Is road pricing effective in abating pollution? Evidence from Milan

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Abstract

In January 2008 Milan implemented a road pricing scheme in the city center to decrease pollution concentration. By adopting a regression discontinuity design to account for potential confounders, we estimate the effect of the policy on the concentration of benzene, carbon monoxide, particulates, nitrogen dioxide, sulfur dioxide. We have found a sizeable effect of the Ecopass on air quality in terms of reduction in the concentration of carbon monoxide and particulates few days after its introduction, although this effect disappears after only one week. We interpret these results as indicative of an inefficient policy design since motorbikes were not charged and the treated area is too limited to generate positive outcomes on the whole city.

Keywords: Road Pricing, Milan, Regression Discontinuity Design, Air Quality.

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1. Introduction

Concentration of pollution is a source of main concern for policy makers. A vast literature has in fact provided empirical support to the potential adverse health impact of temporary or prolonged exposure to airborne pollutant matters (e.g. Brugge et al., 2007; Health Effects Institute, 2010). The situation is particularly worrying in the cities as heating systems and the density of public and private transport activities increase substantially the concentration of several pollutants, among them being particulates and ozone[1].

To deal with pollution and congestion generated by transportation, urban governments have increasingly adopted road pricing schemes to reduce the quantity of transport services consumed and to internalize external costs (Small and Verhoef, 2007). The London Congestion Charge, introduced in 2003 and then modified to extend the treated area, is probably the most known and studied example (Banister, 2003; Givoni, 2012; Ison and Rye, 2005; Prud'homme and Bocarejo, 2005; Quddus et al., 2007; Santos and Bhakar, 2006; Santos and Fraser, 2004; Santos and Shaffer, 2004). However, the literature has not reached a consensus on the socio-economic convenience of such measure since infrastructure and administrative costs seem to exceed benefits in terms of reduction in external costs (Mackie, 2005; Prud'homme and Bocarejo, 2005; Raux, 2005). Other examples of such policy are Hong Kong (Ison and Rye, 2005) Singapore (Santos, 2005), Stockholm (Eliasson et al., 2009) and several Norwegian cities (Ieromonachou et al., 2006). Although most of these schemes were not designed to reduce pollution, their relevance for the air quality is undeniable as they are meant to decrease traffic.

[1] Interestingly enough, some recent literature on urban economics has argued in favor of a comparative efficiency of cities, especially the most compact ones (Glaeser, 2011). Here, we do not intend to contend the argument, but only to state that many environmental policy actions take place in the cities.

The World Health Organization has estimated more than 4,500 deaths due to pollution in 13 major Italian cities (Martuzzi et al., 2006). Among them, Milan is one of the most polluted and heavily affected, so that the municipality decided to adopt a road pricing scheme to contain traffic activities in the city center and increase air quality. On January 2008, a charge was introduced (the so-called Ecopass) and was subsequently enforced in February 2012 (the so-called Area C), with apparently positive outcomes. In fact, as demonstrated in Rotaris et al. (2010), contrary to London, ex post cost benefit analysis seems to support the policy. However, in their paper, the authors made use of data on pollution concentration reduction produced by AMMA (2008a; 2008b; 2008c) which were mainly based on simple and descriptive statistics, not taking into account several factors, among them cyclicality and weather conditions. In this paper, we aim to identify statistically the impact of the introduction of the Ecopass on a set of pollutant matters (benzene, carbon monoxide, particulates, nitrogen dioxide, sulfur dioxide), by adopting a regression discontinuity design and controlling for confounding factors. On this point, Givoni (2012) has in fact argued in favor of a more robust statistical analysis of the effects of road pricing experiences, since figures used in ex post evaluations are in general unreliable and biased by other phenomena not considered in the analysis. To deal with this identification issue, we adopt an econometric framework consisting in the estimation of a parameter measuring a break in the time trend. This parameter hence identifies a Local Average Treatment Effect of the policy, i.e. the introduction of road pricing. To be noted is that this approach, which is gaining increasing popularity in social science (Lee and Lemieux, 2009), has been recently used also in transportation research by Lucas (2008) in analyzing driving restrictions in Mexico City and by Chen and Whalley (2012) in studying the effect of a rail transit system in Taipei.

By using daily observations from 2004 to 2011 and after controlling for cyclicality, a time trend and weather conditions, we found a sizeable effect of the Ecopass on air quality in terms of carbon monoxide and particulates few days after its introduction, while this effect disappears after only one week. We interpret these results as indicative of the inefficient policy design since motorbikes were not charged and the treated area is too limited to generate positive outcomes on the whole city. To test this proposition, we make use of a natural experiment consisting in a temporary suspension of road pricing (namely, Area C) between July and September 2012. For that year we have information on the number of vehicles entering the treated area by type. We have hence found that the policy instrument has in fact increased the usage of motorbikes, hence reducing the effectiveness in terms of pollution abatement.

The remainder of the paper is organized as follows. In section 2 we present the Ecopass and its extension Area C. Section 3 contains a description of the regression discontinuity design we have adopted, whereas results are in section 4. Section 5 reports discussion and conclusion.

2. Road pricing in Milan

Milan has one of the highest rates of car ownership in Europe. More than half of population use private cars and motorcycles, ranking second only after Rome, and among the highest in the world (Percoco, 2010).

The city also has the third-highest concentration of particulate matter among large European cities, both in terms of average annual level and days of exceeding the European Union PM_{10} limit of 50 micrograms per cubic meter, according to a 2007 study supported by several environmental groups. Due to its lingering air pollution problems and associated health problems, in 2007, and for a trial period, the city banned 170,000 older cars and motorcycles that do not pass strict environmental emission standards.

In January 2008 the Ecopass program was launched within a designated restricted traffic zone corresponding to the central “Cerchia dei Bastioni” area of 8.2 km^2 (figure 1). The amount of the charge depended on the vehicle's engine emissions standard and fees vary from €2 to €10 on weekdays from 7:30 a.m. to 7:30 p.m. Free access to the ZTL was granted to several types of alternative fuel vehicles and for conventional fuel vehicles compliant with the European emission standards Euro3 and Euro4 or better. Residents within the restricted zone were exempted only if driving higher emission standard vehicles while owners of vehicles with older more polluting engines a discount only if they buy an annual pass that can go up to €250 depending on the vehicle's engine emission standards. Enforcement is carried out through digital cameras located at 43 electronic gates, with fines for offenders varying between €70 to €275.

