Effects of Milan's Congestion Charge

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Abstract

This paper exploits a natural experiment to evaluate the effect of Milan's congestion charge on ambient air pollution. Suspension of the charge increased average weekday concentrations of CO and PM10 by 15 percent, and TSP by 25 percent. Hourly results show that the effect on TSP builds to a peak of 40 percent in the late afternoon. DRAFT - Please do not cite or distribute without permission.

1 Introduction

A growing number of cities are implementing or planning policies to restrict vehicle traffic in congested downtown areas. Such policies aim to reduce traffic jams and accidents while improving air quality. Some cities are pursuing command-and-control restrictions, for example, prohibiting dirtier vehicles within designated Low Emissions Zones (LEZs). Others are charging fees to enter downtown areas. In Europe, many German cities have implemented or are planning LEZs (Wolff 2011). Stockholm, London, and Milan have congestion charges. In the US, the Department of Transportation is currently sponsoring four road pricing experiments: San Francisco's Golden Gate Bridge, Interstate 95 near Miami, SR520 near Seattle, and Interstate 35W near Minneapolis. Additionally, San Francisco is considering a downtown congestion charge to begin in 2015.

Concern over the health effects of air pollution is one of the forces driving such policies. Cars produce small particles, including PM10 and PM2.5, that bypass the body's natural defenses and enter the bloodstream. Public health studies suggest the ambient levels of PM10 in many cities have substantial impacts on health (Pope et al 1991). Recent medical evidence suggests the smallest particles (PM2.5) do particularly great harm to human health (Mar et al 2005). There is evidence that pollution reductions driven by changes in traffic volume have meaningful effects on infant health outcomes (Currie and Walker 2011).

In light of these facts, driving restrictions might seem like an attractive means of curbing pollution and improving health. But there is very little indication such policies influence ambient air pollution. The strongest such finding is from Henrik Wolff and Lisa Perry, who estimate that German LEZs reduce ambient PM10 by approximately 9 percent. Most other studies have not found an impact on ambient pollution, largely because they have compared pre- and post-policy emissions, rather than carefully specifying a counterfactual emissions path. In London, for example, Transport for London concludes the congestion charge had no clear impact on ambient levels of NOx and PM10 (Transport for London 2005, 2008). In Milan, Invernizzi finds no effect of Ecopass (the predecessor to the policy examined by this paper) on ambient PM10, but does find an effect on black carbon (Invernizzi et al 2011).

Transportation researchers have typically evaluated the impact of driving restrictions on vehicle emissions within the charge area, rather than the impact on ambient pollution. These studies measure the change in traffic and then convert that to emissions using an average emissions factor. Using this method, Milan's transit agency estimates that the Ecopass program reduced emissions within the charge area by 14 to 23 percent. The analysis is based purely on a count of cars and includes no controls (Rotaris et al 2010). London saw 8 percent reductions in NOx and PM10 vehicle emissions, controlling for traffic speed, volume, and composition (Evans, Transport for London 2007). In Stockholm, Eliasson et al found 8.5 to 14 percent reductions (Eliasson et al 2009). In Milan, Rotaris et al (2010) found 14 to 23 percent emissions reductions from Ecopass. While these studies are valuable, they are less relevant for policy than studies of ambient levels. Moreover they do nothing to account for the possibility of spatial substitution (driving around the charge area) or intertemporal substitution (rescheduling trips).

We find suspension of Milan's Area C congestion charge increased weekday concentrations of CO and PM10 by 15 percent, and TSP by 25 percent. Hourly results show that the effect on TSP builds to a peak of 40 percent in the late afternoon. To our knowledge this is the first study to find an effect of road pricing on ambient pollution, and the second to find any effect of driving restrictions on ambient pollution. It is also the first to find meaningful within-day heterogeneity in the effect of road pricing, which may matter for welfare analysis. We are able to examine a broader range of pollutants than previous literature, including CO, which has a particularly negative effect on infant health (Currie and Walker 2011), and PM2.5, the most damaging class of particulates. Because we exploit the natural experiment created by a plausibly exogenous judicial intervention, we avoid many of the confounding problems that would arise under more straightforward research designs.

