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

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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 2004-2015 period. We find that lowering the speed limit from 80 to 60 km/h reduces travel speed by 5.8 km/h, but we find no effect on local air pollution. A conservative cost–benefit calculation suggests a net social loss from the speed limit reductions of 0.52 billion USD each year. 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

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1. Introduction

Policy makers increasingly search for new ways to reduce air pollution related to transport. In the EU, transport is the only major sector where greenhouse gas emissions are still rising (European Commission 2017) and air pollution is projected to be the top environmental cause of mortality worldwide by 2050 (OECD 2012). As a new policy tool, cities like Amsterdam, Barcelona and Oslo have lowered speed limits to improve local air quality. Speed limits have the desirable properties of being easy to enforce and difficult to circumvent, and their effects would be immediate. However, the evidence on the relationship between speed and air quality is weak. Although engineering simulation models tend to find that reduced speed improves air quality (EEA 2011a, UK Government 2017), the few empirical economics studies that exist offer mixed conclusions (Benthem 2015, Bel and Rosell 2013, Dijkema, et al. 2008, Keuken, et al. 2010).

In this paper, we estimate the effects of Oslo’s large-scale introductions of Environmental Speed Limits (ESL) on air quality in terms of Nitrogen Oxides (NO₂ and NOₓ) and Particulate Matter (PM₂.₅ and PM₁₀). We also estimate the effects on travel speed and traffic volume. We use the estimates to undertake a cost-benefit analysis of the policy. In 2004, Oslo lowered the maximum speed limit from 80 km/h to 60 km/h on National Road 4 during the winter (Norwegian Ministry of Transport and Communications 2004). The aim was to improve local air quality by reducing the level of Particulate Matter. Oslo later expanded the 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). The end-effects of ESL on air quality is an empirical question, as it depends on both the ex-ante unknown behavioural responses among drivers and the, in practice, unknown technical relationship between speed and pollution for the affected vehicle fleet.

Our first finding is that a 20 km/h reduction in the maximum speed limit reduces travel speed by 5.8 km/h, from about 75 km/h to 69 km/h. This indicates imperfect compliance with the ESL, but still a statistically significant and robust reduction in travel speed. Traffic volume (the number of passing vehicles) is unaffected by the ESL-policy. Our second and most central
finding is that the ESL does not improve air quality. The estimates take an unexpected positive sign across all air pollutants and are in most specifications statistically undistinguishable from zero. Our third finding is that the ESL-policy implies a net loss to society of 0.52 billion USD each ESL season. This is equivalent to 8% of the operating expenses of Oslo Municipality. The lack of effects of the ESL-policy on air pollution suggest that other actions are necessary to improve the city’s air quality.

Speed limit reductions add to a set of policies aimed at reducing air pollution from road traffic, such as driving restrictions, congestion charges, stricter emission standards and expansions of public transport. Simulations frequently inform policy decisions in this domain. Based on simulations, EEA (2011a) states that “Lowering speed limits [on motorways] […] would reduce NO\textsubscript{X} and PM emissions and consequently help improve Europe’s air quality.” Similarly, the UK Government (2017) finds reductions of NO\textsubscript{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. They stress 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. This paper contributes to the policy debate on air pollution with rigorous real world evidence on pollution and traffic from an increasingly popular but potentially costly policy option.

Only a handful of academic economics papers have investigated the effect of speed limits on air pollution and they have reached mixed conclusions. Benthem (2015) finds that higher speed limits in western U.S. states are associated with a 15% increase in concentrations of NO\textsubscript{2} and no statistically significant change in the concentration of PM\textsubscript{10}. Bel and Rosell (2013) study the effect of two separate policies implemented by the regional government of Catalonia (Spain) on concentrations of NO\textsubscript{X} and PM\textsubscript{10}. They find that lowering the fixed speed limits to 80 km/h increases the level of NO\textsubscript{2} by 2–3% and PM\textsubscript{10} by 5–6%. In contrast, the effect of introducing variable speed limits reduces the level of NO\textsubscript{2} by 8–17% and PM\textsubscript{10} by 14–17%. Dijkema et al. (2008) analyse the consequences of a similar reduction in the maximum speed limit in the Netherlands on NO\textsubscript{X}, PM\textsubscript{1} and PM\textsubscript{10}. Their findings suggest that the policy lead to

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\footnote{For more on alternative traffic policies meant to reduce local air pollution, 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.}
a decrease in PM$_{10}$ of about 7%. However, they find no evidence for an improvement in the level of NO$_2$. Some of these results were disputed by Keuken et al. (2010), who 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 enforcement” lead to a reduction of 5–30% for NO$_X$ and 5–25% for PM$_{10}$. Table 1 in the online appendix summarizes the previous research on speed management policies and air quality.