[Figure 1]

An estimated 98,000 vehicles were entering the restricted area before the Ecopass came into force. According to an evaluation conducted by the Milanese Agency of Mobility and the Environment in December 2008, during the first month traffic inside the ZTL fell to

82.2 thousand vehicles, and for the first eleven months the average traffic flow was 87.7 thousand vehicles . This represents 12.3% fewer vehicles entering the ZTL, while outside of the Ecopass area traffic decreased by 3.6%. Meanwhile, surface public transportation service grew by 1,300 additional daily runs, carrying an average of 19,100 additional daily passengers, an increment of 7.3% for this eleven month period. For the morning rush hour during the same months the number of congested kilometers in the interior traffic network fell by 25.1% and average travel speed improved 4.0%, translating into 9.3 million euros saved by year. Traffic accidents inside the ZTL also fell by 20.6% (AMMA, 2008c).

A comparison of the type of vehicles entering the ZTL by engine standard with respect to the months of October and November 2007 found that there has been a change in the composition of the fleet entering the restricted area, with a sharp reduction of older vehicles with lower emission standard engines. The number of vehicles subject to the charge fell by 56.4%, representing an average reduction of 21,274 vehicles per day, with a greater variation among auto drivers when compared to commercial vehicles. The number of exempt vehicles grew by 4.3%, for an average increase of 2.248 vehicles a day.

The Milanese Agency of Mobility and the Environment report shows that during the first eleven months of the Ecopass program the number of days exceeding the permitted level of Diesel particulate matter of 50 $\mu g/m^3$ fell to 83 days, in contrast to the period January to November 2002 to 2007, when the average number of days exceeding this limit was 125 days. This study also found that between January and November (excluding August when the charge was temporarily suspended), all traffic related emissions were lower. PM10 decreased by 23%, particulate matter decreased by 18%, NH_3 fell 47%, NO_X was reduced by 15%, and CO_2 emission were cut by 14% (AMMA, 2008c).

By conducting a cost-benefit analysis similar in spirit to the one proposed by Prud'homme and Bocarejo (2005), Rotaris et al. (2010) find that social welfare variation associated to the introduction of the tax is slightly positive and amounting to 6 million euros per year.

In a public consultation on June 13 2011, the vast majority of voters (79%) approved the introduction of the Ecopass, which was re-established on January 16 2012 under the name of Area C. Area C is a congestion charge introduced in Milan, Italy, on January 16, 2012, replacing the previous pollution charge Ecopass and based on the same designated traffic restricted zone.

Area C started as an 18-month pilot program based on the partial implementation of the results of a referendum that took place on June 2011. The objective of the program was to drastically reduce the chronic traffic jams that take place in the city of Milan, to promote sustainable mobility and public transport, and to decrease the existing levels of smog that have become unsustainable from the point of view of public health. Area C was definitively approved on 27 March 2013.

Area C was temporarily suspended between 25 July and 17 September 2012 due to a ruling by the Council of State after protests by parking owners in the center of Milan. This event is of particular interest for our research since we will use this natural experiment to test some of the propositions we propose to explain the poor performance of the Ecopass/Area C in terms of pollution abatement.

The main difference between Ecopass and Area C is that all types of vehicles (with the exception of electric ones) are charged under the Area C scheme, whereas vehicles with a Euro 4 engine were not charged under the Ecopass scheme. In both cases, however, motorbikes are not charged.

3. Methodology and data

An increasing literature is addressing the effectiveness of road pricing schemes from the point of view of reduction in the levels of congestion and pollution, although most of the studies fail in identifying the causal effect of the tax (Givoni, 2012).

In this paper we deal with this issue by adopting a regression discontinuity design in which we estimate the reduction in the concentration of certain pollutants in the near aftermath of the introduction of the Ecopass. Furthermore, by using daily average concentration, we also control for seasonality, for a global trend as well as for general weather conditions. In a simple parametric framework, the function we aim to estimate takes the following form:

$$(1) \qquad y_t = \alpha + \beta \text{trend}_t + \gamma \text{Ecopass}_t + \delta \text{seasonality}_t + \omega \text{controls}_t + \varepsilon_t$$

Where the dependent variable is the daily average concentration of one of the pollutants in our dataset, i.e. benzene (C_6H_6), carbon monoxide (CO), particulates (PM_{10}, $PM_{2.5}$), nitrogen dioxide (NO_2), sulfur dioxide (SO_2). Variable trend_t indicates a temporal trend, which can take also the form of several order polynomials, Ecopass_t is a variable indicating the treatment period (i.e. the period after January 2nd 2008), seasonality_t is a set of variables controlling for seasonality in the concentration of pollution (i.e. fixed effects for day of the week, month and year), controls_t is a set of weather variables (average temperature, total rainfalls, average pressure, average wind speed, average humidity). Our parameter of interest is γ as it measures the impact of the Ecopass on the concentration of pollutant as a deviation for the trend. In other words, γ identifies a break in the temporal trend and it is assumed to identify locally the effect of the policy, that is it measures a Local Average Treatment Effect (Imbens and Lemieux, 2008). In our case, “local” means that γ can reasonably identify the impact of the Ecopass only few days after the introduction of the policy, that is the power of the estimated treatment effect far from the threshold is low. This issue is of great relevance for our study since policy makers are interested in the global effects of the policy, i.e. whether or not the Ecopass has reduced pollution structurally and not only few days after its introduction.

The literature has not reached a consensus yet on how to obtain robust estimates on the whole support of the running variable (time, in our case), but we will provide a simple and intuitive test to elicit information on the global effect of the road pricing scheme.

Our sample consists in hourly average concentration levels for seven pollutants (benzene (C_6H_6), carbon monoxide (CO), particulates (PM_{10}, $PM_{2.5}$), nitrogen dioxide (NO_2), sulfur dioxide (SO_2)) over the period 2004-2011 provided by ARPA Lombardia, i.e. the public entity in charge of environmental monitoring in the whole region[2]. Furthermore, from the same source, we have information on weather conditions. In the statistical analysis we will mainly use daily average concentration. Data have been extensively checked by researchers at AMAT (Agenzie per la Mobilità, l’Ambiente ed il Traffico, i.e. the Milan Agency for Mobility, Environment and Traffic).

[Figure 2; table]

[2] For the evaluation of the Ecopass we make use of a 4 years window, i.e. between 2004 and 2011. However, when we study the introduction of Area C, we make use of data also for 2012.

In figure 2 we report daily concentration of the pollutants. To be noted is that we also draw local Wald regressions with optimal bandwidth for showing a general picture of the pattern in the data. Interestingly enough, only in the case of C_6H_6, CO, PM10 and $PM_{2.5}$ we could find a sizeable decrease in the concentration in a narrow interval around the introduction of the Ecopass, whereas no change in the cyclical component and in the global trend seems to be apparent.

Table 1 further shows average concentrations before and after the treatment. The table documents a significant reduction in the concentration of all pollutants but ozone, for which an increase by 4.5 $\mu g/m^3$ is detected[3]. However, as stated above, these results need to prove robust to the consideration of a global trend, seasonality and weather conditions.

