# The effects of maximum speed limit policy on $NO_2$ levels: evidence from the Netherlands

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### Abstract

Speed limits on many highways in the Netherlands were increased to 130 km/h in the period of 2011 to 2015. We use a difference-in-difference approach to assess the impact of four different speed limit policy implementations on $NO_2$ emission levels. Our analysis shows that in most cases the implementation of 130 km/h has done little to $NO_2$ emissions, because despite the higher speed allowance, average speeds have not increased substantially. The traffic situation on highways pre implementation determines whether speeds can increase and subsequently, if emissions increase. Estimations show that where speeds did increase, the increase in $NO_2$ can be up to 33% compared to the control group for a regular increase from 120 km/h to 130 km/h and up to 8.5% for a night-time increase from 120 km/h to 130km/h, or about 0.9% and 0.78 % per 1 km/h speed limit increase respectively.

*Keywords:* Highways, Air pollution, Environment, $NO_2$, Difference-in-Difference, Two-way Fixed Effects

## 1 Introduction

The adoption of the automobile as a way of transport has certainly provided many benefits to society, but has also carried along numerous negative side effects. The wide range of science fields that concern themselves with the consequences of the wide use of automobiles, such as environmental studies, epidemiology and transport economics is not only indicative of the concern, but also of the complexity of the matter. Economists like to call these side effects *externalities* and while there are many types of externalities one can think of, this thesis will focus on air pollution. More specifically, we analyse the effects on nitrogen dioxide ($NO_2$), a major air pollutant. Its increased presence is caused by anthropogenic influence on the nitrogen cycle, the transformation of which creates serious problems for nature and human health (Akimoto, 2003). Recently, concerns about nitrogen deposition in Natura2000 areas (and the lack thereof) have culminated in a *nitrogen crisis* in the Netherlands. One of the counter measures taken to lower nitrogen deposition was a maximum speed limit change from 130km/h to 100km/h on all highways. This hotly debated measure stresses the importance of understanding the close ties between the economy, nature and society and draws attention to their inherent relationships.

The effects of $NO_2$ have been researched in a myriad of studies. Most researched is the relationship between $NO_2$ and human health. Exposure to traffic-induced $NO_2$ has been linked to reduced lung function and asthmatic symptoms for children (McConnell et al., 2010; Studnicka et al., 1997) and adults (Brunekreef et al., 1997; Guarnieri and Balmes, 2014; McCreanor et al., 2007). While its effects on human health are substantial, $NO_2$ deposition also has an effect on the environment through acidification of both aquatic and terrestrial ecosystems (Camargo and Alonso, 2006; Gadsdon and Power, 2009). In addition, deteriorative effects of other air pollutants are worth noting as they often interact or coexist with $NO_2$ (Xie et al., 2015). One important effect is that of particulate matter (PM) on human health, studied by Dockery et al. (1993), Pope et al. (1995), and Raaschou-Nielsen et al. (2013), who have carried out large-scale cohort studies, all concluding that PM is positively correlated with lung cancer mortality rates. The study by Raaschou-Nielsen et al. (2013) associates an increase in vehicle kilometres close to residences with a higher hazard ratio for lung cancer. Health effects of $NO_2$ trickle down further into monetary effects such as a decrease in house prices because economic agents take a healthy environment into consideration for their utility (Rehdanz and Maddison, 2008), although maybe not always in a rational way (Chasco and Gallo, 2013).

Other noteworthy effects of air pollution are the effect of ozone ($O_3$) on agricultural yields (Avnery et al., 2011; Chameides et al., 1999) and perhaps a more modern effect: reductions in solar energy production due to air pollution (Bergin et al., 2017). Not only is air pollution itself a broad topic, considering all the different pollutants that fall under it, but also its consequences are so widespread that properly understanding air pollution is of great importance to many aspects of society.

In this thesis, we analyse the effect of increases in maximum speed limits on highways on $NO_2$ emissions in the Netherlands. A number of studies have analysed the effects of maximum speed policies on highways. Bel et al. (2015) gives a comprehensive overview of research on the effects of lowering speed limits in metropolitan environments (for a full overview, see Table 6 in Appendix A). We extend this list with two studies: Perez-Prada and Monzon (2017) and DCMR (2013). We do this for the sake of completeness, as the former was published after Bel et al. (2015) and because the latter is relevant to our research setting. Namely, the study by DCMR (2013) has looked at the effects of an *increase* in the speed limit, whereas the other studies have all looked at a *decrease*. The previous studies show that a change from 120km/h to 100km/h decreases $NO_x$ by 1% to 11% and a change from 100km/h to 80km/h about 1% to 25% decrease in $NO_x$. A variable speed system shows greater decreases in $NO_x$ within the same study than a fixed decrease in the maximum speed.

The difference in methodological approaches taken by the authors divides the studies in two categories. There is a clear distinction between studies adopting a modeling approach and studies that use econometric methods. On the whole, modeling studies seem to estimate greater changes in air pollution than econometric studies. The exception is Gonçalves et al. (2008), but their approach is contestable. They have taken the actual speeds of two typical days in Barcelona as the base scenario. They argue that an 80 km/h speed limit does little compared to the base scenario because speeds are already lower than 80 km/h on some road stretches. However, they do not consider how flow and traffic behaviour could change as a result of the 80 km/h speed limit. A general reason why modeling studies have higher estimates could be that they are based on *what-if* parameters. Although the models used are quite extensive, they are still based on numbers such as emission standards, which are likely to differ substantially in reality. Another reason for the difference could be that econometric studies underestimate the effect because they look at mean pollution levels. Bel et al. (2015) argue that using means to describe skewed distribution functions is not ideal and that the distribution function of a pollutant might change after a policy change. This implies that focusing on the mean change pre- and post-treatment is not a precise measure of the change in pollutant levels. Therefore, they use quantile regressions to estimate the effect at different levels of pollution concentrations.

A different development in the literature is the debate about a variable speed limit versus a fixed speed limit. While only Gonçalves et al. (2008) and later, Bel and Rosell (2013) have specifically looked at this, other studies that have looked at speed limit reductions implicitly also recognize this distinction. This is because a lower speed limit is thought to increase the smoothness of traffic flow and thereby decrease the stop-and-go nature of traffic, a point Panis, Broekx, and Liu (2006) raise in their modelling-based paper. They find that including stop-and-go traffic in their simulations increases emissions. The study by DCMR (2013) also finds higher standard deviations in average speed after the increase in speed limit. This hints at the idea that not the speed change itself is the biggest factor in reducing emissions, but the traffic flow that is a result of the speed limit change. Keuken et al. (2010) conclude with the same idea, namely that reducing "traffic dynamics" is a more important driver of emission reduction than a reduction in average speed change. That is also the reason why they report wide confidence intervals for their results (5%-20% for $PM_{10}$): the reduction in emission is highest on roads with high congestion prior to the 80km/h speed change.