2 Background

The center of Milan, called Area C, measures approximately $8.2km^2$ (4.5 percent of city land area) and $77,000$ residents (6 percent of population). The boundary follows the *cerchia dei bastioni,* the route of the walls built under Spanish control in 1549. Many of the portals still stand today, though the walls are largely gone.

Figure 1: Area C

Milan is one of the most polluted large cities in Europe. From 2002 through 2007 the city exceeded the EU standard for PM10 on 125 days (Rotaris et al 2010). Since the mid 1990s the city has experimented with traffic policies intended to curb the pollution problem.

Milan's first major road pricing program, called Ecopass, ran from January 1, 2008 to December 31, 2011. Drivers paid a fee to enter Area C that varied with the emissions from their vehicle. Vehicles meeting the Euro 3 standard or better paid nothing, while the dirtiest diesel vehicles paid €10.[1] The charge applied weekdays 7:30AM-7:30PM. Drivers could pay by internet, phone, at the bank. The city enforced the charge using license plate-reading cameras located at the 43 entrances to Area C (Danielis et al 2011). Violators paid fines of €70-€275 (*la Repubblica* 2010). Approximately 2 percent of entering vehicles each day incurred fines (Martino 2011).

In June 2011 the voters of Milan overwhelmingly approved continued road pricing, with 79 percent in favor (Danielis et al 2011).[2] As of January 16, 2012, the city implemented a €5 congestion charge for all vehicles entering Area C

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[1] Vehicles built prior to imposition of EU emissions standards were prohibited from October 15 through April 15. Drivers received a 50% discount on the first 50 entries and a 40% discount on the next 50 entries. Residents of Area C were also eligible for discounts (Rotaris 2010).

[2] 49 percent of voters participated. The referendum did not specify the exact form the continued program would take.

weekdays 7:30AM-7:30PM.[3] Administrative details were largely the same as those for Ecopass. Drivers gained the option to pay by direct debit, using a radio reflector placed in the vehicle (similar to FasTrak or E-ZPass in the US). Violators were fined €87 (Carra 2012). On July 26, 2012, a court unexpectedly suspended the congestion charge in response to a lawsuit by Mediolanum Parking (Povoledo 2012). The charge was reinstated on September 27, 2012.[4] This sequence of events provides a natural experiment, allowing evaluation of how suspension of the congestion charge affected ambient pollution.

3 Data

Our pollution and weather data come from ARPA Lombardia, the air quality agency for the province of Lombardy. We have hourly pollution and weather data at the monitor level, from 2003 through 2012. There are nine pollution measurement stations in the city of Milan proper, of which two are inside Area C and one is on the boundary. The number of monitors varies by pollutant and over time. We drop monitors that do not span our entire period, creating a consistent panel. The one exception is PM2.5, where there is only one monitor 2005-2007, replaced by another 2007-present. We present evidence on PM2.5 below, but when interpreting the results one should keep in mind the possible bias introduced by the monitor change.

Table 1: Pollution descriptive statistics

	Units	EU std.	Mean	Stdev	Min	Max	N
Bz	$\mu g/m^3$	5*	2.89	2.07	0	15.53	3525
CO	mg/m^3	10**	1.25	.590	.327	8.37	3571
NO2	$\mu g/m^3$	40*	62.0	22.9	15.3	201	3571
NOx	ppb	n/a	71.9	54.8	8.97	408	3571
O3	$\mu g/m^3$	120**	41.5	29.9	0	133.5	3568
PM10	$\mu g/m^3$	40*	47.3	29.5	2	228	3438
PM2.5	$\mu g/m^3$	25*	32.5	26.9	0	177	2256
SO2	$\mu g/m^3$	125***	5.75	6.74	0	54.5	3441
TSP	$\mu g/m^3$	n/a	45.9	21.5	7.75	209	3555