4. Results

We start our empirical analysis with baseline specifications reported in Panel A in table 2. These regressions, estimated across different pollutants, include a linear time trend and dummies for day of the week, month and year. Point estimates indicate that few days after the introduction of the Ecopass, concentration of CO, PM_{10}, $PM_{2.5}$ reduced significantly, whereas almost no effect was found for C_6H_6, O_3 and NO_2. Surprisingly, concentration of SO_2 increases by 7.8 $\mu g/m^3$. In Panel B, we introduce a 5^{th} order polynomial of the time trend to account for possible non-linearities in the concentration of pollution confounding the effect of the policy. Results are generally confirmed, although the magnitude of

[3] This apparently surprising result may be due to NO_2, a matter which captures oxygen. A reduction in the concentration of nitrogen dioxide may hence increase the concentration of ozone.

coefficients for CO, PM_{10}, $PM_{2.5}$ slightly increases, whereas the increase in SO_2 is 6.5 $\mu g/m^3$ in this case. Furthermore, in this specification we have estimated a reduction in the concentration of ozone by 8.03 $\mu g/m^3$, significant at 95%.

In Panel C, we report estimates of regressions including weather variables and also in this case, the sign and significance of coefficients of interest are confirmed. As a robustness check, in Panel D we restrict the sample to the years 2007 and 2008, i.e. one year before and one year after the introduction of the Ecopass. Besides the slight change in the magnitude of coefficients, results are generally confirmed, with the sole exception of SO_2 which shows a variation statistically not different from zero.

[Tables 2, 3]

For CO, PM_{10} and NO_2 we have data across several monitoring stations, so that it is possible to estimate the impact of the Ecopass within and outside the treated area. Results in table 3 indicate that the reduction in the concentration of CO and PM_{10} is larger outside the Ecopass area, indicating that the eventual increase in social welfare is not limited to the city center. An increase in NO_2 is detected out of the treated area, although this latter result is not confirmed when we restrict the sample to the years 2007-2008 as in Panel B.

Table 4 reports estimates investigating the effect of the Ecopass within the day. Regressions where the dependent variable is the maximum hourly concentration within the day are in Panel A and confirm the short run effectiveness of the charge for reducing extreme values of CO, O_3, PM_{10} and $PM_{2.5}$. Panels B and C look into the temporal heterogeneity of the effect by considering average concentration during the time the charge is on and off respectively. Also in this case, results are confirmed with an interesting spillover effect also during the off hours concentration.

[Tables 4, 5, 6]

Results of specifications in tables 2-4 point at a large reduction in the concentration of several pollutants in the aftermath of the introduction of the Ecopass. However, as also stated in the methodological section, estimates of the policy impact obtained from a regression discontinuity design have only local power. In other words, our estimates hold only for "few days" after the introduction of the policy. The issue on how to extrapolate global impact in a regression discontinuity framework is still a debated issue in econometrics (Angrist and Rokkanen, 2012). In this paper, in recognizing the relevance of this policy impact estimate, we take a heuristic approach. In particular, we drop from our sample observations of the week during which the Ecopass was introduced. If the reduction in pollution were permanent, then our parameter of interest, γ, should be still significant and negative. Estimates of these regressions are in table 5 and show no support to the view of a long run impact, i.e. all coefficients are not statistically different from zero. This result means that there is no substantial difference between pre-treatment and post-treatment trend[4].

[4] We have also estimated models for changes in the seasonality after the treatment but, as in the case of the time trend, the fit of the model reduced significantly.

Taken together, estimates in tables 2-5 indicate that the road pricing scheme has had only a very short run and transitory effect in terms of air quality and that after only one week, no significant improvement is detectable[5].

In february 2012 Ecopass was substituted by Area C, which was an enforcement of the road pricing scheme since also vehicles with a Euro 4 engine were charged. It is hence interesting to estimate the impact of this policy change in terms of pollution concentration. To this end, we have extended our sample to 2012 and estimated our model on 2011 and 2012. In particular, in this case the regression is:

(2) $$y_t = \alpha + \beta \text{trend}_t + \gamma \text{AreaC}_t + \delta \text{seasonality}_t + \omega \text{controls}_t + \varepsilon_t$$

Where AreaC_t now measures a departure from the trend, differentially from Ecopass. Estimates in table 6 point at a slight decrease in the concentration of benzene, but also at a substantial increase in the concentration of ozone (Panel A), a result confirmed also in the long run (Panel B).

Taken together, results of our analysis show unsatisfactory effects of the road pricing policy in Milan, although we think that a thorough discussion is needed for a compelling interpretation.

5. Discussion and conclusion

5.1 Discussion

[5] As further robustness checks, we have included among the regressors, the lagged dependent variable and one to three day lags for weather variables. We could not find variations in our results.

To sum up results in previous section, we can state that the introduction of the Ecopass has generated positive and significant effects in reducing the concentration of particulates in the short run, but it does not seem to have affected structurally air quality. Empirical evidence is in fact mixed and calls for an interpretation, although the lack of reliable data on the channels through which the charge would work makes our interpretation more speculative than how it should be.

In general, we think that the positive short run effect has been probably due to a behavioral response of drivers, not driving private cars and hence reducing emissions in the short run. However, the ineffectiveness in the long run needs to be explained and probably the reasons are in the structure of the road pricing scheme, although similar patterns in the environmental effects were found in London (Givoni, 2012) and in Stockholm (Eliasson et al., 2009).

In table 7 we report a comparison of road pricing schemes for a range of cities. As it emerges clearly is the limited size of the treated area in Milan. This issue is of great importance since Milan is in the middle of one of the most polluted areas in Europe, i.e. the *Pianura Padana*, an area of about 47,000 km^2, with high population and firm density. This would imply that the eventual gains form a reduction in the concentration of pollution in an area of 8 km^2 are then dispersed in a wider area.

[Table 7; figure 3]

Secondly, under both Ecopass and Area C motorbikes were not taxed, although their environmental efficiency is questionable. Figure 3 shows the monthly number of cars, vans and motorbikes entering the city center. Unfortunately, the only data available before the the introduction of Ecopass is November 2007, so that it is not possible to infer reliable conclusions from the figure. However, it seems that, by comparing November 2008 to November 2007, no substantial change occurred if not a drop (but statistically unreliable) in the number of cars of about 17%.

5.2 Further evidence from a natural experiment

One of our hypothesis for the limited effectiveness of the road pricing policy concerns the structure of the charge, i.e. the fact that motorbikes were not charged, although they accounted for about 15% of vehicles entering in the treated area.