The previous papers on 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 identification strategies are prone to omitted variable bias, e.g., speed limits are not set randomly but depend on, for the researcher, unobserved characteristics. To mitigate omitted variable bias, we implement a regression discontinuity design (RDD). The key identifying assumption 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 in our setting. 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 aspects make our setting ideal for a regression discontinuity design. First, and in contrast to the variable speed limit policy introduced in Barcelona, the ESL in Oslo has been in effect the entire winter seasons for the roads that we study. This means that drivers could not easily adapt to the policy by for example substituting driving inside the active period with driving outside the active period. Such strategic behaviour around the cut-off date would invalidate the RDD approach. Second, the nature of the ESL-policy in Oslo, with introductions every active year on November 1st allows us to investigate a set of quasi-experiments, which enables us to use more data to identify the effect of the policy and to evaluate the external validity across different sub-sample estimates. Third, to construct meaningful counterfactuals and placebo tests, we utilize that ESLs were introduced gradually across different roads as well as completely abandoned for 3 years at the end of our sample period. We use this also to obtain difference-in-difference estimates, as an alterantive to our RDD-estimates. Forth, hourly high quality data exist on all three key components needed to evalatue the policy:
traffic, air pollution and weather. Monitoring stations of traffic provides us with hourly data on the entire population of passing cars, which allows us to investigate whether any impact works via speed or traffic volume. Monitoring stations of air quality, located close to the roads with the purpose of measuring pollution related to traffic, provide us with data on the four key air pollutants NO\textsubscript{2}, NO\textsubscript{X}, MP\textsubscript{2.5} and PM\textsubscript{10}. A weather station located relatively close to the other monitoring stations offers data on temperature, precipitation, wind speed and wind direction. These factors are important to control for, as they potentially correlate with speed and the number of cars on the one hand and air pollution on the other hand. Our large amount of data also allows us to control for a large set of dummies to capture unobservables.

The estimated effects of the ESL are very stable across different roadways and years in Oslo. This indicates that our estimates for single roadways in Oslo have external validity for other roadways in Oslo. Given the variation in results across the studies presented above, more research is needed to confidently inform policy makers on how to reduce air pollution from traffic in modern cities. This paper contributes by studying a change in speed in the range relevant for many city roads.

The paper proceeds as follows. In section 2, we present background information about the ESL-policy in Oslo and the data used in our analysis. Section 3 presents our identification strategy. Section 4 presents the estimation results and section 5 the cost–benefit analysis. The final section concludes. An online appendix provides supplementary material.

2. **Background and Data**

2.1 **Background for the ESL-policy in Oslo**

Nitrogen oxides (NO\textsubscript{X}) and particulate matter (PM) are held to have large negative health impacts (OECD 2012), and limit values have been widely exceeded. For example, in 2012, 64% of the total EU urban population were exposed to PM\textsubscript{10} levels exceeding the World Health Organization (WHO) air quality guidelines (EEA 2015). In EU-28’s in 2010, the contributions of road transport were about 40% for NO\textsubscript{X} and about 15% for PM. For PM\textsubscript{2.5}, road transport is the second most important source. Exhaust fumes is a source of NO\textsubscript{X}, and wear of brakes, tires and asphalt are sources of PM (www.luftkvalitet.info 2017). The relationship between
speed and vehicle emissions is often described by a U-shaped relationship (Bel and Rosell 2013, Benthem 2015), but acceleration and decelerations make the relationship more complicated as they increase vehicle emissions. EEA (2016) reports that the levels of NO\textsubscript{X} and PM sank with more than 25% and about 20%, respectively, over the 2005-2014 period. NO\textsubscript{X}-reductions have been slower than anticipated, however, partly due to diesel vehicles. Further PM\textsubscript{2.5}-reductions from residential combustions may also be politically challenging for many governments to achieve (EEA 2016).

