Title

The Effects of Driving Restrictions on Air Quality and Driver Behavior

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The effects of driving restrictions on air quality and driver behavior

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Abstract

We evaluate whether driving restrictions improve air quality. While Milan's restriction decreases overall air pollution, there is a significant behavioral response that attenuates the effect. Our study exploits the natural experiment created by an unanticipated court injunction suspending Milan's restriction. Drivers respond to the restriction with: 1) intertemporal substitution toward the unpriced period; 2) substitution toward exempt vehicles; and 3) spatial substitution toward unpriced roads. Importantly, the net effect on traffic varies with public transit availability.

1 Introduction

Concern over the health effects of air pollution has produced increasing interest in policy remedies. Many cities suffer from high concentrations of small particles, including PM10 and PM2.5, that bypass the body's natural defenses and enter the bloodstream. Many also have high levels of ozone, which causes lung damage. Such pollutants decrease short-run productivity (Graff Zivin & Neidell 2012) and cause long-term harm via their effects on infant health (Chay & Greenstone 2003, Currie & Walker 2011). In addition, recent research suggests that fetal air pollution exposure may have long-run impacts on intelligence and academic performance (Edwards et al 2010, Sanders 2012).

Local governments have several available types of pollution control policies, including restrictions on point sources, energy and gasoline taxes, and energy conservation measures. In addition to these efforts, a growing number of cities are implementing or planning driving restrictions. Many German cities have created Low Emissions Zones (LEZs; Wolff 2011), which prohibit dirtier vehicles within their borders. Stockholm, London, and Milan charge fees to enter

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congested downtown areas. 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. Such proposals are very difficult to evaluate because behavioral responses can be so large as to negate the intended effects entirely.

Our study examines the air pollution and traffic effects of Milan's congestion charge, which requires drivers entering the city center ("Area C") to pay €5, weekdays 7:30AM - 7:30PM. We also investigate behavioral responses to the policy. To do so we exploit a natural experiment: in late July 2012, an Italian court unexpectedly suspended the Area C charge. The city reinstated the charge approximately eight weeks later. We find the Area C restriction decreases air pollution by 5 to 15 percent and traffic by 6 percent.

Drivers respond to the restriction in three ways: 1) shifting trips to the unpriced period, just before 7:30AM or after 7:30PM; 2) using motorcycles, which are exempt from the charge; and 3) driving around the boundary of Area C.[1] The net effect on traffic varies with public transit availability. Routes without public transit experience large traffic changes from pricing, while those with public transit experience little or no change.

If the policy goal is reduction of congestion and accident externalities, then these substitution effects may be desirable. If the goal is improved air quality or reduced carbon emissions, however, these substitutions undermine the policy. If ambient pollution is approximately linear in daily vehicle count, then intertemporal substitution offsets 14 percent of the air quality improvements due to reduced trips 7:30AM - 7:30PM. Recent research has identified an increasingly broad array of negative effects from air pollution (Graff Zivin & Neidell 2012). Losing more than 14 percent of air quality gains to substitution is important. Spatial substitution further reduces the benefit from the restriction. The effects of substitution toward motorcycles are ambiguous. While motorcycles use less fuel per kilometer than cars do, they typically emit more CO and NO2 per kilometer traveled (Chan et al 1995). The fatal accident rate is much higher for motorcycles (NHTSA 2008).

Policymakers might reduce spatial substitution by expanding the geographic area subject to pricing, such that driving around the priced area would be impractical. They might reduce intertemporal substitution by charging all 24 hours, or charging a lower but non-zero price for "shoulder" periods adjacent to peak periods. (Some drivers might still choose the shoulder period, or switch back to the peak period, but others might switch to public transit or carpool.) If a city wished to avoid substitution toward motorcycles, it could simply subject them to the same restriction that applies to cars.

Because our study exploits a sudden exogenous policy change, it avoids many of the confounders that complicate studies of driving restrictions. Drivers typically know the policy start date well in advance and may begin to adjust their

[1] Anecdotal evidence indicates a small number of drivers avoid the charge by driving backward down one-way streets. Alas, we are unable to measure this (Star 2013).

behavior beforehand. This will tend to attenuate estimated effects on traffic and 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 restriction in isolation. For example, Eliasson et al (2009) point 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. Milan first implemented a congestion charge concurrent with, "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 unanticipated July 2012 court injunction created an unconfounded natural experiment free of these problems.

