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Abstract

Two speed management policies were implemented in the metropolitan area of Barcelona aimed at reducing air pollution concentration levels. In 2008, the maximum speed limit was reduced to 80 km/h and, in 2009, a variable speed system was introduced on some metropolitan motorways. This paper evaluates whether such policies have been successful in promoting cleaner air, not only in terms of mean pollutant levels but also during high and low pollution episodes. We use a quantile regression approach for fixed effect panel data. We find that the variable speed system improves air quality with regard to the two pollutants considered here, being most effective when nitrogen oxide levels are not too low and when particulate matter concentrations are below extremely high levels. However, reducing the maximum speed limit from 120/100 km/h to 80 km/h has no effect – or even a slightly increasing effect – on the two pollutants, depending on the pollution scenario.

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Highlights

Two speed management policies – a variable speed system and an 80 km/h speed limit – have been implemented on Barcelona's urban motorways to mitigate NO_x and PM_{10} air pollution.

We use a quantile regression approach that enables us to identify the policy impact in terms of mean concentrations, as well as its effects during low and high pollution episodes.

The variable speed system reduces NO_x and PM_{10} levels in most scenarios, although the impact varies according to the initial pollution level and the type of pollutant.

We confirm that reducing the maximum speed from 120 or 100 km/h to 80 km/h has no impact on pollution levels and can even increase some pollution levels slightly.

1. Introduction

Improving air quality is a major objective in most urban areas, but in metropolitan residential zones located near motorways, poor air quality is a particular concern. With pollution limits often being exceeded, a number of transboundary policies – including, the reduction in vehicle unit emissions and the introduction of new technologies and alternative fuels – have been adopted in an attempt to mitigate this situation. At the same time, various measures have been implemented at the local level – including, congestion tolling (Percoco, 2013) and traffic signal alignment (Madireddy et al., 2011). In the city of Barcelona, for example, the decision was taken to reduce the maximum speed limit from 120/100 km/h to 80 km/h on metropolitan motorways. Also, a variable speed system was implemented in specific zones of the metropolitan area.

Studies examining the impact of a change in the speed limit in metropolitan areas have failed to find a clear pattern; yet, a reduction in pollutants would appear to be the principal outcome. Here, our prime concern is in detecting whether the effects of Barcelona's speed limit policy (i.e., a fixed 80 km/h limit and a variable speed system) vary depending on the atmospheric pollution state. To do so, we generalize Bel and Rosell's (2013) findings when taking into account various pollution scenarios and combine them with a new econometric approach.

All previous econometric approaches have been conducted using average values, and so overlook the fact that policy impacts might vary with levels of pollution. Here, the quantile regression approach allows us to analyse the effects of speed limit policies at different pollution concentrations. As such, the main contribution of this paper is determining whether different atmospheric scenarios have a differentiated impact on a given speed limit policy. To the best of our knowledge, this is the first time that this methodology has been applied to such an analysis.

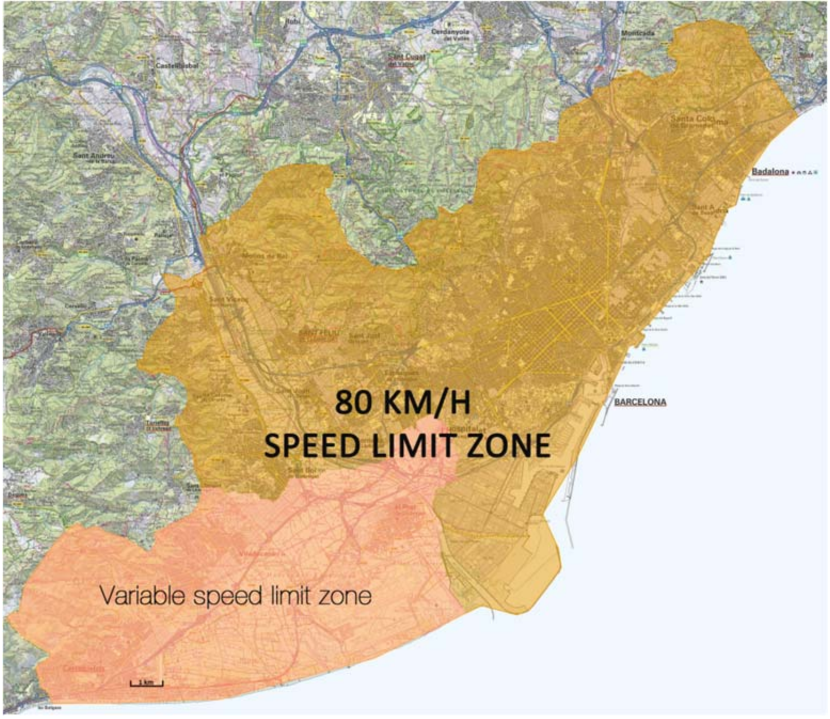
The rest of this paper is organized in five sections. In the first section, we briefly describe the two speed limit policies and, in the second, we review the empirical evidence reported to date on the impact of such policies on air pollution. Third, we explain the quantile regression methodology and, in the fourth, we report our empirical results. Finally, we highlight the conclusions to be drawn from our analysis and discuss the main policy implications.

