New Jersey: Princeton University Press.

Ashenfelter, Orley, and Michael Greenstone. 2004. "Using Mandated Speed Limits to Measure the Value of a Statistical Life." *Journal of Political Economy 2004* 112 (1): 226-267.

Bel, Germà, and Jordi Rosell. 2013. "Effects of the 80 km/h and variable speed limits on air pollution in the metropolitan area of barcelona." *Transportation Research Part D* (Elsevier Ltd) 90–97.

Bel, Germà, Catalina Bolancé, Montserrat Guillén, and Jordi Rosell. 2015. "The environmental effects of changing speed limits: A quantile regression approach." *Transportation Research Part D* 76–85.

Benthem, Arthur van. 2015. "What is the Optimal Speed Limit on Freeways." *Journal of Public Economics* 44-62.

Chen, Yishu, and Alexander Whalley. 2012. "Green Infrastructure: The Effects of Urban Rail Transit on Air Quality." *American Economic Journal: Economic Policy* 58-97.

Dahl, Gordon B., Katrine V. Løken, Magne Mogstad, and Kari Vea Salvanes. 2016. "What is the case for paid maternity leave?" *The Review of Economics and Statistics* 655–670.

Dannevig, Petter. 2009. *Store Norske Leksikon.* 17 June. Accessed May 21, 2017. https://snl.no/Oslo_-_klima.

Davis, Lucas W. 2008. "The Effect of Driving Restrictions on Air Quality in Mexico City." *Journal of Political Economy* 116 (1): 38-81.

Dijkema, Marieke B.A., Saskia C. van der Zee, Bert Brunekreef, and Rob T. van Strien. 2008. "Air quality effects of an urban highway speed limit reduction." *Atmospheric Environment* (Elsevier) 9098–9105.

Directorate of Public Roads. 2018. "Konsekvensanalyser, Veiledning, Håndbok V712." 14 November. Accessed March 2019. Håndbok V712 Konsekvensanalyser.pdf.

EEA. 2011a. *European Environment Agency.* 30 March. Accessed July 14, 2017. https://www.eea.europa.eu/articles/reducing-speed-limits-on-motorways.

Elvik, Rune, Knut Veisten, and Stefan Flügel. 2010. *Den norske verdsettingsstudien. Ulykker - Verdien av statistiske liv og beregning av ulykkenes samfunnskostnader.* TØI.

European Commission. 2017. *European Commission.* Accessed 07 17, 2017. https://ec.europa.eu/clima/policies/transport_en.

Eurostat. 2017. *Passenger transport statistics.* April. Accessed July 3, 2017. http://ec.europa.eu/eurostat/statistics-explained/index.php/Passenger_transport_statistics#Main_tables.

Gately, Conor K., Lucy R. Hutyra, Scott Peterson, and Ian Sue Wing. 2017. "Urban emissions hotspots: Quantifying vehicle congestion and air." *Environmental Pollution* 496-504.

Gelman, Andrew, and Guido Imbens. 2014. "Why High-order Polynomials Should not be Used in Regression Discontinuity Designs." *NBER Working Paper No. 20405.*

Gonçalves, Marıa and Pedro Jimenez-Guerrero and Eugeni Lopez and Jose M. Baldasano. 2008. "Air quality models sensitivity to on-road traffic speed representation: Effects on air quality of 80 km/h speed limit in the Barcelona Metropolitan area." *Atmospheric Environment* 42: 8389–8402.

Hagen, Leif Otto, Steinar Larssen, and Jan Schaug. 2005. *Miljøfartsgrense i Oslo - Effekten på luftkvaliteten av redusert hastighet på rv 4.* NILU.

Hahn, Jinyong, Petra Todd, and Wilbert Van der Klaauw. 2001. "Identification and Estimation of Treatment Effects with a Regression-Discontinuity Design." *Econometrica* 69 (1): 201-209.

Hausman, Catherine, and David S. Rapson. 2018. "Regression Discontinuity in Time: Considerations for Empirical Applications." *Annual Review of Resource Economics* 10 (1).

Hultgren, John, Bentzrød Sveinung Berg, and Per Anders Johansen. 2011. "Du kan kjøre fort uten konsekvenser." *Aftenposten*, 14 October: 8-9.

ICCT. 2017. *The International Council of Clean Transportation* . 5 January. Accessed June 16, 2017. http://www.theicct.org/nox-europe-hdv-ldv-comparison-jan2017.

Imbens, Guido W., and Thomas Lemieux. 2008. "Regression Discontinuity Designs: A Guide to Practice." *Journal of Econometrics* 615-635.

Jiang, Yan-Qun, Pei-Jie Ma, and Shu-Guang Zhou. 2018. "Macroscopic modeling approach to estimate traffic-related emissions in urban areas." *Transportation Research Part D* 60: 41-55.

Keller, Johannes and Sebnem Andreani-Aksoyoglu and Michel Tinguely and Johannes Flemming and Juerg Heldstab and Mario Keller and Rene Zbinden and Andre S.H. Prevot. 2008. "The impact of reducing the maximum speed limit on motorways in Switzerland to 80 km/h on emissions and peak ozone." *Environmental Modelling & Software* 23: 322-332.

Keuken, M.P., S. Jonkers, I.R. Wilmink, and J. Wesseling. 2010. "Reduced NOx and PM10 emissions on urban motorways in The Netherlands by 80 km/h speed management." *Science of the Total Environment* (Elsevier) 2517–2526.

Knudsen, AK, MC Tollånes, ØA Haaland, JM Kinge, V Skirbekk, and Vollset SE. 2017. *Disease Burden in Norway 2015. Results from the Global Burden of Diseases, Injuries, and Risk Factors Study 2015 (GBD 2015).* Report, Public Health Institute Norway. https://www.fhi.no/en/publ/2017/sykdomsbyrde-i-norge-2015/ .

Låg, Marit, and Magne Refsnes. 2017. *Norwegian Institute of Public Health* . 3 February. Accessed February 14, 2017. https://www.fhi.no/en/op/public-health-report-2014/risk--protective-factors/air-pollution-in-norway---public-he/.

Lee, Davis S., and Thomas Lemieux. 2010. "Regression Discontinuity Designs in Economics." *Journal of Economic Literature* (48): 281-355.

Lejria, Delphine, Arnaud Can, Nicole Schipera, and Ludovic Leclercq. 2018. "Accounting for traffic speed dynamics when calculating COPERT." *Transportation Research Part D* 63: 588-603.

Lemieux, Thomas, and Kevin Milligan. 2008. "Incentive Effects of Social Assistance: A Regression Discontinuit Approach." *Journal of Econometrics* 807-859.

Lovdata. 1990. *Forskrift om bruk av kjøretøy*. 01 04. Accessed May 4, 2017. https://lovdata.no/dokument/SF/forskrift/1990-01-25-92/KAPITTEL_1#.

Ludwig, Jens, and Douglas L. Miller. 2007. "Does Head Start Improve Children´s LIfe Chances? Evidence From a Regression Discontinuity Design." *Quarterly Journal of Economics* 159-208.

Madireddy, Madhava, Bert De Coensel, Arnaud Can, Bart Degraeuwe, Bart Beusen, Ina De Vlieger, and Dick Botteldooren. 2011. "Assessment of the impact of speed limit reduction and traffic signal coordination on vehicle emissions using an integrated approach." *Transportation Research Part D* 16: 504–508.

Makridis, Michail, Georgios Fontaras, Biagio Ciuffo, and Konstantinos Mattas. 2019. "MFC Free-Flow Model: Introducing Vehicle Dynamics in Microsimulation." *Transportation Research Record* 2673 (4): 762–777.

Norman, Michael, and Christer Johansson. 2006. "Studies of some measures to reduce road dust emissions from paved roads in Scandinavia." *Atmospheric Environment* 6154-6164.

Norwegian Directorate for the Environment. 2016. *Lokal luftforrurensning.* Miljødirektoratet. 26 May. Accessed March 13, 2016. http://www.miljostatus.no/Tema/Luftforurensning/Lokal-luftforurensning/.

Norwegian Ministry of Transport and Communications. 2004. *Nasjonal transportplan 2006–2015.* Regjeringen.no (Det Kongelige Samferdselsdepartement). Accessed February 24, 2017. https://www.regjeringen.no/no/dokumenter/stmeld-nr-024-2003-2004-/id197953/sec6.

Norwegian Public Roads Administration. 2012. *Miljøfartsgrense i oslo 2004-2011 - oppsummeringsrapport.* Region Øst, Statens vegvesen.