* annual mean limit
** 8hr mean limit
*** 24hr mean limit

The table above provides descriptive statistics based on the daily data, averaging across monitors and hours of the day. The first row includes EU pollution

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[3] Vehicles classified diesel Euro 3 or below, or gasoline Euro 0 or below, were prohibited. Private vehicles over 7m long were also prohibited. Scooters, motorcycles, and alternative-fuel vehicles, including hybrids, were exempted. Residents paid €2 per entry (City of Milan 2012b, Milan Tourism 2012).

[4] The reinstated charge now ends at 6 on Thursdays, rather than at 7:30 as before (*Corriere Della Sera* 2012).

standards for comparison. (The PM2.5 standard will not go into force until 2015.) The European Commission (EC) has the power to levy large fines against nonattainment cities. For example, the EC fined Leipzig €700,000 per nonattainment day for failing to meet the PM10 standard (Wolff and Perry 2011).

Table 2: Weather descriptive statistics

	Units	Mean	Stdev	Min	Max	N
Atmospheric pressure	hPa	1004.42	8.30	850	1031.86	3500
Global radiation	W/m^2	156.79	99.63	.8	446.25	3550
Humidity	%	62.25	18.25	16.01	99.6	3571
Precipitation	mm	.073	.23	0	4.77	3571
Temperature	°C	15.00	8.36	-5.33	31.94	3571
Min temperature	°C	10.30	8.01	-29.9	27.1	3571
Max temperature	°C	19.18	9.18	-3.7	38.4	3571
Wind speed	m/s	1.40	.61	.15	5.38	3571
Max wind speed	m/s	2.98	1.26	.8	10.6	3571
Wind direction	°	179.20	55.8	55.5	317.00	3571

(all statistics calculated over daily means unless otherwise indicated)

In subsequent analysis each pollution monitor is matched to the nearest weather station.[5]

4 Identification

Because our study exploits a sudden exogenous policy change, it avoids many of the confounders that complicate studies of road pricing. Imagine examining the initial implementation of a congestion charge. Consumers typically know the start date well in advance and may begin to adjust their behavior beforehand. This will attenuate any estimated effect on ambient pollution. Still more problematically, municipalities usually increase public transit service at the same time they implement a congestion charge. This makes it impossible to estimate the effect of the charge in isolation. For example, Eliasson et al 2009 points out that Stockholm expanded bus service at the same time it implemented a congestion charge. Because the buses used for the expansion were older and dirtier, the reduction in emissions within the charge area was muted.

In Milan, the Ecopass program included not only road pricing, but also, "traffic calming measures, new bus lanes, increased bus frequency, increase in parking restriction and fees, and medium-term policies such as park-and-ride facilities and underground network extensions" (Rotaris et al 2010). The Area C congestion charge began two weeks after the end of Ecopass. The Ecopass

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[5] In some instances the weather instruments and pollution sensors are located at the same site. Not all weather stations report all variables, so some pollution stations were matched to multiple weather stations.

confounders and the short period between policies make an analysis of the congestion charge, relative to a counterfactual world with no charge and other factors constant, impossible. Even an evaluation of the congestion charge relative to Ecopass would be problematic due to the Ecopass confounders. The natural experiment created by the court injunction enables us to avoid these problems. We are able to compare an unpriced period to temporally adjacent priced periods and we are confident there are no confounding policy changes.