The goal of this thesis is to assess whether, and to what extent, the increase of maximum speeds on highways in the Netherlands increased $NO_2$ emissions. We contribute to the literature in three ways. First, we simultaneously analyse changes to fixed speed limits and day-night regime limits. Second, we estimate the effects on $NO_2$ of speed limit increases, whereas all published articles have looked at decreases. Third, we estimate the effect on a nation-wide scale by using a difference-in-difference (DiD) approach for the Netherlands. Furthermore, we investigate the traffic flow and speed as a result of the speed limit policy change, something which other studies do not investigate thoroughly. The effect has not been estimated on a nation-wide scale using an econometric approach in any country, nor have any general estimations been carried out for the Netherlands. We believe this approach has more rigour than the case-studies carried out in metropolises or pre-treatment simulation-based studies, because it allows us to conclude on the relationship between $NO_2$ and speed limit policy in a general setting and is not based on any presumptions or assumptions about air pollution or traffic dynamics.

The remainder of this thesis consists of four sections. In section two, we give some policy context and provide a description of the data we have used.Section three gives an explanation of the methodology we have used to come to our estimates. In section four, we show our results in tables and graphs and elaborate on the results. Section five concludes on the results and provides scope for further research.

# 2 Data and Context

## 2.1 Context

During the Rutte I and II administrations (2010-2017), maximum speeds on a number of highways were increased to 130 km/h. The speed limit policy change was one of the main promises to the electorate by the liberal party VVD. The maximum speed on highways had been 120 km/h since 1988 and some argued it was time for a change. According to the minister in charge at the time, 130 km/h would better suit the "driving experience of the car user" and you would "arrive at your destination earlier" (Ven, 2019). Before the measure was fully implemented, studies were carried out to see if the increase would comply with environmental standards (Rijkswaterstaat, Grontmij, 2011). The conclusion was that there was room for an increase to 130 km/h on more than half of all the highways in the Netherlands. Where there was a chance of exceeding air quality limits, air screens and dynamic maximum speeds would be a solution. Still, the measure was contested. Five years later, researchers raised their concerns about air quality when plans were made to increase speed limits on more highways (Weijer, 2016). They contested the small margins of error used and pointed out that diesel cars emit much more nitrogen oxides than emission standards suggest, a hot topic amidst the Volkswagen scandal.

## 2.2 Data

### *2.2.1 Sources*

Our main source of data are air quality measurement stations (hereafter: AQMS). Management and monitoring of AQMS is divided between regional environment/health service bodies[1] and the RIVM, the National Institute for Public Health and the Environment. Recently, this data has been centralized on the open data initiative Luchtmeetnet. First, we identified AQMS close to highways from the overview on Luchtmeetnet and retrieved hourly $NO_2$ values. Second, we identified which stretches of highways have undergone speed limit changes and when these have occurred. This was done through official government publications and checked through Google's Street View history tool where possible. As a result, we obtained a list of AQMS close to highways which had seen speed limit policy changes and crucially, AQMS which had not, to define a group with treated highways and a control group.

We obtained data from the Koninklijk Nederlands Meteorologisch Instituut (KNMI) (the national meteorology institute) for meteorology data and from the Nationale Databank Wegverkeersgegevens (NDW) for traffic data. The KNMI obtains data from fifty measurement stations throughout the Netherlands and makes the data publicly available. We used Geo-information science (GIS) tools to identify which meteorology stations are closest to the AQMS we are studying. The same procedure was used for traffic data. The NDW monitors more than 10,000 induction loops in highways all over the Netherlands. On these induction loops, traffic volume and traffic speed are continuously measured. Although traffic data is not essential for our policy evaluation on $NO_2$, controlling for traffic speed or flow can reveal the main drivers of our results. An example of one of the geographical matches on an NDW induction loop and a KNMI weather station can be found in Figure 1. For a full overview of all sites, see Appendix C.

### *2.2.2 Description and Trimming*

Figure 2 shows histograms of three main variables of interest: $NO_2$, speed and flow. Where the distributions of $NO_2$ and speed show no extraordinary patterns, the distribution of flow is problematic for our linear regression

1. Regional bodies such as the GGD in Amsterdam, the DCMR in the region of Rotterdam, the OMWB in Middle and West Brabant and the RUDZL in the province of Limburg


**Figure 1.** Close-up of the situation around the city of Eindhoven. Air quality measurement station NL10247 is matched to KNMI station 370 approximately five kilometres away and to an NDW induction loop on the A67, 1167 metres away. AQMS NL10237 is matched to KNMI station 370 approximately five kilometres away and to the nearest induction loop on the A2.

method due to some severe outliers. Further inspections of the individual induction loops shows that there are some periods where the flow goes to zero. We think road works are causing this decrease in traffic flow. In other periods, we see flow values of >10,000 vehicles per hour, which is extremely high. These events have an influence on $NO_2$-emissions, but have nothing to do with speed limit policy. To avoid that our results are influenced too much by some extreme observations, we trim our observations per AQMS by removing observations with flow values that fall outside the range given in (1), where Q1 stands for first quartile, Q3 for third quartile and IQR stands for *interquartile range*.