—. 2014. *Renhold av Veger.* 31 12. Accessed 05 03, 2017. http://www.tiltakskatalog.no/e-2-2.htm.

OECD. 2012. *OECD Environmental Outlook to 2050.* OECD. Accessed May 14, 2017. http://www.oecd.org/newsroom/environmentactnoworfacecostlyconsequenceswarnsoecd.htm.

Percoco, Marco. 2015. "Environmental Effects of the London COngestions Charge: A Regression Discontinuity Approach." *Working Paper.*

Staiger, Douglas, and James H. Stock. 1997. "Instrumental Variables Regression with Weak Instruments." *Econometrica* 557-586.

UK Government. 2017. *Draft UK Air Quality Plan for tackling nitrogen dioxide.* Technical Report, London: Department for Environment, Food & Rural Affairs and Department for Transport.

van Benthem, Arthur. 2015. "What is the Optimal Speed Limit on Freeways." *Journal of Public Economics* 44-62.

Viard, V. Brian, and Shihe Fu. 2015. "The effect of Beijing´s Driving Restrictions on Pollution and Economic Activity." *Journal of Public Economics* 125: 98–115.

Zhang, Kai, Stuart Batterman, and François Dion. 2011. "Vehicle emissions in congestion: Comparison of work zone, rush hour and free-flow conditions." *Atmospheric Environment* 1929-1939.

Online Appendix

Going Fast or Going Green?
Evidence from Environmental Speed Limits in Norway

Ingrid Kristine Folgerø, Torfinn Harding and Benjamin S. Westby*

3 October 2019

* NHH Norwegian School of Economics, Helleveien 30, 5045 Bergen, Norway, torfinnh@gmail.com.

A. LIST OF SUPPLEMENTARY, FIGURES AND TABLES

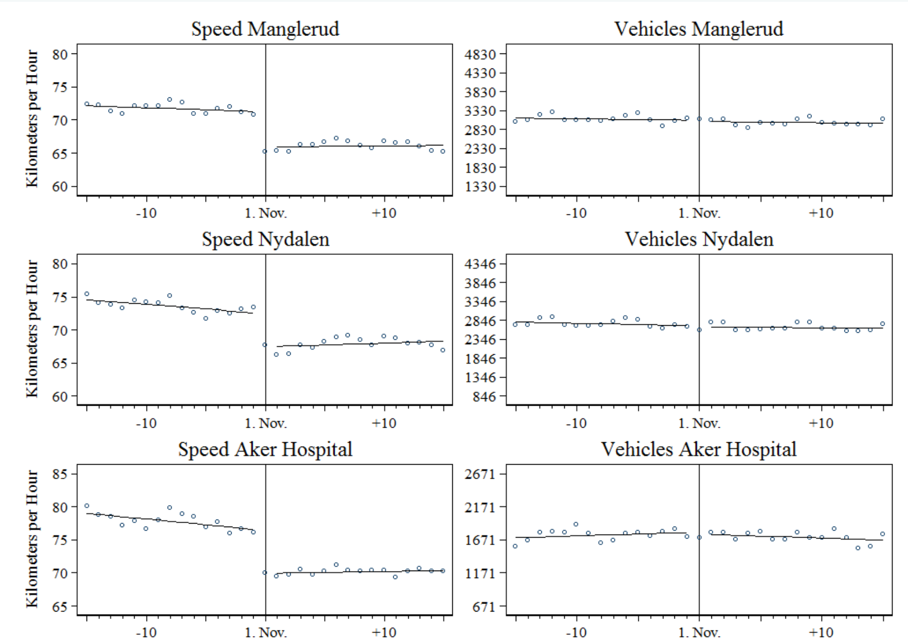
B. ROBUSTNESS

C. COST-BENEFIT CALCULATION, TABLES

D. OLS-ESTIMATES

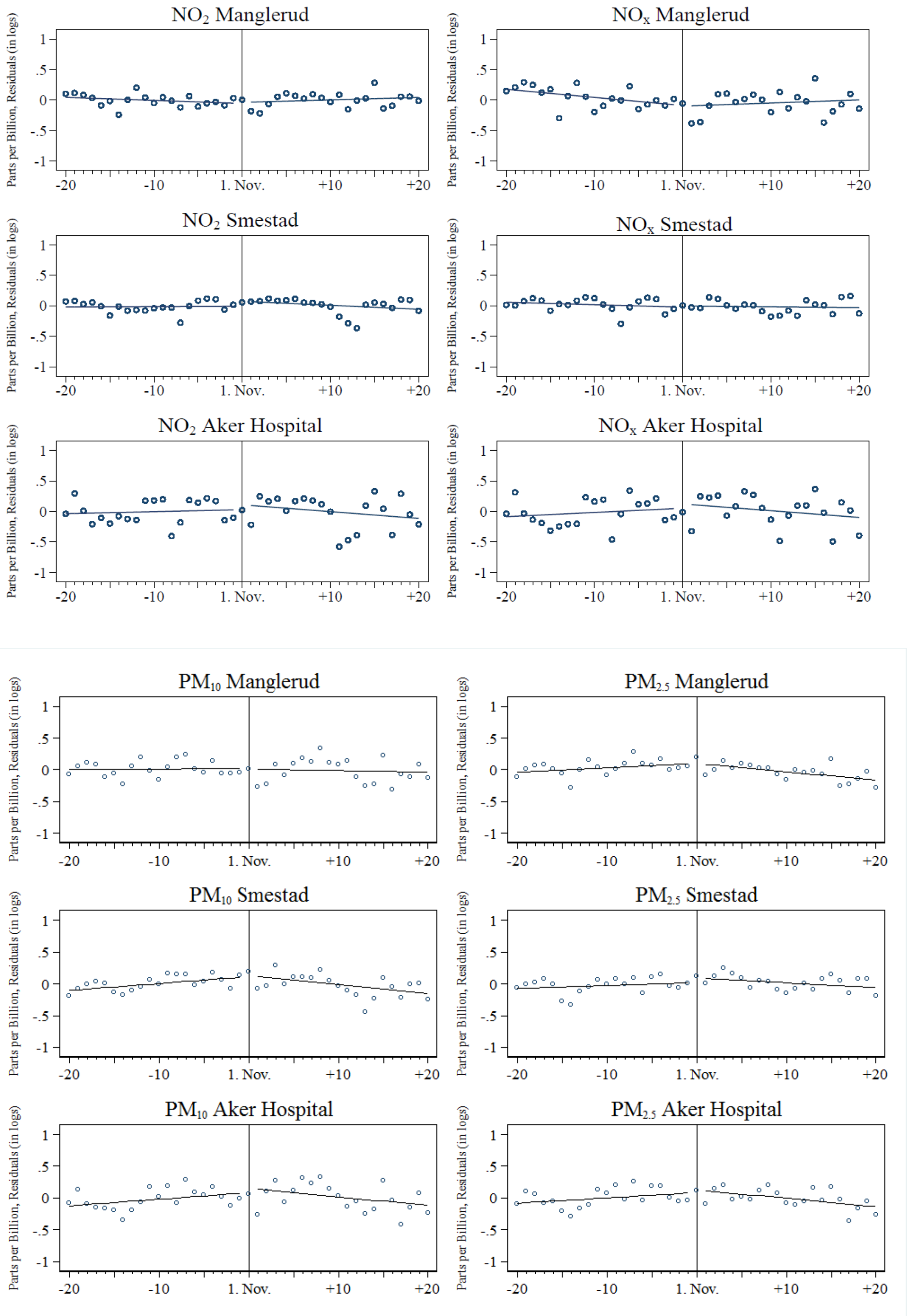
A. Supplementary figures and tables

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



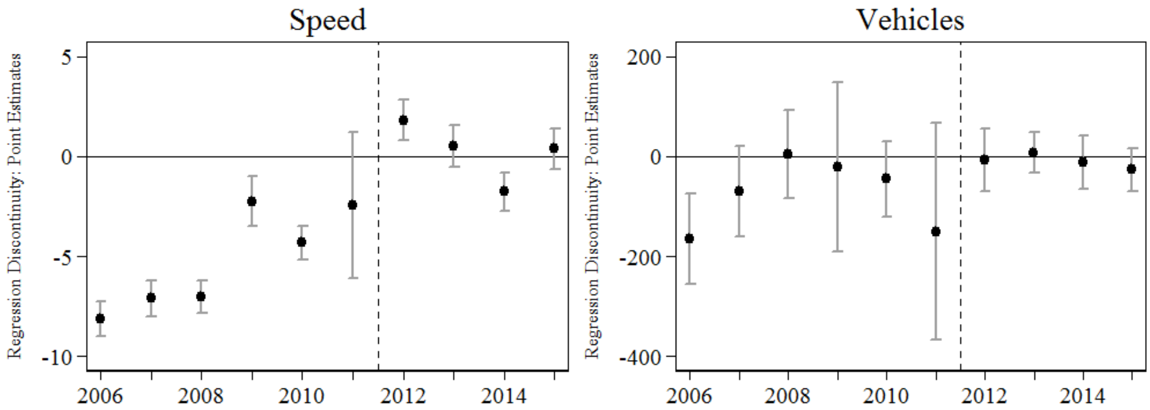
Notes: Visible discontinuity in speed at all stations. No visible jump in passing vehicles. We use a bandwidth of 15 days, and the sample period is 2006-2011.