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. From November 1\textsuperscript{st} 2004 to March 2005, the policy temporarily 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) analysed the effect of the pilot project. They found evidence suggesting a decrease in the levels of PM\textsubscript{10} of 35–40%, a decrease of NO\textsubscript{X} of 12–13% and no change in PM\textsubscript{2.5}. The report also suggested that the introduction of environmental speed limits reduced travel speed by approximately 10 km/h and the number of cars by 2.7%. Their conclusion resulted in permanent implementation of the ESL 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. The latter
introduced the ESL during daytime only, with a speed limit of 60 km/h between 06:00 a.m. and 22:00 p.m., and 80km/h otherwise (Norwegian Public Roads Administration 2012).

The authority of the police to impose fines for violations of the temporary speed limits was uncertain, however. In a letter to the state attorney, Oslo police district specified that they would not enforce the environmental speed limits before their authority to impose fines was clarified. A lack of legal basis could mean that imposed fines would eventually have to be paid back (Hultgren, Berg og 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. Figure 1 shows the time-line of the ESL in Oslo. In this paper, we use data covering the period 2001-2015.

2.2 Data

2.2.1 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. 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, 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 connect the same

2 According to an article in Aftenposten, the main newspaper in Oslo, 14.10.2011.
3 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.
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).\(^4\)

**Figure 2. Map Over Monitoring Stations and Roadways in Oslo**

![Map showing the location of the Monitoring 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. Source: Modified map from Elvik (2013).](image)

*Notes:* Map showing the location of the Monitoring 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. Source: Modified map from Elvik (2013).

Table 1 shows a summary of the main characteristics for each monitoring station, including the percentage of missing observations for October and November during the years 2006–2011. None of the monitoring stations shows any signs of patterns in the missing values. Moreover, the missing values seem evenly distributed before and after November 1\(^{st}\).

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\(^4\) 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 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, our judgement is that the traffic monitoring station at Nydalen captures the traffic close to the air pollution monitoring station located at Smestad reasonably well, as it is 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).
8.2.2 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. 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 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. The simple test statistic reports a significant reduction in speed of 6.8 km/h from October to November and a significant decrease in the number of passing vehicles of nearly 80 vehicles each hour. There is large variation in the number of passing vehicles, reflecting variations over

5 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
the course of the day and over the different days in the week. Traffic is higher during the day compared to the night, with peaks during the morning and evening commutes.

### 2.2.3 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 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 NO₂, NOₓ, PM₁₀ and PM₂·₅ measured in μg/m³.6 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

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6 Mg/m³ is microgram (i.e. one millionth (1×10⁻⁶) of a gram) per cubic metre of air. 1 μg/m³ = 1 parts per billion (ppb) = 0.001 parts per million (ppm).
pollutants, NO₂, NOₓ, PM₁₀ and PM₂.₅. 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.⁷ 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.

2.2.4 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, and has been included because of its ability to interact with existing air pollutants to create secondary ones and because of its ability to wash away particles from the air and minimise their formation (Viard og 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.⁸ 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.

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⁷ Table A.2 in the online appendix lists current Air Pollution Regulations.
⁸ 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°
3. Empirical Strategy

3.1 Regression discontinuity design

We estimate the effect of introducing the ESL on speed and traffic as well as on the four air quality outcomes NO₂, NOₓ, PM₁₀ and PM₂.₅ by the following econometric model:\(^9\)

\[ y_t = y_0 + \tau_1(ESL_t) + \gamma_1 f(X - c) + \gamma_2 1(ESL_t) \times f(X - c) + \gamma_3 Z_t + \varepsilon_t \]  \hspace{1cm} (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, i.e. the reduced form effect of the policy. \(Z_t\) is a set of control variables, i.e. 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 average 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 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:\(^10\)

\[ y_t = \alpha_0 + \tau_2 \delta_t + \alpha_1 f(X - c) + \alpha_2 1(ESL_t) \times f(X - c) + \alpha_3 Z_t + u_t \]  \hspace{1cm} (2)

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\(^9\) We follow the approach laid out in Lee og Lemieux (2010) and Dahl et al. (2016).