$$x < Q1 - 1.5 * IQR \quad \vee \quad x > Q3 + 1.5 * IQR \tag{1}$$

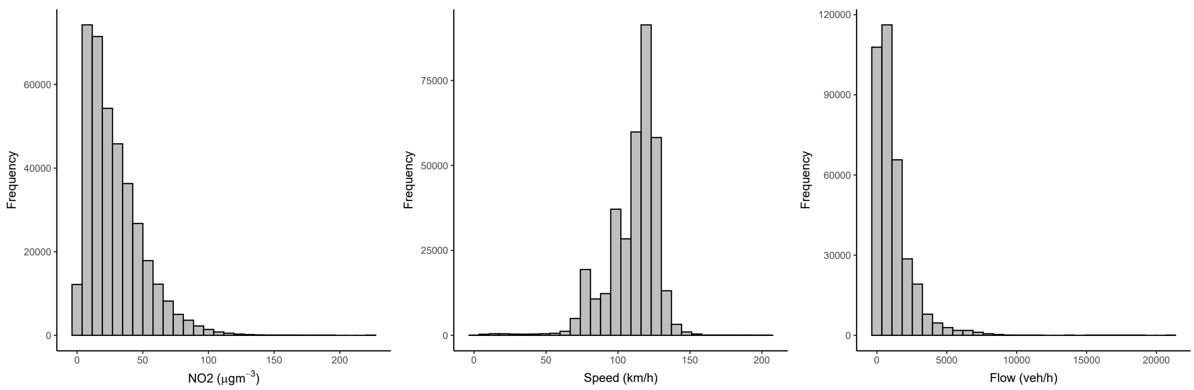


**Figure 2.** Distributions of $NO_2$, speed and flow

Combining all data after trimming gives an unbalanced panel dataset summarized by Table 1. In total, we use 347,271 hourly observations of $NO_2$. Our variables of interest are the speed limit policy changes. Because we have multiple speed limit policy changes in our period of interest, we have a dummy variable that takes the value of unity after a change has come into force and the value of zero when the speed limit is reverted. Between 2011 and 2015, there have been seven different speed limit policy changes on the highways we consider. Table 2 gives an overview of the different policy changes over time. There are seven AQMS close to highways that have undergone a policy intervention. We group the policy interventions into four groups; (1) 120km/h to 130km/h, (2) 120km/h to 120/130(AN)[2], (3) 80km/h to 100km/h, (4) 100 km/h to 100/130(AN). Additionally, we also have four AQMS where nothing has changed in terms of speed limit policy in the period 2011-2015. These AQMS serve as control units.

**Table 1.** Descriptive statistics at hourly level.

| Variables | Description | n | mean | min | max | sd |
|---|---|---|---|---|---|---|
| $NO_2$ | Hourly value of $NO_2$ in $\mu gm^{-3}$ | 347271 | 28.08 | 0.00 | 223.52 | 20.85 |
| Wind direction | Wind direction, 360 degrees * | 358565 | 194.99 | 0.00 | 359.99 | 113.96 |
| Wind speed | Wind speed in 0.1 m/s | 358565 | 44.28 | 0.00 | 240.00 | 25.44 |
| Temperature | Temperature, in 0.1 degrees Celsius ** | 358565 | 107.61 | -195.00 | 357.00 | 65.02 |
| Sunshine | Sunshine in 0.1 hours | 358565 | 2.03 | 0.00 | 10.00 | 3.52 |
| Radiance | Radiance in J/cm2 | 358565 | 42.87 | 0.00 | 350.00 | 69.90 |
| Precipitation | Precipitation in 0.1 hours | 358565 | 0.72 | 0.00 | 10.00 | 2.27 |
| Precipitation | Precipitation in 0.1 mm | 358565 | 0.94 | 0.00 | 481.00 | 5.08 |
| Air pressure | Air pressure in 0.1 hPa | 358565 | 10150.34 | 9687.00 | 10446.00 | 94.68 |
| Overcast | Overcast, categorical 1-9 | 358533 | 5.29 | 0.00 | 9.00 | 3.37 |
| Humidity | Humidity in % | 358565 | 80.47 | 16.00 | 100.00 | 14.48 |
| Vehicle flow | Hourly number of vehicles, summed over lanes | 348431 | 1145.52 | 0.00 | 10551.00 | 1241.08 |
| Vehicle speed | Average speed of vehicles over all lanes | 344686 | 110.78 | 1.50 | 205.51 | 17.60 |
| Maximum speed change | Dummy variable for policy change | 358565 | 0.38 | 0.00 | 1.00 | 0.48 |

* Used as a categorical variable in 15° bins in the regressions. Also see Figure 6 in Appendix B for a wind rose graph.
** Used as categorical variable in 10°C bins in the regressions

# 3 Methodology

## 3.1 Difference-in-Difference

The aim of this thesis is to estimate the change in $NO_2$ levels due to speed limit policy changes. As mentioned in the Introduction, we use DiD as our method of estimation. We think DiD is the preferred estimation method in this setting. Because the policy changes have not been implemented everywhere and have also been reverted, we are naturally provided with intervention and control groups and intervention and non-intervention periods. Combined with a DiD framework and with the right assumptions, this allows us to carry out causal inference.

$$Y_{it} = \alpha_i + \delta_t + \beta_g w_{it} + \boldsymbol{x_{it}\gamma} + \zeta s_{it} + \eta f_{it} + \epsilon_{it} \tag{2}$$

The regression specification we use is given in (2) where $i$ denotes an AQMS, $t$ denotes time (hours) and $g$ denotes a group. The unit and hourly time fixed effects are denoted by $\alpha_i$ and $\delta_t$, respectively. Our policy indicator is denoted by $w_{it}$. The coefficients for the policy indicators are $\beta_g$. We index by group because we suspect the effect to be different for our different maximum speed increases. We add individual-specific covariates in $\boldsymbol{x}$, $s_{it}$ and $f_{it}$. The weather variables are contained in the vector $\boldsymbol{x}$ and speed and flow are contained in $s_{it}$ and $f_{it}$ respectively. We cluster the standard errors on individual AQMS, because we expect within-unit error correlation and we cluster over every hour, because certain AQMS might receive the same shocks on a certain moment.

Because groups 3 and 4 have only seen their speed limit change during night times, we run a separate regression for groups 1 and 2 and for groups 3 and 4. The methodology is exactly the same for both procedures,

2. AN stands for day-night regime, daytime being defined as 07:00-19:00.

**Table 2.** Overview of speed limit policy changes in km/h, changes in boldface.

| | **Policy Change** | | | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Group /Ind.*** | **Intervention AQMS** | **Road** | **24-10-10** | **01-03-11** | **07-07-11** | **02-07-12** | **01-09-12** | **30-11-12** | **28-06-13** | **29-03-14** |
| 1/1 | NL49007 | A10 | 80 | 80 | 80 | **100** | 100 | 100 | 100 | **80** |
| 2/2 | NL10538 | A7 | 120 | **130** | 130 | 130 | 130 | 130 | 130 | 130 |
| 2/3 | NL49564 | A5 | 120 | 120 | 120 | 120 | 120 | 120 | **130** | 130 |
| 2/4 | NL10246 | A59 | 120 | 120 | **130** | 130 | 130 | 130 | 130 | 130 |
| 2/5 | NL10247 | A67 | 120 | 120 | 120 | 120 | **130** | 130 | 130 | 130 |
| 3/6 | NL10437 | A29 | 120 | 120 | 120 | 120 | **120-130 (AN)**** | 120-130 (AN) | 120-130 (AN) | **120** |
| 4/7 | NL10641 | A2 | 100 | 100 | 100 | 100 | 100 | **100-130 (AN)**** | 100-130 (AN) | 100-130 (AN) |
| **Group** | **Control AQMS** | | | | | | | | | |
| 0 | NL49561 | A9/A4 | 120/100 | 120/100 | 120/100 | 120/100 | 120/100 | 120/100 | 120/100 | 120/100 |
| 0 | NL49021 | A9 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 0 | NL10237 | A2/N2 | 120/80 | 120/80 | 120/80 | 120/80 | 120/80 | 120/80 | 120/80 | 120/80 |
| 0 | NL10136 | A76 | 120 | 120 | 120 | 120 | 120 | 120 | 120 | 120 |

* Individual, in section Individual Effects on $NO_2$, ** (AN) = day-night regime

but we only use observations between 19:00 and 07:00 for the regression with groups 3 and 4. So in that case, we are only comparing night time emission levels of intervention AQMS 3 and 4 to the night time emission levels of the control group.