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



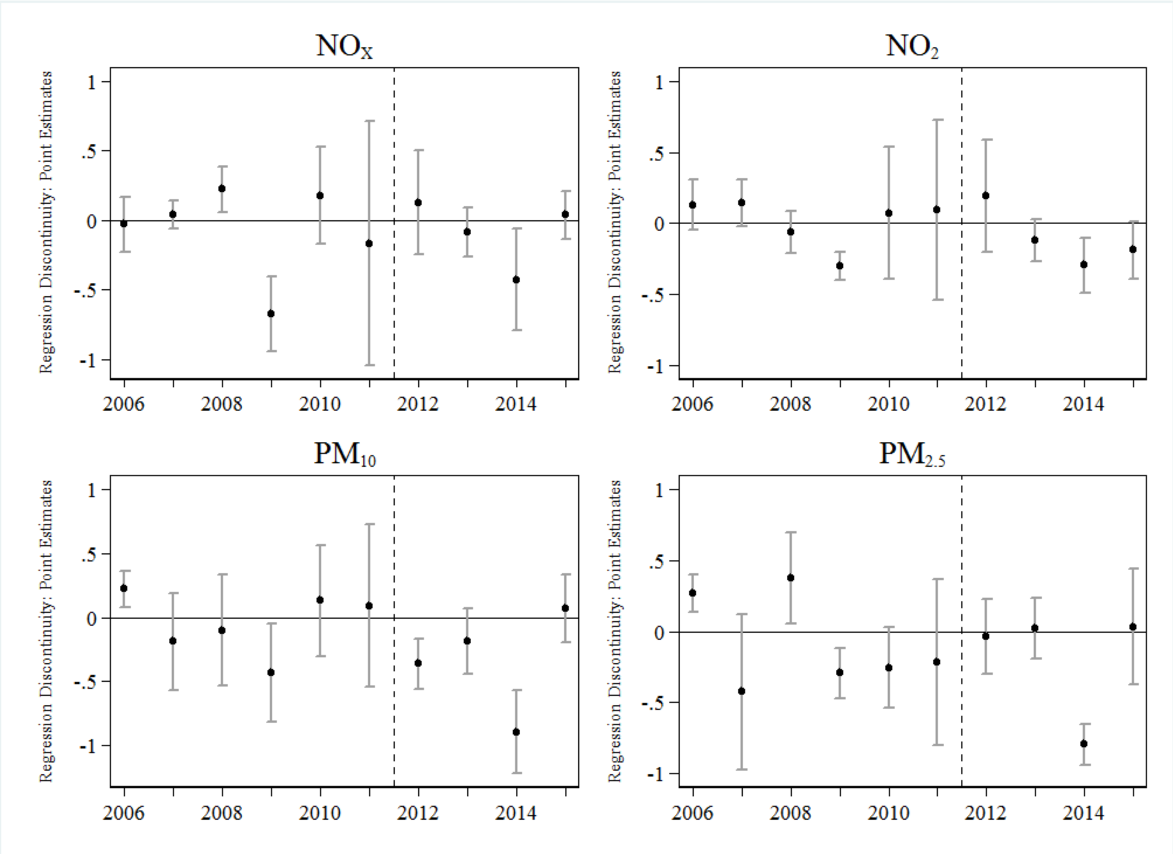
Notes: No visible discontinuity for neither of the four air pollutants at the individual air pollutant stations. We use bandwidth of 20 days, and the sample period is 2006 – 2011.

Figure A.3. 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. Standard errors are clustered by week. All point estimates for speed are negative when the ESL-policy was active (2006-2011). It is also statistically significant for all those years, except for 2011, for which we have few observations because of missing weather observations. The coefficients on speed are smaller and around zero in the years without the ESL-policy (2012-2015), with two statistically insignificant coefficients, one positive significant coefficient and one negative significant coefficient. 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 exception being the point estimate for 2006, which suggests that the implementation of ESL in 2006 reduced the number of passing vehicles per hour by 165 vehicles. In 2006, the ESL was implemented on Ring Road 3 for the first time. Thus, a possible explanation is that this was a one-off effect, as drivers may have substituted away from using Ring Road 3 on November 1st as a precaution to potential adverse traffic effects. However, the statistically significant result for 2006 is small relative to the average number of passing vehicles each hour. Excluding 2006 from our sample hardly changes the estimated treatment effects of the ESL on any of the pollutants: NO_x, NO_2, PM_{10} or $PM_{2.5}$.

Figure A.4. Yearly Estimates of the Treatment Effect on Air Quality

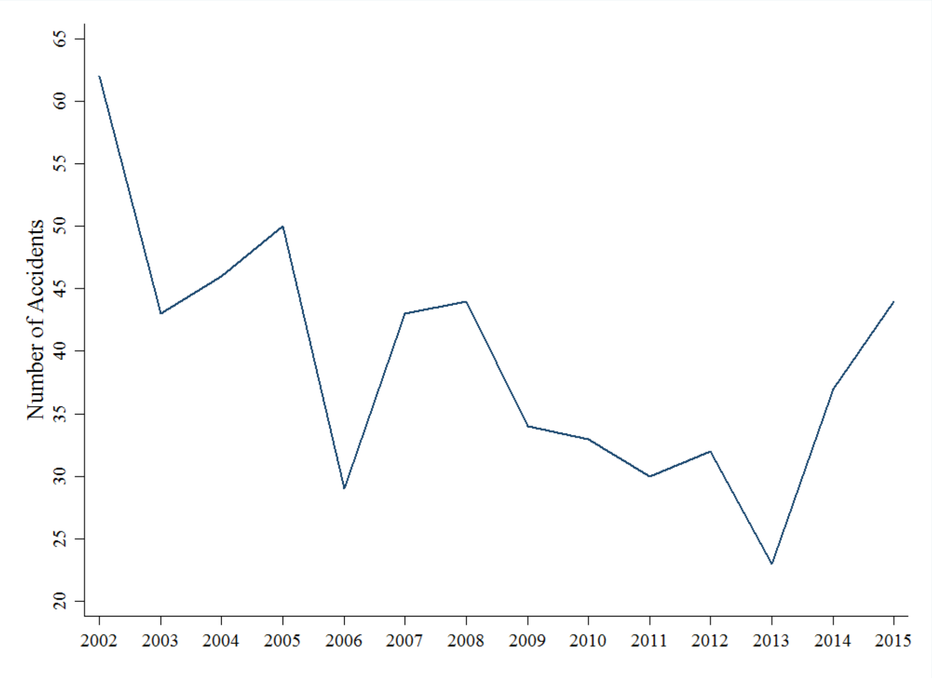


Notes: This figure illustrates the point estimate from estimating equation (5) on each of the air pollutants NO_X, NO_2, PM_{10} and $PM_{2.5}$ for each separate year using the same specifications as in Table B.2, Panel A. The vertical dashed line indicates the end of the environmental speed limit policy. 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.