To estimate the effect of suspension on daily average pollution we estimate the following equation using OLS, where t indexes dates:

$$\begin{aligned}\ln(avg\_rdng)_t = {} & \alpha + \bar{\gamma} * \overline{time\_FEs_t} + \bar{\delta}_1 * \overline{weather_t} + \bar{\delta}_2 * \overline{weather_{t-1}} \\ & + \bar{\theta} * \overline{trend_t} + \beta * NO\_CC_t + \lambda * NO\_CC_t * wkend_t + \varepsilon_t\end{aligned}$$

The dependent variable is the daily average level of a pollutant. The NO_CC variable is a dummy equal to one for days when the charge was suspended. The time fixed effects include controls for year, month, day of week, day of week interacted with month, and day of week interacted with year. (We do not explicitly control for Ecopass because such a variable would be perfectly collinear with the year dummies 2008-2011.)[6] The weather controls include three-knot cubic splines in: temperature (mean, minimum, and maximum), precipitation[7], global radiation, pressure, humidity, and wind speed (mean and maximum). Additionally there are dummies for wind direction (4 bins). In order to allow for unobserved time-varying factors, the model includes a seventh-degree time trend.

We estimate a second specification at the hourly level:

$$\begin{bmatrix} \ln(avg\_rdng_0) \\ \ln(avg\_rdng_1) \\ \vdots \\ \ln(avg\_rdng_{23}) \end{bmatrix} = \bar{\alpha} + \bar{\gamma} * \overline{time\_FEs_t} + \bar{\delta}_1 * \overline{weather_t} + \bar{\delta}_2 * \overline{weather_{t-1}} + \bar{\theta} * \overline{trend_t}$$

$$+ \begin{bmatrix} \beta_0 & 0 & \cdots & 0 \\ 0 & \beta_1 & & \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & \beta \end{bmatrix} * \begin{bmatrix} NO\_CC_0 \\ NO\_CC_1 \\ \vdots \\ NO\_CC_{23} \end{bmatrix} + \begin{bmatrix} \lambda_0 & 0 & \cdots & 0 \\ 0 & \lambda_1 & & \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & \lambda_{23} \end{bmatrix} * \begin{bmatrix} NO\_CC_0 * wkend_0 \\ NO\_CC_1 * wkend_1 \\ \vdots \\ NO\_CC_{23} * wkend_{23} \end{bmatrix} + \bar{\varepsilon}_t$$

The variable avg_rdng_0 is average pollution between midnight and one AM, $avg_rdng_1$is the average between one AM and two AM, and so on. Weather and time controls are as in the daily model, except maximum and minimum temperature and maximum wind speed are no longer available. The index t

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[6] The interactions of day of week with year and month were chosen after preliminary specifications without these interactions showed spikes in residual autocorrelation at 7, 14, and 21 days.

[7] The spline in precipitation is constructed over days with non-zero precipitation. In addition, the specification includes a dummy for non-zero precipitation.

is still over days, so the lagged weather controls are the readings for the same hour of the day, 24 hours earlier. We estimate this system using equation-by-equation OLS, which is consistent under the assumption $E\left[X_i \varepsilon_i\right] = 0$, where i indexes equations and X_i is the vector of all regressors. Note consistency does not require $E\left[X_i \varepsilon_j\right] = 0$, where $i \neq j$.[8]

5 Estimation

5.1 Graphical analysis

The plots in Figure 2 allow an "ocular econometric" evaluation of charge suspension. The vertical red lines demarcate the suspension period. We construct the plots by running the daily specification above without the time trend or the NO_CC dummy. We then fit separate seventh-degree polynomials to the period before suspension, the suspension period, and the period after suspension. While the data are noisy, there is visual evidence of increased pollution in the suspension period for CO and TSP. The plot for PM10 is less compelling, but note that the magnitude of the negative residuals is greatly reduced during the suspension period. The plots for other pollutants show no discernible change. (The May 2012 break in the benzene plot reflects a near doubling of the mean reading at the one benzene sensor available throughout our study period. We are investigating.)[9]