2. Speed management policies

The regional government of Catalonia introduced regulations to reduce the maximum speed limit from 120 or 100 km/h to 80 km/h on motorways in the Barcelona metropolitan area, with the aim of attenuating pollution and the number of traffic accidents and reducing congestion (Figure 1). Before the new limit was introduced, a speed limit of 100 km/h operated on 63.2% of the roads, while a limit of 120 km/h operated on 20.4% of them (the remaining roads correspond to the Barcelona ring roads which already had an upper limit of 80 km/h). The new measure came into force on the first day of 2008 and remained in place until December 2010 when the newly elected regional government lifted the 80 km/h maximum speed limit, in fulfilment of its electoral promise. Most roads returned to similar speed limits to those in force in 2007, although a central government regulation issued in March 2011 reduced the maximum speed on all Spanish motorways from 120 to 110 km/h, which affected some of Barcelona's metropolitan motorways.

In January 2009, a second measure, a variable speed limit on the city's southern motorways, was introduced. Henceforth, the limit was to vary in accordance with traffic density, specific incidents impacting road safety (accidents, construction and maintenance work, etc.), air pollution levels and poor weather conditions (rain, fog, winds, etc.). The system provided for incremental reductions of 10 km/h from a maximum of 80 to a minimum of 40 km/h, the speed limit being communicated to drivers via variable message boards located approximately every kilometre and enforced by means of radar detection and traffic authority penalties. In addition to seeking to improve environmental conditions, this variable speed limit system also sought to reduce stop-and-go traffic. In this case, the newly elected regional government did not restore the previous system but rather, after cancelling the 80 km/h speed limit, expanded the variable speed system to other highways in the area.

Figure 1 80 km/h and variable speed zones



3. Related literature

It is widely accepted that lower speeds result in lower traffic emissions, adhering to a U-shaped curve that describes the relationship between emissions and average speed, especially at constant speeds (LAT, 2006). However, when vehicle accelerations and decelerations (stop-and-go traffic) are included in the model, the reduction in emissions attributable to the reduction in speed is much lower (Int Panis et al., 2006). As such, reducing the speed limit might eventually be counterproductive in terms of environmental controls, though these are not the only reasons for implementing these policies (Int Panis et al., 2011). Additionally, inconsistent results are reported for trucks, when their maximum speeds are reduced from 90 to 80 km/h, on levels of nitrogen oxides (NO_x) and on particulate matter less than 10 μm in diameter (PM_{10}). Their results illustrate the scientific uncertainties that policy makers face when considering the implementation of speed management policies.

Most previous studies of the environmental impact of reductions in speed limits involve computations based on theoretically established parameters, as shown in table 1 below. For example, Keller et al. (2008) examine modelled effects according to changing scenarios (a reference scenario with a maximum speed limit of 120 km/h on motorways and a limited scenario with a maximum of 80 km/h). They conduct a simulation for Switzerland, in which they analyse the impact on ozone levels of such a reduction in speed. The authors employ an air quality model package and examine different emission factors depending on speed. The modelled effects imply a 1% reduction in ozone concentrations, which translates into an equivalent decrease of about 4% in NO_x emissions.

In one of the first metropolitan studies, Keuken et al. (2010) study the effect of speed management in Amsterdam and Rotterdam. They adopt two different approaches: (a) one based on air quality monitoring in combination with dispersion modelling, and (b) one based on applying relevant emission factors relating to the change in traffic dynamics. The authors conduct a linear regression of the measured and modelled contributions of NO_x and PM_{10} during periods with and without the 80 km/h restriction. The study found no significant change in PM_{10} emissions and a reduction in NO_x of between 30 and 32%, depending on the city. However, when reducing traffic dynamics (i.e., decreasing congestion), pollutant levels fell in both cities between 16 and 24%. Overall they find that reducing traffic dynamics is more important than reducing the average speed. Moreover, they report that the impact of the measure is more significant if a high proportion of heavy vehicles use the highway.