Most closely related to our analysis is Davis (2008), which examines Mexico City's "hoy no circula" (HNC) program. HNC bars cars from the road one day per week based on their license plate numbers. Davis finds that many drivers responded to the policy by purchasing second vehicles. As a result the program did not reduce air pollution. Foreman (2013) finds evidence of intertemporal substitution in response to variable bridge tolls. Also related is Wolff and Perry (forthcoming), which finds that German LEZs reduce ambient PM10 by approximately 9 percent. Most other studies of driving restrictions have not found an impact on ambient pollution (Transport for London 2005, 2008; Invernizzi et al 2011).

Our study is unique in its use of a natural experiment to obtain unconfounded causal estimates of driving restriction effectiveness and behavioral responses. Despite these responses, Milan's driving restriction improves air quality and this result should be of interest to policymakers. Our analysis contributes both to the literature on driving restrictions and, more broadly, to the literature on environmental regulation in the presence of behavioral responses (see, for example, Greene 1992). Our finding that the net effect of the restriction varies with public transit availability is novel. It contributes to the literature on public transit and air quality (Friedman et al 2001) and adds a new dimension to the literature on driving restrictions.

2 Background

The center of Milan, called Area C, includes approximately 8.2 square kilometers (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 vehicles. Vehicles meeting the Euro 3 standard paid nothing, while the dirtiest diesel vehicles paid €10.[2] The charge applied weekdays 7:30AM-7:30PM. Drivers could pay by internet, phone, or 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).[3] As of January 16, 2012, the city implemented a €5 congestion charge for most vehicles entering Area C weekdays 7:30AM-7:30PM.[4]Motorcycles were exempted. Administrative details

[2]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).

[3]49 percent of voters participated. The referendum did not specify the exact form the continued program would take.

[4]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 2012,

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 25, 2012, a court unexpectedly suspended the congestion charge in response to a lawsuit by Mediolanum Parking (Povoledo 2012). Charge enforcement halted the next day, July 26. There was no press coverage prior to the court injunction, suggesting the price change was completely unanticipated. The city did not alter public transit service in response to the injunction. On September 6, the city announced the charge would be reinstated as of September 17, 2012.[5]

3 Data

Our traffic data come from AMAT and the Settore Pianificazione e Programmazione Mobilità e Trasporto Pubblico Comune di Milano. For Area C, we have entries by vehicle type and entry portal at 15-minute resolution, 2008-2012. There are 43 entry portals. These data are recorded by the license plate cameras used to enforce the Area C charge. In addition, we have counts of passing vehicles at 15-minute resolution, 2008-2012. These data are measured by 748 buried sensors, mostly outside Area C.[6] Table 1 reports descriptive statistics for both data sets at the daily level (summing over sensors/cameras and 15-minute intervals).

Table 1: Traffic descriptive statistics, daily level

	Mean	Stdev	Min	Max	N
Area C entries	169,743.7	47,627.8	3,905	261,172	1,737
Passing vehicles	2,720,704	1,428,747	0	5,918,492	1,783

(all statistics calculated over daily means)

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 February 2013. 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. We use data from all nine stations. The number of monitors varies by pollutant and over time. We drop monitors that do not span our entire period, creating a balanced panel.

Table 2 provides descriptive statistics based on the daily data, averaging across monitors and hours of the day. The third column includes EU pollution standards for comparison. The European Commission (EC) has the power to levy large fines against non-attainment cities. For example, the EC fined Leipzig

Milan Tourism 2012).

[5]The reinstated charge now ends at 6PM on Thursdays, rather than at 7:30PM as before (*Corriere Della Sera* 2012). Other features are unchanged.

[6]According to AMAT, the buried sensors are less precise than the cameras.

€700,000 per non-attainment day for failing to meet the PM10 standard (Wolff and Perry 2011).