Daily data on the number and types of vehicles in the city for the period 2004-2011 are not available, but we have this information for 2012 for vehicles entering the "Cerchia dei Bastioni" area. Estimates of the differential impact of Area C on the basis of these data are not reliable for the insufficient number of observations in the pre-treatment period. However, we can exploit the exogenous variation imposed by an unexpected and temporary suspension of Area C between 25 July and 17 September 2012 due to a ruling by the Council of State after protests by parking owners in the center of Milan.

In particular, we estimate the following regressions to estimate the impact of the temporary suspension[6]:

[6] To be noted is that the suspension of Area C meant a suspension of road pricing schemes and not a return to Ecopass.

$$(3) \qquad y_t = \alpha + \beta \text{trend}_t + \gamma \text{AreaC}_t + \delta \text{seasonality}_t + \omega \text{controls}_t + \phi \text{Suspension}_t + \eta \text{End\_suspension}_t + \varepsilon_t$$

Where Suspension_t is a variable indicating the start of the suspension (i.e. it take the value of 1 after July 25 and 0 before that date) and End_suspension_t is a variable indicating the end of the suspension (i.e. it take the value of 1 after September 17 and 0 before that date).

[Tables 8, 9]

Tables 8 and 9 report estimates of (3) in which the dependent variable is either one of the pollutants considered in section 4 or the number of vehicles entering the "Cerchia dei Bastioni" area. In particular, we have information for 9 vehicle categories: electric cars (type 1), GPL, bi-fuel and hybrid cars (type 1b), Euro 1-4 fuel and Euro 4 diesel cars (type 2), Euro 0 fuel and Euro 1-3 diesel cars (type 3); electric vans (type 1); GPL, bi-fuel and hybrid vans (type 1b), Euro 1-4 fuel and Euro 4 diesel vans (type 2), Euro 0 fuel and Euro 1-3 diesel vans (type 3) and motorbikes.

Regressions in panels A and B in table 8 point at a reduction in benzene and carbon monoxide when Area C is re-introduced. A positive effect is found also in the case of SO_2. In panel C, we exclude the days in 2012 before the introduction of Area C. Results remain qualitatively unchanged.

In table 9, we report estimates of regressions for the composition of traffic. It emerges that the suspension of road pricing reduced the number of circulating GPL, bi-fuel and hybrid vehicles, which increased after the re-introduction of Area C. Interestingly enough, the suspension reduced the number of motorbikes by 7,000-7,500 (model 9), with a subsequent increase after the end of the suspension by 9,000-9,300. This result could hence be interpreted as a re-allocation of car drivers to uncharged motorbikes because of the policy.

5.3 Concluding remarks

Road pricing is increasingly being adopted by municipal governments to manage congestion and to gain eventual environmental benefits. Despite its popularity, few analyses have been conducted to evaluate its effectiveness. In this paper, we have adopted a regression discontinuity design to evaluate the impact of road pricing policies in Milan over the period 2004-2012. By exploiting several policy changes (i.e. the introduction of Ecopass, the enforcement imposed by Area C, the temporal suspension of Area C), we have had a complete picture of the environmental impact of such policy.

In particular, we have found that the charge has decreased significantly the concentration of some pollutants (especially carbon monoxide and particulates) but only in the short run, while one week after its implementation, pollution returned to its pre-treatment levels. By using information on traffic composition around a natural experiment such as the temporary suspension of Area C, we have argued that the poor performance of the policy could be due to the fact that motorbikes have not been charged under both the Ecopass and Area C regimes.

References

AMAT (2011), Valutazione Nuovi Scenari di Regolamentazione degli Accessi alla ZTL Cerchia dei Bastioni, Comune di Milano, Milan.

AMMA (2008a), Ecopass – Primi Dati di Marzo, Comune di Milano, Milan.

AMMA (2008b), Monitaraggio Indicatori Ecopass. Prime Valutazioni, Comune di Milano, Milan.

AMMA (2008c), Sintesi Risultati Conseguiti e Scenari di Sviluppo, Comune di Milano, Milan.

Banister, D. (2003), Critical Pragmatism and Congestion Charging in London, *International Social Science Journal*, 176:248-264.

Brugge D., Durant J.L., Rioux C. (2007), "Near-highway pollutants in motor vehicle exhaust: A review of epidemiologic evidence of cardiac and pulmonary health risks", *Environmental Health*, 6(23).

Chen, Y. and W. Whalley (2012), Green Infrastrucutre: The Effects of Urban Rail Transit on Air Quality, *American Economic Journal: Economic Policy*, 4(1):58-97.

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

Eliasson, J., Hultkranz L., Nerhagen L., Smidlfet Rosqvist L. (2009), The Stockholm Congestion Charging Trial 2006: Overview of the Effects, *Transportation Research Part A*, 43(3):240-250.

Givoni, M. (2012), Re-assessing the Results of the London Congestion Charging Scheme, *Urban Studies*, 49(5): 1089-1105.

Glaeser E.L. (2011), *Triumph of the city*, New York: Penguin.

Health Effects Institute, 2010: 'Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects', HEI Special Report n. 17, Boston, MA, USA.

Ieromonachou, P., Potter, S. and Warren, J.P. (2006). Norway's urban toll rings: evolving towards congestion charging, Transport Policy, 13(5), 29-40.

Imbens, G.W. and Lemieux, T. (2008), Regression discontinuity designs: A guide to practice, *Journal of Econometrics*, 142(2):615-635.

Ison S. and Rye T. (2005), Implementing Road User Charging: the Lessons Learnt from Hong Kong, Cambridge and Central London, *Transport Reviews*, 25(4):451-465.

Lee D.S. and Lemieux T. (2009), Regression Discontinuity Designs in Economics, NBER 14723.

Mackie, P. (2005), The London Congestion Charge: A Tentative Economic Appraisal – A Comment on the Paper by Prud'homme and Bocarejo, *Transport Policy*, 12(3):288-290.

Martuzzi M., Mitis R., Iavarone I., Serinelli M. (2006), Health Impact of PM_{10} and Ozone in 13 Italian Cities, World Health Organization, Copenhagen.

Percoco, M. (2010), Urban Transport Policy and the Environment: Evidence from Italy, *International Journal of Transport Economics*, 37(2):223-245.

Prud'homme R. and Bocarejo J.P. (2005), The London Congestion Charge: A Tentative Economic Appraisal, *Transport Policy*, 12(3):279-287.

Quddus M.A., Carmel A. and Bell M.G.H. (2007), The Impact of Congestion Charge on Retail: The London Experience, *Journal of Transport Economics and Policy*, 41(1):113-133.

Raux C. (2005), Comments on "The London Congestion Charge: A Tentative Economic Appraisal", *Transport Policy*, 12(4):368-371.