Figure A.5. The Share of Drivers Using Studded Tires

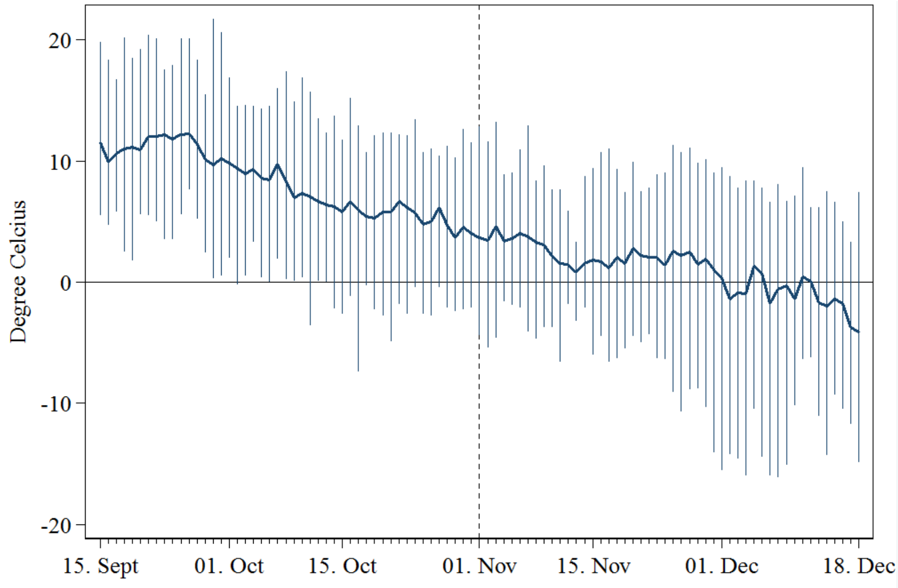
Notes: The figure shows the share (%) of drivers using studded tires for each separate year during the period 2001 to 2016. The share of studded tires has been relatively stable the last five years, about 15%. The fraction of studded tires has decreased greatly from 2004.

Figure A.6. The Number of Injury Accidents for National Road 4 and Ring Road 3



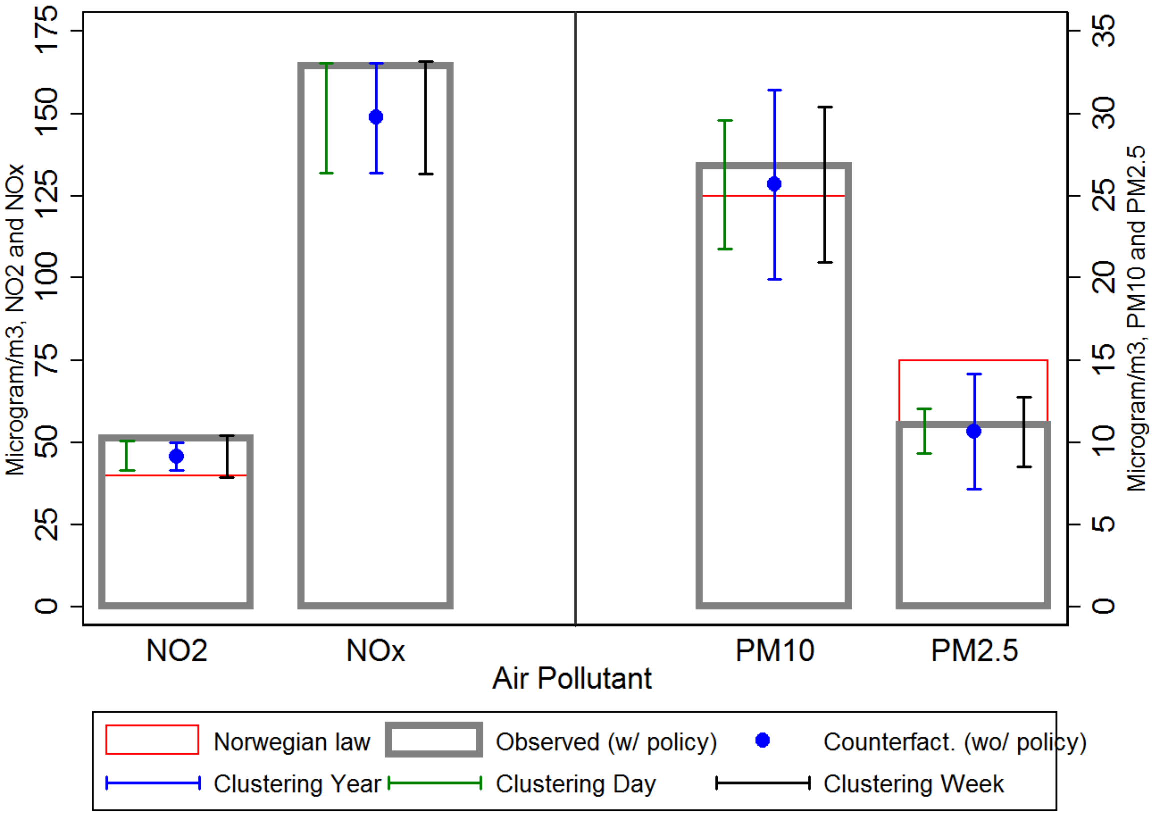
Notes: The figure describes the number of injury accidents for the National Road 4 and Ring Road 3 in the period 2002 to 2015. The number of injury accidents include slight, serious and fatal accidents. The average number of accidents in the period of 2002 – 2015 is about 39 accidents annually.

Figure A.7. 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.8. Estimated Counterfactual Levels of Air Pollution, Different Clustering



Notes: The figure presents the levels of the four air pollutants, as regulated by the Norwegian law (thin red) and as observed in our sample under treatment (thick grey). The blue circles indicate the estimated counterfactual level of air pollution, had the policy not been implemented. The blue 95% confidence intervals are based on clustering on year, the green 95% confidence intervals to the left are based on clustering on date and the black 95% confidence intervals to the right are based on clustering on week. The estimates are our baseline reduced-form estimates presented in the upper panel of Table 3. The different levels of clustering does not affect the conclusions of this study.

Table A.1. Current Regulatory Environment for Air Quality Standards

		(1)		(2)	(3)		(4)	(5)
		Recommenced		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.2. Effect of ESL on Air Quality Validity Tests
RD

	(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)			
	Speed		NO_X	NO_2	PM_{10}	$PM_{2.5}$
(τ) ESL	-7.2705**		0.1332	0.0634	-0.1900	0.0123
	(0.0508)		(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 ESL 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. Standard errors in parentheses are clustered by year.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A.3. Traffic Substitution and Weather Effects: RD

	(1)	(2)	(3)	(4)	(5)
	Traffic Volume	Wind Speed	Precipitation	Temperature	Wind Direction
(τ) ESL	-46.6432	-0.3130	-0.0739	-0.4761	0.1722
	(25.8332)	(0.7336)	(0.0748)	(0.5821)	(0.1668)
Observations	10462	5903	4917	5904	5903
R^2	0.9325	0.0702	0.0550	0.3628	0.0600

Notes: This table displays the main results for the effect of ESL 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 week 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.

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

Table A.4. Effect of ESL on Air Quality by Monitoring Station
RD

	(1)	(2)	(3)	(4)	(5)
	Panel A: Manglerud				
	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 B: Smestad				
	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 C: Aker Hospital				
	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

Notes: This table displays the primary results of the effect of the ESL (ESL) on NO_X, NO_2, PM_{10} and $PM_{2.5}$ and travel speed for each individual monitoring station. All pollutants are measured in logs. The models are estimated by using hourly observation and the same specifications as in Table B.2. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table A.5. 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 ESLs were introduced for each roadway.

B. Robustness

As mentioned in the main text, we undertake a host of different robustness checks. First, we examine the robustness of our result along four dimensions of our RD specification: bandwidth (number of days around the cut-off), the order of the polynomial trend, the inclusion of covariates and the role of outliers. We do also run a robustness check with alternative clustering. Finally, we run our analysis for the years with the largest change in speed, to get an "upper bound" for the effect of the policy. We focus on the first stage estimates and the ITT-estimates.

B.1 Choice of bandwidth and polynomial in the assignment variable

Table B.1 reports the estimates of the effect of the ESL on speed and traffic volume using different combinations of order of the polynomial and bandwidths. For speed, all the point estimates are negative. The magnitude is also stable, except for the smallest bandwidth in combination with fifth-order polynomials. All the coefficients are statistically significant at the 5%-level, except for two with fifth-order polynomials. Even though the optimal order of polynomial given by Akaike´s information criteria suggests a polynomial of fifth order, we use a linear trend in our baseline specification to keep the model as simple as possible.[1] Gelman and Imbens (2014) find that specifications with high order polynomials (higher than second order) can be misleading and should not be used.

[1] 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 B.1. Effect of Environmental Speed Limits on Traffic Robustness Regression Discontinuity

	Speed			Traffic Volume		
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: The optimal order of the polynomial based on Akiake's Information Criterion (AIC). The note of Table 3 provides further description.