Table 2: Pollution and weather descriptive statistics

	Units	EU std.	Mean	Stdev	Min	Max	N
Benzene	$\mu g/m^3$	5*	2.88	2.01	0	14.77	3469
CO	mg/m^3	10**	1.26	.57	.32	4.64	3710
NO2	$\mu g/m^3$	40*	62.31	22.89	15.34	201.32	3710
O3	$\mu g/m^3$	120**	40.36	29.97	0	133.52	3707
PM10	$\mu g/m^3$	40*	47.48	29.38	2	228	3577
TSP	$\mu g/m^3$	n/a	45.66	21.39	7.75	209.33	3694
Precipitation	mm	n/a	2.20	7.02	0	92	3696

(all statistics calculated over daily means)
* annual mean limit

** 8hr mean limit

4 Estimating equations

Because our study relies on a natural experiment, it avoids many of the confounders that complicate studies of road pricing. In the case of Milan, it would be difficult to evaluate the introduction of Area C because it began just two weeks after the end of Ecopass. Similarly, it would be problematic to evaluate the introduction of Ecopass because of the concurrent changes in parking, road infrastructure, and public transportation. 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 traffic we estimate equations like the following using OLS:

$$\begin{aligned} traffic_t = \beta * suspension_t + \lambda * suspension_t * wkend_t \\ + \bar{\gamma} * \overline{time\_FEs}_t + \bar{\theta} * \overline{trend}_t + \bar{\eta} * \overline{weather} + \varepsilon_t \quad (1) \end{aligned}$$

The $traffic$ variable measures either Area C entries or passing cars, over a day or a 15-minute period, with t indexing days. The time fixed effects include controls for year, month, weekend, day of week, holidays, and the two-week period between Ecopass and Area C.[7] In our primary results below we report estimates using a 7th-degree trend, following Davis (2008). Weather controls include temperature and a precipitation dummy. (Weather plausibly influences the choice of public versus private transportation, or car versus motorcycle.) The *suspension* variable is a dummy equal to one for the period when the charge was suspended. The error term ε includes shocks to traffic not captured by our controls, for example, an unusually bad auto accident or the Pope's visit on June

[7] We do not explicitly control for Ecopass because of the year dummies 2008-2011.

2, 2012. In this and all subsequent equations, the coefficient of interest is β, the weekday effect of charge suspension. The weekend effect ($\beta+\lambda$ in equations 1-2, and λ in equations 3-4) is generally not statistically different from zero, so we do not report it in the estimation results. The lack of weekend effect suggests there is little scope for substitution between weekend and weekday trips, and serves as a placebo test.

To analyze heterogeneity by public transport availability, we estimate a panel version of this model with portal fixed effects (p indexes portal):

$$\begin{aligned} traffic_{pt} = \beta * suspension_t * \overline{pubtrans_p} + \lambda * suspension_t * \overline{pubtrans_p} * wkend_t \\ + \overline{\alpha_p} + \bar{\gamma} * \overline{time\_FEs_t} + \bar{\theta} * \overline{trend_t} + \bar{\eta} * \overline{weather} + \varepsilon_{pt} \end{aligned} \tag{2}$$

In the equation above, $\overline{pubtrans_p}$ is a vector containing a dummy for the presence of public transit, and another for the absence of public transit. We also estimate versions of the model comparing portals with and without bus, tram, and metro service.

For the analysis of spatial substitution, we estimate two panel models at the sensor-day level, with sensor fixed effects. The first specification is as follows (s indexes sensor):

$$\begin{aligned} traffic_{st} = \bar{\beta} * suspension_t * \overline{distance_s} + \bar{\lambda} * suspension_t * wkend_t * \overline{distance_s} \\ + \overline{\alpha_s} + \bar{\gamma} * \overline{time\_FEs_t} + \bar{\theta} * \overline{trend_t} + \bar{\eta} * \overline{weather} + \varepsilon_{st} \end{aligned} \tag{3}$$

In equation (3) $\overline{distance_p}$ is a vector of dummies for sensors in several distance bins. The second specification is similar, but instead of grouping sensors by distance, we group them into ring and non-ring roads (described in more detail below).