## 3.2 Control variables

### 3.2.1 *Weather variables*

Meteorology data is useful because $NO_2$ shows great variability under different weather conditions. For simplicity, we do not strive to study and control for other complex interactions between substances in the air and between air layers here. Adding meteorology data as control variables will help capture variability of $NO_2$ in the data. For the weather control variables, we include: wind direction[3], wind speed, temperature, sunshine, humidity, precipitation and air pressure. One of the main influences on the level of $NO_2$ in the air is how much $O_3$ is produced. Because $O_3$ is produced by sunlight, we control for sunshine. Additionally, we need to know wind direction and wind speed at every moment in time. On a large scale, high wind speeds can transport contaminants far away from the source and on a more local scale, wind direction determines emission capture in an AQMS. Note however that when using hourly fixed effects, including weather variables only explains some extra variability in the data when weather patterns are substantially different between two studied locations. Although two of our AQMS lie about as far apart as can be in the Netherlands (Geleen in the south and Medemblik in the north), the Netherlands remains a small country with roughly one climate. Nevertheless, we include the weather variables because they increase the efficiency of our estimates.

### 3.2.2 *Traffic variables*

For the traffic data, we use the hourly sum of flow over all the lanes of all vehicle types and the average speed over all the lanes for the vehicle types affected by the speed limit change.

3. For wind direction the reference level is SSW, which is the predominant wind direction averaged over all the weather station we use. See Figure 6 in Appendix B for a wind rose graph.

## 3.3 Potential bias

There are three crucial assumptions that need to hold for a valid use of DiD. The most important one being that the trends of the treatment and control groups before the moment of treatment, *t*, follow an equal trajectory (stable trends assumption). For validity, we need to verify that the difference between the two units, treatment and control, is stable would the treatment not have happened. Otherwise, the measured difference is not caused by the treatment alone. Figure 3 shows no unequal trends prior to the intervention moments. In fact, all the groups move relatively close in conjunction with one another, likely caused by weather and seasonal variability. The second assumption is that the situation after *t = 0* does not determine which units get the treatment at *t*. We do not suspect a bias here because, from a policy perspective, air quality was only one of the environmental standards the government considered. Noise levels and in particular the presence of nature conservation areas (Natura 2000) close to highways were more restrictive than air quality for determining which stretches of highways had room for a maximum speed increase (Rijkswaterstaat, 2011). Therefore, we see no reason for baseline bias. The third assumption is stable unit treatment value assumption (SUTVA). Intervention and control groups should stay stable over time and should not influence one another. Although some air quality measurement stations lie close to one another, there is no reason to believe that stations can influence each other. In our setup, stations lie much further away from each other than in the study of Bel and Rosell (2013).

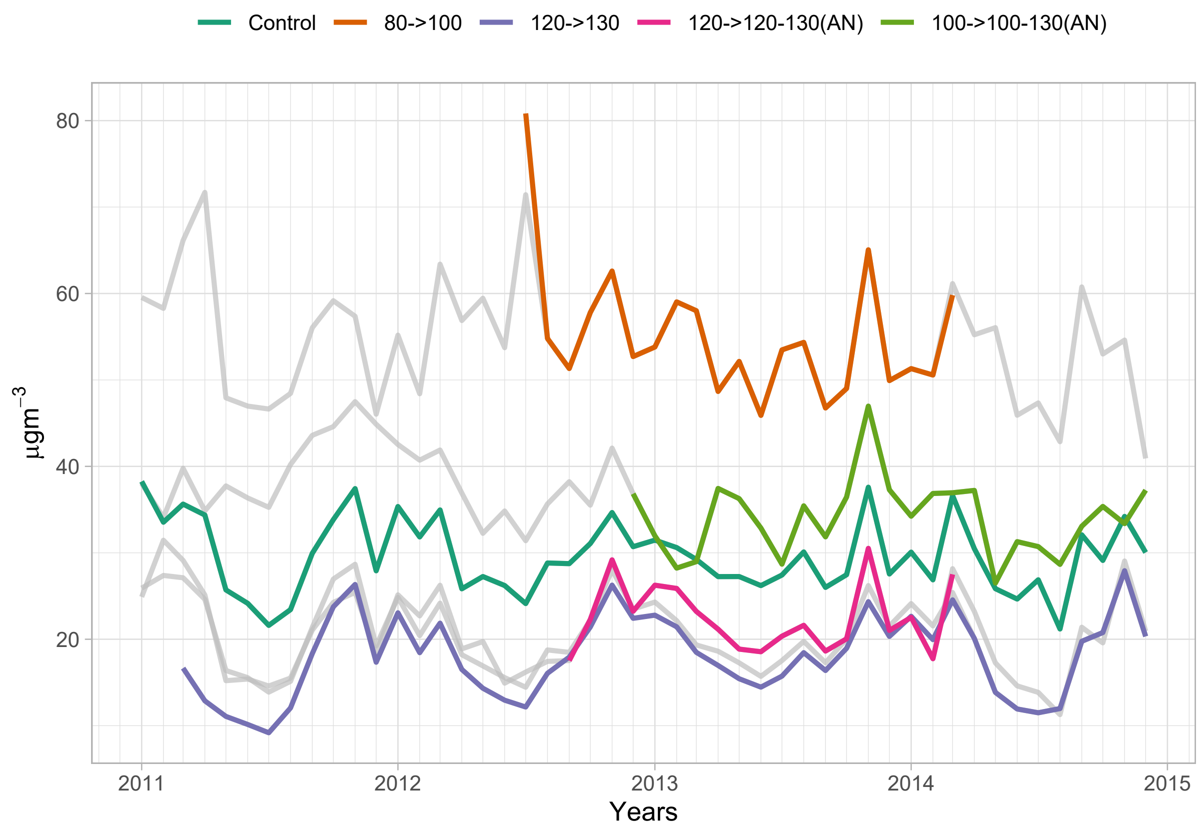


**Figure 3.** Monthly averages of $NO_2$ of the control and intervention groups. *Notes:* Greyed out sections of lines are non-intervention periods. Group 120->130 (group 2) contains four different AQMS with different intervention periods, so it has no greyed out part in this graph. For more details on this group, see Individual Effects on $NO_2$.