For traffic volume, we maintain our conclusion of no effect on traffic volume, as most of the estimates are statistically insignificant and the magnitudes are relatively small compared to the average number of passing vehicles (2588 in October). Although 5 out of 18 estimates are statistically significant at the 5%-level, 3 of them are based on a zero-order polynomial. This is equivalent to a simple mean comparison before and after the cut-off date (Lee and Lemieux 2010). The estimates simply pick up a decreasing trend over the cut-off, reflecting that the number of cars gradually decreases as winter is coming.

Table B.2. Effect of Environmental Speed Limits on Air Quality Robustness Regression Discontinuity

	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: The optimal order of the polynomial based on Akiake's Information Criterion (AIC). The note of Table 3 provides further description.

Table B.2 presents the estimated treatment effect of the ESL on NO_X, NO_2, PM_{10} and $PM_{2.5}$ for different order of polynomials and bandwidths. Only 3 out of the 48 point estimates are statistically significant using a 5% significance level. The 3 statistically significant point estimates are positive and are for NO_2 and NO_X. Only 8 of the 48 point estimates takes the expected negative sign. The robustness of the positive signs underpins our previous conclusion that the implementation of the ESL did not improve local air quality in Oslo.[2]

B.2 Controls

Inclusion of covariates should not affect the estimated jump at the cutoff-date, no matter how correlated they are with the outcome, if the "no-manipulation" assumption holds (Lee and

[2] The cross-validation function for NO_X, NO_2 and PM_{10} suggest that using a bandwidth of about 40 days is optimal, whereas the cross-validation function for $PM_{2.5}$ suggests that using a bandwidth of about 20 days is optimal. In robustness checks not shown to save space, we use the optimal bandwidth suggested by the cross-validation function and it does not change the sign for any of the air pollutants. Furthermore, the point estimates are all statistically insignificant at the 5%-level. These checks and figures plotting the values of the Cross-Validation function over a range of bandwidths are available on request from the authors.

Lemieux 2010). Table B.3 in this online appendix repeats baseline Table 3, excluding control variables. The point estimate for speed is similar to our baseline estimate and is still statistically significant at the 5%-level. Also for the air pollutants, our baseline results hold. All the coefficients take the same sign and are statistically insignificant at the 5%-level. As expected, the precision of the point estimates is reduced compared to our baseline estimates, since the main reason for including control variables in a well-specified RD is to reduce sampling variability (Lee and Lemieux 2010).

B.3 Outliers

We now exclude outliers by only including values that lie below the 95th percentile and above the 5th percentile for each separate air pollutant. Table B.4 in this online appendix presents the results and we find no substantial changes in magnitude, sign or statistical significance. Thus, excluding outliers does not alter the conclusions from our baseline results.

B.4 Clustering of standard errors

Our observations are likely to be correlated across time and space and we therefore cluster the standard errors. Since too few clusters may lead to an underestimation of the standard errors (Angrist and Pischke 2009), we now cluster the standard errors at the weekly [or daily] level, rather than the yearly level (see Table B.5).[3] This increases the number of clusters from 6 to 40 [or 213] for the air pollutants and from 6 to 29 [or 164] for speed.[4] The choice of clustering does not alter the conclusion of this study. The only notable difference is that the effect on NO_2 is statistically insignificant with weekly clusters, which underlines that the statistically significant estimate for NO_2 in our baseline estimation is not robust. Figure A.8 in the appendix illustrates graphically the differences in confidence bands due to different levels of clustering.

[3] Clustering at the week or date level instead of the year level does not always give lower standard errors in our setting, as can be seen in Table B.5. Davis (2008) also uses clustering on week as a robustness test. When our 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.

[4] 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.

B.5 Maximum observed compliance

As the ESL-policy in Oslo was active, it became increasingly clear that the Police was hesitant to enforce it.[5] Compliance may therefore have decreased over time. Figure A.3 shows that the drop in speed at November 1st is smaller for later years. Perhaps the drop in speed was simply too small to make a detectable improvement in air quality? As our estimates take the unexpected positive sign, this is unlikely to be essential. However, we now estimate the ITT-effect of the ESL on the four air pollutants on the sub-sample of years with the greatest estimated changes in speed, i.e. 2007–2008, to get an “upper bound”. Panel C in Table A.2 reports the results from this estimation. The estimates for NO_X, NO_2, and $PM_{2.5}$ are similar to our baseline estimates, with positive and statistically insignificant coefficients. The coefficient for PM_{10} now takes a negative sign, but is still statistically insignificant.

[5] For example, NRK, the Norwegian Broadcasting Corporation, posted in 2008 an article with a statement from the police saying that they would not prioritise resources to enforce the environmental speed limits.

Table B.3. Effect of ESL on Pollution Using No Control Variables: RD

	(1)	.	(2)	(3)	(4)	(5)
	Panel A: Sharp RD 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

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. None of the models includes 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. Columns (2) through (5) use a bandwidth of ±20 days, column (1) a bandwidth of ±15 days. Standard errors in parentheses are clustered by year. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Table B.4. Effect of ESL on Air Quality Trimmed Sample RD

	(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 ESL 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. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table B.5. Effect of ESL on Air Quality S.E. Robustness
RD

	(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
Clustered year	(0.7968)***	(0.0357)*	(0.0435)	(0.0874)	(0.1270)
Clustered week	{0.5026}***	{0.0686}	{0.0569}	{0.0911}	{0.0986}
Clustered date	[0.4113]***	[0.0498]*	[0.0568]	[0.0768]	[0.0641]
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 speed, NO_X, NO_2, PM_{10} and $PM_{2.5}$. 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) use a bandwidth of ±20 days, column (1) a bandwidth of ±15 days. Standard errors in parentheses are clustered by year. Standard errors in curly braces are clustered by week. Standard errors in brackets are clustered by date. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

C. Cost – Benefit Analysis

In the following section, we quantify the monetary costs and benefits of implementing ESL based on our estimates of the effects of the policy. The key aspects are time costs and the benefits of cleaner air. We start out with a thorough discussion of time costs. Because our analysis indicates no changes in air quality, we assume that the implementation of ESL has no impact on health outcomes. All numbers are adjusted for inflation, reported in 2017 NOK, except for the alternative time costs calculations provided by Directorate of Public Roads (2018), which are in 2016 NOK. As any cost-benefit analysis, the analysis is not complete but based on previous literature and assumptions.

Time costs

We first estimate the cost of travel time by the time loss associated with the implementation of ESL for a ten-kilometre distance, adjusted for average vehicle occupancy. For reference, the distance between Manglerud and Smestad along the treated road in the map in Figure 2 in the main text is about 13 km. We assume on average 1.5 persons per vehicle, based on research published by Elvik et al. (2010). To estimate the number of affected vehicles each period we use the average number of passing vehicles per hour from Table 2 in the main text. Thus, 57 576 vehicles use National Road 4 or Ring Road 3 each day.[6] The average length of an ESL-period is 159.2 days. Table 2 in the main text of the paper reports the average speed before ESL-implementation to be 74.6 km/h. The estimated average speed after ESL-implementation is 68.8 km/h, based on the estimated 5.8 km/h speed reduction in section 5.1. Consequently, each vehicle loses 40 seconds every day in the environmental speed limit period for a ten-kilometre drive, which is 1.77 hours (1 Hour and 46 minutes) for the entire environmental speed limit period.

As a simple benchmark for the value of time, we use the average salary in Norway. Based on Statistics Norway (2016), we assume the average monthly salary before tax measured in 2017 NOK to be 42,400 NOK. We assume average working hours to be 40 hours per week and end up with an estimate of the average hourly salary, after tax, of 199 NOK.[7] With this value of time, the time cost related to the estimated speed reduction is 352 NOK[8] per person and 528

[6] Passing vehicles environmental speed limit period: 2399 vehicles hourly x 24 hours per day = 57 576 vehicles per day
[7] Hourly salary after tax: 40,300 NOK x 1.052 x 0.75 tax / (40 hours x 4 weeks) = 199 NOK
[8] Total time loss per person each environmental speed limit period: 1.77 hours x 199 NOK per hour = 352 NOK

NOK per vehicle. This implies a total cost of 30 million NOK in each environmental speed limit period.[9] Table C.1 presents the details of our benchmark time cost calculation. We also refer to this calculation as "simple wage" in Table C.2 (the second column).