To investigate the effect of suspension on daily average pollution we estimate the following equation:

$$\begin{aligned} \ln(avg\_pollution)_t = \beta * suspension_t + \lambda * suspension_t * wkend_t \\ + \bar{\gamma} * \overline{time\_FEs_t} + \bar{\theta} * \overline{trend_t} + \eta \ln(avg\_rdng)_{t-1} + \bar{\delta} * \overline{atmosphere_t} + \varepsilon_t \end{aligned} \tag{4}$$

The dependent variable is the log average level of a pollutant measured over a day, with t indexing days. We conduct the analysis in logs to make the estimates for different pollutants more easily comparable. In order to control for the persistence of pollutants emitted on the previous day, we include one lag of the dependent variable. (This also serves to control for the previous day's weather.) ARPA normalizes the pollution measurements for temperature and pressure. Atmospheric controls were chosen based on the chemistry literature (in particular Seinfeld and Pandis 2006) and vary by pollutant, as indicated in Table 3.

Table 3: Weekday pollution effect from charge suspension

	(1) Benzene	(2) CO	(3) NO2	(4) O3	(5) PM10	(6) TSP
Suspension (pct. change)	0.0810	0.0552*	0.0345	0.118**	0.0580	0.159**
	(0.0627)	(0.0232)	(0.0278)	(0.0423)	(0.0518)	(0.0617)
Ozone	Yes	Yes	Yes	No	No	No
NO2	Yes	No	No	Yes	No	No
Precipitation	No	No	No	No	Yes	Yes
Observations	3436	3705	3705	3703	3519	3685

Standard errors in parentheses

Newey-West SEs. All specs include yr, mo, and dow FEs, 7th-degree trend.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

5 Results

5.1 Pollution

Table 3 reports the pollution effect of charge suspension on weekdays.[8] The dependent variable is the daily average measurement across all nine stations in the city of Milan. We find statistically significant increases in carbon monoxide (CO), ozone (O3), and total suspended particulates (TSP), all pollutants closely associated with vehicle emissions (Gallego et al 2011). These pollution estimates are of similar in magnitude to those from our traffic models (below).

5.2 Traffic

Previous work provides some suggestive evidence that road pricing changed traffic patterns in Milan. The city of Milan estimates that entrances into Area C decreased by 34 percent, comparing the period January 16-June 30, 2012 to the same dates in 2011 (under Ecopass). Traffic outside Area C decreased approximately 7 percent (City of Milan 2012). These estimates are implausibly large given that the change in price from the 2011 Ecopass program (€0-10) to the Area C program (€5) was modest.

There is also evidence from the Ecopass program. Rotaris et al (2010) cites government estimates that entries into Area C declined 14.2 percent in the first nine months under the Ecopass program relative to the prior year. Entries

[8] We use Newey-West standard errors. Lag length varies by pollutant, with the choice determined by the highest lag at which we can reject a null hypothesis of zero correlation (at the 5 percent level). Lag lengths are: benzene (21), CO (14), NO2 (28), O3 (12), PM10 (3), and TSP (1).

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.

We first provide some non-parametric evidence on the effect of charge suspension for vehicle types subject to the charge (buses and motorcycles are excluded). Figure 2 plots the residuals from a daily model that omits the *suspension* variable. We fit separate local linear relationships for the period June-July 2012 (charge), August-September (no charge), and October-November (charge). The graph demonstrates an increase in weekday entries into Area C during charge suspension.