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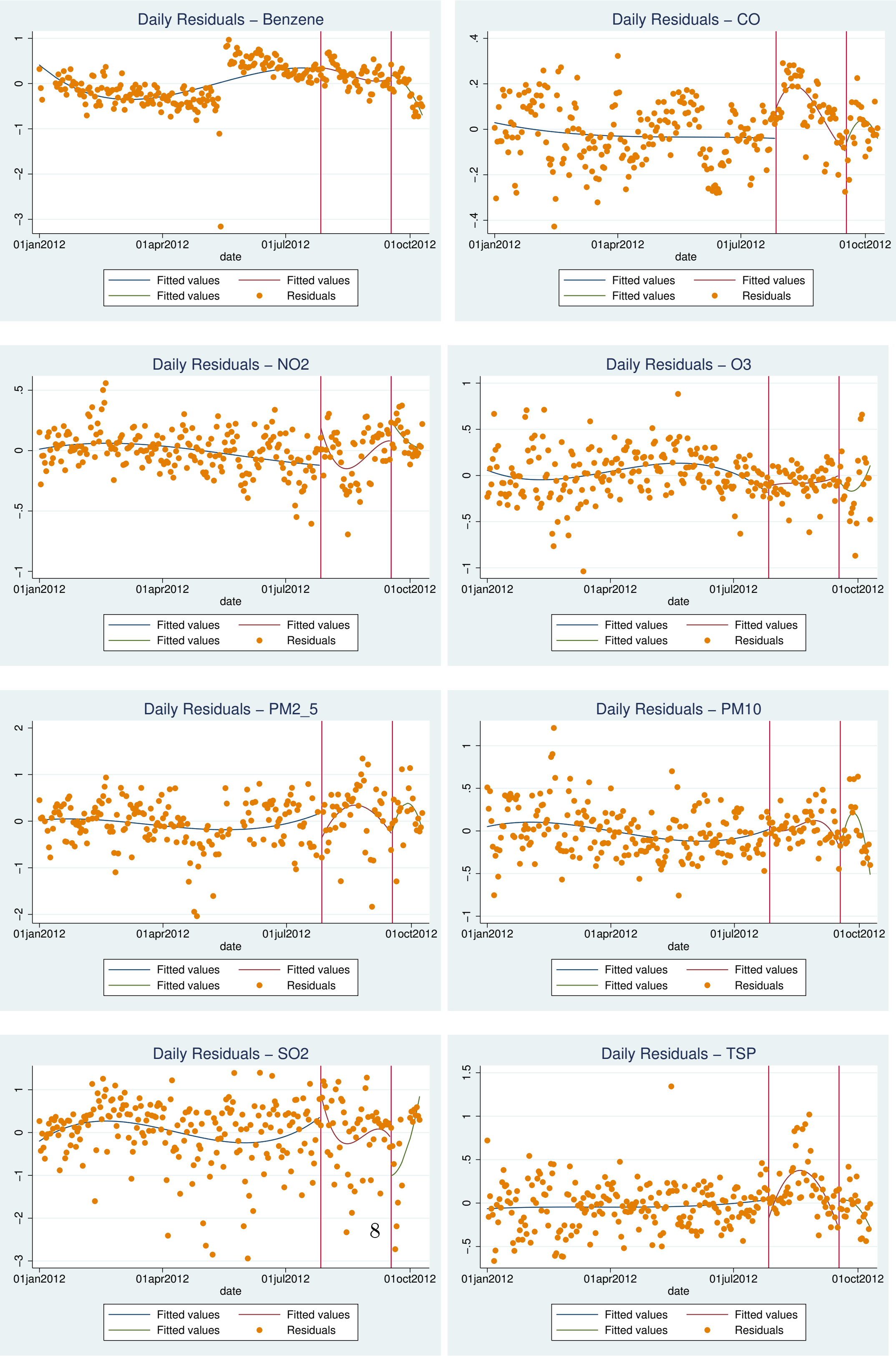
[8] If one is willing to make a system homoskedasticity assumption, it is more efficient to estimate using FGLS (Zellner's SUR). We opted to estimate using OLS and Newey-West SEs for robustness to heteroskedasticity.