Table C.1. Value of time based on hourly wage

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**^{C}
Seconds lost per ESL period	-6368	*(B x C)*	
Hours lost per ESL period	**-1.77**^{D}	*((B x C)/3600)*	
Number of vehicles	**57,576**^{E}		
Number of passengers in vehicles	**1,5**^{G}		Source: TØI (2010)
Total loss ESL Period	30,420,000		**A x D x E x G**

[9] Total time loss cost: 1.77 hours x 199 NOK x 1.5 passengers x 57576 Vehicles = 30 419 992 NOK

Table C.2. Value of time under different assumptions about time costs

	Simple wage	Public Estimates of time costs and traffic composition								
Seconds lost per vehicle (10 km drive)	40	40	40	40		40	40			
No. of days of per ESL-period	159.2	159.2	159.2	159.2		159.2	159.2			
Hours lost each ESL-period per car	1.77	1.77	1.77	1.77		1.77	1.77			
Accumualted no. of vehicles in 1000s on average per 24 hours	57.58		52.30				5.27			
	All Vehicles	**Light Vehicles**				**Heavy Vehicles**			**Sum**	**% HV**
		Costs if country mean distance				All distances				
		Mean 0-70, 70-200, >200 km								
		work	commute	leisure	Sum	Trucks	Busses	Sum		
Costs	199	449	112	95		676	487			
Share	1	0.18	0.21	0.60		0.50	0.50			
People in the car	1.5	1.15	1.11	2.00		1.00	1.00			
Sum	**30.40**	8.60	2.42	10.55	**21.56**	3.15	2.27	**5.43**	**26.99**	20 %
		Costs if all 0-70km								
		work	commute	leisure	Sum					
Costs		449	100	85						
Share		0.2	0.23	0.56						
People in the car		1.15	1.1	1.9						
Sum		9.55	2.34	8.37	**20.26**			**5.43**	**25.69**	21 %
		Costs if all 70-200km								
		work	commute	leisure	Sum					
Costs		449	217	169						
Share		0.09	0.15	0.77						
People in the car		1.2	1.2	2.2						
Sum		4.49	3.61	26.49	**34.59**			**5.43**	**40.01**	14 %

Notes: Calculations as explained in the text. Note that the simple wage calculation are in 2017 NOK and the public estimates are in 2016 NOK. HV refers to heavy vehicles. Costs refer to NOKs per hour, share to the weight used when aggregating across the different travel purposes (work/business, commute back and forth to work and leisure). People in the car is self-explanatory. For convenience, we assume 50/50 Trucks/Busses for heavy vehicles.

As an alternative to the time cost of 199 NOK per hour, we now use the figures recommended by the Directorate of Public Roads (2018) for new road projects. They separate between light vehicles and heavy vehicles.

The figures for light vehicles are based on Østli et al. (2015), and they are broken down in short, medium and long distance travels, the average number of people travelling in each car and three types of travels (work-related travel, commute back and forth to work, and leisure travel). The time spent on work-related travel is valued according to the salary costs of employers, whereas the value of the time spent on commute and leisure travels are based on survey information from Ramjerdi et al. (2010).

For heavy vehicles, the Directorate of Public Roads (2018) base their figures on Norwegian Public Roads Administration (2017) and separate between trucks on the one hand and busses on the other. There is no separation according to the length of travel and there is no heterogeneity in terms of purpose of travel.

We use our data to estimate the share of light versus heavy vehicles (about 9% of the traffic is by heavy vehicles, as shown in table C.2). We assume that 50% of the heavy traffic are busses and 50% are trucks.

In the right part of table C.2, we present three calculations based on the figures from Directorate of Public Roads (2018): mean distance trips, short distance trips and medium distance trips. In the mean scenario, the time costs sum to 27 million NOK for each ESL-period, 20% of which is due to heavy traffic.[10]

We provide time cost calculations for two other scenarios: all travel based on short travel or all travel based on medium length travel. The Directorate of Public Roads (2018) provides figures for travels of 0-70 km and for travels of 70-200 km, in addition to the national-average type of travel. Different travel-distance entails different assumptions about perceived time costs, type of travels and number of passengers in the car. We calculate a cost of 26 million NOK if we assume all travels are short (0-70 km) and 40 million NOK if we assume all travels are of medium length travel (70-200 km).

Time cost estimates are debatable due to the many required assumptions, including assumptions about preference, productivity and wage variations across the country. The national estimates may not be entirely representative for the road users in Oslo. Furthermore, the composition of long and short travel and the purpose of the travels on the ESL-roads in Oslo may also differ from the assumptions made by the public road authorities. One insight from the above, however, is that the heavy traffic is a relatively important part of the costs, in spite of counting for less than 10% of the traffic.

[10] The public figures allow us to assign different costs to light and heavy vehicles. We use traffic data broken down on light and heavy vehicles and find that heavy vehicles account for 20% of the costs of 27 million NOK, although they account for only about 9% of the traffic. The reason is that an hour with a heavy vehicle is valued at 582 NOK (assuming 50% trucks and 50% busses) and an hour with a light vehicle is valued at 233 NOK (based on the national average of travelling distance and type of travel).

Fuel consumption

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, et al. 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 (The Norwegian Petroleum Industry Association 2009)[11]. 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.[12] This implies a benefit of 83 NOK per vehicle.

Accidents and noise

We now 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 social benefits related to a reduction in accidents and noise pollution.[13] 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.[14] This implies a likelihood of being involved in an accident of 0.00019%.[15] 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.6 illustrates the development in the number of

[11] Average cost based on both diesel and gasoline

[12] 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

[13] 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.

[14] These estimates are based on data obtained from Norwegian Public Road Administration. This estimate is conservative as it only includes accidents with reported injuries. From Figure A.6 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.

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

accidents during the period 2002–2015 for National Road 4 and Ring Road 3. Even though the likelihood of an accident is small, a study by Elvik (2013) suggests that the implementation of ESL 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 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 and Flügel 2010).[16] 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.[17] This estimate 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.[18]

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 and 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 (Agency for Urban Environment, City of Oslo 2013). Thus, we assume there are about 300 vulnerable citizens per km.[19] 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.[20] Meland et al. (2005) estimate that the reduction in traffic noise related to the implementation of ESL is 2 dB. We assume that this result is generalizable 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 and Schroten 2007). In our calculation, we

[16] The costs include medical, material, administrative costs and costs of lost output in addition to valuations of statistical lives and injuries.
[17] 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
[18] We value a statistical life to 30.5 MNOK, measured in 2017 NOK. This estimate is based on the study by Elvik et al. (2010) on the valuation of statistical life related to traffic accidents.
[19] Number of citizens per km: 392,400 citizens / (170 km + 1140 km) = 299.54
[20] Number of citizens close to the environmental speed limit roadways: 299.54 citizens x 29 km = 8,687

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[21], this corresponds to 0.3 NOK for each vehicle.

Our cost-benefit calculation indicates a time loss of 30 MNOK each ESL-period (3.8 million USD). In addition comes potential saving in terms of fuel, noise and accidents of in total 4.7, 5.7 and 3 MNOK, respectively, adding up to total social cost of 17 MNOK (2.2 million USD) under the hourly wage scenario. We regard these benefit estimates as speculative, however, since we do not have the data to estimate the effect on these outcomes of the ESL policy and they rely on strong assumptions.

[21] Social Benefit Noise: 8,687 citizens x 335 NOK x 1.142 x 2 dB x 160/365 = 2,913,653 NOK

D. OLS estimates

For completeness, we present OLS-estimates of the association between speed and air pollution in Panel A, Table G.1. Only for PM_{10} do we estimate a statistically significant and positive coefficient on Speed, suggesting that a decrease in speed of 6 km/h is associated with a decrease in the concentration of PM_{10} of about 3.9%. The estimated coefficients on speed are negative and statistically insignificant for the three other pollutants. The OLS-estimated coefficient on the ESL-dummy, presented in Panel B, Table G.1, is negative for all pollutants and statistically significant for three of them. The coefficients suggest that the ESL-period was associated with better air quality, by 13.46% for NO_2, 20.91% for NO_X and 12.92% for PM_{10}.

However, the divergence between the RDD and the OLS estimates when it comes to PM_{10} are no longer present when we estimate with OLS for each station (results not presented to save space). The OLS estimate for PM_{10} on speed is statistically insignificant across all stations and the estimates for the ESL-coefficient are statistically insignificant across all air pollutants and stations.

Trending omitted variables may explain the divergences between the RDD- and OLS-estimates, as the RDD provides an unbiased estimate as long as the omitted variables are trending smoothly across the cutoff-date. One case in point is traffic volume and the ESL-dummy. In Table G.1, we include traffic volume as a control, whereas omitting traffic volume creates a negative bias in the ESL-coefficients (results not presented to save space). This is consistent with the ESL-dummy correlating negatively with traffic volume, and traffic volume having a positive effect on the levels of the air pollutants. The descriptive statistics in Table 2 show that traffic volume is lower in November than in October. This may be due to for example more challenging driving conditions in November. The OLS-estimates may then mistakenly assign the downward trend in traffic volume to the ESL-policy active in November, whereas other factors are in reality explaining the fall in traffic volume. This example illustrates how trending omitted variables create a bias in the OLS-estimates and can lead researcher to draw the wrong conclusions.

