Traffic Air Pollution: Regulation and Impact in Barcelona

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Abstract

In January 2008, the maximum speed on motorways in the metropolitan area of Barcelona was limited to 80 km/h from previously 100 - 120 km/h to reduce air pollution. This paper aims to evaluate the effect of this zone 80 policy. A difference-in-differences estimation shows zone 80 policy significantly reduces NO_2 concentration within zone 80 area. Using wind direction to identify traffic pollution source, we find a U-shape emission-speed curve and velocity gradient positively affect vehicle emission. We also provide evidence that zone 80 policy significantly reduce vehicle velocity on motorways to more efficient speed, while only slightly affect the velocity gradient and car intensity. This effect explains the reduction of NO_2 concentration by zone 80 policy.

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1 Introduction

Air pollution has becoming one of the biggest problem and the main threat to health of citizens in many European countries. The 2015 report of air quality by European Environment Agency (EEA 2015e)[5] point out that in 2013, 87% of urban population in EU-28 countries was exposed to $PM_{2.5}$ concentration exceeding stricter WHO AQG value, while this number is 98% for O_3, 37% for SO_2 and 12% for NO_2. Figure 1 from EEA[1] also clearly shows that Madrid and Barcelona are two of the most polluted cities in Europe.

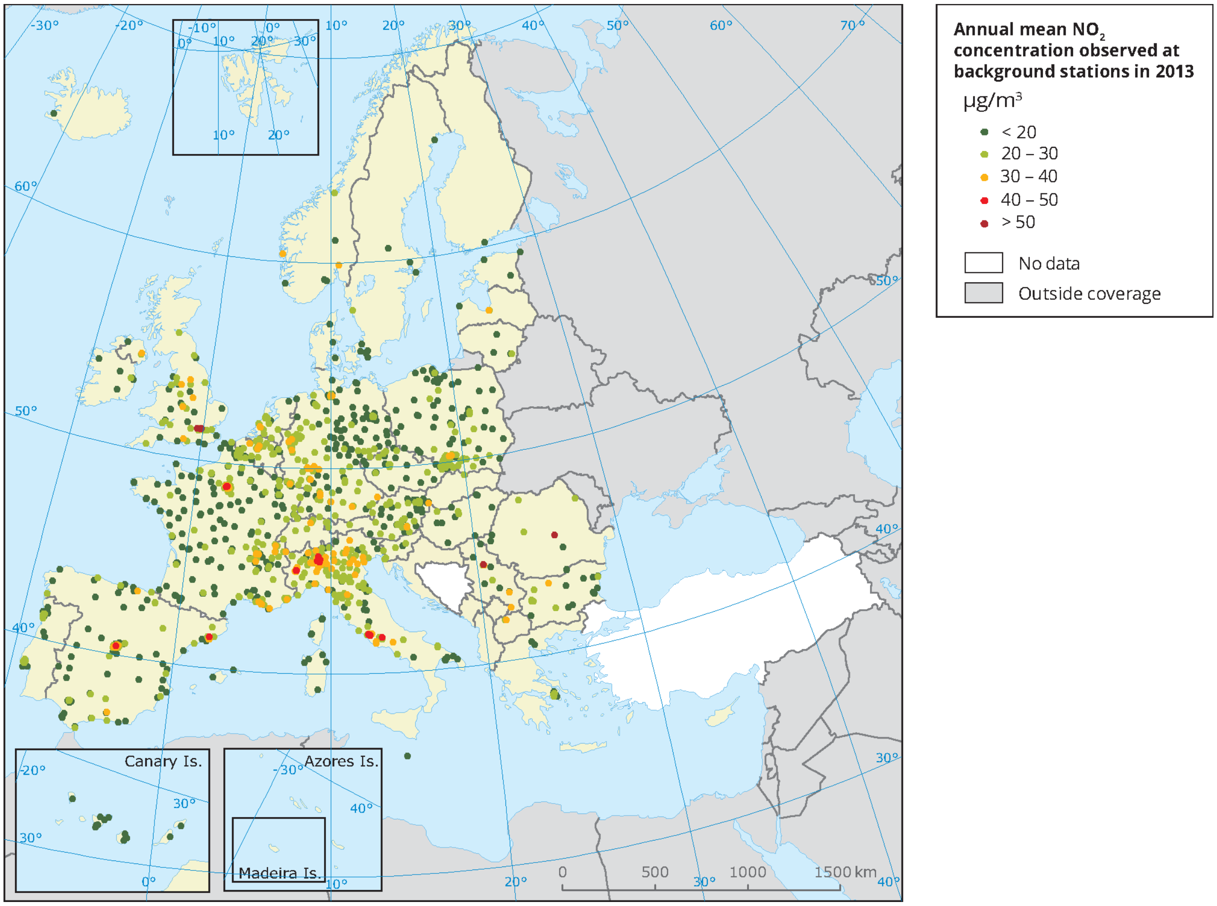

Figure 1: Annually NO2 concentration in Europe, 2013

Transportation is the one of the main source of air pollution in modern cities, especially for nitrogen oxides pollutants (NO, NO_2) which is mainly generated by the combustion

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[1] http://www.eea.europa.eu

process of fossil fuels. This is supported by numerous researches that aim to evaluate the contribution of traffic on air pollution. For example, Sundvor *et al.*(2012)[28] suggests that road traffic accounts for over 40% total NO_x emission in Europe. Covile *et al.*(2001)[13] uses UK data and estimates that transport contributes about 50% of NO_2 concentration. Using data from Pamplona of Navarra, Parra *et al.*(2009)[24] also show that transportation is the dominant source of NO_2 in urban area. Another feature of NO_2 pollution is that it has a large within-city spatial variation: concentration is relatively higher near road and fall rapidly with distance. Past literatures also find wind, as the media of pollutant spreading, also shape the distribution of NO_2 within urban area. Pollutant level decays extremely rapid in the upwind direction while disperse to farer locations in the downwind direction. These facts are proved by researches like Parra *et al.*(2009)[24], Vardoulakis *et al.*(2011)[29], Karner *et al.*(2010)[17] and Quiros *et al.*(2013)[25].

To control air pollution under the EU air quality 24-hour limit level, EU put high pressure to its member countries and suggested several potential regulation policies. Zone 80 is one of the policy among them and was undertaken by the local government of Catalonia since Jan. 1, 2008. This policy reduces the maximum speed limit from previously 100 - 120 km/h to 80 km/h on the metropolitan area of Barcelona. According to Bel and Rossel (2015)[11], 63.2% area of motorway had speed limit of 100 km/h and 20.4% had 120 km/h limit prior to the policy. Figure 2 shows the area of zone 80 policy: all areas that lies within the violet boundary is zone 80. Specifically, the speed limit of 80 km/h has been applied on ring road (Ronda Dalt and Ronda Litoral) of Barcelona down-town area, which is represented by the shadow in Figure 2, long before the execution of zone 80 policy. Hence the traffic within down-town is not affected by such policy post to 2008. Since Feb. 2011, the newly elected right-wing government announced that the zone 80 policy was not as efficient as expected. Hence they abandoned the zone 80 policy and replaced it with a loose variable speed limit on the original region of zone 80 policy, where speed limit changes according to different road and weather condition, and be showed to drivers via screens on the motorways.

