Congestion Pricing, Air Pollution, and Urban Health

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Congestion pricing was originally proposed as a solution to the negative externalities associated with traffic congestion (Vickrey, 1969). Research on congestion pricing focuses on commuting times, fuel costs, and business activity (Leape, 2006). However, recent work suggests that the health costs of pollution from motor vehicles are considerable, especially for children (Currie et al., 2014). Within cities, rates of both asthma and traffic congestion have increased considerably (Center for Disease Control 2011). Asthma is now the leading cause of hospitalization among children in the United States.

This study examines the link between traffic congestion, ambient air pollution, and inpatient and outpatient visits for asthma in the context of a congestion pricing program in Stockholm, Sweden. Since August 2007 Stockholm has levied charges on most vehicles entering the city center. Permanent implementation of the charges followed a seven-month trial period between January and July, 2006. We compare outcomes within the Stockholm city center to outcomes in other Swedish city centers that did not have congestion pricing. The findings suggest that congestion pricing in Stockholm reduced nitrogen dioxide (NO2) and particulate matter (PM10) levels by 5 and 10 percent, respectively. This policy-induced reduction in air pollution levels accompanied significant reductions in the incidence of childhood asthma in Stockholm in the months and years after the program went into place.

A rigorous investigation of the link between traffic congestion, pollution, and children's health is important for several reasons. First, there is mounting evidence that health shocks in infancy and childhood have long-lasting impacts on affected children (see e.g., Currie et al. 2014 for a recent review). Given the prevalence of asthma and the fact that childhood asthma negatively affects future health and school attendance (Fletcher, Green, and Neidell, 2010), reducing the

burden of asthma is a public health priority. Second, the mechanisms through which children are affected by traffic-generated pollution may differ from those in adults. Lung development continues post-natally until the adolescent years and is susceptible to negative environmental shocks (c.f. Dietert et al, 2000). For all these reasons, current standards for air pollution may not adequately protect children.

II. Background

The purpose of the Stockholm congestion pricing zone (CPZ) was to reduce traffic entering the central city in order to reduce congestion. The tax varies between 0 and 2.6 USD per vehicle, depending on the time of the day. There are no charges at night, on weekends and public holidays, or during July. The toll is automatically collected using license plate scanning technology as cars cross the perimeter of the congestion zone.

The implementation of the tax started with a seven-month trial period from January 3, 2006 through July 31, 2006. Government estimates suggested reductions in inner city traffic counts of 20 to 25 percent during the trial (Stockholmforsoket, 2006). Based on the success of the trial, the Swedish government decided to make the program permanent starting on August 1, 2007.

In urban areas, motor vehicle emissions are the leading cause of ambient air pollution. The medical literature suggests that particulate matter (PM10 and PM2.5) affects lung growth and lung function in children (c.f. Hoek et al, 2000). Exposure to nitrogen dioxide (NO2) also worsens asthma symptoms and is associated with inferior respiratory health (c.f. Shima et al, 2000).

Asthma is a chronic inflammatory disorder of the airways (U.S. National Asthma Education and Prevention Program, 2007). This inflammation causes wheezing, breathlessness, chest tightness, and coughing. Reversibility of airflow limitation after an initial negative stimulus may be incomplete; once asthma is induced, it may not immediately improve if triggers are removed. Onset of asthma in childhood can be associated with significant permanent deficits in lung growth.

Previous research on air pollution and children's respiratory health focuses on short-term variations in air pollution (Neidell, 2004; Schlenker and Walker, 2016). In contrast, we examine both the short-term reduction in air pollution associated with the trial and the effects of the later permanent reduction in pollution. Because pollution has a cumulative effect on asthma that is not immediately reversed, the full effect of a permanent reduction in pollution may not be apparent immediately, but may be revealed in the future.