Table D.1. Effect of Speed and ESL on Air Pollution: OLS

	(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 ESL 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.

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

References

Agency for Urban Environment, City of Oslo. 2013. *Handlingsplan mot støy i Oslo Kommune 2013–2018.* Bymiljøetaten.

American Thoracic Society . 2002. *American Thoracic Society Statement: Occupational Contribution to the Burden of Airway Disease.* American Thoracic Society .

Amundsen, Astrid H, and Ronny Klæboe. 2005. *A Nordic perspective on noise reduction at the source.* The Institute of Transport Economics (TOI).

Angrist, Joshua D., and Alan B. Krueger. 1999. "Empirical strategies in labor economics." In *Handbook of Labor Economics*, by Orley Ashenfelter and David Card, 1277-1366. New York: Elsevier.

Angrist, Joshua D., and Jörn-Steffen Pischke. 2009. *Mostly Harmless Econometrics: An Empiricist´s Companion.* New Jersey: Princeton University Press.

Bel, Germà, and Jordi Rosell. 2013. "Effects of the 80 km/h and variable speed limits on air pollution in the metropolitan area of barcelona." *Transportation Research Part D* (Elsevier Ltd) 90–97.

Bel, Germà, Catalina Bolancé, Montserrat Guillén, and Jordi Rosell. 2015. "The environmental effects of changing speed limits: A quantile regression approach." *Transportation Research Part D* 76–85.

Benthem, Arthur van. 2015. "What is the Optimal Speed Limit on Freeways." *Journal of Public Economics* 44-62.

Boer, Eelco den, and Arno Schroten. 2007. *Traffic noise reduction in Europe.* CE Delft.

City of Oslo. 2017b. *Folkemengde og endringer.* 1 January. Accessed May 24, 2017. https://www.oslo.kommune.no/politikk-og-administrasjon/statistikk/befolkning/folkemengde-og-endringer/.

—. 2017a. *Oslo kommunes regnskap for 2016.* Accessed June 5, 2017. https://www.oslo.kommune.no/politikk-og-administrasjon/politikk/byradet/arsberetning-2016/?del=4.

Dijkema, Marieke B.A., Saskia C. van der Zee, Bert Brunekreef, and Rob T. van Strien. 2008. “Air quality effects of an urban highway speed limit reduction.” *Atmospheric Environment* (Elsevier) 9098–9105.

Directorate of Public Roads. 2018. “Konsekvensanalyser, Veiledning, Håndbok V712.” 14 November. Accessed March 2019. Håndbok V712 Konsekvensanalyser.pdf.

Elvik, Rune. 2013. *A before–after study of the effects on safety of environmental speed limits in the city of Oslo, Norway.* Elsevier Ltd.

Elvik, Rune, Knut Veisten, and Stefan Flügel. 2010. *Den norske verdsettingsstudien. Ulykker - Verdien av statistiske liv og beregning av ulykkenes samfunnskostnader.* TØI.

European Comission. 2016. *Air Quality Standards.* 8 June. Accessed February 14, 2017. http://ec.europa.eu/environment/air/quality/standards.htm.

—. 2017. *Mobility and Transport.* Accessed 10 10, 2017. https://ec.europa.eu/transport/road_safety/specialist/knowledge/speed/many_drivers_exceed_the_speed_limit/speed_choice_why_do_drivers_exceed_the_speed_limit_en.

Gelman, Andrew, and Guido Imbens. 2014. “Why High-order Polynomials Should not be Used in Regression Discontinuity Designs.” *NBER Working Paper No. 20405.*

Hagen, Leif Otto, Steinar Larssen, and Jan Schaug. 2005. *Miljøfartsgrense i Oslo - Effekten på luftkvaliteten av redusert hastighet på rv 4.* NILU.

Hagen, Leif Otto, Steinar Larssen, and Jan Schaug. 2005. *Miljøfartsgrense i Oslo - Effekten på luftkvaliteten av redusert hastighet på rv 4.* NILU.

Jongens, A. W. D. 2008. *Reducing Road Traffic Noise in South Africa.* University of Cape Town.

Kable. 2011. *Turning Down the Volume on Road Traffic.* 4 August. Accessed June 2, 2017. http://www.roadtraffic-technology.com/features/feature126199/.

Keuken, M.P., S. Jonkers, I.R. Wilmink, and J. Wesseling. 2010. “Reduced NOx and PM10 emissions on urban motorways in The Netherlands by 80 km/h speed management.” *Science of the Total Environment* (Elsevier) 2517–2526.

Lee, Davis S., and Thomas Lemieux. 2010. "Regression Discontinuity Designs in Economics." *Journal of Economic Literature* (48): 281-355.

Leira, Håkon Lasse. 2011. *Kols – ikke bare hos røykere.* 20 September. Accessed May 24, 2017. http://tidsskriftet.no/2011/09/kommentar/kols-ikke-bare-hos-roykere.

Magnussen, Kristin, Ståle Navrud, and Orlando San Martin. 2010. *Den norske verdsettingsstudien: Verdsetting av tid, sikkerhet og miljø i transportsektoren: Luftforurensning.* TØI and SWECO. https://www.toi.no/getfile.php?mmfileid=17580.

Meland, Sondre, Ellen Foslie, Live Hesthagen, Arumugadas Thambiaiyah, Ingvild Kjos, Berit Kreken, Geir Regbo, et al. 2005. *Miljøfartsgrense - riksvei 4.* Statens Vegvesen.

Navrud, Ståle. 2002. *The State-Of-The-Art on Economic Valuation of Noise.* Department of Economics and Social Sciences Agricultural University of Norway.

Navrud, Ståle. 2004. *What is silence worth? Economic valuation of road traffic noise.* Department of Economics and Resource Management.

Nielsen, Rune. 2014. *Kols: Livskvalitet og kostnader (2003).* 28 January. Accessed May 24, 2017. https://www.lhl.no/forskning-og-prosjekter/forsknings-prosjekter/prosjekter/kols-livskvalitet-og-kostnader-2003/.

Norwegian Labour Inspection Authority. 2008. *Samfunnsøkonomiske kostnader av arbeidsrelatert astma.* Direktoratet for arbeidstilsynet, Arbeidstilsynet.

Norwegian Public Roads Administration. 2017. "Oppdatering av enhetskostnader i nytte-kostnadsanalyser i Statens vegvesen."

Østli, Vegard, Askill Harkjerr Halse, and Marit Killi. 2015. "Verdsetting av tid, pålitelighet og komfort tilpasset." TØI-rapport 1389, Transportøkonomisk institutt. https://www.toi.no/publikasjoner/verdsetting-av-tid-palitelighet-og-komfort-tilpasset-ntm6-article32984-8.html.

Ramjerdi, F., Flügel, S., Samstad, H., & Killi, M. 2010. "Den norske verdsettingsstudien - Tid." TØI Rapport 1053B, Transportøkonomisk institutt.

Samstad, Hanne, Farideh Ramjerdi, Knut Veisten, Ståle Navrud, Kristin Magnussen, Stefan Flügel, Marit Killi, Askill Harkjerr Halse, Rune Elvik, and Orlando San Martin. 2010. "Den norske verdsettingsstudien - Sammendragsrapport." TØI ans Sweco.

Statistics Norway. 2016. *Folkemengde og befolkningsendringar, 1. januar 2016.* 19 February. Accessed May 24, 2017. https://www.ssb.no/befolkning/statistikker/folkemengde/aar-per-1-januar/2016-02-19#content.

—. 2016. *Lønn, alle ansatte, 2015.* 3 March. Accessed May 11, 2017. https://www.ssb.no/arbeid-og-lonn/statistikker/lonnansatt/aar/2016-03-03.

—. 2016. *Utslipp til luft av svevestøv, etter kilde. 1 000 tonn.* 13 December. Accessed May 10, 2017. https://www.ssb.no/287171/utslipp-til-luft-av-svevestov-etter-kilde.1000-tonn.

Strand, Arvid, Petter Næss, Aud Tennøy, and Christian Steinsland. 2009. *Gir bedre veier mindre klimagassutslipp?* TØI.

Tempo. 2017. *Vei.* Accessed May 31, 2017. http://www.transportmiljo.no/tema/nokkeltall/vei/.