Figure 2: Weekday effect of charge suspension

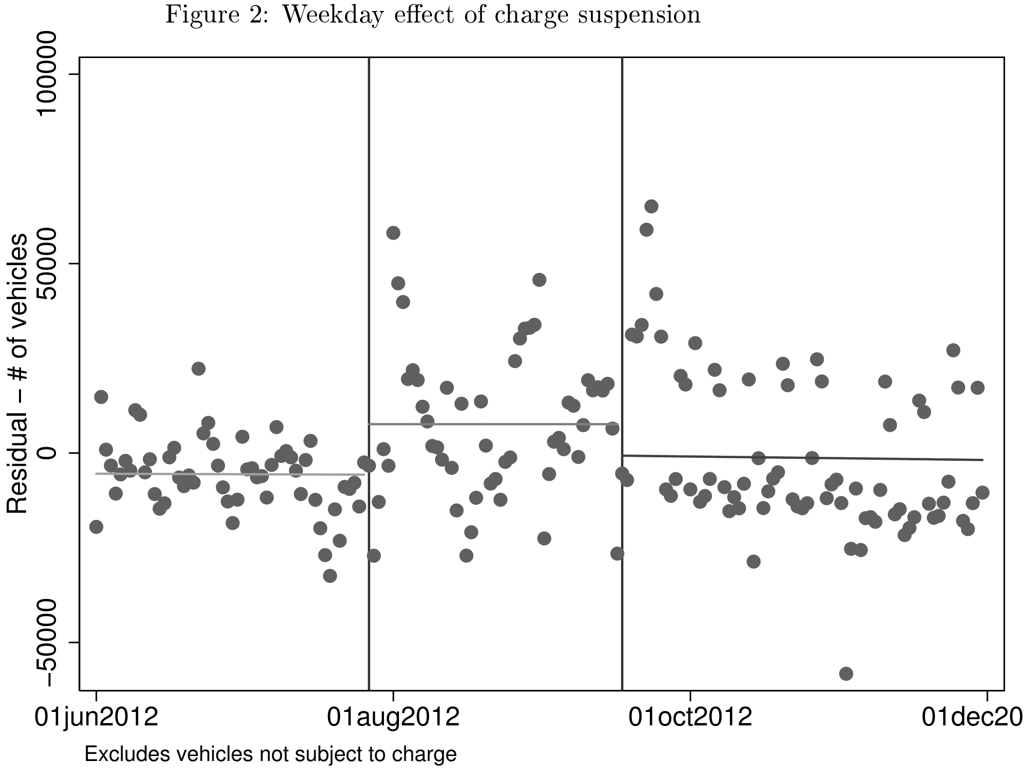


Table 4 records results from our linear model for all vehicles, charged vehicles (buses and motorcycles excluded), and for motorcycles. Charge suspension results in approximately 11,000 additional entries per day. This represents an increase of approximately 6 percent.

Table 4: Weekday traffic change due to charge suspension

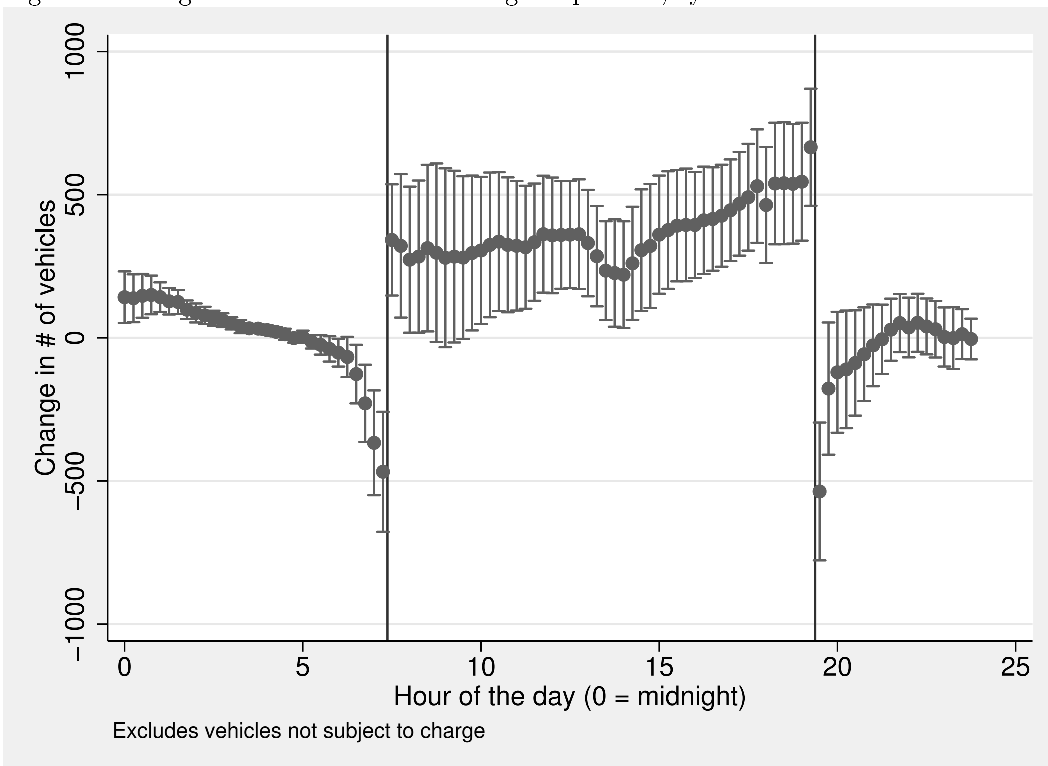
	(1) All vehicles	(2) Charged vehicles	(3) Motorcycles
Charge suspension	10647.8	16532.1**	-5280.2*
	(9886.3)	(6984.2)	(3131.0)
Observations	1737	1737	1720