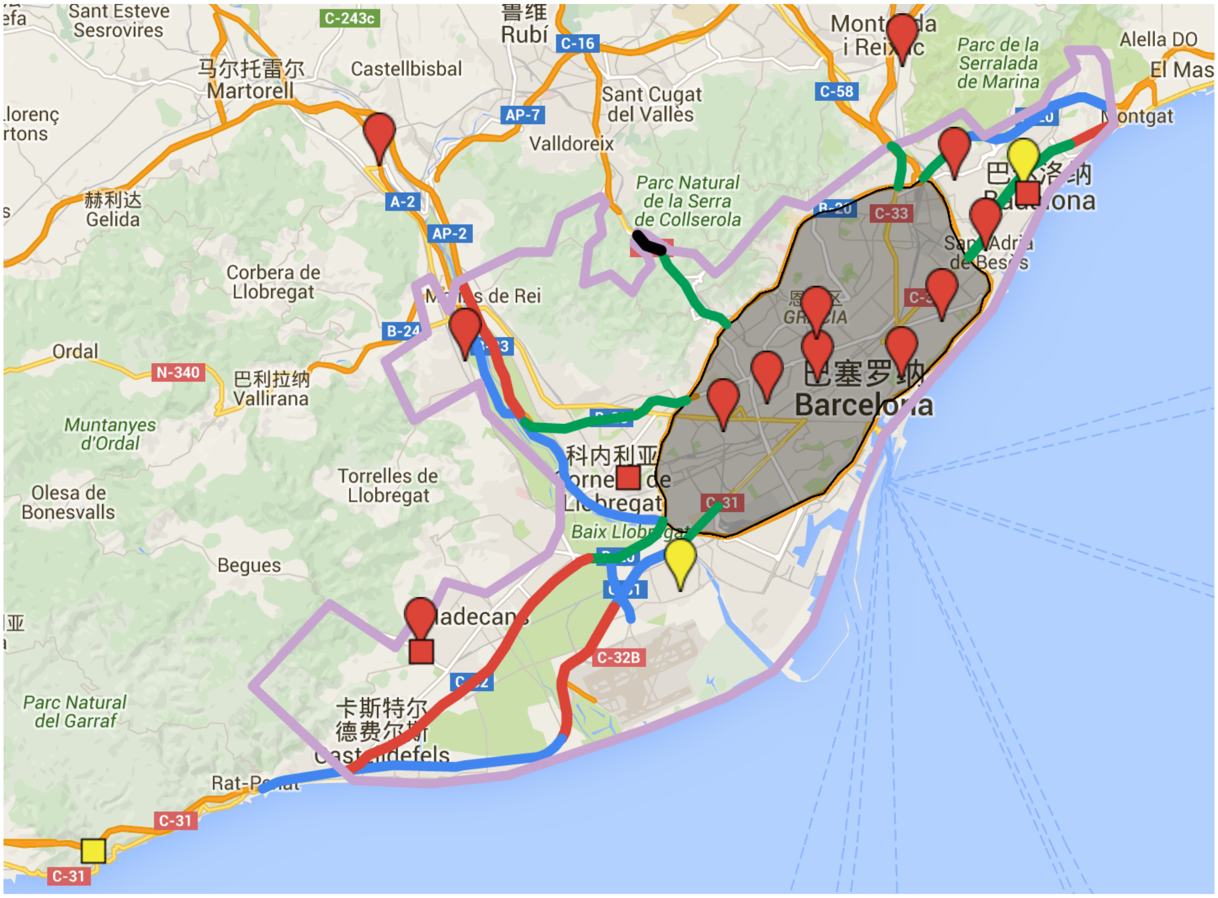

Figure 2: Zone 80 policy area and air quality stations in Barcelona

Zone 80 policy is widely used by governments across Europe to control air pollution. And there is a wide range of previous studies examine the impact of zone 80 policy and other similar speed limitation policies on air quality. The most related literature to our research are two papers that also studies the same policy of Barcelona. Bel and Rossel (2013)[12] use a difference-in-differences econometric setting to evaluate the effect of zone 80 policy on two pollutants: NO_x and PM_{10} employing daily traffic, weather and pollution data from 2006 to 2010. They also analyze another variable speed policy on motorway C-32s that reduce speed limit to 40 km/h under extreme weather. What they find is zone 80 policy actually slightly increased air pollution in Barcelona: 1.7 - 3.2% increasing in NO_x concentration and 5.3 - 5.9% increasing in PM_{10}. Moreover, Bel and Rossel (2015)[11] use same data to conduct a quantile regression analysis. They also find similar result that zone 80 policy have no effect or slightly increasing effect on both two pollutants.

Most of other literatures, on the contrary, show an opponent effect as Bel and Rossel do when evaluating similar policies in other regions. Keuken et al. (2010)[19] study the effect of 80 km/h speed limit in Amsterdam and Rotterdam. They set sensors near motorway to collect data and use a econometrics framework. They estimate that the ″zone 80″ policy in Netherlands reduces NO_2 concentration by 5 - 30% and it is 5 - 25% for PM_{10}. Dijkema *et al*.(2008)[14] study the 80 km/h policy in Amsterdam, Netherlands as well. They find a significant reduction of PM_{10} and PM_1 by 7% and 12.7% respectively. Their estimation on NO_x is overall negative, though not statistically significant. An early paper by Olde *et al*.(2005)[21] also suggest that the 80 km/h policy in large cities of Netherlands reduces NO_2 pollution by 5%. Modelling and computational simulation is another popular method to estimate impact of traffic regulation policy. For example, Keller *et al*.(2008)[18] apply air quality model package MM5/CAMx and simulate that a change of speed limit from 120 km/h to 80 km/h reduces 4% of total NO_2 concentration. Two papers by Baldasano *et al*.(2010)[9] and Gonccalves *et al*.(2008)[15] also use the traffic modelling method to simulate the effect of zone 80 in Barcelona. And they get the result that zone 80 reduces NO_2 pollution by up to 4% and 5.7% respectively.

Another group of literatures that related to this paper are papers that aim to study how different driving behavior affect air pollution. Many literatures have proved the existence of U-shaped emission-speed curve, like Barth and Boriboonsomsin (2009)[10] or Alessandrini *et al*.(2012)[7]. But speed is not the only factor that determines vehicle emission on the highway. Acceleration and deceleration also generates extra vehicle emission, as argued in Ahn *et al*.(2002)[6] and Int Panis *et al*.(2006)[23].

In this paper, we aim to evaluate the impact of 80 km/h policy in Barcelona. All studies above that using an econometric framework applied methods similar to difference-in-differences setting. However, this kind of DID framework has two drawbacks. One, it is relatively hard to find a perfect control group and justify the control. Two, even though we are able to estimate the average treatment effect of policy, it is still impossible for us to quantitatively understand the mechanism from the policy to air pollution. Therefore, it is more interesting to study the chain of policy-traffic-pollution: the impact of zone 80 policy on the driving behavior on motorways, and how this impact further influence the vehicle emission.

The structure of this paper is as following. In section 2, we introduce the data we employ in this research. We present a direct estimation result of zone 80 policy on NO_2 air pollution using a difference-in-differences framework in section 3. Section 4 consists three parts: firstly we will introduce a strategy to identify traffic air pollution source using wind data. Secondly we study the impact of traffic factors on air pollution. Lastly we estimate how zone 80 policy affects traffic pattern and estimate how much this impact predicts change in NO_2. In section 5 we conclude.