The Norwegian Petroleum Industry Association. 2009. *Norsk Petroleumsinstitutt: Priser på oljeprodukter.* 17 September. Accessed May 31, 2017. http://www.np.no/priser/.

Issued in the series Discussion Papers 2018

2018

01/18 January, Øystein Foros, Mai Nguyen-Ones, and **Frode Steen**, "Evidence on consumer behavior and firm performance in gasoline retailing"

02/18 January, **Agnar Sandmo**, "A fundamental externality in the Labour Market? Ragnar Frisch on the socially optimal amount of work"

03/18 February, Pierre Dubois and **Morten Sæthre**, "On the Effect of Parallel Trade on Manufacturers' and Retailers' Profits in the Pharmaceutical Sector"

04/18 March, **Aline Bütikofer**, Julie Riise, and Meghan Skira, "The Impact of Paid Maternity Leave on Maternal Health"

05/18 March, **Kjetil Bjorvatn** and **Bertil Tungodden**, "Empowering the disabled through savings groups: Experimental evidence from Uganda"

06/18 April, Mai Nguyen-Ones and **Frode Steen**, "Measuring Market Power in Gasoline Retailing: A Market- or Station Phenomenon?

07/18 April, **Chang Koo Chi** and Trond Olsen, "Relational incentive contracts and performance"

08/18 April, Björn Bartling, **Alexander W. Cappelen, Mathias Ekström, Erik Ø. Sørensen**, and **Bertil Tungodden**, «Fairness in Winner-Take-All Markets»

09/18 April, **Aline Bütikofer, Sissel Jensen**, and **Kjell G. Salvanes**, «The Role of Parenthood on the Gender Gap among Top Earners»

10/18 May, **Mathias Ekström**, "The (un)compromise effect"

11/18 May, Yilong Xu, **Xiaogeng Xu**, and Steven Tucker, «Ambiguity Attitudes in the Loss Domain: Decisions for Self versus Others»

12/18 June, **Øivind A. Nilsen**, Per Marius Pettersen, and Joakim Bratlie, "Time-Dependency in producers' price adjustments: Evidence from micro panel data"

13/18 June, **Øivind A. Nilsen**, Arvid Raknerud, and Diana-Cristina Iancu, "Public R&D support and firms' performance. A Panel Data Study"

14/18 June, Manudeep Bhuller, **Gordon B. Dahl**, **Katrine V. Løken**, and Magne Mogstad: «Incarceration, Recidivism, and Employment"

15/18 August, Manudeep Bhuller, **Gordon B. Dahl, Katrine V. Løken**, and Magne Mogstad: «Incarceration Spillovers in Criminal and Family Networks"

16/18 August, Pedro Carneiro, Kai Liu, and **Kjell G. Salvanes**: "The Supply of Skill and Endogenous Technical Change: Evidence From a College Expansion Reform"

17/18 August, **Chang Koo Chi**, "An analysis of the two-bidder all-pay auction with common values"

18/18 August, **Alexander W. Cappelen**, Cornelius Cappelen, and **Bertil Tungodden**, "Second-best fairness under limited information: The trade-off between false positives and false negatives"

19/18 September, **Aline Bütikofer, Antonio Dalla Zuanna**, and **Kjell G. Salvanes**: "Breaking the Links: Natural Resource Booms and Intergenerational Mobility"

20/18 September, Juan Pablo Atal, José Ignacio Cuesta, and **Morten Sæthre**, "Quality regulation and competition: Evidence from Pharmaceutical Markets"

21/18 October, Orazio Attanasio, Agnes Kovacs, and **Krisztina M**olnar, "Euler Equations, Subjective Expectations and Income Shocks"

22/18 October, Antonio Mele, **Krisztina Molnár**, and Sergio Santoro, "On the perils of stabilizing prices when agents are learning"

23/18 November, Bjørn-Atle Reme, Helene Lie Røhr, and **Morten Sæthre**, "The Poking Effect: Price Changes, Information, and Inertia in the Market for Mobile Subscriptions"

24/18 November, **Ingrid Hoem Sjursen**, "Accountability and taxation: Experimental evidence"

25/18 November, **Liam Brunt** and Antonio Fidalgo, "Why 1990 international Geary-Khamis dollars cannot be a foundation for reliable long run comparisons of GDP"

26/18 November, **Ola Honningdal Grytten**, "A continuous consumer price index for Norway 1492-2017"

27/18 December, **Liam Brunt** and Antonio Fidalgo, "Feeding the people: grain yields and agricultural expansion in Qing China"

28/18 December, **Kurt R. Brekke**, Chiara Canta, Luigi Siciliani and Odd Rune Straume, "Hospital Competition in the National Health Service: Evidence from a Patient Choice Reform"

29/18 December, Richard Friberg, **Frode Steen** and **Simen A. Ulsaker**, "Hump-shaped cross-price effects and the extensive margin in cross-border shopping"

30/18 December, David Jaume and **Alexander Willén**, "Oh Mother: The Neglected Impact of School Disruptions"

31/18 December, Jesús Crespo Cuaresma, **Gernot Doppelhofer**, Martin Feldkircher and Florian Huber, "Spillovers from US monetary policy: Evidence from a time-varying parameter GVAR model"

32/18 January, **Patrick Bennet** and Amine Ouazad, " Job Displacement, Unemployment, and Crime: Evidence from Danish Microdata and Reforms"

2019

01/19 January, **Aline Bütikofer**, Christopher Cronin, Meghan Skira, "Employment Effects of Healthcare Policy: Evidence from the 2007 FDA Black Box Warning on Antidepressants"

02/19 February, **Ingar Haaland** and Cristopher Roth "Beliefs About Racial Discrimination and Support for Pro-Black Policies "

03/19 February, **Astrid Kunze** and Xingfei Liu, "Universal Childcare for the Youngest and the Maternal Labour Supply"

04/19 February, **Ingvild Almas, Alexander W. Cappelen, Bertil Tungodden**. "Cutthroat capitalism versus cuddly socialism: Are Americans more meritocratic and efficiency-seeking than Scandinavians?"

05/19 February**, Chang Koo Chi**, Kyoung Jin Choi. "Performance Measurement in Agency Models"

06/19 March, **Alexander W. Cappelen**, **Ranveig Falch** and **Bertil Tungodden.** "The Boy Crisis: Experimental Evidence on the Acceptance of Males Falling Behind"

07/19 March, Frode Skjeret, **Frode Steen** and **Timothy G.A Wyndham**. "Paywalls and the demand for online news"

08/19 April, **Ola. H. Grytten** and Viktoriia Koilo. "The Financial Instability Hypothesis and the Financial Crisis in Eastern European Emerging Economies"

09/19 April, **Alexander W. Cappelen**, Johanna Mollerstrom, Bjørn-Atle Reme and **Bertil Tungodden.** "A Meritocratic Origin of Egalitarian Behavior"

10/19 April, **Fanny Landaud**. "From Employment to Engagement? Stable Jobs, Temporary Jobs, and Cohabiting Relationships"

11/19 May, **Ola Honningdal Grytten** and Viktoriia Koilo. "Evidence of the Environmental Kuznets Curve in Emerging Eastern European Economies"

12/19 June. Rune Midjord, Tomás Rodríguez Barraquer, and **Justin Valasek.** "Robust Information Aggregation Through Voting"

13/19 June. Eva M. Berger, **Henning Hermes**, Guenther Koenig, Felix Schmidt, and Daniel Schunk. "Self-regulation Training and Job Search Behavior: A Natural Field Experiment Within an Active Labor Market Program"

14/19 June. **Henning Hermes**, Martin Huschens, Franz Rothlauf and Daniel Schunk. "Motivating Low-Achievers—Relative Performance Feedback in Primary Schools"

15/19 August. Viktoriia Koilo and Ola **Honningdal Grytten.** "The Blue Maritime C luster Crisis Financial Instability and Supply Chain Management Effects"

16/19 Jonas Andersson, Fred Schroyen and Gaute Torsvik. "The impact of international tax information exchange agreements on the use of tax amnesty: evidence from Norway"

17/19 Ingrid Kristine Folgerø, **Torfinn Harding** and Benjamin S. Westby. "Going Fast or Going Green? Evidence from Environmental Speed Limits in Norway"

NHH

NORGES HANDELSHØYSKOLE
Norwegian School of Economics

Helleveien 30
NO-5045 Bergen
Norway

T +47 55 95 90 00
E nhh.postmottak@nhh.no
W www.nhh.no