Standard errors in parentheses
Newey-West SEs w/7 lags. All specs include yr, mo, and day of week FEs.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

To examine intertemporal substitution, Figure 3 plots the coefficients from a series of 96 regressions, with each 15-minute interval of the day modeled separately.[9] The estimates show intertemporal substitution in both morning and evening. Charge suspension results in approximately 500 fewer entries in the 15 minutes just before the charge begins at 7:30AM and just after it ends at 7:30PM. (This indicates that under the charge, drivers were shifting trips into these periods.) Indeed in the morning the negative estimates are statistically different from zero (at the 5 percent level) for the entire hour 6:30-7:30AM. Charge suspension increases entries during the 7:30AM-7:30PM period, consistent with the daily average estimates reported above.

[9] We use Newey-West standard errors to account for serial correlation. For most 15-minute intervals, serial correlation falls to near zero after 7 lags. For the period 11:30PM-5:15AM, however, there are spikes in serial correlation at 14, 21, and 35 days. We hypothesize that this results from the preponderance of public and commercial vehicles during this window.

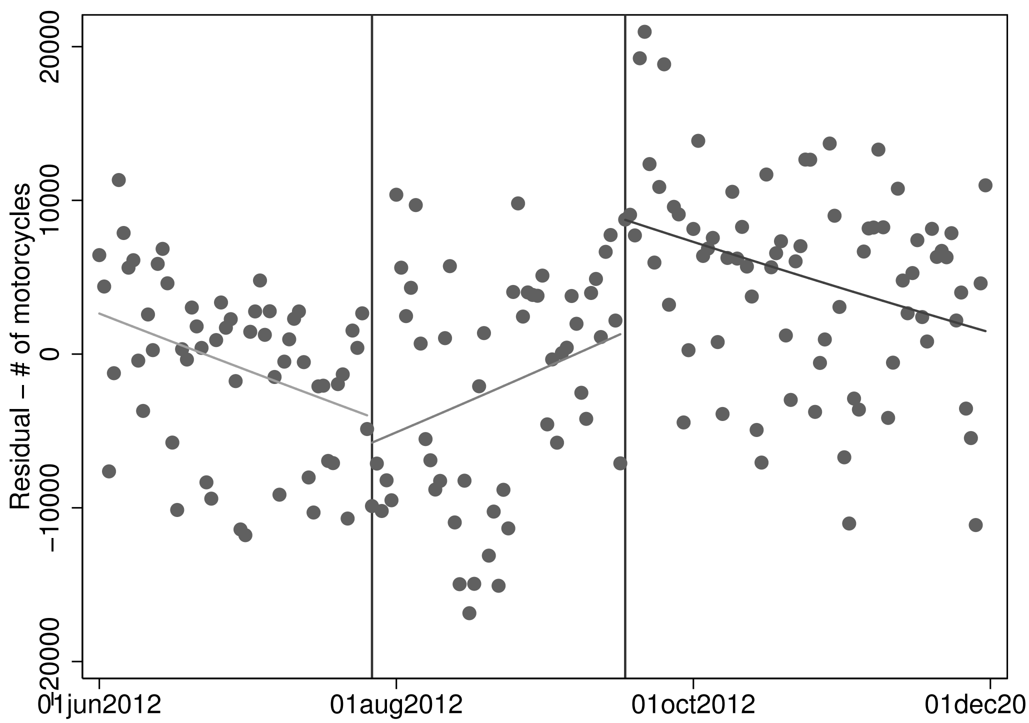
Figure 3: Change in vehicle count from charge suspension, by 15-minute interval



Whiskers represent Newey-West SEs*1.96. Lag length 35 for hours 23.5-5.25, 7 otherwise.