[9] We do not include a separate NOx plot, as it looks nearly identical to the NO2 plot.

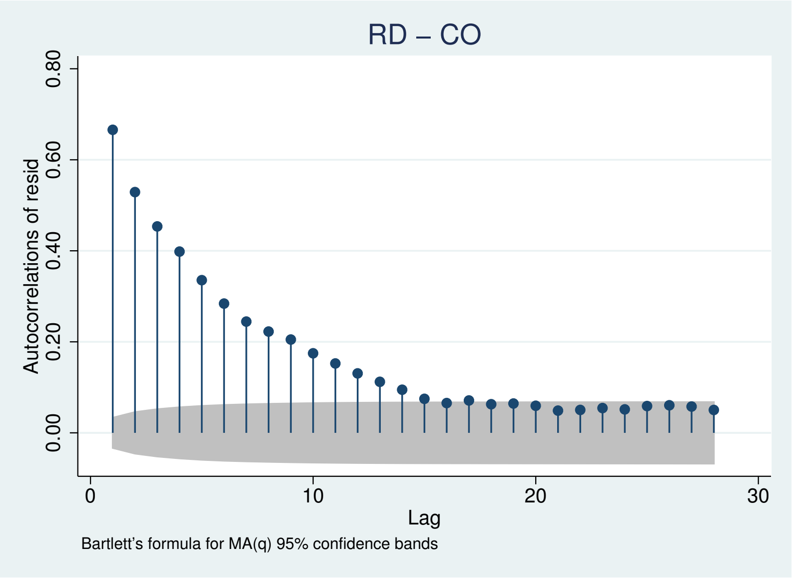
Figure 2: Daily residual plots



5.2 Inference

After initial estimation of the above specifications, it became clear that there was substantial residual autocorrelation. Figure 3 illustrates the problem.

Figure 3: Residual autocorrelation



In order to address this, we use Newey-West standard errors in the results that follow. We use a different lag length for each pollutant, with the choice determined by the highest lag at which we can reject a null hypothesis of zero correlation ($\alpha = .05$).[10]

Table 3: Newey-West lag lengths

	Bz	CO	NO2	NOx	O3	PM10	PM2.5	SO2	TSP
N-W lags	28	14	14	14	28	10	5	30	6

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[10] The autocorrelation was nearly the same in both the hourly and daily models, with the required Newey-West lag length never differing by more than one across specifications for the same pollutant. In cases of disagreement, we chose the higher lag length and used it for both the hourly and daily models.

5.3 Regression results

Table 4: Weekday effects of suspending Area C

	Bz	CO	NO2	NOx	O3	PM10	PM2.5	SO2	TSP
Coeff	.219	.147***	-.028	-.017	-.010	.156*	.146	.328	.251**
NW SE	.180	.056	.084	.092	.048	.087	.149	.267	.106
t	1.22	2.61	-.34	-.19	-.23	1.79	.98	1.22	2.35
p	.223	.009	.733	0.853	.821	.074	.326	.221	.019
N	3449	3486	3486	3486	3469	3350	2091	3273	3457

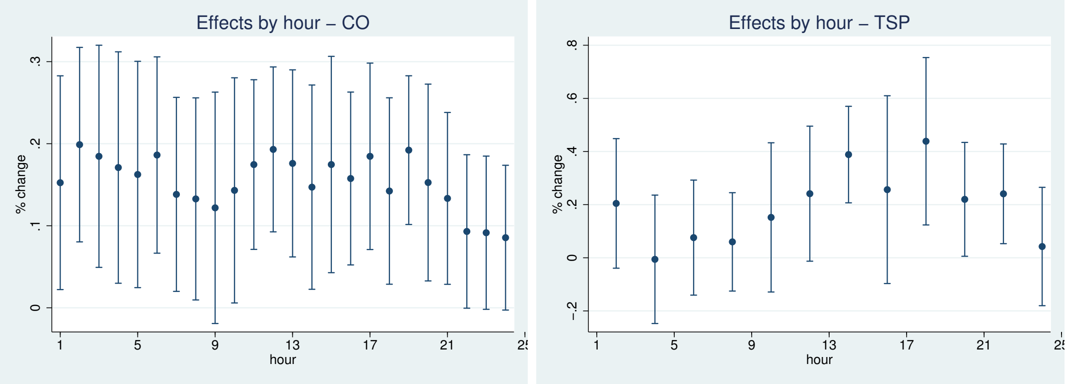
*** = significant at 1% level
** = significant at 5% level