2 Data

Our data was provided by various people and institutions. The traffic data was supplied by Germà Bel and Jordi Rosell at Universitat de Barcelona, which was used in their two papers in 2013 and 2015[11][12]. Originally the database was retrieved from the local government of Catalonia. Since there are a lot of measurement errors in the velocity data of year 2005, in this project we only use the traffic data from 2006 to 2010 as Bel and Rosell did, for the sake of data quality. This dataset includes hourly data of 587 sensors on the motorway of Catalonia that near Barcelona, which covers 8 main motorways of Barcelona, names: A-2, B-20, B-23, C-31, C-31s, C-32s, Ronda Dalt and Ronda Litoral. From 2006 to 2010, there are in total 16267835 observations of hourly average velocity and intensity. It is worth to mention that those sensors are only used for recording the traffic situation but not for putting fine on over-speed driving, which is the function of radars (cameras) on the road. We also obtain the locations of speed radars in Barcelona from the open database at Todo-Poi[2]. There are in total 33 radars of different speed limit on the 8 motorways in Barcelona.

Air pollution data is the core of this project. Our air pollution data is supplied by two different entitles. In Barcelona and Tarragona, we get the data from local government of Catalonia, where there are 19 air quality stations that had active time during 2006 - 2010 in Barcelona and 9 stations in Tarragona. Of all 19 stations in Barcelona, 9 are within zone 80, while 6 stations locate in the down-town area of Barcelona and 3 out of the zone 80. Figure 2 also shows the location of all those 19 stations. Red means the station was found before 2008, while yellow means it is found between 2008 and 2010. Square shape means the station is abandoned now, and stations with drop shape is still working. In Madrid, the air pollution data is provided by the city hall of Madrid, where there are in total 6 stations locate out of Madrid M-30 ring road and we use as control group (please refer to Appendix A for a detailed description of air quality stations). The observed pollutants varies in different air quality stations and at different time. Our dependent pollutant variable is nitrogen dioxide (NO_2). We select NO_2 as dependent variable for two reasons. Firstly, NO_2 is the only pollutant that was observed by all stations in Barcelona, Tarragona and Madrid. Consider that pollution data is relatively sparse compare to traffic data, it is important to make good use of all available air-quality stations. Secondly, compare with other candidates like SO_2, PM_{10} or O_3, NO_2 is more correlated with traffic system. For instance, Colvile *et al*.(2001)[13] find that about 50% of NO_2 is accounted by road traffic using UK data, while only 24% of PM_{10} is from traffic.

The atmospheric data was retrieved from ECMWF ERA-Interim database. This open database provides worldwide 6-hour frequency atmospheric data at surface and all pressure levels with $0.125^\circ \times 0.125^\circ$ resolution, since 1979. In practice, we use linear interpolation to get the atmospheric data at each hour to match the frequency with other data.

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[2] http://www.todo-poi.es/

The climate variables we control as covariates are as following:

- 3-dimension wind speed: three hourly-average wind speed variables at U (west - east), V (south - north) and W (vertical) directions respectively. Continuous variable on $\mathbb{R}$ with measurement unit m/s.
- Temperature: Continuous variable on $\mathbb{R}^+$ with measurement unit K (Kelvin degree).
- Humidity: Specific humidity, which is the ratio of water vapor to the total air on a mass basis. Continuous variable on $(0, 1)$ with no measurement unit.
- Cloud cover: The ratio of cloud to the total sky on an area basis. Continuous variable on $(0, 1)$ with no measurement unit.

And Table 1 shows the main descriptive statistics.

Table 1: Variables and descriptive statistics

Variables	Unit	Mean	Standard deviation	Total observations
NO_2	$\mu g/m^3$	37.53	28.23	1416579
Humidity	N/A	7.59e-3	3.10e-3	1517831
Temperature	K	290.06	6.39	1517831
U Wind	m/s	0.46	2.64	1517831
V Wind	m/s	-0.073	2.57	1517831
W Wind	m/s	0.026	0.15	1517831
Abs. Horizontal Wind	m/s	3.199	1.894	1517831
Cloud Cover	N/A	0.011	0.052	1517831
Intensity	#	1603.73	4547.28	16267835
Velocity	km/h	88.92	18.14	16267835
Velocity gradient	$1/h$	9.955	6.862	581737

3 Difference-in-Differences Approach

3.1 Methodology and Econometric Framework

As first approach, we estimate the effect of zone 80 policy on air pollution with difference-in-differences method, also known as "diff-in-diff" or "DID". The intuition of diff-in-diff method is as following: Ideally we could find a twin city to serve as the control group compare with the treatment group Barcelona zone 80 area. If there wasn't zone 80 policy, the pollution trend in Barcelona would be parallel to pollution trend in the twin city. And difference of average pollution before and after the zone 80 policy in two city would be the same. As zone 80 policy is the only difference in Barcelona and the twin city, the difference of two differences now is the average treatment effect of zone 80 policy at Barcelona. The mathematical expression of diff-in-diff method as follows:

$$\beta_{DID} = [E(Y_t|T=1) - E(Y_t|T=0)] - [E(Y_c|T=1) - E(Y_c|T=0)] \tag{1}$$

where Y_t and Y_c are outcome of treatment group and control group respectively. T is a binary variable where $T = 1$ denotes periods after the shock and *vice versa*.

And in this project, the baseline econometric framework of the DID estimation is as shown below:

$$E_{it} = \alpha + \beta X_{it} + \gamma P_{it} + \theta_t + \eta_i + \epsilon_{it} \tag{2}$$

where E_{it} is the hourly-averaged NO_2 emission observed by each station i at time t. X_{it} is a group of time and station varying independent variables, which includes all atmospheric variables and NO_2 pollution of one hour previously. Specifically, we did not control for U and V wind respectively but control for the absolute value of horizontal wind speed instead, defined as $\text{HorizontalSpeed} = \sqrt{\text{Uwind}^2 + \text{Vwind}^2}$. P_{it} is a dummy where $P_{it} = 1$ denotes that the station i lies within zone 80 and time t after the execution of zone 80 policy. η_i is a group of station dummy for each stations. ϵ_{it} is normal random shock. θ_t is a group of time-specific variables, includes:

- Yearly dummy: dummy for each year. 1 if it is that year and 0 if not. The reference year is 2006 and we drop year 2010 to avoid multicollinearity problem on Policy dummy.

- Policy dummy: 1 if after 01/01/2008 and 0 before 2008.

- Time and time-sqr: We denote 01/01/2004 00:00:00 as $t = 1$. Time is the number of hours after the beginning point and time-sqr is the quadratic term.
- Winter dummy: 1 if the month is November, December, January or February.
- Work Day dummy: 1 if the day is Monday to Friday.
- Morning Peak dummy: 1 if the day is work day and from 08:00 to 11:00.
- Night Peak dummy: 1 if the day is work day and from 19:00 to 22:00.

The key element of difference-in-differences method is to find a proper control group. As argued before, an ideal control group would have air pollution trend parallel to the treatment group, *i.e.*, 10 stations within zone 80. As a first approach, we set three separately regions as control group to test the average treatment effect of zone 80 on NO_2 pollution as follows:

- Rest part of Barcelona. This control group follows the methodology applied in Bel and Rosell (2013, 2015)[11][12]. The advantage of using the rest stations in Barcelona is that they may experience same unobserved shocks as treatment group do, like shock brought by financial crisis on certain specific industry in Barcelona or other unobserved policies. However, there are two problems of using it as control: One, the zone 80 policy might have effect on the traffic out of zone 80 region as well. For example, the traffic within down-town might be slowed down in peak time because of the speed limit on leave town direction. Two, emission produced by traffic within zone 80 does not only spread within zone 80 but could transmit to other areas. Hence such effect would lead to an under-estimation of the overall treatment effect.
- Tarragona. Tarragona is a medium-size Catalan city to the south-west direction, about 50 km away from Barcelona. The pros of using Tarragona as control is that the air quality monitor system of Tarragona is the same as Barcelona. It also lies

by the coast and it's weather is quite similar to Barcelona. Besides, Tarragona has more active air quality stations than every other cities except Barcelona do. Yet it has relatively smaller size compare to Barelona, so the economy of Tarragona may be suffered differently in the way Barcelona do during the financial crisis of 2007-08. As economic activities also produces emission, this might lead to some level of bias.