Computations based on simulations also exist for the metropolitan area of Barcelona, where our own analysis is conducted. Gonçalves et al. (2008), for example, compare emissions from vehicles moving at different speeds, and the impact on air quality. The authors employ an emission model and examine a photochemical pollution episode (17-18 June 2004). The model controls for meteorological variables, as well as for emissions from a variety of industrial and energy facilities, domestic and commercial fossil fuels and solvent uses, road transport, ports and airports. When simulating an 80 km/h limit, the 24-hour average NO_2 concentration over the Barcelona area fell by between 0.7 and 0.8% on the selected day. The greatest reductions were observed in areas directly affected by the speed management, while results were more modest for the centre of Barcelona, with reductions of 0.1 to 0.3% for NO_2 and of 0.1 to 0.2% for

PM_{10}. Staying in Barcelona, Baldasano et al. (2010) conducted an evaluation using data on vehicle speed and daily traffic for 2007 and 2008 (the 80 km/h limit being introduced in the second of these years). The authors modelled emissions to detect changes in air quality. NO_x emissions fell by 10.98% and PM_{10} emissions by 10.99% in those areas in which the 80 km/h speed limit had been enforced, while the levels of both pollutants fell by 4% over the entire metropolitan area. As for air quality levels, they reported a reduction of between 5 and 8% in NO_x concentrations and of 3% for PM_{10} in the most heavily affected areas.

Although econometric analyses have gained ground in recent years, very few studies draw on actual emissions data before and after changes in speed limits. One exception is the study conducted by Dijkema et al. (2008) in Amsterdam to determine whether lowering the maximum speed limit on the city's ring motorway (A10) from 100 to 80 km/h reduced traffic-related air pollution in the neighbourhood of apartment buildings located near the highway. The authors collected emission data (daily mean concentrations of NO_x and PM_{10}) together with information on traffic volumes, traffic congestion and wind direction from the year before and after the limit was introduced. The results of their linear multivariate regressions pointed to no significant changes in NO_x air quality, while PM_{10} concentrations fell by 2.20 ppm (3.6%).

Table 1: Performance of speed limit policies on metropolitan environments

Authors	Place and Year	Speed limit change	Pollutants impact	Method
Dijkema et al. (2008)	Amsterdam (November 2004 to November 2006)	from 100 km/h to 80 km/h (with strict enforcement)	No NO_x air quality improvement and 7.4% PM_{10} air quality improvement	Econometric
Gonçalves et al (2008)	Barcelona metropolitan area (June 2004)	from 120 and 100 km/h to 80 km/h	0.7-0.8% decrease in NO_2 background levels	Modeling System
Baldasano et al. (2010)	Barcelona metropolitan area (2007-2008)	from 120 and 100 km/h to 80 km/h	NO_x emissions decreased by 10.98% and PM_{10} emissions by 10.99%. Both pollutants immission levels decreased by 4%	Modeling System
Keuken et al. (2010)	Amsterdam and Rotterdam metropolitan areas (2005-2006)	from 100 or 80 km/h to 80 km/h	30-32% decrease in NO_x emission and no relevant change in PM_{10}	Modeling System and Econometric
Bel and Rosell (2013)	Barcelona metropolitan area (2006-2010)	1) from 120 and 100 km/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 a 5.2-11.7% and 11.3-13.5%, respectively	Econometric

Bel and Rosell (2013) conduct an econometric (differences-in-differences) analysis of a speed management program in the Barcelona metropolitan area (combining a fixed speed limit of 80 km/h and a variable speed policy). Interestingly, the 80 km/h speed limit policy failed to improve air quality (1.7-3.2% increase in NO_x air levels and 5.3-5.9% increase in PM_{10}), while the variable speed policy had a positive impact (7.7-17.1% fall in NO_x levels and 14.5-17.3% fall in PM_{10}).

The study reported here, therefore, seeks to contribute to those that in recent years have undertaken evaluations of the impact of a variable speed limit by employing real motorway data (Papageorgiou et al., 2008). The positive impact of a variable speed policy on traffic safety is due to speed reduction and speed homogenisation. . The variable speed limits system generally improves the uniformity of traffic flows, reducing the creation of shock waves, decreasing average speeds and variability, and hence the number of lane change manoeuvres (Hegyi et al., 2005). Moreover, the homogenisation of speeds reduces the amount of stop-and-go traffic.

All the studies discussed above are concerned with the way in which a policy shift might impact mean pollution levels. However, it is debateable that the effectiveness of a policy is ever homogeneous across all levels of the pollution concentration distribution and that the policy is equally effective for all pollutants. If the shape of the distribution of pollution indicators changes after introducing a speed policy, the change in the mean pollution concentration is not representative of all pollution levels and, as such, cannot be generalized. Using the mean to characterize highly skewed distributions is obviously dangerous; yet, pollutants present an asymmetric statistical distribution (many days present only small to moderate concentrations and only a few present large to extreme levels) as we show in the data section. In this regard, the quantile regression methodology allows us to model policy impacts at all pollution levels.