\(^10\) Our treatment is continuous and because compliance to the reduction in maximum speed limits is likely to be imperfect, we estimate the effect of a given change in speed on air pollution by applying a two-stages least square estimation (2SLS) (Lee og Lemieux 2010). Thus, we use the implementation of environmental speed limits as an instrument for speed. We focus on speed, as we find no effect (“no first stage”) on the number of passing vehicles.
\( \delta_t \) is the fitted values from the 1st stage. \( \tau_2 \) 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.\(^{11}\) 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 section 4.3).

### 3.2 Potential threats to identification

#### 3.2.1 Strategic driving around the cutoff

Our primary identifying assumption is that, absent of the ESL-policy, the air quality in Oslo would not change discontinuously on November 1\(^{st}\). I.e., all other relevant observable and unobservable characteristics are continuous across the cut-off of date. This is equivalent to the assumption that optimising agents do not have precise control over the assignment variable (Lee og Lemieux 2010). Validity of this “no-manipulation” assumption implies random variation in treatment near the cut-off date. In our setting, drivers could in principle strategically move driving from the days after to the days before November 1\(^{st}\), or change their speed in advance to make up for the lost time after November 1\(^{st}\). However, we view this sort of strategic behaviour among drivers as unlikely to take place. 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. The time loss from a 1 km/h reduction in travel speed is about 7 seconds per 10 km in our setting. In line with this, Figure 3 reveals no suspicious bunching around the cutoff-date, neither in the number of passing vehicles nor in speed.\(^{12}\)

#### 3.2.2 Strategic implementation by policy makers

Another possibility is that public officials wanted and could strategically choose a date of implementation with unusual high or low concentrations of air pollution. However, the policy is set to start on November 1\(^{st}\) every year, and our investigation of both the weather data and the pollution data shows no discontinuities across the cutoff-date in years without the policy and at roads without the policy (see appendix Table A.3). We therefore view this simply as a theoretical possibility, without any empirical relevance.

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\(^{11}\) The IV-estimate is simply the reduced-form impact of the ESL on air quality divided by the first stage impact of environmental speed limits on speed (Lee og Lemieux 2010), both estimated with equation (1).

\(^{12}\) Figure A.1 in the online appendix presents Figure 3 for each monitoring station.
3.2.3 Other policies changing at the same time

Clearly, other policies that change at the same time as the ESL, is a potential threat to our identifying assumption. Unfortunately, two policies related to studded tires complicates our identification. 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 studless 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. Second, on November 1st, 2004, Oslo introduced a fee on the use of studded tires to incentivize the use of studless 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. Unfortunately, we do not have micro data on the use of studded tires.

To deal with the studded tires policies, we implement four strategies. First, we note that, most likely, the use of studded tires would affect only $PM_{10}$ and $PM_{2.5}$ directly. The bias for NO$_2$ and NO$_X$ should be negligible. Second, we look for trends across the years in the discontinuity in $PM_{10}$ and $PM_{2.5}$ on November 1st, as 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). Third, we utilize the fact that in 2012-2015, the ESL-policy was not active. If a discontinuity in the use of studded tires were important, we would expect to see a positive jump for $PM_{10}$ and $PM_{2.5}$ at November 1st for those years (see Figure A.4 and Table A.3 in the online appendix). Forth, we look for discontinuities in locations that did not implement environmental speed limits (see Table A.3 in the online appendix). In short, 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.14

3.2.4 Change in other characteristics around the cutoff

Days before and after November 1st may differ in ways that could affect air quality, e.g. due to seasonal variation in the demand for travel or climate conditions. Our polynomial trend should capture any such differences that change smoothly around the cut-off date. In addition, we control for a host of observable factors and a large set of dummies. To investigate whether our identifying assumption is likely to hold, we test for discontinuities in weather variables (see Table A.4 in the online appendix). In addition, we 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.3 in the online appendix). Finally, we report on the sensitivity of our estimates to different choices of polynomials and bandwidths (see section 4.3). The conclusion from all these exercises is that we do not find any indications of discontinuous changes around November 1st, other than those plausibly caused by the ESL-policy.