III. Data

Air pollution data is available at the monitor level, and pollution is continuously monitored across a majority of Swedish central cities for particulate matter (PM10) and nitrogen dioxides (NO_2). We aggregate the daily monitor data for each city to the monthly level, weighting by the number of monitor observations within each month. Table 1 shows the average 2-year growth rate in PM10 and NO_2 levels for municipalities inside and outside the congestion zone in the 2 years preceding the CPZ trial. Column (3) of Table 1 presents p-values from a test of the null hypothesis that the difference between the pre-trends inside the Stockholm CPZ and outside Stockholm are similar. The p-values in Table 1 are based on permutation tests (Fisher, 1935; Good, 2005; Dinardo and Lee, 2011). In order to conduct the test, we assign treatment status to different Swedish cities and then re-calculate the differences in pre-trends between the index city and all other cities. The p-value corresponds to the percentile of the distribution where the observed difference falls, relative to the other permutations. The results in Column (3) suggest there are no significant differences in pollution trends in the 2 years preceding the trial.

Figure 1 shows the differences in PM10 and NO_2 between the Stockholm CPZ and other Swedish central cities in each month of the sample. The vertical lines indicate the "pre," "trial," "in between," and "permanent CPZ" periods. The points show the difference in monthly averages representing data from the entire set of available monitors, and the horizontal lines show the mean

differences in pollution levels within each time period. In total, we have 72 months of data. For both PM10 and NO_2, one sees a relative reduction in pollution during the trial period, a rebound to original levels in the "in-between" period, and a larger relative reduction in Stockholm compared to other central cities once the CPZ is made permanent.

We then explore how these changes affected health outcomes using detailed administrative data on all inpatient and outpatient visits for children up to age six who were born to Swedish-born mothers in 103 Swedish central cities between 2005 and 2010. Children under the age of six are the most likely to experience acute asthma. For example, U.S. children 0 to 4 are 1.9 times more likely to have an asthma attack than children 12 to 17 (Moorman et al., 2013).

To construct an acute asthma rate, we add the number of overnight hospital visits and the unscheduled outpatient visits which record asthma as the primary reason for the visit. We then calculate the cumulative number of acute asthma episodes for each calendar month among children aged 0 to 5 in the municipality and divide by the total number of resident children. At 18.7 cases per 10,000 children 0 to 5, the asthma rate was higher in central Stockholm than in other central cities, and Table 1 shows that the rate was rising during the pre-period in both Stockholm and in other central cities. There were, however, no significant differences in these trends between Stockholm and other central cities.

For comparison, we also examine visits for injuries (accidents) among children 0 to 5. Injuries are one of the most common reasons for children to seek medical attention, and they should not be mechanically related to air pollution and/or asthma. The baseline incidence of accidents was lower in Stockholm than in other central cities. However, Table 1 shows that there was no difference in pre-trends.

Table 1 also shows pre-trends in several measures of the socioeconomic status of parents as well as a measure of city size. While the Stockholm CPZ is much larger, has higher income,

more college graduates, and fewer people on social assistance than other Swedish central cities, differences in the pre-trends are not generally statistically significant.

In our regression results, we control for weather conditions that may affect the extent of ambient air pollution independently of the congestion pricing policy. We use data from the Swedish Meteorological Institute that come from weather stations in each municipality. The weather data is linked to each city using the inverse distance weighted average of all weather monitors within 100km of the municipal center. Daily data on rain (mm), rain squared, mean temperature, temperature squared, maximum temperature, minimum temperature, average wind speed, and maximum wind speed is calculated for each weather monitor and then aggregated to the municipality by month level.