# 4 Results

## 4.1 Grouped Effects on $NO_2$

The results of the regressions are given in Table 3. We have controlled for weather variables and only show the coefficients for the policy interactions and speed and flow variables. For group 1 (80 km/h to 100 km/h) we find a negative sign and an insignificant result. Only in the case where we control for traffic flow, we find a significant result, but it is still clearly negative. This is unexpected since an increase from 80 km/h to 100 km/h is a big step and should, theoretically, have led to an increase in $NO_2$. The study by DCMR (2013) is similar in set up and found an increase of 20% for $NO_2$. The result for group 2 (120 km/h to 130 km/h) is also unexpected because we expect the speed increase from 120 km/h to 130 km/h, which is a regular increase, to increase $NO_2$ levels. We do not find a significant result and we think there is more at play beneath the surface here. We investigate this by regressing on the individual AQMS in group 2 in Individual Effects on $NO_2$.

**Table 3.** Regression Results Groups 1 (80-100 km/h) and 2 (120-130 km/h) (24h)

| | *Dependent variable:* | | |
|---|---|---|---|
| | NO2 | | |
| | (1) | (2) | (3) |
| Group 1 (80-100 km/h) | −0.774 (0.525) | $-1.126^{*}$ (0.527) | −0.825 (0.541) |
| Group 2 (120-130 km/h) | 0.126 (0.713) | −0.148 (0.706) | −0.092 (0.710) |
| Traffic flow (veh/hr) | | 0.003 (0.002) | 0.003 (0.002) |
| Speed (km/h) | | | −0.014 (0.017) |
| Observations | 279,667 | 271,362 | 259,982 |
| Two-way Fixed Effects | Yes | Yes | Yes |
| $R^2$ | 0.729 | 0.741 | 0.744 |
| Adjusted $R^2$ | 0.690 | 0.703 | 0.704 |

Clustered robust standard errors in brackets. $^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

For the night groups we present the results in Table 4. Only for group 3 (120 km/h -> 120 km/h - 130 km/h (AN)) we find a significant result which indicates that the policy change has caused an increase of about 1.9 $\mu gm^{-3}$ during night times compared to the control group. On an average emission level of around 22.4 $\mu gm^{-3}$ during night times before the intervention for group 3, this is an increase of about 8.5% compared to the control group, which is in line with the literature and quite high for an econometric study with a small speed increase. Group 4 (100 km/h -> 100 km/h - 130 km/h (AN)) shows a clear significant decrease compared to the control group. This is also an unexpected result since allowing a speed increase of 30km/h at night should theoretically lead to an increase in $NO_2$ levels at night. We investigate this decrease in Traffic speed and flow.

Regression specifications (2) and (3) in Table 3 and Table 4 have traffic flow and traffic speed added as controls. When we add traffic flow to the regression, we estimate coefficients in a situation where the traffic flow stays the same throughout the estimation period. For groups 1 and 2 the coefficient for flow is 0.003. Although insignificant, the interpretation of the coefficient is that an increase of one vehicle per hour increases $NO_2$ by 3 $ngm^{-3}$ on average. For groups 3 and 4, the coefficient of the flow variable is also insignificant. Furthermore, in both regressions the coefficient of the speed variable is insignificant. The fact that both control variables prove insignificant is surprising since these are the two main determinants of traffic nature on the road. A possible explanation is that there is no direct relationship between measured $NO_2$ and traffic because the relationship is dynamic in the sense that there is a lag in measuring traffic-related $NO_2$, combined with air pollution interactions in the atmosphere. Another source of variability could be driving behaviour, or the variability of traffic flow. We explore traffic flow and speed in section Traffic speed and flow.

## 4.2 Individual Effects on $NO_2$

So far we have analysed the effects on $NO_2$ as a grouped effect. In this section, we estimate the DiD coefficient of interest $\beta$ as individual effects of the five intervention AQMS that are in groups 1 and 2 against the control group. Effectively we create six groups, of which one is the control group and the other five groups all contain one intervention AQMS. In this way, we can disentangle the results of groups 2 of the previous section and see what could be potential causes of unexpected or insignificant results.

**Table 4.** Regression Results Groups 3 (120-130 km/h (AN) and 4 (100-130 km/h (AN) (night))

| | *Dependent variable:* | | |
|---|---|---|---|
| | NO2 | | |
| | (1) | (2) | (3) |
| Group 3 (120-130 (AN)) | 1.869*** (0.443) | 1.946** (0.503) | 1.999*** (0.394) |
| Group 4 (100-130 (AN)) | −2.278*** (0.305) | −2.310*** (0.284) | −2.119*** (0.268) |
| Traffic flow (veh/hr) | | 0.001 (0.001) | 0.0005 (0.001) |
| Speed (km/h) | | | 0.004 (0.012) |
| Observations | 80,583 | 80,553 | 72,976 |
| Two-way Fixed Effects | Yes | Yes | Yes |
| $R^2$ | 0.687 | 0.687 | 0.692 |
| Adjusted $R^2$ | 0.609 | 0.609 | 0.605 |
| Clustered robust standard errors in brackets. | | | *p<0.1; **p<0.05; ***p<0.01 |

The results are given in Table 5. The insignificant effect of group 2 (120 km/h to 130 km/h) in the Grouped Effects on $NO_2$ is a compound of effects with different signs. Compared to the control group, AQMS 2 (NL10538) shows an increase of about 5.3 µgm$^{-3}$, whereas AQMS 4 shows a decrease of about 2.6 µgm$^{-3}$. In terms of percentages, this is a bandwidth of 33.1% to -9.8% on the local levels compared to the control group. This is a substantial difference for the same policy intervention against the same control group. Station 5 also shows an increase of about 0.7 µgm$^{-3}$ compared to the control group.