Rotaris L., Danielis R., Marcucci E., Massiani J. (2010), The Urban Road Pricing Scheme to Curb Pollution in Milan, Italy: Description, Impacts and Preliminary Cost-Benefit Analysis Assessment, *Transportation Research A*, 44:359-375.

Santos, G. (2005), Urban Congestion Charging: A Comparison Between London and Singapore, *Transport Reviews*, 25(5):511-534.

Santos G. and Bhakar J. (2006), The Impact of London Congestion Charging Scheme on the Generalised Cost of Car Commuters to the City of London from a Value of Travel Time Savings Perspecitve, *Transport Policy*, 13(1):22-33.

Santos G. and Fraser G. (2006), Road Pricing: Lessons from London, *Economic Policy*, 21(46):263-310.

Santos G. and Shaffer B. (2004), Preliminary Results of the London Congestion Charging Scheme, *Public Works Management and Policy*, 9:164-181.

Small, K.A. and E.T. Verhoef (2007), *The Economics of Urban Transportation*, Routledge, London.

Figure 1: Road pricing (Ecopass) in Milan

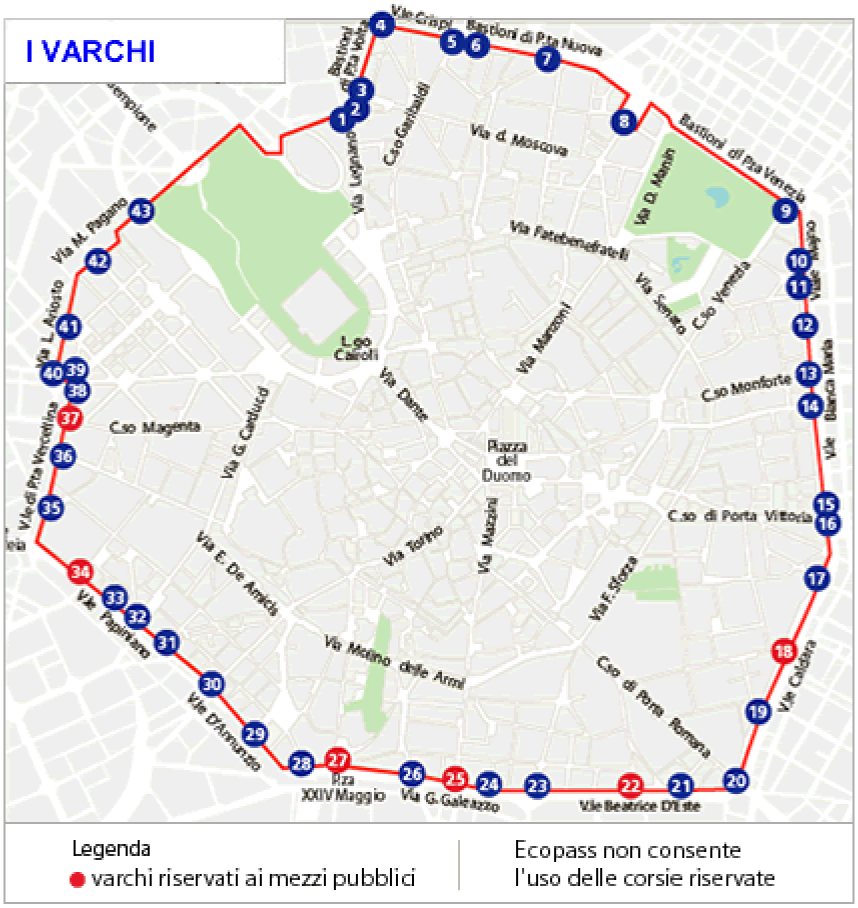
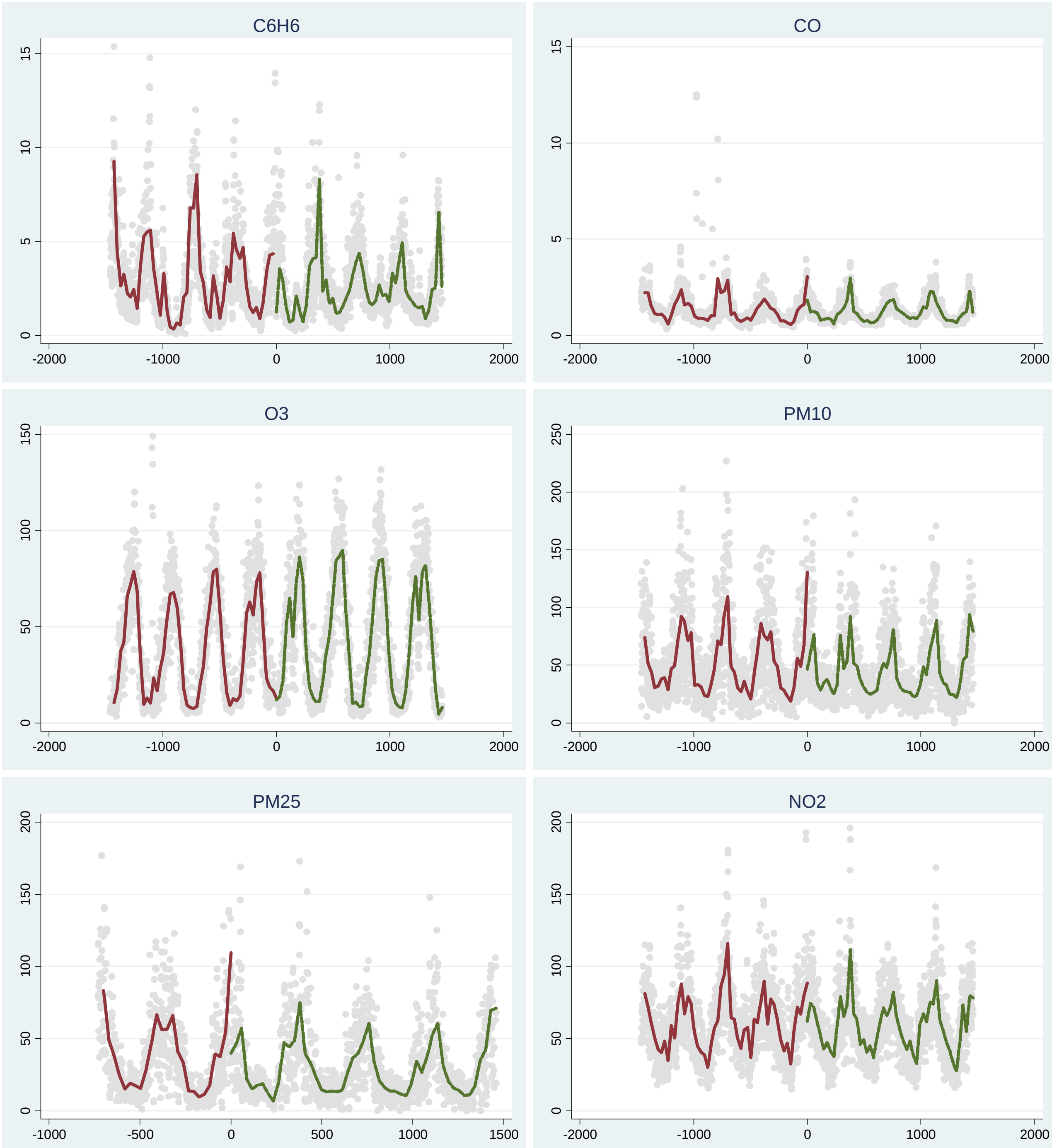