IV. Results

We first investigate the extent to which both the Stockholm congestion trial and the eventual full implementation of the congestion fee affected ambient air pollution. Formally, we estimate the following estimation equation which allows the effects of the trial, the "in-between" period, and the period after the charges were made permanent to be distinguished:

$$(1)\quad Poll_{it} = \alpha + \beta_1 CPZ_i * Trial_t + \beta_2 CPZ_i * InBetween_t + \beta_3 CPZ_i * Permanent_t + Z_{it}\gamma + \upsilon_i + W_{it} + \varepsilon_{it}$$

where *Trial*, *InBetween*, and *Permanent* are dummy variables equal to one during the relevant periods. Pollution at monitor *i* in month *t* ($Poll_{it}$) is regressed on a set of interactions, where, for example, $CPZ_i * Trial_t$ is an indicator equal to one if the congestion trial is in place and the pollution monitor is in the CPZ zone. Equation (1) also includes monitor fixed effects υ_i, weather controls, W_{it}, and year by month fixed effects and monitor-specific time trends, Z_{it}.

The coefficients β_1 and β_3 measure the shorter and longer-run effects of implementing congestion pricing, while β_2 measures whether the dependent variable returned to "baseline"

during the "in-between" period. Monitor fixed effects ensure that the identifying variation comes from within-monitor changes in air pollution in periods with congestion pricing versus periods without. The main identifying assumption is that even if the levels of pollution were different between Stockholm and other municipalities, the trends did not differ systematically for reasons other than the implementation of congestion pricing. This assumption is the motivation for testing for differing pre-trends in pollution, as was discussed above. Since the issue of differential trends is potentially important, we also include both region-specific time trends and interactions between municipality and weather controls. These latter interactions allow for the fact that the same weather patterns could have different impacts on pollution levels in different cities.

Table 2 presents estimates for effects of the CPZ on levels of PM10 and NO_2. We show analytical standard errors in parentheses, and we present two sets of p-values: p-values that correspond to the analytical standard errors in curvy brackets and permutation-based p-values in square brackets. The permutation-based values are based on 300 simulations in which the CPZ "treatment" (trial, in between, or permanent) is randomly assigned across municipality-quarter (of the year) cells (see e.g., Cesarini et al (2016)). For each outcome and each permuted sample we estimate equation (1). We then examine the fraction of the time that the coefficient estimate exceeds the estimated value when the CPZ is correctly assigned to Stockholm.

The analytic p-values in Column 1 and 2 of Table 2 are consistent with Figure 1 in that they suggest that both PM10 and NO_2 declined during the trial, rebounded during the in-between period, and settled at a new lower level similar to that seen during the trial when the CPZ became permanent. The permutation based p-values are more conservative but also support this story.

We examine asthma rates using models that take the same form as equation (1) except that they use measures of asthma rates constructed at the municipality, month, and year level as the dependent variable. Now Z_{jt} is a vector of time-varying controls including the average family

income in municipality j in month t, the proportion of the population on social support, and the proportion with a college degree, as well as a vector of year by month fixed effects. Once again we include controls for monthly weather conditions. Instead of fixed effects for pollution monitors, we include fixed effects for each municipality, so that our models are identified using within-municipality variation in asthma rates.

The identifying assumption is that there would have been parallel trends in asthma in the absence of the CPZ. We provided some evidence in support of this assumption by examining pre-trends in Table 1. We also use all of the data outside the Stockholm CPZ period (that is, excluding data from Stockholm in the months in which the CPZ was in effect) in order to model asthma rates in the rest of the sample, and then ask whether predicted asthma rates from this model change with the implementation of the CPZ. This test assesses the degree to which the underlying demographics changed in Stockholm in a way that would predict reductions in asthma rates during the CPZ period.

The estimated effects of the CPZ on asthma rates are shown in Column 1 of Table 3. All regressions are estimated by weighted least squares using the number of children aged 0 to 5 in the municipality as analytic weights. The congestion pricing trial was associated with a reduction of 2.3 asthma visits per 10,000 children (on a baseline of 19.1 visits per 10,000). The "in-between" period saw a reduction of 4.8 cases per 10,000, while the permanent CPZ reduced asthma visits by about 8.7 per 10,000. These estimates suggest that the trial brought an immediate reduction in asthma rates, but that the permanent CPZ had a much larger effect, reducing urgent visits and hospitalizations for asthma by almost half among children 0 to 5.