Next we examine the possibility of substitution across vehicle types. Figure 4 shows residuals from a daily model fit to motorcycle entries, with the *suspension* variable omitted as above. There is suggestive evidence, particularly at charge reinstatement, that drivers use motorcycles more under the charge to take advantage of their exempt status.

Figure 4: Effects of charge suspension on motorcycle usage



Column (3) of Table 4 reports the result from our linear model of motorcycle entries. The results are marginally significant, but consistent with the hypothesis that drivers substitute toward motorcycles to avoid paying the charge.

In addition, we allow the effect of charge suspension to vary with public transit availability. To that end we estimate a panel model with a portal-day as the unit of observation. The results in Table 5 indicate commuters on routes with public transit available respond much less to the suspension of the charge. Indeed portals on a metro line, for example, show essentially zero effect from charge suspension.

There are at least two plausible explanations for these results. First, assume an identical distribution of preferences for driving on two routes, one with public transit ("Route A") and one without ("Route B"). If a sorting equilibrium holds, commuters on the two routes must achieve equal utility. This implies that if Route A has cheap public transit, it must have expensive car travel. This could be a direct result of public transit, as when road lanes are devoted to tram lines, or a product of transit planning, as when metro lines are placed beneath lower-capacity roads. If a city applies the same charge to cars on both routes, the percentage change in price for Route A is much smaller and theory predicts a smaller traffic response.

Alternatively, the results in Table 5 could spring from preference heterogeneity. Suppose people with strong preferences for public transit live near Route A. They may not own cars. Assume the initial cost of driving is the same for both routes. Then for a given road price change, there will be more infra-marginal drivers on Route B than Route A.

Table 5: Portal-level weekday suspension effect, by public transit availability

	(1) Vehicle count	(2) Vehicle count	(3) Vehicle count	(4) Vehicle count
No metro	593.7***			
	(140.1)			
Metro	-22.89			
	(255.6)			
No bus		619.4***		
		(121.9)		
Bus		91.66		
		(201.0)		
No tram			502.3***	
			(127.1)	
Tram			297.6	
			(244.0)	
No public trans.				773.2***
				(193.8)
Public trans.				232.6**
				(109.2)
Observations	71862	71862	71862	71862

Standard errors in parentheses
SEs clustered at gate level. All specs include yr, mo, and day of week FEs.
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Finally we investigate spatial substitution toward roads outside Area C. Table 6 presents results from a panel model at the sensor-day level, estimated from the buried sensor data. (Note these data measure passing cars and the resulting estimates are not directly comparable to those from camera data.) Traffic at the average sensor increases approximately 2 percent, but the estimate is not significant. Consistent with the models based on camera data, suspension of the charge increases traffic inside Area C. Traffic on the roads within 1km of the Area C boundary, however, decreases by approximately 20 percent. This suggests that some drivers respond to the charge by driving around Area C. Roads more than 2km from the boundary see traffic increases.[10] This is consistent in with an increase in radial trips (e.g. commutes from a residential neighborhood into the center) from charge suspension. For drivers seeking to avoid Area C, the natural route typically involves the Circonvallazione Esterna, a ring of larger roads located .6km-2km from the Area C boundary. Table 6 shows the estimated effect of charge suspension on these roads is large, negative, and highly significant. Some of this decrease may reflect reduced circumferential commuting to public transit stations.

[10]The significance of the estimates for roads beyond 2km is sensitive to the time trend in the model. With a fourth-degree trend, for example, these coefficients are significant at the 5 percent level.

Table 6: Sensor-level weekday effect, by distance from Area C boundary

	(1) Vehicle count	(2) Vehicle count	(3) Vehicle count
All roads	116.9		
	(124.5)		
Area C		727.0**	
		(328.4)	
0-1km from boundary		-1371.4**	
		(587.0)	
1-2km from boundary		-480.2	
		(353.8)	
2-4.2km from boundary		299.7	
		(253.1)	
>4.2km from boundary		228.5	
		(385.1)	
Non-ring roads			119.5
			(148.1)
Ring roads			-2774.3***
			(1015.9)
Observations	803086	801442	801442

Standard errors in parentheses

SEs clustered at sensor level. All specs include sensor, yr, mo, and day of week FEs.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Endpoints for distance dummies set at the 25th, 50th, and 75th percentiles of the distance distribution.