- Madrid. We use 6 air quality stations that lies out of M-30 ring road of Madrid as another potential control group. As the biggest city in Spain, we believe that the economy of Madrid might be affected by financial crisis in the similar way as Barcelona did. And we also use air quality stations that lie out of the down-town area to mock the environment of zone 80 region. The cons of Madrid is it locates too far away from Barcelona and the weather condition is quite different.

Since every potential controls have its specific characters, a simple DID might not only reflect the average treatment effect of zone 80 but also some other pre-policy differences that affect the trend of pollution afterwards. And the estimation might be hence biased. A more complicate approach follows the "synthetic control method" proposed in Abadie *et al.*(2003, 2011, 2012)[2 3 4]. Here we simply introduce the basic intuition of synthetic control method and for a formal theoretical discussion please refer to Abadie *et al.*(2012)[3].

The goal of synthetic control method is to find a proper weight and use all other available control groups to construct an "artificial control group", which behaves as parallel as possible to period of Barcelona previous to the execution of zone 80 policy. And then we could compare the artificial control group without zone 80 policy versus the post-policy Barcelona.

Assume there are in total J potential control groups (3 in our case) and 1 treatment group each with same size time-series data (T_0 periods) prior to the execution of zone 80 policy. For each group, we control for K covariates. Let $\mathbf{W}$ is a $J \times 1$ vector of optimal weight for all potential controls that $w_j \geq 0$ and $\sum_j w_j = 1$. $\mathbf{V}$ is a $K \times K$ size diagonal matrix with all elements non-negative. $\mathbf{X_{0t}}$ is a $K \times 1$ vector of covariates that vary with both groups and time in treatment group at period t, and $\mathbf{X_{1t}}$ is a $K \times J$ matrix of K covariates in all J control groups. Then we aim to find optimal $\mathbf{W}^*$ and $\mathbf{V}^*$ such to minimize the sum of residuals between the new synthetic control's covariates and the treatment group's covariates:

$$\sum_{t=1}^{T_0}(\mathbf{X_{0t}} - \mathbf{X_{1t}W})'\mathbf{V}(\mathbf{X_{0t}} - \mathbf{X_{1t}W}) \tag{3}$$

Then, assume $\mathbf{Y_1}$ is a $T \times J$ matrix of the dependent variable (NO_2 in our study) in all potential control groups. We are hence able to construct an artificial control group with $\mathbf{Y_{arti}} = \mathbf{Y_1W}^*$ as dependent variables and $\mathbf{X_{arti}} = (\mathbf{X_{11}W}^*, \mathbf{X_{12}W}^*, ..., \mathbf{X_{1T}W}^*)'$ as independent variables. Therefore, we could apply the typical DID analysis to compare the treatment group and this new artificial control group.

3.2 Difference-in-Differences Estimation Result

3.2.1 Use simple control group

As a first step in the empirical analysis, the diff-in-diff estimation result using simple control group is shown in Table 2. Column (1) of Table 2 is the regression result using the observation at air quality stations in the rest part of Barcelona as control. In column (2) and (3) we use only the observation in Tarragona and Madrid respectively as control, while in column (4) we pool Tarragona and Madrid's observations and use it for control group. Specifically, we also control the crossing variable of policy dummy with dummies that indicate air quality stations that located outside of zone 80 or inside down-town area in the last three regression, names Policy$\times I^{\text{Downtown}}$ and Policy$\times I^{\text{Outter}}$ respectively. We control for these two covariates aim to examine whether there exists the systematic bias we argued before that air pollution produced in zone 80 spreads to other area in Barcelona.

In all regressions, the coefficients of Policy $\times I^{\text{zone80}}$ variable are significantly negative, which implies an overall negative average treatment effect of zone 80 policy on NO_2

Table 2: DID Estimation with Different Simple Control Groups

	Dependent variable: NO_2			
Controls:	Barca Rest	Tarragona	Madrid	Tarragona and Madrid
	(1)	(2)	(3)	(4)
NO2lag1	0.862***	0.855***	0.860***	0.857***
	(0.0009)	(0.0008)	(0.0008)	(0.0007)
Policy	-0.772***	-0.874***	-1.612***	-1.390***
	(0.2422)	(0.1762)	(0.2104)	(0.1620)
Policy $\times I^{\text{zone80}}$	-0.461***	-0.512***	-0.519***	-0.503***
	(0.0660)	(0.0565)	(0.0736)	(0.0552)
Policy $\times I^{\text{Downtown}}$		-0.001	-0.031	-0.0004
		(0.0633)	(0.0788)	(0.0620)
Policy $\times I^{\text{Outter}}$		-0.108	-0.102	-0.091
		(0.0908)	(0.1024)	(0.0900)
Time	6.8e-5***	1.6e-5	-9.5e-6	-3.5e-5*
	(2.1e-5)	(1.5e-5)	(1.8e-5)	(1.4e-5)
Time Sqr	-7.0e-10**	4.0e-11	6.3e-10**	8.9e-10***
	(2.4e-10)	(1.8e-10)	(2.1e-10)	(1.7e-10)
Workday	1.306***	1.190***	1.048***	1.020***
	(0.0331)	(0.0237)	(0.0290)	(0.0222)
Morning Peak	-0.247***	-0.356***	-0.184***	-0.322***
	(0.0609)	(0.0446)	(0.0514)	(0.0407)
Night Peak	2.639***	2.095***	3.936***	3.081***
	(0.0546)	(0.0401)	(0.0498)	(0.0387)
Winter	0.823***	0.724***	1.239***	1.046***
	(0.0463)	(0.0343)	(0.0397)	(0.0313)
Weather Variables	Yes	Yes	Yes	Yes
Station Dummy	Yes	Yes	Yes	Yes
Yearly Dummy	Yes	Yes	Yes	Yes
Const	42.516***	43.044***	16.617***	20.052***
	(1.7787)	(1.3124)	(1.0585)	(0.9321)
R^2	0.821	0.837	0.817	0.833
Observation	584211	957305	813368	1186462

***: $p \leq 0.001$, **: $p \leq 0.01$, *: $p \leq 0.05$

air pollution. In the mean while, we assume that the dispersion process of NO_2 at any location follows an $AR(1)$ process, and we estimate a significant coefficient of pollution concentration of previous hour on this hour's air pollution. About 86% of NO_2 are explained by the NO_2 concentration level of last hour. Let the coefficient of 1 hour previous air pollution is $beta$. Then we could derive the share of pollution that not explained by autocorrelation: $\text{Diff}_{it} = \text{NO2}_{it} - \text{NO2lag1}_{it}$. Taking the average of Diff, we find a decreasing in NO_2 concentration by 8.94%, 9.45%, 9.92% and 9.41% respectively for the four regressions in Table 2.

Further more, although the point estimation of coefficients of $\text{Policy}\times I^{\text{Downtown}}$ and $\text{Policy}\times I^{\text{Outter}}$ are always negative especially for stations out of zone 80, all of them are not statistically different from 0 at 5% significance level. In this sense, the rest part of Barcelona could still serve as a usable control group. Time dummies are also significant for NO_2 pollution. The concentration of NO_2 are significantly higher between Monday to Friday, during the night peak period or in the winter when heating facilities are used. The negative coefficient of morning peak is a strange result, yet it might be explained by the low concentration of NO_2 in the dawn.