14 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 questions the effectiveness of these measures. Norman and Johansson (2006), suggest that the use of sweeping and washing have none or marginal effects on the concentration of Particulate Matter. This is also supported by Aldrin et al. (2008). The impact of salting have been evaluated to be more propitious especially on larger particles and during dry weather (Norman and Johansson 2006, Aldrin, Haff and Rosland 2008, Aldrin, Steinbakk and Rosland 2010). The effects of salting are only temporary and disappear within few days.
4. Empirical Results

4.1 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.\(^\text{15}\)

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.

\(^\text{15}\) 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 \((\text{years}) \times 3 \,(\text{stations}) \times 24 \,(\text{hours}) = 432\) observations.
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 section 4.3 and treat the number of vehicles as a control variable in the rest of the paper.\textsuperscript{16}

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 choose to use a simple linear time trend, as the data presented in Figure 3 reveals no obvious nonlinear trends, and simple specifications are in general preferred over more complex specifications (Lee og Lemieux 2010, Gelman og Imbens 2014).\textsuperscript{17} A narrow bandwidth offers less risk of biased estimates at the expense of lower precision because of a smaller range of data. In addition to visual examination and inspection of estimates for a wide range of bandwidths, we base our choice of bandwidth on the "leave-one-out" cross-validation procedure proposed by Lemieux og Milligan (2008) and Ludwig og Miller (2007). The procedure suggests the optimal bandwidth to be approximately 15 days for speed and traffic volume, based on the minimization of the cross-validation criterion. The choice of bandwidth prevents clustering of the standard errors at the monthly level, so we cluster by year. We explore the sensitivity to the choices concerning the polynomial, the bandwidth and clustering in section 4.3.

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

\textsuperscript{16}We show in section 4.3 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.

\textsuperscript{17}There are several data-driven strategies to choose the most appropriate functional form. One approach is to use the Akaike information criterion (AIC). In our case, the AIC tends to select very flexible time trends, i.e. polynomials of order 9 or higher. Another approach is to use the F-test approach suggested by Lee and Lemieux (2010). Applied to our data, this method tends to select polynomials of order 5 or higher.
speed limit in the U.S. was associated with a 0.3-0.4 km/h increase in travel speed. However, our results are somewhat lower than the evaluation rapport by Hagen et al. (2005), who estimated that the introduction of the ESL 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. We comment further on Hagen et al. (2005) in section 4.4.

4.2 The effects on air pollution

4.2.1 Intention-to-Treat estimates of ESL on air pollution

In this section, we present ITT-estimates of the ESL on the four air pollutants. Figure 4 plots the residuals from estimating equation (1) excluding the ESL-dummy.¹⁸ As we did for speed,

¹⁸ 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.
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 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. The “leave-

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

<table>
<thead>
<tr>
<th>(τ$_1$) ESL</th>
<th>(τ$_1$) 1st stage</th>
<th>(τ$_2$) 2nd stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>NO$_2$</td>
<td>NO$_X$</td>
</tr>
<tr>
<td>-5.7762***</td>
<td>0.1175*</td>
<td>0.1053</td>
</tr>
<tr>
<td>Observations</td>
<td>12371</td>
<td>12420</td>
</tr>
<tr>
<td>R$^2$</td>
<td>0.0135</td>
<td>0.0079</td>
</tr>
</tbody>
</table>

**Panel A: First stage and intention to treat estimates**

**Panel B: Scaling with speed using 2SLS**

**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 & 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.
one-out” cross-validation procedure suggest an optimal bandwidth of approximately 40 days for most air pollutants. However, because of concerns about shifting traffic due to a school holiday, we have chosen a bandwidth of 20 days for air pollution. Again, we use linear polynomials and cluster the standard errors at the year-level. In section 4.3, we present sensitivity checks to these choices.

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.

4.2.2 The effect of a 1 km/h-reduction in speed on air pollution

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. 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).

4.2.3 Conclusion: no evidence that the ESL-policy improves air quality in Oslo

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$_X$), but those estimates are not robust. The lack of significant results for PM$_{10}$ is in line with the results of Bel et al. (2015) and Benthem (2015). Our findings

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19 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.

20 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$_X$.

21 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.
differ from the results of Hagen et al. (2005), both in terms of sign and magnitude. We provide a more detailed comment on the findings of Hagen et al. (2005) in section 4.4.