**Table 5.** Regression Results Groups 1 and 2 (24h) Individual AQMS

| | *Dependent variable:* | | |
|---|---|---|---|
| | NO2 | | |
| | (1) | (2) | (3) |
| Group 1 (80-100) | −0.787 (0.547) | −1.075* (0.561) | −0.742 (0.554) |
| Group 2 (120-130) (2) | 5.396*** (0.625) | 5.372*** (0.641) | 5.442*** (0.625) |
| Group 2 (120-130) (3) | 0.410 (0.535) | −0.624 (0.760) | −0.750 (0.783) |
| Group 2 (120-130) (4) | −2.706** (0.844) | −2.612** (0.901) | −2.537** (0.906) |
| Group 2 (120-130) (5) | 0.722* (0.334) | 0.685* (0.322) | 0.782** (0.308) |
| Traffic flow (veh/hr) | | 0.003 (0.002) | 0.003 (0.002) |
| Speed (km/h) | | | −0.016 (0.017) |
| Observations | 279,667 | 271,362 | 259,982 |
| Two-way Fixed Effects | Yes | Yes | Yes |
| $R^2$ | 0.729 | 0.742 | 0.744 |
| Adjusted $R^2$ | 0.690 | 0.703 | 0.704 |
| Clustered robust standard errors in brackets. | | | *p<0.1; **p<0.05; ***p<0.01 |

## 4.3 Traffic speed and flow

The same policy intervention clearly does not have the same effect on every highway. The question is: what is the driver of this variety in effects? To answer this question, we repeat our main hypothesis here. First, we hypothesise that an increase in maximum speed increases the average speed on highways, because it allows people to drive with higher speeds. Second, the increase in speed on highways should also increase emissions of $NO_2$ because a combustion engine emits more air pollutants with higher speeds. In the case of group 2, we are looking at a maximum speed increase of 10 km/h on 120 km/h. It is questionable whether this actually increases the average speed on highways in all cases. Test results by Rijkswaterstaat (2011) show that the average speed only increases by about 3 km/h after a change of the limit to 130 km/h. This means that we are looking at minor speed increases in most cases, especially when traffic density is high already.

The weekly average speeds of the individual intervention stations and the average of the control stations are plotted in Figure 4. The same data is given in regression results in Appendix D in Table 7 and Table 8 for speed and flow respectively. In Figure 4 we can see that for groups 80->100, 120->130(2), 120->130(AN) and 100-130(AN) the average speed has increased after the intervention, but for the others it has not. Although a stable speed pattern pre and post intervention could explain insignificant DiD coefficients in the results, the results seem to be more complex than that. For instance, group 1 (top-middle sub-figure in Figure 4) has clearly seen a speed increase during the intervention period, but shows an insignificant change in Table 3. There are also instances where local particularities have a big influence on the results. The negative coefficient for group 4(7) can be explained by the sharp drop before the intervention period. Around the start of 2011, the A2 highway was increased to 2x5 lanes with a maximum speed of 100 km/h. In the 1.5 years after the road expansion, the average speed by automobiles was much higher than 100 km/h (see Figure 4, sub-figure 5, 2011-2012). It was well known by the time that people drove much faster on this highway than was allowed and the highway quickly received its nickname 'the airstrip'. But suddenly, we see a sharp drop in speed in the summer of 2012. This drop coincides with the introduction of speed controls with strict enforcement on the A2. Three to four months later, the 100-130 (AN) scheme is introduced and the average speed slightly increases. This is an example of the complex interactions between road policy and driver behaviour. Although it strictly falls outside the scope of speed limit policy, based on the results in Table 5 we can turn around our argumentation and conclude that a higher *driven* average speed of about 10km/h increases $NO_2$ by about 2.2 $\mu gm^{-3}$. Furthermore, looking at the average speeds of group 2, we are able to conclude that the motive for increasing the maximum speed to 130 km/h is mainly politically motivated. If average speeds do not increase, there is no promised time gain. An evaluation from the Ministry of Infrastructure and Water Management on the 130 km/h measure came to the same conclusion. On road stretches where 130 km/h had been implemented, travel times have stayed equal, or in most cases slightly increased (De Algemene Rekenkamer, 2019).

The obvious follow up question that comes to the fore is why some roads undergo a maximum speed increase but do not see their average speed increase. Figure 5 shows the traffic flow per intervention AQMS and control AQMS. Group 2 (120 km/h to 130 km/h) shows a well-known pattern: roads that have a high average speed, have a relatively low flow and vice versa. From this we can conclude that on some roads, depending on the capacity, there might be too much traffic to actually allow an increase in speed during most parts of the day. In a report by SWOV (2020), the increase from 120 km/h to 130 km/h is analysed with more detail. The researchers conclude that after the increase in speed limit, the average speed has increased on average by 2 km/h on highways with two lanes and 4 km/h on highways with three lanes. Furthermore, their report shows that on 30% of the highway stretches they have analysed, the average speed has decreased after the speed limit increase. They argue that the mixed results are due to specific location characteristics and traffic behaviour pre and post intervention. A point which is also raised in the literature by Keuken et al. (2010): not the maximum speed increase itself per se, but the nature of the traffic flow and speed pre- and post-intervention determine the change in $NO_2$.

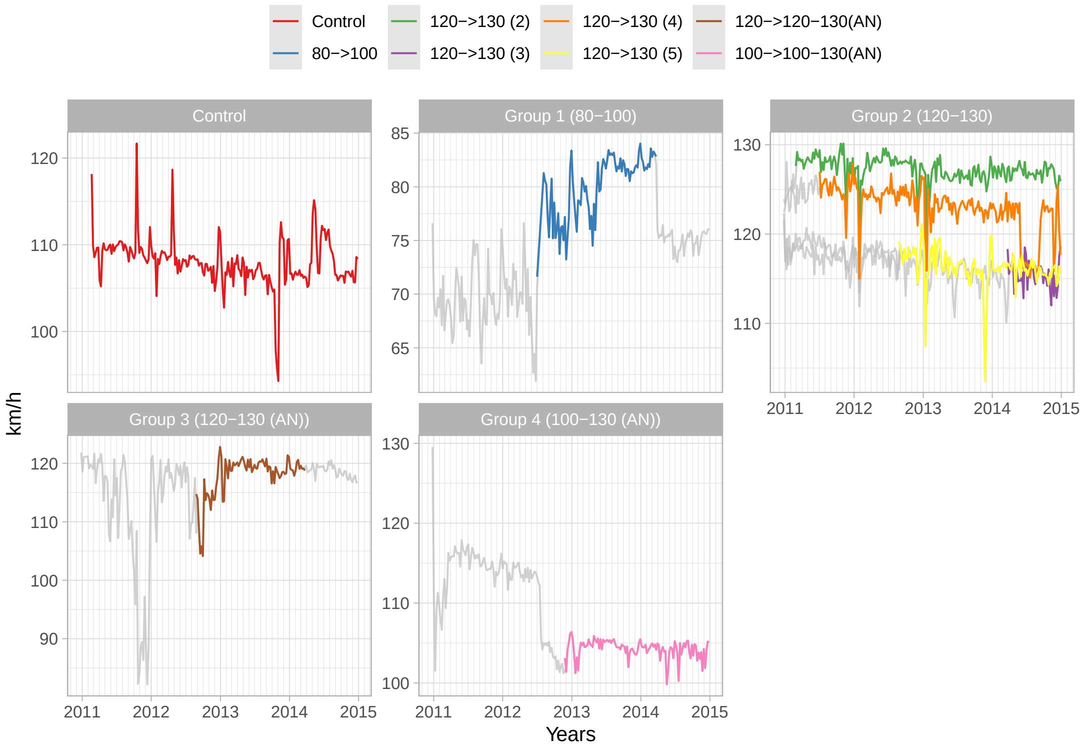


**Figure 4.** Average speeds per intervention AQMS and control group. *Notes:* Greyed out sections are non-intervention sections. Note the different vertical scales.