Figure 2: Discontinuity at the threshold



(Figure 2 continued)

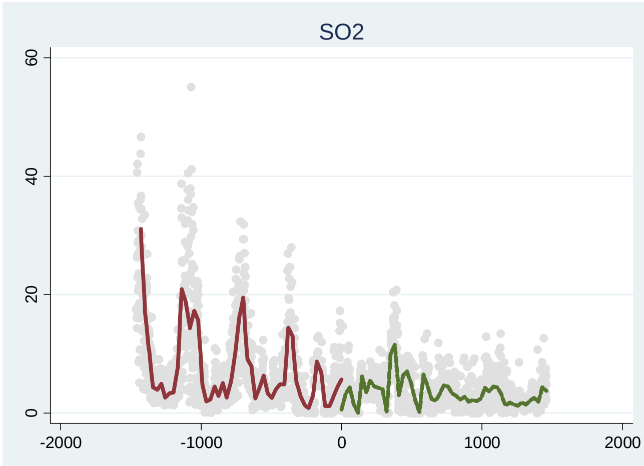


Figure 3: Number of vehicles entering the treated area

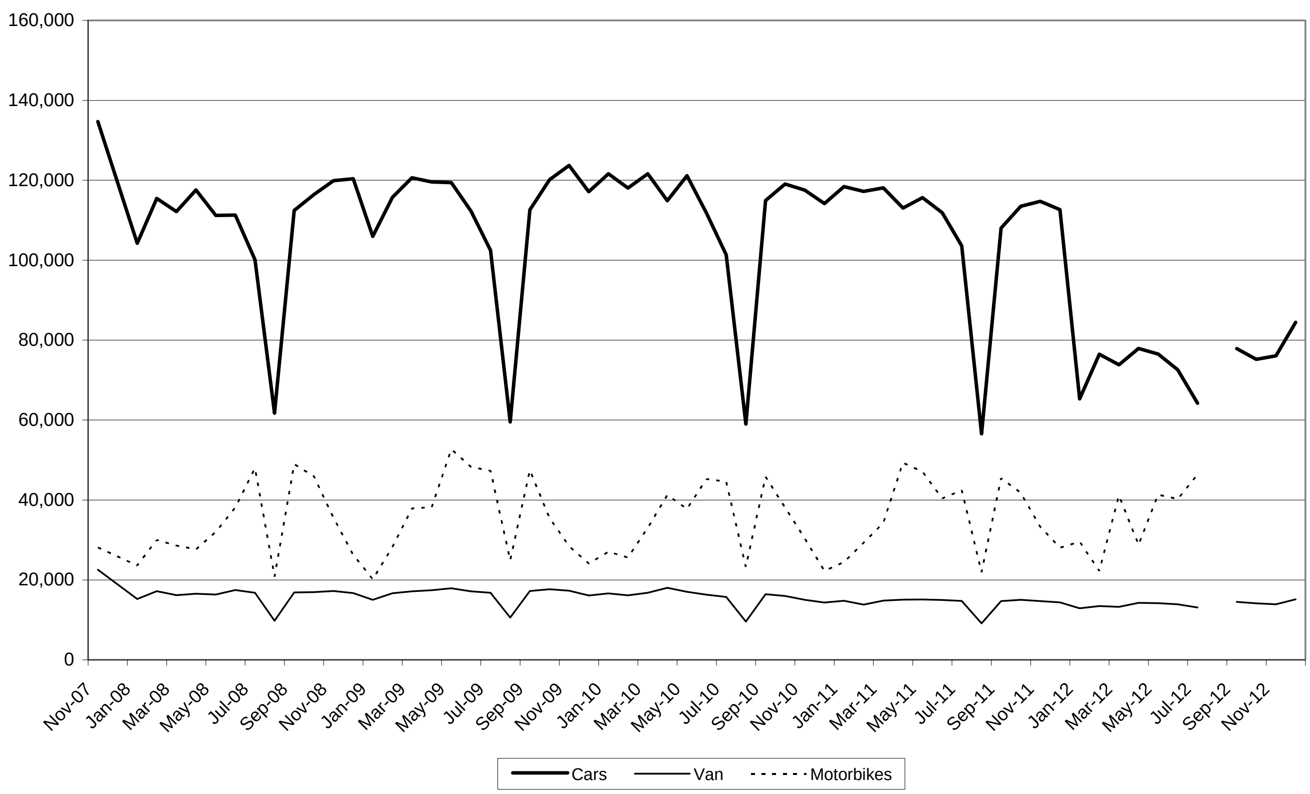


Table 1: Average daily concentration by pollutants

	Before	After	Difference
C6h6	2.927	2.561	-0.366***
CO	1.338	1.218	-0.120***
O3	37.457	42.026	4.568***
PM10	51.409	44.319	-7.091***
PM25	38.795	29.926	-8.870***
NO2	60.079	58.295	-1.784**
SO2	7.565	3.479	-4.086***

Significance: ***: p<0.01; **: p<0.05; *: p<0.1.