3.2.2 Apply synthetic control method

We apply the *R* package that is introduced by Abadie *et al.*(2011)[2] to derive the optimal weights. It is worth noting that this package requires treatment and all potential control groups data must be in form of time-series. Hence, we take average over all air-quality stations with observation at each time within each area (zone 80, Barcelona Rest, Madrid and Tarragona) and use this averaged database as the input.

Firstly, we apply this method on the combination of all the three potential control groups we mentioned above: Barcelona rest, Madrid and Tarragona. Table 3 shows the statistics of controlled covariates as well as the elements of the optimal diagonal matrix $\mathbf{V}^*$. Column (2) of Table 3 is the synthetic zone 80 area. In term of mean, it is shown

Table 3: Pre-Policy Characteristics, Barca Rest, Tarragona and Madrid

	Zone 80	”Synthetic” Zone 80	All Samples	V weights
NO2lag1	42.134	43.205	39.929	0.08
Humidity	0.008	0.008	0.007	0.193
Temperature	289.738	289.864	290.421	0.04
Horizontal Wind	3.151	3.174	3.087	0.325
W wind	0.035	0.032	0.024	0.277
Cloud Cover	0.010	0.010	0.009	0.086

to be more comparable to actual zone 80 area than the all samples do. And the optimal weight $\mathbf{W}^*$ is positive for all three controls with values 0.672, 0.064 and 0.264 respectively. Secondly, since we still concern the impact of zone 80 policy on NO_2 concentration in the rest part of Barcelona, we also do a robustness check with only Madrid and Tarragona in the combination of controls. And we estimate an optimal weight of 0.554 and 0.446 respectively.

The DID estimation result that uses synthetic control method is shown in Table 4. All controlled variables are defined the same as the estimation using simple control group do but we now using the average of those variables within each area instead of station-specific previously. Similar to previous estimation, we find an overall negative impact of zone 80 policy on the NO_2 pollution within zone 80, and a point estimation of percentage decreasing is 7.6% and 10.3% respectively as a result.

4 Policy, Traffic Pattern and Air Pollution

In this section, we aim to divide the impact from policy to air pollution that estimated by difference-in-differences approach into two steps. Firstly, which traffic factors have impact on the air pollution, and by how much? Secondly, how speed limitation policy affects the traffic pattern, and how much air pollution reduction could be explained by the change of traffic pattern?

Table 4: Synthetic Control DID Estimation

	Dependent variable: NO_2	
Controls:	Barca Rest, Madrid and Tarragona	Madrid and Tarragona
	(1)	(2)
NO2lag1	0.871***	0.792***
	(0.0016)	(0.0022)
Policy	2.714***	2.695***
	(0.3694)	(0.3722)
Policy$\times I^{\text{zone80}}$	-0.415***	-0.901***
	(0.0816)	(0.0830)
Time	-1.7e-5	-3.0e-5
	(2.1e-5)	(2.2e-5)
Time Sqr	-7.2e-10**	-4.6e-10
	(2.8e-10)	(2.8e-10)
Workday	0.806***	0.700***
	(0.0434)	(0.0445)
Morning Peak	-1.681***	-1.084***
	(0.0830)	(0.0807)
Night Peak	1.578***	2.850***
	(0.0713)	(0.0757)
Winter	0.521***	0.903***
	(0.0515)	(0.0502)
Weather Variables	Yes	Yes
Yearly Dummy	Yes	Yes
Const	-10.917***	-2.066***
	(0.3223)	(0.2578)
R-Sqr	0.879	0.883
Observation	105164	105164

***: $p \leq 0.001$, **: $p \leq 0.01$, *: $p \leq 0.05$

There are two reasons that drive us to study the mechanism of zone 80 policy on air pollution instead of just accept the diff-in-diff estimation result. One, our estimation is to the opposite of the estimation of Bel and Rosell (2013, 2015)[12 11]. Therefore, we need this study to serve as a strong robustness check of our estimation on average treatment effect. Two, via studying the chain from zone 80 policy to air pollution, we could assess the pros and cons of zone 80 policy better, which would shed light in the researches on similar traffic regulation policies in the future.

We apply a similar general framework as proposed by Schmutzler (2011)[26]. Assume the total pollution observed in location r equals to:

$$E_r(\theta) = T_r(\theta)\eta_r(\theta) + E_r^Y(\theta) \tag{4}$$

where $T_r(\theta)$ is the total amount of vehicles in the surrounding. $\eta_r(\theta)$ reflects the average emission per car. And $E_r^Y(\theta)$ is the background emission. Hence, with a change in policy θ, the total effect will be:

$$\frac{dE_R}{d\theta} = \frac{dT_r}{d\theta}\eta_r + \frac{d\eta_r}{d\theta}T_r + \frac{dE_r^Y}{d\theta} \tag{5}$$

This differential equation shows three channels that policy may affect emission. The first term via the change of total amount of vehicles; the second term captures the change of behavior per car, further it changes the average emission per car. And the last term, which we will ignore in the following discussion, is the effect on the non-transportation background emission.

The structure in this section is as follows. We firstly introduce the strategy we use to identify traffic pollution source. Then we will introduce the method and empirical result on how traffic patterns affect air pollution. Lastly, we will discuss the impact of zone 80 policy on traffic pattern within policy area.

4.1 Traffic Pollution Source Identification

To study which traffic factors determine emission, the first question we have to address is: how could we identify the source of traffic air pollution? Consider the complexity of road map, this is not a simple question to answer. For example, if there are three main motorways near one air quality station, how can we define the distance from air quality station to pollution source? Do we use the nearest distance, or the simple average distance, or the average distance weighted by car intensity? Each definition seems quite casual and almost impossible to justify.