5.3 Robustness checks

5.3.1 Traffic

We estimated all models with the following trends: 1) no trend; 2) linear trend; 3) 4th-degree trend; 4) 7th-degree trend. In nearly all cases the choice of trend had negligible influence on the sign, magnitude or significance of the estimates.

The one notable exception is the model of motorcycle entries into Area C. As evident in Table 7, the motorcycle estimate is sensitive to the trend. It is not significant without the inclusion of weather controls. (In other traffic models the weather controls have no meaningful impact on the estimates.)

Table 7: Motorcycle model without weather controls

	(1)	(2)	(3)	(4)
	No trend	No trend	7th-degree trend	7th-degree trend
Charge suspension	-3260.9	-4254.3	-4720.8	-5280.2*
	(2689.8)	(2906.5)	(2989.3)	(3131.0)
Precipitation	No	Yes	No	Yes
Temperature	No	Yes	No	Yes
Observations	1720	1720	1720	1720

Standard errors in parentheses

Newey-West SEs w/7 lags. All specs include yr, mo, and day of week FEs.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

5.3.2 Pollution

We estimated the same daily model 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 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.

In truth the explanation for our finding is probably a combination of these mechanisms. Our results 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 evaluate the robustness of our results with respect to the set of atmospheric controls. Table 8 reports results from a version of our pollution model in which the maximum set of atmospheric controls (O3, NO2, and precipitation) is included for all pollutants (counter to what the atmospheric chemistry literature suggests). Estimates of the suspension effect are slightly larger for all pollutants. The pattern of significance is largely unchanged, save for the CO result, which is no longer significant at the 10 percent level.

[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.

Table 8: Weekday pollution effect from suspension, all atmospheric controls

	(1) Benzene	(2) CO	(3) NO2	(4) O3	(5) PM10	(6) TSP
Suspension (pct. change)	0.0890	0.0657	0.0412	0.127**	0.113	0.198*
	(0.0604)	(0.0424)	(0.0297)	(0.0430)	(0.0708)	(0.0866)
Ozone	Yes	Yes	Yes	No	Yes	Yes
NO2	Yes	Yes	No	Yes	Yes	Yes
Precipitation	Yes	Yes	Yes	Yes	Yes	Yes
Observations	3436	3705	3705	3703	3515	3681

Standard errors in parentheses

Newey-West SEs. All specs include yr, mo, and dow FEs, 7th-degree trend.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

6 Conclusion

Our analysis leverages a natural experiment to examine behavioral responses and recover causal effects of Milan's Area C driving restriction. We find the restriction reduces traffic and improves air quality. Drivers respond with: 1) intertemporal substitution toward the unpriced period; 2) substitution toward exempt vehicles; and 3) spatial substitution toward roads outside the charge area.

These substitution effects may be desirable if the policy goal is reduction of congestion and accident externalities. The primary declared goal of Milan's restriction, however, is air quality improvement. Given that, these substitutions undermine the policy. Based on the coefficients from Figure 3, for example, approximately 14 percent of the trip reduction 7:30AM-7:30PM is offset by intertemporal substitution toward the unpriced period. Spatial substitution further reduces the benefit from the restriction, but we cannot precisely quantify the effect because the Area C camera data and the buried sensor data are not directly comparable. The net effect of substitution toward motorcycles is unclear.

In addition to analyzing behavioral responses, we show that the effect of the restriction on traffic depends on the availability of public transportation. Routes without public transit experience large traffic changes from the Area C charge, while those with public transit experience little or no change.

Note that our analysis yields only short-run estimates of behavioral responses and policy effectiveness. The suspension of the Area C charge lasted approximately eight weeks. This is too short a period to expect, for example, changes in the vehicle fleet. Assuming that some aspects of driver optimization are fixed in the short run, our estimates generally represent lower bounds on the long-run effects.

We find suspension of the charge increased weekday concentrations of CO by 5.5 percent, ozone by 12 percent, and TSP by 16 percent. 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 have been smaller in 2012 than 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.

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