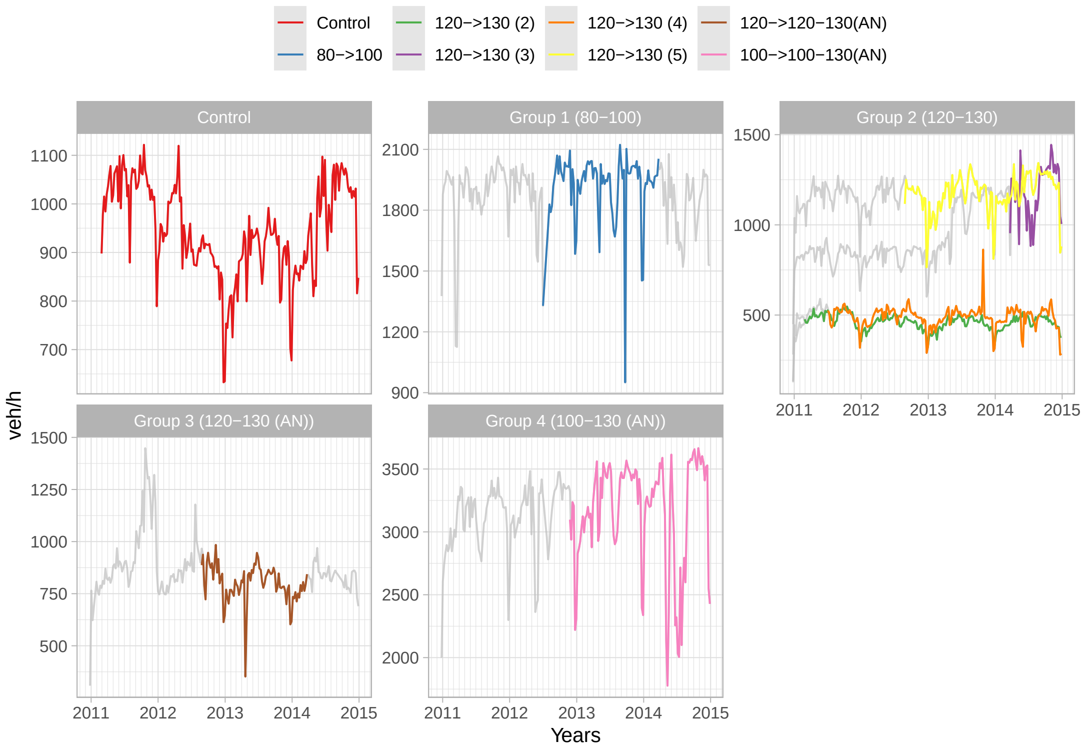


**Figure 5.** Traffic flow per intervention AQMS and averaged for the control group. Greyed out sections are non-intervention sections. Note the different vertical scales.

# 5 Conclusion

This thesis has analysed the effect of speed limit policy changes on $NO_2$ emissions on highways in the Netherlands. We have focused our attention on five speed limit policy changes: (1) 80 km/h to 100 km/h, (2) 120 km/h to 130 km/h, (3) 120 km/h to 130 km/h (with a day-night regime) and (4) 100 km/h to 130 km/h (with a day-night regime). Using hourly data from 2011 to 2015 from eleven air quality measurement stations we have used a difference-in-difference methodology to estimate the effect of the speed limit increases. The results of the analysis are mixed. We find no increase in $NO_2$ for the increase from 80 km/h to 100 km/h. We do find positive estimates for the change from 120 to 130 km/h (day-night regime) of about 1.9 $\mu gm^{-3}$ (8.5% increase) during night times compared to the control group. Group 2, with a change from 120 km/h to 130 km/h, shows results in a bandwidth of $-2.6$ $\mu gm^{-3}$ to 5.3 $\mu gm^{-3}$ (-9.8% to 33.1%) compared to the control group. The results in this group appear to depend on the traffic density pre-treatment. The traffic density on a road pre-intervention determines whether the increase in speed limit significantly increases the average speed and thereby also $NO_2$ emission levels. However, driving behaviour also plays a role in emission levels. We find a decrease of about $-2$ $\mu gm^{-3}$ going from 100 km/h to 130 km/h (day-night regime) during night times. However, this is caused by a sharp drop in actual driven speeds after implementation of speed controls with strict enforcement before the speed limit was increased. If we look at actual *driven* speeds in this group and revert our difference-in-difference estimate, we find an increase in $NO_2$ of about 2 $\mu gm^{-3}$ on a 10km/h increase. Once more, it shows how not only speed limit policy itself is able to lower emissions. We conclude that in most cases the increase to 130 km/h has not increased $NO_2$ emissions. This is mainly due to the fact that average speeds have not increased. However, where there is room to drive faster, emissions can increase substantially. The implication for the latest speed limit policy in the Netherlands, which is purely aimed at reducing emissions of $NO_2$ from highway traffic, is that reducing the speed limit alone might not be enough to decrease $NO_2$ concentrations to the desired levels. However, it has to be noted that a speed limit decrease such as in the latest speed limit policy change in the Netherlands, is more likely to substantially change the driven average speed than an increase from 120 km/h to 130 km/h. A suggestion for further research is to investigate how speed limit policy changes change the nature of traffic flow and speed on a road and subsequently, how these two phenomena have an influence on $NO_2$ levels.