* = significant at 10% level

The estimates above correspond to $\hat{\beta}$ in our daily specification, the effect of charge suspension on weekdays. We find statistically significant increases in CO, PM10, and TSP, all pollutants closely associated vehicle emissions (Gallego et al 2011). The lack of an effect in NO2 is somewhat surprising, and we comment on it further below. We also tested the linear combination $\hat{\beta} + \hat{\lambda}$, the effect of charge suspension on weekends, against a null hypothesis of zero effect. The result was never significant at any conventional level, for any pollutant. While the signs of the point estimates $\hat{\beta} + \hat{\lambda}$ varied, they were more often positive than negative. Thus we found no evidence of intertemporal substitution across weekdays and weekends.

The figures below show the results of our hourly model, with the dots indicating the point estimates and the whiskers the 95 percent confidence intervals.

Figure 4: Weekday hourly plots



Those pollutants that showed no change in the daily model also showed no change in the hourly model. Hourly data for PM10 and PM2.5 were not available. The plots for CO and TSP tell quite different stories. Charge suspension leads to roughly proportional increases in CO, in the 15 to 20 percent range, at all hours of the day, with a possibly smaller effect in the three hours before midnight. The effect on TSP is negligible at night, but rises to a peak of 40 percent in the afternoon. In isolation, this finding is of limited interest, as TSP has modest effects on human health. It is suggestive in one respect, however. If PM10 and PM2.5 follow similar patterns during the day, and if more people are outside during the day than at night, then the health benefits of the congestion charge may be larger than our daily estimates suggest. There is no evidence for intertemporal substitution within the day, as none of the point estimates (in particular those for the hours just outside the charge period) are negative. As in the daily model, test of $\hat{\beta} + \hat{\lambda}$ against a zero null hypothesis provide no evidence for substitution between weekend and weekday trips.

5.4 Mechanism

Without traffic data we cannot be certain of the channels by which the suspension of the congestion charge increased pollution, but the most likely candidate is a net increase in trips. The city of Milan estimated that entrances into Area C decreased by 34 percent, comparing the period January 16-June 30 to the same dates in 2011. Traffic outside Area C decreased approximately 7 percent (City of Milan 2012).

There is also suggestive evidence from the Ecopass program. Rotaris et al (2010) found that entries into Area C declined 14.2 percent in the first nine months under the Ecopass program. Entries increased by an unspecified amount in the half hour after 7:30 PM, when the charge no longer applied, indicating that intertemporal substitution at least partially offset the reduction in trips during the charge period. Rotaris et al argue that people who chose not to drive largely used public transit instead. Exits from the subway inside the charge area increased by 9.2 percent under Ecopass. (Rotaris et al do not have data on buses and trams.)

5.5 Robustness checks

We estimated the same daily and hourly models using averages over the two monitors inside Area C, and using averages over the two interior monitors plus the one border monitor.[11] Neither the point estimates nor the standard errors changed appreciably.[12] While this finding is somewhat counterintuitive, the are two reasonable explanations available.

First, suppose the congestion charge reduces traffic only within Area C. If pollutants disperse sufficiently rapidly, this spatial difference in emissions may not result in a spatial difference in ambient concentrations.

Second, suppose pollutants do not disperse at all. The congestion charge reduces traffic both inside and outside Area C. Many of the trips not taken as

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[11] The Senato and via Verziere monitors are inside Area C. Piazza Zavattari is on the border of Area C.