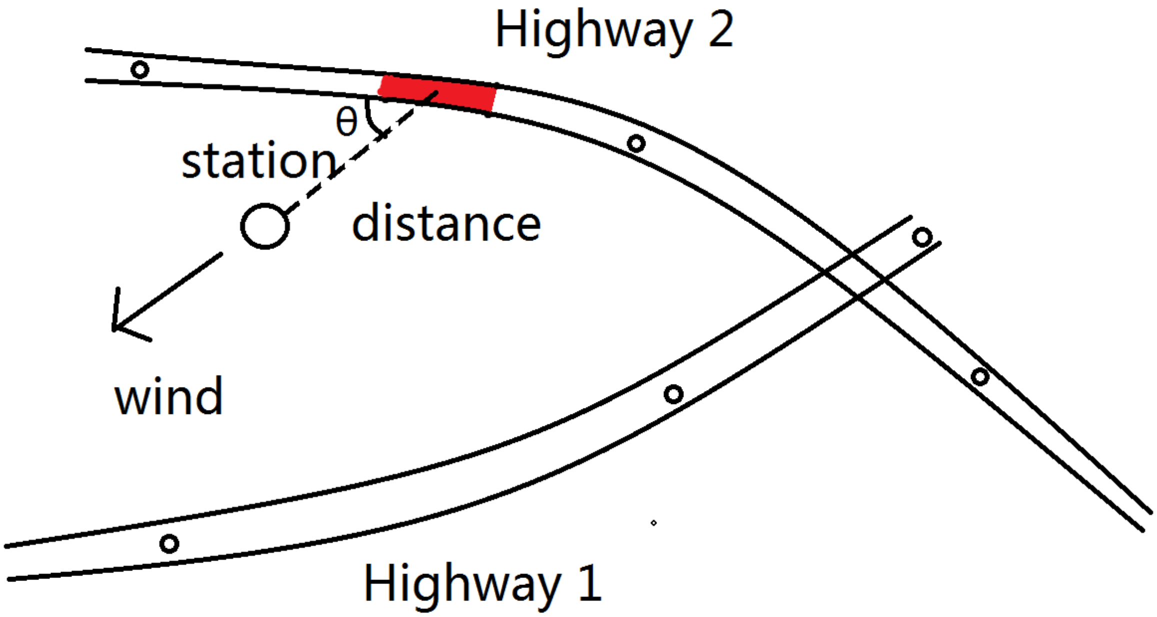

Figure 3: Schematic graph of identification strategy

Past literatures clearly shows that the dispersion of air pollution is highly influenced by the wind direction. This fact inspired us to design a new strategy to identify the source of motorway air pollution, as illustrated in Figure 3. At every moment and every station location in Barcelona, we have the wind direction information by linear interpolation. Hence, we can therefore find a crossover point of the motorway with the ray to the upwind direction. And we assume a neighbourhood of this crossover point on the motorway contributes to the emission at station location. In the mean while, we can also identify the distance d from the pollution source to air-quality station at each moment and the angle θ between wind direction and motorway direction at crossover point. Lastly, at every crossover point, we estimate the car intensity and average velocity by linear interpolation using the observation of nearest two sensors on the highway.

4.2 From Traffic to Pollution

By the identification strategy we introduced in section 4.2, we now have distance, angle at crossover point, car intensity and velocity at each moment and each station. Hence we set the OLS econometrics framework as shown below:

$$\begin{aligned} E_{it} = \alpha_0 + \Sigma exp(-\alpha_1 d_{it}) n_{it} [f(v_{it}) + \beta_R I^{\text{Radar}} + \beta_\nabla \nabla v_{it}] / sin(\theta_{it}) \\ + \gamma X_{it} + \delta_t + \eta_i + \eta_i \times Dir_j + \eta_i \times Dir_j \times w_t + \epsilon_{it} \end{aligned} \quad (6)$$

where i is station, t is time and j is the wind direction. Follow literatures like Su *et al.*(2009)[27], we use the term $exp(-\alpha_1 d_{it})$ to represent the exponent decay process of air pollution with distance. $n_i t$ is the car intensity. We control for three different traffic factors: $f(v_{it})$, I^{Radar} and ∇v_{it}. We assume a quadratic emission-speed function $f(v) = \beta_0 + \beta_1 v + \beta_2 v^2$ as $f(v)$, which is used to fit the U-shape emission-speed curve that was found in the past literature. I^{radar} is an dummy indicator. 1 means the crossover point is within 300 meters to the nearest radar. We control for this term since many drivers slow down before radar and speed up after radar, which might generate extra emission. And ∇v_{it} is the gradient of velocity at the crossover point which is derived by the data of nearest two sensors, with measurement unit $1/h$. This term also controls for the emission caused by acceleration and deceleration. Lastly, the smaller the crossover angle is , the longer motorway would contribute to the NO_2 concentration at air-quality station if we assume all motorways within certain small angle contribute pollution to the stations. Hence, we use the $1/sin(\theta_{it})$ term to control for this effect. In practice, to avoid our observation goes to very large when θ_{it} is very small, we actually take the maximum of θ_{it} and 0.1. It is worth mentioning that by OLS, we could only estimate the product of α_1 and $\beta = (\beta_0, \beta_1, \beta_2, \beta_R, \beta_\bigtriangledown)'$ but we could not disentangle α_1 and β by all means.

As for X_{it}, we control for a series of covariates that vary with different station and different time. There are two kinds of covariates in X_{it}. One is the observation of NO_2 one hour previously, which reflects the autocorrelation nature of air pollution dispersion. Two is a bunch of atmospheric variables as we do in section 3, including temperature, horizontal wind speed, vertical wind speed, humidity and cloud cover. We control for similar time variables δ_t as in section 3. The only difference is since we have already controlled the traffic factors, it will make no sense to control for morning peak dummy and night peak dummy again. Instead, we control for a dummy that indicates whether the moment is work hour or not, and we define work hour as 8:00 - 18:00 in the work day (Mon. - Fri.). This term is to control for the different background emission at different time in a day. For example, if there is a plant near an air quality station, it will produce emission during only the work hour.

Finally, we control for station fixed effect via a bunch of station-specific dummies in η_i, which implies that background emission can vary among all air quality stations. We also try to control the impact of wind direction on background emission since as wind blows from different directions, emission might be very different for economic activities are not evenly distributed around each station. This effect is controlled by the crossing dummy $\eta_i \times Dir_j$, where Dir_j is seven dummies that represents the upwind direction, from north-north-east (45° - 90°) to east-east-south (315° - 360°). And north-east-east (0° - 45°) is the reference direction. Lastly, we allow this effect vary in different time in a day. We cross $\eta_i \times Dir_j$ dummy and dummies denote workday and work hour to control for this possibility.

We use traffic data near 8 air quality stations (08015001, 08015021, 08089003, 08089005, 08194008, 08245012, 08263001, 08301004) that within zone 80 area and 1 station (08019004) in the down-town of Barcelona to carry on this empirical test. We select only those 9 stations for the following reasons. Firstly, the sensor is relatively sparse out of zone 80 area, and the traffic data quality is lower on the ring road near Parc de la Llobregat. Secondly, there is no sensors on B-22 motorway, which connects airport of Barcelona with motorway C-31 and C-32s in our database. The period we test is from 2006 - 2010, since the traffic data quality is not as good in 2005.

Table 5 shows the empirical estimation of traffic pattern on pollution. Column (2) is the estimation using baseline econometrics framework. In column (1) we ignored terms of Radar dummy and velocity gradient. Column (3) and column (4) are two robustness checks. In column (3), we consider the possibility that when wind speed is relatively low, wind actually not bring the traffic air pollution at this moment but one or more hours ago. And we use the wind speed and distance to derive the time wind spend to carry air pollution to air-quality station. If it takes more than one hour, we use lag value of traffic data rather than current value. In column (4) we consider an alternative speed-emission curve. Theoretically, emission per kilometer would go to infinity when speed of vehicle tends to zero, while a quadratic speed-emission function can not account for this character. Therefore, we add a new term $\beta_3 \frac{1}{v}$ to $f(v)$ to fit the infinity left tail. Our hypothesis is $\alpha_1 \beta_3 > 0$.

Looking first at column (1). we estimate a significantly positive $\alpha_1 \beta_0$ and $\alpha_1 \beta_2$, while $\alpha_1 \beta_1$ is negative. All are statistically significant at 0.001 level. This give us an U-shape emission speed curve with most efficient speed at 75.8 km/h, which is consistent with estimation in past literatures. Column (2) to column (4) consider the effect of velocity gradient and radar nearby. The coefficient for velocity gradient is significantly positive as we expected, since change speed would cause more pollution. Though $\alpha_1 \beta_R$ is positive