Although our RD design should help us achieve high internal validity, a caveat regarding the external validity of our results is in order. 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\textsubscript{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 held to be U-shaped (Bel and Rosell 2013, Benthem 2015). These are not concerns for our results for Oslo, as we have directly tested the policy on the outcomes of interests, but they may affect the generalizability of our findings.

4.3 Robustness

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. For completeness, we include a section with OLS-estimates in the online appendix.

4.3.1 Choice of bandwidth and polynomial in the assignment variable

Table 4 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. Gelman and Imbens (2014) find that specifications with high order polynomials (higher than second order) can be misleading and should not be used.

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 4. Effect of Environmental Speed Limits on Traffic Robustness

<table>
<thead>
<tr>
<th>Bandwidth:</th>
<th>Speed</th>
<th>Traffic Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>±20 days</td>
<td>±15 days</td>
</tr>
<tr>
<td>The polynomial of Order:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zero</td>
<td>-6.2064***</td>
<td>-6.0621***</td>
</tr>
<tr>
<td></td>
<td>(0.3232)</td>
<td>(0.3823)</td>
</tr>
<tr>
<td>One</td>
<td>-5.8169***</td>
<td>-5.7762***</td>
</tr>
<tr>
<td></td>
<td>(0.7113)</td>
<td>(0.7968)</td>
</tr>
<tr>
<td>Two</td>
<td>-5.8492***</td>
<td>-6.0489***</td>
</tr>
<tr>
<td></td>
<td>(0.7812)</td>
<td>(0.6175)</td>
</tr>
<tr>
<td>Three</td>
<td>-6.0152***</td>
<td>-5.5537***</td>
</tr>
<tr>
<td></td>
<td>(0.5646)</td>
<td>(0.5994)</td>
</tr>
<tr>
<td>Four</td>
<td>-5.3925***</td>
<td>-5.8634**</td>
</tr>
<tr>
<td></td>
<td>(0.7173)</td>
<td>(1.1311)</td>
</tr>
<tr>
<td>Five</td>
<td>-5.8642**</td>
<td>-5.8213</td>
</tr>
<tr>
<td></td>
<td>(1.2472)</td>
<td>(2.3519)</td>
</tr>
<tr>
<td>Optimal order of the polynomial</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Observations</td>
<td>13802</td>
<td>10462</td>
</tr>
</tbody>
</table>

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

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\[ \text{We calculate AIC as } AIC = N \ln(\hat{\sigma}^2) + 2p \text{ where } N \text{ is the number of observations used in the regression, } \hat{\sigma}^2 \text{ is the mean squared error of the regression, and } p \text{ is the number of parameters in the regression model (Lee & Lemieux, 2010).} \]
Table 5 presents the estimated treatment effect of the ESL on NO\textsubscript{X}, NO\textsubscript{2}, PM\textsubscript{10} and PM\textsubscript{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\textsubscript{2} and NO\textsubscript{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.\textsuperscript{23}

4.3.2 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 og Lemieux 2010). Table A.6 in the online appendix repeats baseline Table 3, excluding control

\textsuperscript{23} The cross-validation function for NO\textsubscript{X}, NO\textsubscript{2} and PM\textsubscript{10} suggest that using a bandwidth of about 40 days is optimal, whereas the cross-validation function for PM\textsubscript{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.
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 og Lemieux 2010).

4.3.3 Outliers

We now exclude outliers by only including values that lie below the 95\textsuperscript{th} percentile and above the 5\textsuperscript{th} percentile for each separate air pollutant. Table A.7 in the 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.

4.3.4 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 og Pischke 2009), we now cluster the standard errors at the weekly level rather than the yearly level (see Table A.8 in the online appendix).\textsuperscript{24} This increases the number of clusters from 6 to 40 for the air pollutants and from 6 to 29 for speed.\textsuperscript{25} Clustering by week produces slightly larger standards errors for speed, NO\textsubscript{2}, NO\textsubscript{X} and PM\textsubscript{10} and slightly smaller standard errors for PM\textsubscript{2.5}. Few clusters tend to underestimate the serial correlation of a random shock, which may explain why our standard errors are higher with more clusters. The choice of clustering does not alter the conclusion of this study. The only notable difference is that the effect on NO\textsubscript{2} is statistically insignificant with weekly clusters, which underlines that the statistically significant estimate for NO\textsubscript{2} in our baseline estimation is not robust.