4. Data

This study draws on the database created by the authors using information supplied by various entities of the regional government of Catalonia, as used previously in Bel and Rosell (2013)[1]. Ambient pollutant levels are reported by 15 air quality surface stations in the Barcelona metropolitan area for the period 2006 to 2010, and include 1,826 daily observations. Traffic stations and meteorological measurement stations were selected as close as possible to the pollutant monitoring stations.

Our dependent variables are nitrogen oxide (nitric oxide and nitrogen dioxide) and particulate matter 10 µm or less in aerodynamic diameter. NO_x and PM_{10} are designated as priorities and we focus specifically on these.

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[1] An extended description of the data can be found in Bel and Rosell (2013).

- NO_x: originating from transport emissions, power plants, cement factories, ceramic factories, glass factories, incinerators, natural gas, liquid and solid combustion and refineries. The origin is almost completely anthropogenic.

- PM_{10}: the fraction that penetrates most deeply into the lungs. Querol et al. (2001) report the chemical determination of 83% of the PM_{10} mass in the Barcelona metropolitan area and quantify anthropogenic sources as accounting for 54% of the load. Crustal and marine sources account for 26 and 4%, respectively; although, Saharan air mass intrusions can raise the crustal contribution up to 44%. The main anthropogenic sources are transport emissions, as well as emissions from power plants, cement factories, agricultural burning, mining and aggregate extraction, and incinerators, among others.

Our two policy dummy variables are the 80 km/h speed limit and the variable speed indicator. The 80 km/h dummy takes a value of one between 2008 and 2010 if the maximum speed limit was reduced to this new limit (note the Barcelona ring road stations take a value of one for the entire period as no change was made to the maximum speed). However, some stations never receive a one as they lay outside the 80 km/h restriction area. The variable speed dummy takes a value of one between 2009 and 2010 if the stations lay inside the variable speed area, and 0 otherwise. Note that all the variable speed limit traffic stations are inside the 80 km/h restriction area, so they take a value of one for the 80 km/h dummy while the measure was in force.

The covariates can be classified into three groups: the pollutant lag, and the traffic and atmospheric variables. Table 2 shows the main descriptive statistics.

- Pollutant lag: the atmosphere is not a watertight compartment, which means pollutant concentrations are related to the levels recorded on the previous day.
- Traffic: the number of vehicles is expected to be related to the concentration of the two pollutants, given that traffic emissions are their main source. We include the log number of all vehicles in both models.
- The atmosphere is characterized by multiple interactions, all of which we try to capture:
    - Atmospheric pressure: this is a continuous variable with air mass movements being related to pressure.
    - Wind speed: we include the average daily speed since pollutants are likely to be transported by the wind.
    - Rainfall: this is a continuous variable with pollutants interacting with water or forming sediments.
    - Relative humidity: even when it does not rain, atmospheric humidity can increase contaminant sedimentation and impact the reaction balance.
    - Temperature: a continuous variable included because pollutants react according to the level of solar irradiance.
    - Sahara desert dust: a dummy variable taking a value of 1 if the Ministry of the Environment reports dust from the Sahara in the zone, 0 otherwise.
    - Fire: a dummy variable taking a value of 1 if the Ministry of the Environment reports a large fire affecting the zone, 0 otherwise.

Table 2: Main descriptive statistics

Variables	Description	Mean	Standard deviation	Average observations per pollutant station
NO_x	Nitrogen oxide daily average concentration ($\mu g \cdot m^{-3}$)	84.46	59.95	1743
PM_{10}	Particulate matter daily average concentration with less than 10 µm ($\mu g \cdot m^{-3}$)	40.7	19.11	626
$NO_x(-1)$ and $PM_{10}(-1)$	One period lag variables (1 day)			
80km/h speed limit zone	Binary variable: 1 if 80km/h speed limit is implemented. 0 otherwise	0.47	0.50	2191
Variable speed	Binary variable: 1 if variable speed is implemented. 0 otherwise	0.07	0.25	2191
Traffic	Daily vehicles on both ways (taken in logarithms)	11.352	0.43	1500
Temperature	Daily average temperature (ºC)	16.51	6.32	1472
Relative humidity	Daily average relative humidity (%)	66.85	11.65	1472
Precipitation	Daily rainfall (mm)	1.56	5.86	1473
Wind speed	Daily average wind speed ($m \cdot s^{-1}$)	3.298	2.74	1020
Atmospheric pressure	Daily average atmospheric pressure (hPa)	1014.8	25.42	1035
Sahara desert dust	Binary variable: 1 if there was a Sahara dust event. 0 otherwise	0.156	0.363	2191
Fire	Binary variable: 1 if there was a fire in the area. 0 otherwise	0.013	0.114	2191