Table 2: Baseline regressions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	C_6H_6	CO	O_3	PM_{10}	$PM_{2.5}$	NO_2	SO_2
Panel A: Baseline specifications							
Ecopass	0.033	-1.054***	-5.973*	-67.38***	-76.41***	4.280	7.808***
	(0.196)	(0.0389)	(3.311)	(3.690)	(2.035)	(2.653)	(0.930)
Observations	2,877	2,922	2,922	2,921	1,968	2,922	2,759
R-squared	0.506	0.406	0.762	0.412	0.482	0.518	0.418
Panel B: Baseline with 5th order polynomial trend							
Ecopass	-0.583	-1.127***	-8.030**	-68.75***	-81.67***	2.356	6.530***
	(0.392)	(0.0375)	(3.373)	(5.052)	(3.409)	(1.981)	(1.197)
Observations	2,877	2,922	2,922	2,921	1,968	2,922	2,759
R-squared	0.507	0.407	0.763	0.419	0.493	0.519	0.448
Panel C: Including weather variables							
Ecopass	0.122	-1.209***	-7.069***	-74.04***	-86.45***	2.280	7.069***
	(0.333)	(0.0463)	(1.942)	(4.169)	(3.097)	(1.775)	(1.228)
Observations	2,877	2,922	2,922	2,921	1,968	2,922	2,759
R-squared	0.578	0.458	0.847	0.525	0.576	0.667	0.500
Panel D: Only years 2007-2008							
Ecopass	0.628	-1.429***	-10.41**	-94.38***	-97.94***	1.977	0.406
	(2.623)	(0.0433)	(4.025)	(3.171)	(3.122)	(1.793)	(1.052)
Observations	707	731	731	731	656	731	682
R-squared	0.652	0.759	0.860	0.591	0.610	0.694	0.439

Note: Baseline specification includes a constant, a temporal trend, and fixed effects for day of the week, month and year. In Panel B we add time trend polynomials of the 5^{th} order; in Panel C we add daily average temperature, daily average wind speed, cumulative daily rainfalls, average daily humidity. Standard errors are clustered by month of the year. Significance: ***: p<0.01; **: p<0.05; *: p<0.1.

Table 3: Spatial heterogeneity

	(1)	(2)	(3)	(4)	(5)	(6)
	CO in	CO out	PM_{10} in	PM_{10} out	NO_2 in	NO_2 out
			Panel A: Whole sample			
Ecopass	-0.375***	-1.453***	-65.24***	-80.50***	-3.973	6.107**
	(0.0557)	(0.0822)	(5.035)	(4.975)	(2.305)	(2.204)
Observations	2913	2922	2857	2774	2915	2922
R-squared	0.601	0.266	0.401	0.421	0.557	0.484
			Panel B: Only 2007-2008			
Ecopass	-0.696***	-1.726***	-83.11***	-99.68***	-4.504	5.425
	(0.0923)	(0.0537)	(3.677)	(2.943)	(3.424)	(3.374)
Observations	729	731	706	704	725	731
R-squared	0.558	0.696	0.461	0.474	0.612	0.489

Note: Baseline specification includes a constant, a temporal trend, and fixed effects for day of the week, month and year, daily average temperature, daily average wind speed, cumulative daily rainfalls, average daily humidity. Standard errors are clustered by month of the year. Significance: ***: p<0.01; **: p<0.05; *: p<0.1.

Table 4: Heterogeneity in within-the-day concentrations

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	C_6H_6	CO	O_3	PM_{10}	$PM_{2.5}$	NO_2	SO_2
				Panel A: Maximum concentration			
Ecopass	0.221	-1.209***	-7.069***	-74.04***	-86.45***	2.280	7.069***
	(0.321)	(0.0463)	(1.942)	(4.169)	(3.097)	(1.775)	(1.228)
Observations	2,877	2,922	2,922	2,921	1,968	2,922	2,759
R-squared	0.578	0.458	0.847	0.525	0.576	0.667	0.500
				Panel B: Concentration during peak hours			
Ecopass	0.156	-0.785***	-10.86***	-74.04***	-86.45***	15.76***	8.431***
	(0.322)	(0.0445)	(2.279)	(4.169)	(3.097)	(1.995)	(1.338)
Observations	2,876	2,922	2,921	2,921	1,968	2,922	2,758
R-squared	0.563	0.452	0.856	0.525	0.576	0.679	0.500
				Panel C: Concentration during off-peak hours			
Ecopass	0.113	-1.805***	-1.636	-74.04***	-86.45***	-16.62***	4.987***
	(0.345)	(0.0509)	(1.819)	(4.169)	(3.097)	(1.672)	(1.113)
Observations	2,877	2,922	2,922	2,921	1,968	2,922	2,757
R-squared	0.546	0.436	0.741	0.525	0.576	0.588	0.428

Note: Baseline specification includes a constant, a temporal trend, and fixed effects for day of the week, month and year, daily average temperature, daily average wind speed, cumulative daily rainfalls, average daily humidity. Standard errors are clustered by month of the year. Significance: ***: p<0.01; **: p<0.05; *: p<0.1.

Table 5: The effect of Ecopass after one week

	(1) C_6H_6	(2) CO	(3) O_3	(4) PM_{10}	(5) $PM_{2.5}$	(6) NO_2	(7) SO_2
	Panel A: Average concentration						
Ecopass	9.053	0.657	-25.47	-133.5	-183.9	4.081	60.92
	(18.86)	(6.239)	(232.0)	(314.3)	(150.5)	(210.1)	(81.93)
Observations	2,870	2,914	2,914	2,913	1,960	2,914	2,751
R-squared	0.580	0.456	0.847	0.526	0.575	0.667	0.503
	Panel B: Maximum daily concentration						
Ecopass	9.058	0.657	-25.47	-133.5	-183.9	4.081	60.92
	(18.86)	(6.239)	(232.0)	(314.3)	(150.5)	(210.1)	(81.93)
Observations	2,870	2,914	2,914	2,913	1,960	2,914	2,751
R-squared	0.580	0.456	0.847	0.526	0.575	0.667	0.503
	Panel C: Concentration during peak hours						
Ecopass	0.112	-0.132	-85.02	-133.5	-183.9	-14.20	12.22
	(0.256)	(5.697)	(261.8)	(314.3)	(150.5)	(208.4)	(56.77)
Observations	2,869	2,914	2,913	2,913	1,960	2,914	2,750
R-squared	0.566	0.451	0.856	0.526	0.575	0.679	0.503
	Panel D: Concentration during off-peak hours						
Ecopass	15.08	1.716	62.93	-133.5	-183.9	27.88	44.17
	(20.11)	(7.044)	(200.8)	(314.3)	(150.5)	(225.0)	(59.73)
Observations	2,870	2,914	2,914	2,913	1,960	2,914	2,749
R-squared	0.548	0.434	0.740	0.526	0.575	0.588	0.432

Note: Baseline specification includes a constant, a temporal trend, and fixed effects for day of the week, month and year, daily average temperature, daily average wind speed, cumulative daily rainfalls, average daily humidity. Standard errors are clustered by month of the year. Significance: ***: p<0.01; **: p<0.05; *: p<0.1.

Table 6: The effect of a policy change from Ecopass to Area C.