\textsuperscript{24} Clustering at the week level is less conservative compared to our main specification. 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.

\textsuperscript{25} 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.
4.3.5 Maximum observed compliance

As the ESL-policy in Oslo was active, it became increasingly clear that the Police was hesitant to enforce it.\textsuperscript{26} Compliance may therefore have decreased over time. Figure A.3 in the online appendix shows a falling drop in speed at November 1st over the 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.3 in the online appendix reports the results from this estimation. The estimates for NO\textsubscript{X}, NO\textsubscript{2}, and PM\textsubscript{2.5} are similar to our baseline estimates, with positive and statistically insignificant coefficients. The coefficient for PM\textsubscript{10} now takes a negative sign, but is still statistically insignificant.

4.4 Comment on the study that provided the basis for the ESL-policy in Oslo

We end this section with comments on the study by Hagen et al. (2005), which suggested that the introduction of the ESL in Oslo in 2004 improved air quality by reducing concentrations of both PM\textsubscript{10} and NO\textsubscript{2}. As this is the only evaluation of the ESL-policy in Oslo that we have found, it forms the basis for the permanent implementation of the policy between 2004 and 2012 and for the re-introduction of the policy in fall 2016. The online appendix provides an augmented replication of Hagen et al. (2005). The essence of our replication is that we, in contrast to Hagen et al. (2005), formally estimate difference-in-difference models. We also extend the sample to cover 2001-2012 and to two more road stretches. The results show that our conclusion of no effect of the ESL-policy on air pollution is robust to the research design of Hagen et al (2005).

\textsuperscript{26} 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.
5. Cost-Benefit Analysis

The ESL-policy involves potential private costs in the form of time loss and private benefits in terms of lower fuel consumption due to lower speed, as well as potential social benefits in terms of fewer accidents, less noise and better health outcomes due to better air quality. Table 6 presents our calculations of these costs and benefits. The online appendix provides more details. We present the calculations in the local currency NOK. The exchange rate between NOK and USD is about 8 NOK/USD.

We calculate the private cost of travel time by computing the value of time based on the average salary in Norway and the time loss associated with the implementation of 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 vehicles and 9,166,099 vehicles using National Road 4 or Ring Road 3 each ESL-period. The private cost related to the estimated speed reduction is then 356 NOK per person, or 533 NOK per vehicle, and 4,888 MNOK in total. Based on previous research on fuel consumption and our estimates of the speed reduction, we calculate the total private benefit related to a reduction in fuel consumption to 83 NOK per vehicle, or 759 MNOK in total per ESL-period.

We find no effects on air quality and hence set the value of improved air quality to zero. With few accidents on Norwegian roads, the estimate of the social benefit related to fewer accidents due to the ESL is 5.7 MNOK each ESL-period, or 0.6 NOK per vehicle. This is approximately equal to the value of saving one life every fifth year, given a value of a statistical life (VSL) of 30.5 MNOK. The basis for this estimate is data on the number of accidents, the seriousness of the injuries involved and estimates of the reduction in accidents from the ESL according to previous research. The social benefit related to a likely noise reduction of 2 dB for the stipulated 8,687 vulnerable citizens close to the ESL-roads exposed to at least 55 dB, is calculated to 3 MNOK, or 0.3 NOK for each vehicle, within the ESL-period.

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27 Total time loss each environmental speed limit period: 199 NOK x 1.79 hours = 355 NOK. Total time loss cost: 1.79 hours x 199 NOK x 1.5 passengers x 9,166,099 Vehicles = 4,888,100,859 NOK

28 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

29 Social Benefit Noise: 8,687 citizens x 335 NOK x 1.142 x 2 dB x 160/365 = 2,913,653 NOK
Our cost–benefit calculation indicates a net loss to society of 4,120 MNOK each ESL-period (0.52 billion USD), or 8% of the operating expenses (OPEX) of the municipality of Oslo in 2016 NOK (Oslo Municipality 2017). Our cost–benefit calculation is conservative, and our judgment is that it most likely underestimates the actual net loss of the ESL-policy. For example, we use the after tax salary to calculate the time costs.