5. Methodology

We work with unbalanced panel data. The goal is to analyse a dependent variable Y_{it}, representing cross-sectional data related to pollution monitoring at n stations, where $i = 1, \dots, n$ refers to station i and $t = 1, \dots, T_i$ is the point in time when pollution measures are available for each station i, and T_i is the total number of days for which measures are available for station i. The classical linear model with individual fixed effects is:

$$Y_{it} = \beta X_{it} + \gamma Z_{it} + \theta_i + \varepsilon_{it} \tag{1}$$

where, for each station i and time t, X_{it} is a vector with k control covariates and Z_{it} is a vector with the dummy policy variables to be evaluated. The individual effects are represented by θ_i, the vector of individual effects by θ and, finally, ε_{it} is a random error. The classical linear model evaluates the influence of the covariates, the policies and the individual effect on the mean of the dependent variable and supposes that the influence is constant in the domain of the distribution of the dependent variable. However, there are models where a constant influence will not necessarily be true. For example, policies are unlikely to be equally effective when pollution levels are high or when they are low. In a classical approach (differences-in-differences), a policy is effective if it reduces $E(Y_{it})$ significantly; thus, testing whether γ is negative and significantly different from zero leads to the conclusion that a policy action is successful. Here, we study the reduction from a much wider perspective.

When working with panel data an alternative to the linear model with individual fixed effects is the quantile regression with fixed effects, which is defined as (see Koenker and Bassett, 1978, and Koenker, 2004):

$$Q_{Y_{it}}(\tau) = \beta(\tau)X_{it} + \gamma(\tau)Z_{it} + \theta_i \tag{2}$$

where $Q_{Y_{it}}(\tau)$ is the quantile function at τ confidence level. The model in (2) allows the influence of covariates X_{it} and Z_{it} to depend on the quantile confidence level τ. Koenker (2004) proposes estimating the parameters in model (2) simultaneously for all quantiles under study, $\tau_q,\ q = 1, \ldots, Q$, and to do so proposes solving:

$$\min_{(\beta,\gamma,\theta)} \sum_{q=1}^{Q} \sum_{i=1}^{n} \sum_{t=1}^{T_i} w_q\, \rho_{\tau_q}\left(Y_{it} - \beta(\tau_q)X_{it} - \gamma(\tau_q)Z_{it} - \theta_i\right) \tag{3}$$

where $\rho_\tau(\cdot)$ is a function defined by Koenker and Bassett (1978) (see also Koenker, 1984) as:

$$\rho_\tau(u) = \begin{cases} \tau|u|, & u \geq 0 \\ (1-\tau)|u|, & u < 0 \end{cases} \tag{4}$$

The terms w_q are weights and they control the influence of the quantiles on the estimation of the fixed effects. In our case we assume that the weights are the same for all the quantiles analysed.

An essential feature of the estimator resulting from the minimization of (3) is its robustness, i.e., neither the Gaussian condition nor the classical hypothesis related to the random error term is necessary. The main difficulty we face, however, is the actual minimization of expression (3). Here, we adopt the approach discussed in Koenker and Ng (2003), available on the *rqpd* package for R, and obtain our results in a relatively straightforward manner.

The quantile regression specified in (2) can be interpreted as a quantile generalization of the differences-in-differences model (see Bel and Rosell, 2013) which, given the control variables, measures the difference between the change in the quantile of air pollutant concentrations for the treatment group (i.e., zones with an 80 km/h speed limit or zones with a variable speed limit, G=1) and the change in the same quantile in the control group (i.e., zones with neither an 80 km/h speed limit nor a variable speed limit, G=0). For a given confidence level, these differences are:

$$\left[Q_{Y_{B|G=1}}(\tau) - Q_{Y_{A|G=1}}(\tau)\right] - \left[Q_{Y_{B|G=0}}(\tau) - Q_{Y_{A|G=0}}(\tau)\right],$$

where Y_B and Y_A denote the air pollutant concentrations after (A) and before (B) the implementation of the policy.

6. Results

Figure 2 shows the transformed kernel density estimations[2] (see Alemany et al., 2013; Bolancé et al., 2008; Bolancé, 2010) associated with the NO_x and PM_{10} variables. We compared the probability distribution functions for three scenarios: (i) without the 80 km/h and without the variable speed limits, (ii) with the 80 km/h and without the variable speed limits and (iii) with the 80 km/h and with the variable speed limits. From Figure 2, it can be concluded that when the policies are in force they not only shift the mean of the distribution, they also affect the shape of the distributions, especially when the impact of speed is included; in other words, the effect of the speed policy is not only reflected in a shift in distribution.

Figure 2: Density estimations for pollution data under different policies.