[12] The authors will provide these results upon request.

a result of the charge would have originated some distance outside the charge area. When a driver chooses not to take such a trip, emissions are reduced at all points between her home and her destination within Area C.

In truth the explanation for our finding is probably a combination of these mechanisms. Our findings dovetail with those of Invernizzi et al 2011, which found no gradient in particulates between the center and the edge of the city.

We also estimated our specifications without the seventh-degree time trend. Results were broadly similar in sign and significance to those presented above.

5.6 Remaining technical problems

The finding of increased CO and particulates without an increase in NO2 is surprising, given that vehicle emissions are a substantial source of NO2 in most cities (EPA 2007). This could be an artifact of noise in the NO2 series; note that the standard error is three times the magnitude of the point estimate. It's also possible that our models for benzene, NO2, and O3 are misspecified because these pollutants are linked by a complex set of chemical reactions. O3, for example, is involved in both the creation and destruction of NO2. Our benzene model failed most of the placebo tests we implemented.

The SO2 data are problematic because of interval censoring. At the hourly level, five percent of observations are zero. We plan to correct for this.

6 Conclusion

We have analyzed the effect of suspending Milan's congestion charge on ambient air quality. Our study avoids many common confounders by looking at the natural experiment created by an unexpected court decision. In addition to the pollutants examined by previous authors, we have also presented evidence on CO and PM2.5, pollutants with particularly deleterious health effects.

We find charge suspension increased weekday concentrations of CO and PM10 by 15 percent, and TSP by 25 percent. Our hourly analysis finds that for TSP the peak effect, in the early afternoon, is approximately 40 percent. If one is willing to assume symmetric responses to imposition and suspension of the charge, our estimates may be thought of as the additive inverse of the effect of the congestion charge.

This is a remarkable change in air quality given that the charge area represents only 5 percent of the city, and a smaller fraction of the broader metropolitan area. It is perhaps still more surprising in light of Milan's vehicle fleet. The Ecopass program, which applied from 2008 through 2011, provided an incentive for drivers to purchase cleaner vehicles and many did so (Rotaris 2010). This means that for a given number of foregone trips, the effect on pollution would be smaller in 2012 than it would have been in 2007. Were a city with a dirtier vehicle fleet, for example Chicago or New York, to implement a congestion charge, it might see larger pollution reductions than those we have identified in Milan.

To date welfare analysis of congestion charging and related policies typically has focused on the benefits from reduced congestion and accident externalities. These may well be larger than the air quality benefits. But given the large magnitude of the effects in Milan, and the strong evidence of health effects from such changes, future welfare analysis should not neglect the air quality benefits of congestion charging.

6.1 Extensions

The municipal government of Milan has pledged to provide us with traffic data that will allow us to extend the analysis. We will look for evidence of intertemporal substitution, both within weekdays and across weekdays and weekends. While we found no evidence of such substitution in the air quality data, this may be due to the high variability of the series and the persistence of air pollutants once they are emitted.

Additionally, by comparing entries under the congestion charge to entries under the previous Ecopass charge scheme, we hope to estimate the price elasticity of demand for trips to Area C, disaggregated by vehicle type. The suspension of the congestion charge provides an exogenous shock to the volume and composition of traffic in Milan. We will use this shock to estimate the reduced-form relationship between these traffic changes and ambient air quality.

As a benchmark, we plan to estimate the effect of the Ecopass program on ambient air pollution using a similar reduced-form framework. Should we find modest or zero effects, that would suggest that the confounding factors alluded to previously (e.g. public transit expansions) indeed pose problems for policy evaluation.

We are also interested in whether the Ecopass and congestion charge programs induced any long-run spatial reallocation of economic activity. The Milan Chamber of Commerce has provided us with establishment data, including location and other characteristics, going back to the 1950s. This will enable us to compare rates of business formation, destruction, and migration inside and outside Area C.

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