Table 5: Impact of Traffic Factors on Pollution

	Dependent variable: NO_2			
	Baseline		Traffic Time-lag	Alt. Function
	(1)	(2)	(3)	(4)
NO2lag1	0.828***	0.828***	0.828***	0.828***
	(0.0016)	(0.0016)	(0.0016)	(0.0016)
Car Intensity	.00264***	.00217***	.00219***	.00192
	(.00026)	(.00029)	(.00029)	(.00113)
N×Vel	-.00464***	-.00467***	-.00471***	-.00431*
	(.00064)	(.00068)	(.00068)	(.00173)
N×Vel-sqr	.00306***	.00310***	.00310***	.00292***
	(.00039)	(.00040)	(.00040)	(.00083)
N/Vel				5.5e-5
				(.00022)
N×Gradient		.00063***	.00062***	.00062***
		(.00017)	(.00017)	(.00017)
N×I^{Radar}		.00196	.00195	.00192
		(.00638)	(.00635)	(.00635)
Workday	1.099***	1.100***	1.101***	1.102***
	(0.1537)	(0.1537)	(0.1537)	(0.1537)
Work hour	2.098***	2.047***	2.047***	2.048***
	(0.1808)	(0.1812)	(0.1812)	(0.1812)
Winter	0.652***	0.647***	0.648***	0.649***
	(0.0728)	(0.0728)	(0.0728)	(0.0728)
Weather Variables	Yes	Yes	Yes	Yes
Station Dummy	Yes	Yes	Yes	Yes
Station×Dir	Yes	Yes	Yes	Yes
Station×Dir×wd/wh	Yes	Yes	Yes	Yes
Const	-14.471***	-14.792***	-14.752***	-14.764***
	(2.8747)	(2.8761)	(2.8758)	(2.8768)
R-Sqr	0.827	0.827	0.827	0.827
Observation	202902	202902	202900	202900

***: $p \leq 0.001$, **: $p \leq 0.01$, *: $p \leq 0.05$

in all three estimations, they are not statistically different from 0, which is a little bit surprising and calls for more research in the future, since our prior is cars on highway would change speed to avoid being fined when driving near a radar. We also observe similar U-shape emission-speed curve by point estimation from column (2) to column (4). In column (4), the estimation of $\alpha_1\beta_3$ is, although not significantly, positive, which is consistent to our hypothesis above.

As for other covariates we controlled for, we estimate a similar coefficient of NO_2 autocorrelation compare with the estimation by DID in section 3. As we expected, the background air pollution in the workday or work hour is significantly higher. And in the winter the pollution concentration is higher as well.

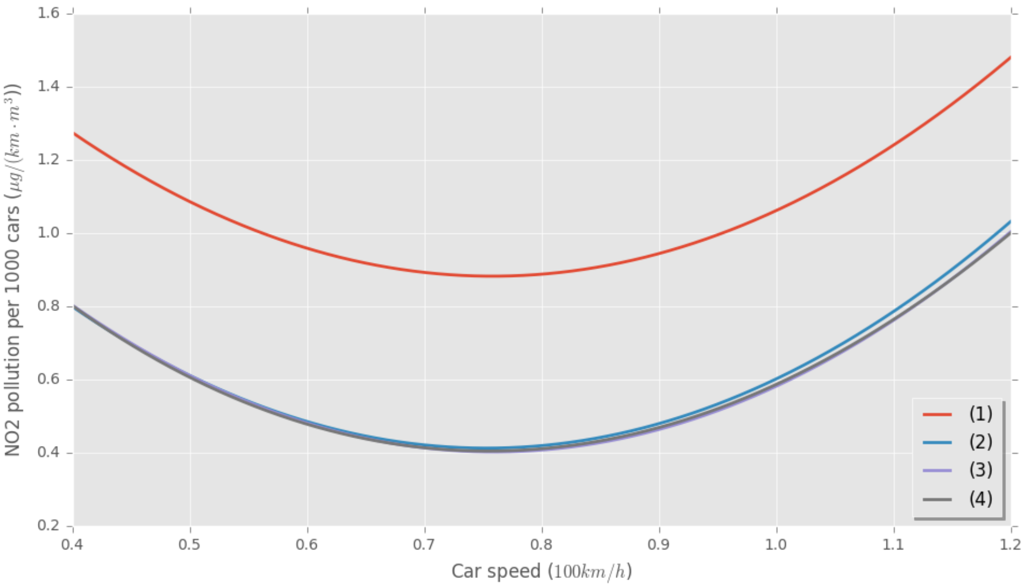

Figure 4: Estimated emission-speed curve

Figure 4 shows the estimated emission-speed curve that estimated by the four regressions in Table 5. The x-axis is speed in unit of 100 km/h. The unit of y-axis is NO_2 emission concentration that generated by every 1000 cars per kilometer. This graph shows that except column (1), the emission-speed curve that estimated by all other three regressions are very similar to each other. The most efficient speed in all estimations varies from 75.3

- 76.2 km/h. Using the average of NO_2 concentration net of autocorrelation and the NO_2 emission estimated by traffic pattern based on those observations that we could identify at least one motorway as traffic pollution source, we estimate that the traffic pattern that identified by wind direction explains 18.4% of total NO_2 pollution. As a comparison, literatures such as Sundvor *et al.*(2012)[28] and Colvile *et al.*(2001)[13] point out that traffic contributes to 40 - 50% of NO_2 pollution in urban region of Europe. Consider that the motorway traffic that we controlled here is only a part of all traffic pollution source, the identification strategy we applied here seems reasonable.

4.3 Impact of Zone 80 Policy on Traffic Pattern

Next, we examine the effect of zone 80 policy on traffic pattern within zone 80 area. From section 4.2, we learn two important facts: there exists a U-shape emission-speed curve with most efficient speed at around 76 km/h, and the aggregate velocity gradient generates extra emission. Hence, we study the impact of zone 80 policy on three traffic factors on motorways: average car intensity, average velocity and aggregate velocity gradient.

We use a difference-in-differences framework to estimate the average treatment effect on those three traffic factors. The treatment group includes 6 motorways that we have sensors on: A-2, B-20, B-23, C-31, C-31s and C-32s. And each motorway has 2 directions (leave town, enter town) so to make 12 different roads in total in the treatment group. As for control group, we use the two motorways of Barcelona's ring road: Ronda Dalt and Ronda Litoral. Each has two directions as well.

We apply econometrics framework similar to the one in section 3 as shown below:

$$Y_{it} = \alpha + \beta X_{it} + \gamma P_{it} + \theta_t + \eta_i + \epsilon_{it} \tag{7}$$

where Y_{it} could take three different variables: average car intensity n_{it}, average velocity v_{it} and aggregate velocity gradient ∇v_{it}, where i denotes motorway. Since errors and malfunctions are common in the sensor data, the observation on each road is very unbalanced. And it is impossible for us to select only those time that all sensors have observation. Hence, we take simple average among all sensors with observation on each road at each moment as the dependent variable. As for other control variables, we use exactly the same covariates as we do in section 3 except the 1 hour lag of NO_2 concentration.

Table 6: Average Treatment Effect of Zone 80 on Traffic Pattern

Dep. Variable:	Vel. Gradient	Ave. Velocity	Ave. Intensity
	(1)	(2)	(3)
Policy × I^{zone80}	0.240***	-10.602***	-85.968***
	(0.0409)	(0.0537)	(15.771)
Policy	-0.971***	-0.365*	369.992***
	(0.1153)	(0.1453)	(80.447)
Workday	0.614***	-0.950***	140.101***
	(0.0176)	(0.0170)	(9.0131)
Morning Peak	0.860***	-8.023***	1524.595***
	(0.0249)	(0.0408)	(9.2148)
Night Peak	0.448***	-4.443***	1007.686***
	(0.0237)	(0.0327)	(14.450)
Winter	0.259***	-0.314***	219.673***
	(0.0217)	(0.0265)	(12.977)
Time	-0.0004***	-0.0007***	-0.0139*
	(1.2e-5)	(1.5e-5)	(0.0057)
Time-sqr	4.5e-9***	7.9e-9***	9.8e-8
	(1.3e-10)	(1.5e-10)	(5.0e-8)
Weather Variables	Yes	Yes	Yes
Motorway Dummy	Yes	Yes	Yes
Yearly Dummy	Yes	Yes	Yes
Const	19.97***	134.73***	-25940.75***
	(0.8623)	(1.0452)	(302.653)
R-Sqr	0.311	0.670	0.083
Observation	581737	651824	651824

***: $p \leq 0.001$, **: $p \leq 0.01$, *: $p \leq 0.05$

Table 6 shows the average treatment effect of zone 80 policy on 3 different traffic factors. The dependent variable in column (1) is aggregate velocity gradient, while column (2) is average velocity and column (3) is average car intensity. The coefficient of

Policy$\times I^{\text{zone80}}$ term shows that the zone 80 policy slightly increased velocity gradient, while reduced average velocity and average car intensity in the treatment group. Also, we find that during the workday, morning peak, night peak or winter, velocity gradient increases, average velocity decreases and average car intensity increases. This is not surprising during the workday or traffic peak time. In the winter, it might be explained by the fact that people tend to substitute public transportation by private cars when weather is cold. And therefore there are more cars on the road and average speed is lower.