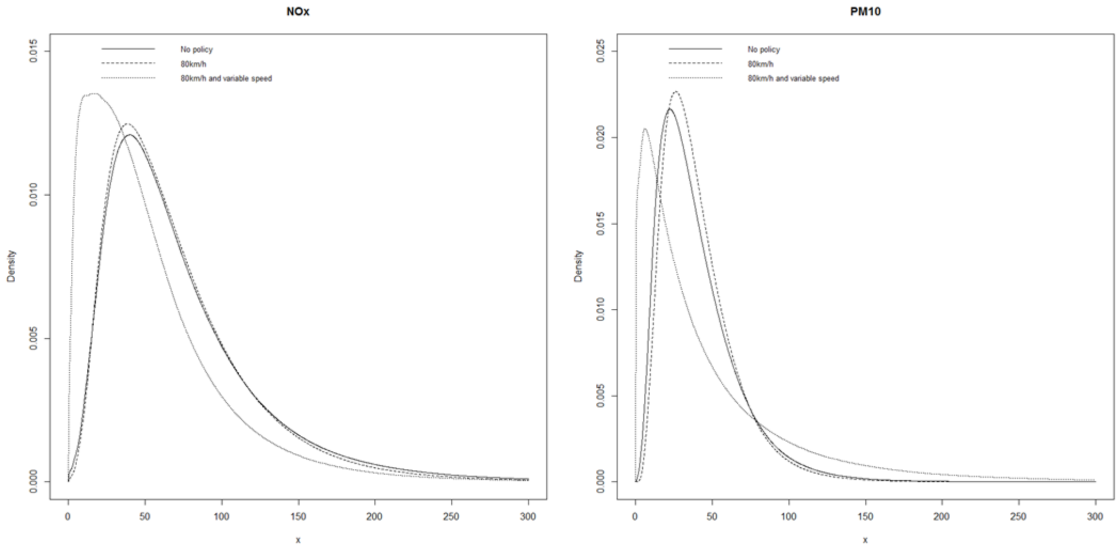

Table 3 shows the estimated quantiles with confidence levels τ ranging from 0.05 to 0.95 for the two pollutant concentrations (i.e., NO_x and PM_{10}). The first column in each case shows the behaviour of the observations when neither policy is implemented; the second column shows the observations when the 80 km/h speed limit is in place but the variable speed limit is not; the third column shows the observations when both policies are implemented; and, the fourth column is a composite for all the observations. Interestingly, the risk of high pollution levels falls more steeply when variable speed management is incorporated. However, the values in Table 3 are crude, there being no controls for such exogenous conditions as temperature, traffic, relative humidity and so on.

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[2] Transformed kernel density estimation is a nonparametric method that outperforms the classical kernel density estimation when the statistical distribution of the variable is right skewed.

Table 3: Empirical quantiles (expressed in $\mu g \cdot m^{-3}$) of the statistical distribution of the pollutant concentration for all data and under different policies by confidence level $\boldsymbol{\tau}$.

	NO_x				**PM_{10}**			
τ	**No policy**	**80km/h**	**80 km/h and variable speed**	**All Data**	**No policy**	**80km/h**	**80 km/h and variable speed**	**All data**
0.05	19.1	21.7	22.7	21.0	18.0	17.5	18.9	17.7
0.10	26.1	26.6	26.6	26.4	21.0	21.0	21.0	21.0
0.25	39.8	38.3	37.1	38.7	27.0	27.1	28.0	27.1
0.50	60.0	57.9	51.1	58.2	35.1	35.0	35.0	35.0
0.75	84.6	86.2	68.7	85.3	45.9	44.7	46.7	45.0
0.90	111.5	114.0	104.0	113.1	58.0	56.3	57.0	57.0
0.95	134.1	134.9	125.5	134.4	65.8	64.1	62.2	64.8

When no policy is in place, there is a 10% risk that the concentration of NO_x is above 111.5 and a 5% risk that the pollution level is above 134.1. If both policies are in force there is a 90% probability that the pollution level is lower than 104.0 and a 95% probability that it is under 125.5. Likewise, in the case of PM_{10}, if no policy is in place, there is a 10% risk that the level of concentration is above 58.0 and a 5% risk that it is above 65.8, whereas if both policies are in force, there is a 10% risk that the level is greater than 57.0 and a 5% risk that the PM_{10} concentration is above 62.2.

Table 4 shows the estimated parameters associated with the policy variables for different confidence levels τ in the quantile regression estimation.

Table 4: Estimated coefficients of both policies on the quantiles of the **NO_x** and **PM_{10}** pollutant distributions. Significance (p-value) levels are given in brackets (n=sample size).