We now calculate the potential monetary values of improving the key health outcomes related to air pollution. Chronic Obstructive Pulmonary Disease (COPD) and asthma are two major and growing diseases related to air pollution and traffic emissions. We calculate the social cost of COPD in Oslo within the ESL-period to be 369 MNOK, and the social cost of asthma to be 125 MNOK. Together, the potential social benefits of reducing COPD and asthma is 494 MNOK. The loss to society each ESL-period would be 3,626 MNOK (0.453 billion USD), even if the policy made the incidences of COPD and Asthma related to traffic pollution go away completely.

Table 6. Cost-Benefit Analysis for each Environmental Speed Limit Period

<table>
<thead>
<tr>
<th>Cost (-) / Benefits (+):</th>
<th>Estimate based on estimation results</th>
<th>Estimate with optimistic safety and health benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Per Vehicle (NOK)</td>
<td>All Drivers (MNOK)</td>
</tr>
<tr>
<td>Travel time</td>
<td>- 533</td>
<td>- 4,888</td>
</tr>
<tr>
<td>Fuel</td>
<td>83</td>
<td>759</td>
</tr>
<tr>
<td>Total Private Cost</td>
<td>- 450</td>
<td>- 4129</td>
</tr>
<tr>
<td>Air quality</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Accidents</td>
<td>0.6</td>
<td>5.7</td>
</tr>
<tr>
<td>Noise</td>
<td>0.3</td>
<td>3</td>
</tr>
<tr>
<td>Total Social Benefits</td>
<td>0.9</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Net Result (NOK)           | - 449 NOK         | - 4,120 MNOK       | - 100.0%                  | - 3,609 MNOK      |
Net Result (USD)           | - 56 USD          | - 515 Million USD  | -451 Million USD          |
% of OPEX Oslo Municipality | 8%                |                     |                          |

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.

30 Society loss 4,120 MNOK / (OPEX 53,000 MNOK x 1.0015) = 8.4%
31 Social cost COPD: (7400 NOK x (3788 + 378 patients) + 26 deaths x 30.5 MNOK) x 160/365 = 369 MNOK
32 The social cost of Asthma is based national cost estimate of 2,262 MNOK, measured in 2017 NOK (Norwegian Labour Inspection Authority 2008), which includes medicines, treatments, absence of work and financial support, among other costs. We assume equal distribution in Norway and relate 12.5% of the cost to Oslo.
Above we assumed that the ESL-policy reduced accidents by 25%. If we instead assume that the ESL-policy removed accidents completely, we add $3 \times 5.7$ MNOK to the benefits. Our most optimistic estimate for the net social benefits of the ESL-policy is therefore 3,609 MNOK or 0.451 billion USD.

In our sample, the policy is in place for one road in the period 2004/05-2011/12 (8 winters) and for two roads in the period 2006/07-2011/12 (6 winters). Conservatively, we can then estimate a net cost of the ESL-policy in our sample of at least 3 billion USD.

6. Conclusion

Countries and cities increasingly search for cost-effective policy measures to improve local air quality. Road transport is an important contributor to air pollutants such as NOX and PM$_{2.5}$ and reducing speed limits on certain highways is one of the options considered, e.g. in the UK. As cars are very important means of transportation, accounting for 83% of the passenger-km travelled in the EU over the 2004-2014 period (Eurostat 2017), lower speed may also involve high time costs. Current policy advice usually draws on simulation models, which can only give uncertain answers due to unknown behavioural responses among drivers and complex relationships between speed, emissions and air quality. EEA (2011b) and UK Government (2017) point to the need for more scientific evidence based on implemented policies and real world data. The two key questions are whether theoretical relationships between speed and air quality carries over to improvements of air quality, and, if so, whether the benefits are large enough to overcome the costs of longer journey times.

We provide answers to these questions for the environmental speed limit policy in Oslo, implemented in various degrees since 2004. The reduction of the maximum speed limit from 80 km/h to 60 km/h reduced travel speed by 5.8 km/h. However, we find no evidence that the policy improved air quality. We estimate a net social loss from the policy of about 0.5 billion USD every year. We conclude that policymakers should focus on other actions to improve local air quality and, consequently, reduce the adverse health effects related to air pollution.
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2017

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