Additionally, using the average of 3 dependent variables after the execution of zone 80 policy in treatment group, we estimate that zone 80 policy increased 2.47% velocity gradient, while it reduced 12.82% average velocity and 4.70% average car intensity. Next, we do a preliminary estimation on how much policy change the air pollution via the change of traffic pattern. The strategy is as follows. For all observations that we could identify the traffic air pollution source by wind direction and average speed over 75 km/h after the policy, we calculate how the traffic pollution would be if velocity increases 10.6 km/h, velocity gradient decreases $0.24/h$ and car number increases 86, as we estimated in Table 6. And we use the coefficient that estimated by column (3) in Table 5 to carry on the estimation. Then we take average of the difference in traffic-source pollution, and compare it with the average of NO_2 pollution in the same times that net of autocorrelation part. We estimate that the change in velocity gradient and average velocity reduces 2.18% of NO_2 pollution and the reduction in car intensity predicts a 0.86% reduction on NO_2 concentration. In sum, our policy-traffic-pollution chain explains 3.04% out of 7.6 - 10.3% total NO_2 reduction estimated by DID estimation in section 3.

It is also worth mentioning that this estimation of 3.04% is quite preliminary and conservative for two reasons. We add same speed and velocity mark up to observations after the execution of policy. However, in reality the treatment effect of zone 80 policy might be heterogeneous at different time. Since we estimate a convex U-shape emission-speed curve, by Jensen's inequality Theorem, the reduction of air pollution would be higher if we could account for the heterogeneity in the speed mark-up.

5 Conclusion

In this paper, we studied the effect of zone 80 policy, which reduces the maximum speed limit from 100 - 120 km/h to 80 km/h on motorways in Barcelona. We focused our attention on pollutant NO_2. We applied two methods to estimate the two treatment effect: difference-in-differences method and the policy-traffic-pollution chain.

In contrast to previously study on the same policy, our analysis using both methods shows that zone 80 policy significantly increased air quality in Barcelona. By DID, we found that zone 80 policy reduced NO_2 concentration in zone 80 area by between 7.6 and 10.3%. This result is robust to different simple control groups and synthetic control groups. Furthermore, we used the wind direction to identify the region on nearby motorways that contributes to the NO_2 concentration at air quality stations in Barcelona. With traffic data, we showed a U-shape emission-speed curve with most efficient speed at 75.3 - 76.2 km/h, and aggregate velocity gradient produces extra emission. On average, the traffic source identified by wind direction explains 18.4% of overall NO_2 concentration at air quality stations. Lastly, using DID setting, we found that zone 80 policy increased 2.47% velocity gradient on motorways, while reduced 12.82% average velocity and 4.70% average car intensity. This policy-traffic-pollution chain predicts a reduction of 3.04% on NO_2 pollution, which is about 30 - 40% of the DID estimation result.

This paper belongs to a large pool of literatures that examine the effect of 80 km/h speed limitation in European countries. The main contribution of this paper is that we developed a new method that using wind direction to identify the source of traffic air pollution from motorways. And our data shows this identification strategy accounts a relatively big share of overall traffic pollution. To some extent, this method solves the spatial misaligned problem of air-quality data and traffic data, as well as the non-linear distribution of air pollution within city. We hope this research could shed light on further studies on transportation regulation policy, as well as those researches that study the impact of traffic air pollution on health or educational issues.

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Appendix

A. Air Quality Station Locations

Table 7: Barcelona Air Quality Stations

Code	Coordinate	Functional Period	Area Type	Zone type
08015001	41.44553, 2.24013	06/1982 - 11/2008	Urban, Traffic	Zone 80
08015021	41.44569, 2.23884	12/2008 - present	Urban, Traffic	Zone 80
08194008	41.42757, 2.22325	04/1990 - present	Suburban, Traffic	Zone 80
08245012	41.44921, 2.21064	01/1990 - present	Urban, Traffic	Zone 80
08125002	41.48389, 2.18927	01/1984 - present	Suburban, Industry	Outter
08019004	41.4058, 2.20557	01/1982 - present	Urban, Traffic	Down town
08019050	41.38804, 2.18898	06/2004 - present	Urban, Bottom	Down town
08019044	41.40057, 2.15446	01/1982 - present	Urban, Traffic	Down town
08019043	41.38698, 2.15462	01/1984 - present	Urban, Traffic	Down town
08019042	41.38061, 2.13404	01/1986 - present	Urban, Traffic	Down town
08101001	41.37225, 2.11613	07/1985 - present	Urban, Traffic	Down town
08073001	41.3586, 2.07725	12/1985 - 05/2013	Urban, Traffic	Zone 80
08263001	41.39385, 2.01092	06/1982 - present	Suburban, Industry	Zone 80
08196001	41.45343, 1.9758	06/1985 - present	Suburban, Industry	Outter
08169008	41.32328, 2.09874	12/2009 - present	Suburban, Traffic	Zone 80
08301004	41.31552, 2.0148	01/2009 - present	Suburban, Traffic	Zone 80
08089003	41.3051, 1.99272	01/2005 - 07/2009	Suburban, Bottom	Zone 80
08089005	41.30503, 1.99266	01/2009 - present	Suburban, Bottom	Zone 80
08270005	41.24406, 1.85866	01/2010 - 02/2013	Rural, Industry	Outter

Table 8: Madrid Air Quality Stations

Code	Coordinate	Functional Period	Area Type
28079027	40.47693, -3.58003	01/2003 - present	Urban, Bottom
28079016	40.44005, -3.63923	01/2003 - present	Urban, Bottom
28079036	40.40796, -3.64529	01/2003 - present	Urban, Traffic
28079040	40.38815, -3.65152	01/2003 - present	Urban, Bottom
28079017	40.34710, -3.71333	01/2003 - present	Urban, Bottom
28079018	40.39478, -3.73183	01/2003 - present	Urban, Bottom

Table 9: Tarragona Air Quality Stations

Code	Coordinate	Functional Period	Area Type
43005002	41.28023, 1.18099	01/2006 - present	Rural, Industry
43103001	41.19544, 1.23778	07/1990 - present	Rural, Industry
43148001	41.16130, 1.24078	06/1990 - present	Suburban, Industry
43148023	41.11924, 1.24273	07/2003 - present	Urban, Bottom
43047001	41.15678, 1.21879	06/1990 - present	Suburban, Industry
43148022	41.10553, 1.20184	01/1993 - present	Suburban, Industry
43148003	41.11773, 1.19305	06/1990 - present	Suburban, Industry
43171001	41.11394, 1.15290	06/1990 - present	Suburban, Industry
43123005	41.15263, 1.12124	02/1992 - present	Suburban, Traffic