	NO_x (n=9159)		**PM_{10}** (n=1910)	
τ	**80 km/h speed limit**	**Variable speed**	**80 km/h speed limit**	**Variable speed**
0.05	2.847 (0.056)	1.125 (0.259)	3.201* (0.027)	-8.892** (0.000)
0.10	1.760 (0.265)	-1.134 (0.254)	3.119 (0.070)	-9.124** (0.000)
0.25	0.567 (0.713)	-4.203** (0.006)	2.335 (0.181)	-10.085** (0.000)
0.50	1.249 (0.495)	-9.042** (0.000)	1.945 (0.197)	-4.022** (0.000)
0.75	3.748 (0.080)	-17.277** (0.000)	1.714 (0.189)	-3.009* (0.011)
0.90	6.408* (0.016)	-16.168** (0.000)	1.813 (0.190)	-4.292** (0.000)
0.95	4.568 (0.249)	-21.258** (0.000)	2.101 (0.139)	-2.307 (0.062)

Quantile regression coefficients control for traffic, temperature, relative humidity, precipitation, wind speed, atmospheric pressure, Sahara desert dust and fire. * Significant at 5% and ** significant at 1% levels

The results indicate that while the 80 km/h speed limit does not improve NO_x air quality the variable speed system clearly does. A fixed 80 km/h speed system is not significantly effective in the majority of the quartiles and, in some case, the policy effect even presents a positive coefficient, indicating that the 80 km/h speed limit is counterproductive resulting in an increase in nitrogen oxide concentration in the 90th percentile. In contrast, the variable speed system is effective in all quartiles except the lower quantiles of NO_x; thus, the results indicate that this variable system is effective in reducing NO_x pollution emitted by traffic, except in scenarios characterized by low levels of pollution.

A similar pattern is found in the case of PM_{10} concentrations. A fixed 80 km/h speed system has no impact except in the lowest quartile, where again the policy is counterproductive, with the coefficient presenting a positive and significant value. As such the 5th quantile presents an increase in PM_{10} concentrations when this policy is implemented. Interestingly, the variable speed system clearly reduces concentrations in all quartiles except the highest. In the case of this policy, the impact is greater in the low-medium than in the medium-high quartiles.

Table 5 shows the impact of the policies in terms of the estimated coefficients by quantile regression (reported in Table 4) and in terms of the pollution levels (some of which are reported in Table A.1). Once non-significant impacts are omitted, we obtain a clear picture of the effect of the two speed management policies on the quantiles of the NO_x and PM_{10} concentration distributions. Model coefficients with significance levels between 10 and 5% are not taken into account because of the large number of observations. The magnitude of the impact reported in Table 5 presents a clear decreasing effect of the variable speed policy on PM_{10} as the quantiles of concentration increase: thus, in the 10th quantile, the implementation of this policy reduces the quantile by 56.3%, whereas in the 75th it reduces the quantile by just 6.3%. In the case of NO_x, concentrations do not fall so sharply in response to the variable speed policy; however, there seems to be a maximum effect between the 25th (an 11.7% reduction) and 75th quantiles (a 20.1% reduction) of NO_x. The effect of the variable speed limit policy is negligible for quantiles below the 25th quantile of the NOx distribution and it is also non-significant for extremely high quantiles (above the 90th) of the PM_{10} distribution.

Table 5: Significant policy impacts on distribution quantiles.

	NO_x		**PM_{10}**	
τ	**80 km/h speed limit**	**Variable speed**	**80 km/h speed limit**	**Variable speed**
0.05	-	-	24.1%	-68.4%
0.10	-	-	-	-56.3%
0.25	-	-11.7%	-	-38.1%
0.50	-	-16.6%	-	-11.7%
0.75	-	-20.1%	-	-6.3%
0.90	3.9%	-9.4%	-	-5.1%
0.95	-	-10.7%	-	-

Only 5% and 1% level

This abatement of pollutant levels as concentrations increase can be attributed to two possible causes: the origin of the pollutants and limitations on the impact of the policies. The origin of NO_x is primarily anthropogenic, with vehicle emissions constituting the main source. However, in the case of PM_{10}, there is a non-negligible natural origin, with concentrations being heavily influenced by Sahara desert dust and coastal salt episodes that increase the presence of particulate matter in the urban air.

The pollutant lag coefficients for all regressions are significant at the 1% level (Table A.2). Thus, in the 1st quantile, 25.6% of NO_x concentration can be explained by the previous day's concentration, while in the case of PM_{10} this figure is 18.6%. As concentrations increase so does the pollutant lag effect, reaching 69.6% in the last NO_x quantile and 91.5% in the last PM_{10} quantile. This underscores the fact that in highly polluted environments, the next day's pollutant concentrations are always heavily influenced by the presents day's levels, leaving little margin for other factors, such as active policies, to have any influence. Thus, while speed management policies may or may not have an impact, their effect will always be limited to some extent by conditions on the previous day.