	(1) C_6H_6	(2) CO	(3) O_3	(4) PM_{10}	(5) $PM_{2.5}$	(6) NO_2	(7) SO_2
	Panel A: Average concentration						
Area C	-1.719*	-0.317	19.49***	-0.725	-2.854	1.049	-0.194
	(0.883)	(0.221)	(6.247)	(10.77)	(8.328)	(5.466)	(0.530)
Observations	725	730	730	730	658	730	702
R-squared	0.529	0.719	0.835	0.509	0.524	0.633	0.398
	Panel B: Average concentration after one week						
Area C	-2.032**	-0.385*	21.02***	-5.698	-6.783	-0.374	-0.458
	(0.738)	(0.198)	(6.393)	(12.01)	(9.099)	(6.263)	(0.602)
Observations	717	722	722	722	650	722	694
R-squared	0.539	0.722	0.834	0.501	0.517	0.631	0.399

Note: Baseline specification includes a constant, a temporal trend, and fixed effects for day of the week, month and year, daily average temperature, daily average wind speed, cumulative daily rainfalls, average daily humidity. Standard errors are clustered by month of the year. Significance: ***: p<0.01; **: p<0.05; *: p<0.1.

Table 7: Road pricing schemes

City	Treated area (km^2)	Time of application	Charge (€)
Bergen	18	0:00-24:00	2-4
Bologna	3.3	7:00-20:00	3-5
London	41	7:00-18:00	10-14
Milan	8.2	7:30-19:30	2-10
Oslo	64	0:00-24:00	3.3
Stockholm	47	6:30-18:30	1-2

Source: AMAT (2011)

Table 8: The effect of a temporary suspension of Area C

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	C_6H_6	CO	O_3	PM_{10}	$PM_{2.5}$	NO_2	SO_2
Panel A: Baseline regressions							
Suspension	-0.126	0.0161	6.904*	-1.232	1.812	-2.020	0.721***
	(0.201)	(0.0633)	(3.191)	(3.525)	(3.630)	(1.568)	(0.143)
End suspension	-0.582**	-0.0799	-12.78***	2.946	5.336*	-2.765**	-0.959***
	(0.191)	(0.0592)	(2.930)	(2.536)	(2.836)	(1.136)	(0.181)
Area C	0.187	0.151**	0.926	12.74***	11.12***	1.340	-0.231
	(0.196)	(0.0609)	(3.026)	(2.742)	(2.900)	(1.232)	(0.192)
Observations	362	366	366	366	331	366	355
R-squared	0.489	0.763	0.844	0.454	0.483	0.641	0.599
Panel B: Including weather variables and 5th order polynomial							
Suspension	-0.0404	0.0303	5.152	-5.289*	-3.194	-0.563	1.127***
	(0.207)	(0.0403)	(2.991)	(2.464)	(2.437)	(1.780)	(0.217)
End suspension	-0.698***	-0.147***	-6.369*	-3.263	-0.597	-2.145	-0.577**
	(0.207)	(0.0378)	(3.275)	(3.612)	(2.676)	(1.487)	(0.197)
Area C	0.0579	0.283*	12.26	24.38**	21.07**	0.417	-0.208
	(0.310)	(0.130)	(8.559)	(10.04)	(8.144)	(4.621)	(0.875)
Observations	361	365	365	365	330	365	354
R-squared	0.636	0.829	0.896	0.575	0.609	0.759	0.642
Panel C: Only after treated with Area C							
Suspension	-0.125	0.00100	4.922	-6.937*	-4.590	-2.061	1.041***
	(0.240)	(0.0417)	(3.079)	(3.605)	(3.178)	(2.101)	(0.288)
End suspension	-0.723***	-0.159***	-6.220*	-3.541	-0.749	-2.789	-0.632**
	(0.230)	(0.0428)	(3.403)	(3.970)	(2.783)	(1.794)	(0.238)
Observations	346	350	350	350	316	350	339
R-squared	0.624	0.832	0.892	0.572	0.611	0.757	0.640

Note: Baseline specification includes a constant, a temporal trend, and fixed effects for day of the week, month and year. In Panel B we add time trend polynomials of the 5^{th} order, daily average temperature, daily average wind speed, cumulative daily rainfalls, average daily humidity. In Panel C we exclude all observations before the introduction of Area C. Standard errors are clustered by month of the year. Significance: ***: p<0.01; **: p<0.05; *: p<0.1.

Table 9: The effect of a temporary suspension of Area C on traffic composition

	(1) Cars type 1	(2) Cars type 1b	(3) Cars type 2	(4) Cars type 3	(5) Vans type 1	(6) Vans type 1b	(7) Vans type 2	(8) Vans type 3	(9) Motorbykes
Panel A: Baseline regressions									
Suspension	-1.963	-2390***	-905.2	299.0	1.110**	-250.5**	-178.6	180.6**	-6932***
	(3.318)	(526.8)	(2730)	(210.3)	(0.460)	(82.51)	(300.0)	(79.44)	(1612)
End suspension	7.513**	3123***	-2958	-791.9***	2.223***	285.4***	-83.29	-379.3***	9381***
	(3.344)	(564.2)	(2593)	(159.0)	(0.706)	(91.30)	(348.3)	(61.06)	(1355)
Area C	10.81	397.8	-23727**	-2267***	-0.263	311.4	-774.1	-428.7*	-4514
	(8.545)	(1594)	(9372)	(650.8)	(1.608)	(231.4)	(907.2)	(207.8)	(4639)
Observations	365	365	365	365	365	365	365	365	365
R-squared	0.582	0.772	0.609	0.689	0.698	0.850	0.832	0.745	0.837
Panel B: Only after treated with Area C									
Suspension	-2.027	-2568***	-2797	175.4	0.946*	-290.0***	-347.8	140.6	-7541***
	(3.564)	(497.1)	(2213)	(189.1)	(0.492)	(77.92)	(298.4)	(82.51)	(1868)
End suspension	7.294*	2988***	-4048*	-860.7***	2.186***	260.3**	-174.0	-396.8***	9068***
	(3.528)	(538.7)	(2216)	(130.8)	(0.699)	(88.55)	(335.8)	(59.97)	(1382)
Observations	350	350	350	350	350	350	350	350	350
R-squared	0.564	0.775	0.617	0.679	0.700	0.854	0.839	0.753	0.837

Note: Baseline specification includes a constant, a temporal trend, and fixed effects for day of the week, month and year, time trend polynomial of the 5th order, daily average temperature, daily average wind speed, cumulative daily rainfalls, average daily humidity. In Panel B we exclude all observations before the introduction of Area C. Standard errors are clustered by month of the year. Type 1 car are electric cars; type 1b cars are GPL, bi-fuel and hybrid cars, type 2 cars are Euro 1-4 fuel and Euro 4 diesel cars, type 3 cars are Euro 0 fuel and Euro 1-3 diesel cars. Type 1 vans are electric vans; type 1b vans are GPL, bi-fuel and hybrid vans, type 2 vans are Euro 1-4 fuel and Euro 4 diesel vans, type 3 vans are Euro 0 fuel and Euro 1-3 diesel vans. Significance: ***: p<0.01; **: p<0.05; *: p<0.1.