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# 6 Appendix A

**Table 6.** Studies on speed limit policies and metropolitan environments. Source (and adapted): Bel et al. (2015)

| Authors | Place and year | Speed limit change | Pollutants impact | Method |
|---|---|---|---|---|
| Dijkema et al. (2008) | Amsterdam (November 2004 - November 2006) | From 100km/h to 80km/h (with strict enforcement) | No $NO_x$ air quality improvement and 7.4% air quality improvement | Econometric |
| Gonçalves et al. (2008) | Barcelona metropolitan area (June 2004) | (1) Variable speed system (2) From 120km/h and 100km/h to 80/km/h | (1) 5.6% decrease for $NO_x$ and a 4.8% decrease for $PM_{10}$ (2) A further 1.0% decrease for $NO_x$ and 0.9% decrease for $PM_{10}$ compared to (1) | Modeling system |
| Baldasano et al. (2010) | Barcelona metropolitan area (2007-2008) | From 120 and 100km/h to 80 km/h | $NO_x$ emissions decreased by 10.98% and $PM_{10}$ emissions by 10.99%. Both pollutants emission levels decreased by 4% | Modeling system |
| Keuken et al. (2010) | Amsterdam and Rotterdam metropolitan areas (2005-2006) | From 100 to 80km/h | 20-30% decrease in $NO_x$ emission and 5-20% decrease in $PM_{10}$ | Modeling system and economet-ric |
| DCMR (2013) | Rotterdam (2011-2012) | 80km/h to 100km/h (with strict enforcement) | 20%, 20% and 17% increases for $NO_x$, $NO_2$ and EC (soot) respectively, no significant change in PM | Econometric |
| Bel and Rosell (2013) | Barcelona metropolitan area (2006-2010) | (1) From 120km/h and 100km/h to 80/km/h (2) Variable speed system | (1) Air quality deterioration, 1.7-3.2% for $NO_x$ and 5.3-5.9% for $PM_{10}$ (2) Variable speed reduces $NO_x$ and $PM_{10}$ air pollution by 5.2-11.7% and 11.3-13.5%, respectively | Econometric |
| Bel et al. (2015) | Barcelona metropolitan area (2006-2010) | (1) From 120km/h and 100km/h to 80/km/h (2) Variable speed system | (1) No effect on quantiles for $NO_x$ and $PM_{10}$ (2) Depending on quantiles -20.1% to -9.4% for $NO_x$ and -68.4% to -5.1% for $PM_{10}$ | Econometric |
| Perez-Prada and Monzon (2017) | Madrid (2010) | 90km/h to 70km/h | Decrease in $NO_x$ of 16.4% | Modeling system |

# 7 Appendix B

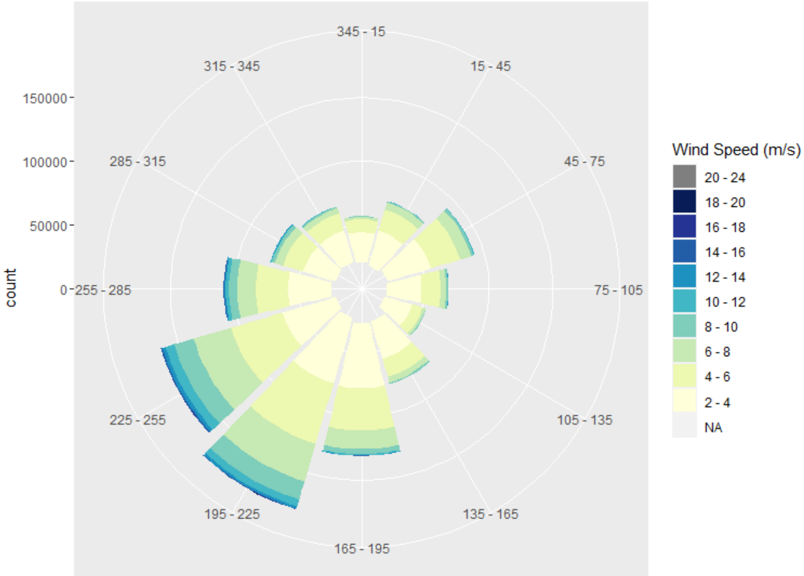


**Figure 6.** Wind rose graph of hourly average wind direction (0-360°) and hourly wind speed averaged over all the weather stations used. South-south-western (SSW) and west-south-western (WSW) winds are predominant.

# 8 Appendix C


**Figure 7.** Overview of all AQMS sites and geographical matches.

# 9 Appendix D

**Table 7.** Regression results with speed as dependent variable

| | *Dependent variable:* | |
|---|---|---|
| | Speed (km/h) | |
| | (1) | (2) |
| 80-100 km/h | $-38.000^{***}$ (0.091) | |
| 120-130 km/h (2) | $12.610^{***}$ (0.410) | |
| 120-130 km/h (3) | $8.405^{***}$ (0.074) | |
| 120-130 km/h (4) | $14.049^{***}$ (0.189) | |
| 120-130 km/h (5) | $7.578^{***}$ (0.103) | |
| 120-130 km/h (AN) | | $0.653^{***}$ (0.166) |
| 100-130 km/h (AN) | | $2.499^{***}$ (0.183) |
| Intervention 80-100 km/h | $10.502^{***}$ (0.132) | |
| Intervention 120-130 km/h (2) | $6.169^{***}$ (0.414) | |
| Intervention 120-130 km/h (3) | $-1.024^{***}$ (0.183) | |
| Intervention 120-130 km/h (4) | $0.605^{***}$ (0.200) | |
| Intervention 120-130 km/h (5) | $0.826^{***}$ (0.130) | |
| Intervention 120-130 km/h (AN) | | $8.140^{***}$ (0.256) |
| Intervention 100-130 km/h (AN) | | $-3.843^{***}$ (0.254) |
| Observations | 277,788 | 76,763 |
| Fixed Effects | Time | Time |
| $R^2$ | 0.693 | 0.188 |
| Adjusted $R^2$ | 0.649 | -0.025 |

$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

**Table 8.** Regression results with flow as dependent variable

| | *Dependent variable:* | |
|---|---|---|
| | Flow (veh/h) | |
| | (1) | (2) |
| 80-100 km/h | 752.699*** (4.896) | |
| 120-130 km/h (2) | −379.549*** (19.604) | |
| 120-130 km/h (3) | 3.055 (3.495) | |
| 120-130 km/h (4) | −394.136*** (8.789) | |
| 120-130 km/h (5) | 232.701*** (4.851) | |
| 120-130 km/h (AN) | | 30.062*** (5.517) |
| 100-130 km/h (AN) | | 964.920*** (6.072) |
| Intervention 80-100 km/h | 71.285*** (7.163) | |
| Intervention 120-130 km/h (2) | −78.198*** (19.784) | |
| Intervention 120-130 km/h (3) | 319.406*** (8.687) | |
| Intervention 120-130 km/h (4) | −31.987*** (9.284) | |
| Intervention 120-130 km/h (5) | 33.759*** (6.155) | |
| Intervention 120-130 km/h (AN) | | −49.136*** (8.452) |
| Intervention 100-130 km/h (AN) | | 86.341*** (8.408) |
| Observations | 282,062 | 84,665 |
| Fixed Effects | Time | Time |
| $R^2$ | 0.667 | 0.651 |
| Adjusted $R^2$ | 0.620 | 0.569 |

*p<0.1; **p<0.05; ***p<0.01