Given the possible interaction of the two policies, we opted to analyse their effects separately. However, in practice, it is only possible to examine those attributed to the fixed speed limit in isolation, because the variable speed limit policy coincides with this earlier policy in both time and space. To identify the separate impact of the fixed speed limit, we undertook the same analysis but limited to the period 2006 to 2008 (i.e., before the introduction of the variable speed limit policy). We found that for the seven quantiles analysed and for both pollutants, a positive and significant effect was only recorded in the 90th NO_x quantile (at the 5% significance level). This confirms our previous finding that the 80 km/h speed limit has no significant effect on the quantiles of the distribution of pollutants. As a result, the distribution does not change its shape significantly.

Our results have a number of interesting implications for policymakers. First and foremost, they indicate that policy impact will not necessarily be greater during high pollution episodes, which is important, as politicians might be tempted to implement certain policies only during such episodes. Moreover, our results show that policy impacts on pollution concentrations do not always decrease as pollution levels rise. Second, we present convincing empirical evidence in favour of implementing a variable speed limit, regardless of the severity of the pollution scenario (be it high or low) and of the type of pollutant. The only situation in which the policy fails to have a substantial effect is during very extreme PM_{10} pollution episodes. Finally, reducing the maximum speed limit of 80 km/h does not result in improved air quality in any scenario or for either of the pollutants considered here. More strikingly, in some cases, increased pollution concentrations are found. For example, in the case of highly contaminated NO_x environments and slightly polluted PM_{10} environments, the fixed speed limit is detrimental.

7. Conclusion

This paper has analysed the effects of reducing a maximum speed limit to a fixed threshold (from 120 or 100 km/h to 80 km/h) on roads accessing the city of Barcelona and the impact of a smart speed system (of variable speeds) on some of the motorways in the metropolitan area. We have specifically examined the impact on mean levels of NO_x and PM_{10} in the air. In contrast to most previous studies, we have also studied pollutant abatement during different pollution scenarios, specifically during low and high pollution episodes.

We show that the shape of the pollution concentration distribution changes depending on the speed management policy implemented. Furthermore, we find that the risk of extreme NO_x pollution is considerably reduced when a variable speed policy is in force. We have used a fixed effect quantile regression model for an unbalanced data panel that allows us to isolate the policy effects in the different quantiles and we conclude that these effects depend on the pollution level and on the type of pollutant.

Our results confirm that a variable speed system, rather than a policy that reduces the maximum speed limit to 80 km/h, abates NO_x and PM_{10} concentrations. This abatement is recorded in most scenarios, but the impact of the policy is heavily dependent on the initial pollution level. A variable speed limit is particularly recommended when nitrogen oxide concentrations are high and when particulate matter concentrations are low (that is, when the pollution is attributable to non weather-related sources). By way of a general rule, a variable speed limit has a substantial effect in reducing the risk of nitrogen oxide pollution above the pollutant's first quartile and that of particulate matter pollution below the pollutant's third quartile.

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Appendix

Table A.1: Pollutants average concentration per years and areas for 10th, 50th and 90th percentiles.

	80 km/h speed limit zone											
	NO_x ($\mu g/m^3$)						***PM_{10} ($\mu g/m^3$)***					
	80 zone			Outside 80 zone			80 zone			Outside 80 zone		
	10th	50th	90th	10th	50th	90th	10th	50th	90th	10th	50th	90th
2006	17.0	53.8	171.3	18.9	54.4	165.9	21.8	34.6	74.5	16.2	34.3	81.9
2007	18.9	54.0	164.9	18.7	54.4	174.3	18.9	34.6	78.6	17.5	34.6	80.6
2008	18.7	54.4	160.9	16.8	54.4	165.2	16.2	34.3	80.4	16.2	34.4	77.2
2009	15.4	54.2	162.5	16.6	54.3	165.2	15.8	34.5	73.5	15.2	34.5	70.1
2010	16.5	54.1	155.1	18.3	54.2	161.4	16.0	34.3	75.8	16.0	34.2	75.7

	Variable speed limit zone					
	NO_x ($\mu g/m^3$)			***PM_{10} ($\mu g/m^3$)***		
	10th	50th	90th	10th	50th	90th
2006	14.9	54.3	169.5	16.2	34.4	85.2
2007	14.8	54.3	170.5	16.2	34.4	84.8
2008	14.8	54.4	171.4	16.3	34.3	84.9
2009	14.9	54.2	170.8	16.0	34.4	85.4
2010	14.8	54.3	170.8	16.2	34.4	85.4

Table A.2: Estimated pollutants coefficients lags (all significant at 1% level)

τ	80 km/h speed limit	Variable speed
0.05	0.256	0.186
0.10	0.307	0.279
0.25	0.378	0.447
0.50	0.477	0.566
0.75	0.574	0.741
0.90	0.641	0.833
0.95	0.696	0.915

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"Technology, Business Models and Network Structure in the Airline Industry"
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