Column (2) of Table 3 shows estimates from a model using predicted asthma rates as the dependent variable. These estimates suggest that any underlying changes in demographic characteristics in Stockholm during the trial and/or after the permanent CPZ would predict

increases in asthma rates in Stockholm during the Trial and "in-between" periods and a small decrease in asthma rates after the permanent CPZ. Thus, there seems to be limited scope for changes in underlying characteristics of the population to explain the observed large reductions in asthma rates.

Column (3) of Table 3 presents estimates where the dependent variable is the accident rate. This model takes the same form as the model of asthma. While the analytical standard errors suggest small but significant effects, the permutation-based p-values do not. This "placebo" like test suggests that the CPZ implementation had limited effects on health outcomes that should not be directly related to the trial.

V. **Conclusions**

Our findings indicate that the congestion tax in central Stockholm reduced ambient air pollution by 5 to 10 percent. This policy induced change in pollution has been assocated with a significant reduction in the rate of urgent care visits for asthma among children 0 to 5 years of age. Our estimates show that permanent reductions in air pollution from automobiles, even in locations which have average pollution levels well below the current EPA standards, can have significant positive effects on children's respiratory health.

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Tables and Figures

Figure 1: Differences in PM10 and NO2, CPZ and other central cities

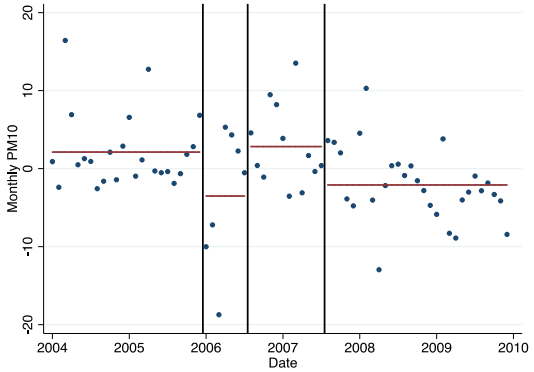
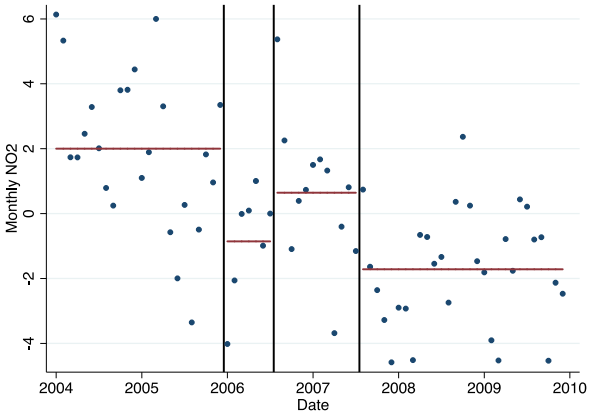


Table 1: Pre-trends in the pre-CPZ period

	(1)	(2)	(3)
	Difference Jan. 2006-Jan. 2004		p-value
	inside cpz	other cities	(2)-(1)
NO2 µg/m3	-0.153	-0.105	0.981
PM10 µg/m3	0.237	-0.067	0.854
Asthma*	1.2	1.4	0.835
Accidents*	-2.32	0.0	0.641
Ln Annual Income	-0.005	-0.002	0.913
Ln Ratio College	0.084	0.046	0.320
Ln Ratio Soc Assist	-0.129	-0.021	0.592

Log # children 0-5	0.114	0.050	0.078

*per 10000. Column (3) shows p-values from a permutation test of the null that the differences between columns (1) and (2) are equal to zero.



Notes: Differences between the average PM10 and NO_2 levels inside and outside the CPZ by month after controlling for month of year fixed effects. Vertical lines indicate the beginning and end of the trial period and the beginning of the permanent CPZ implementation. Red lines indicate the mean difference in means for each period.

Table 2: Congestion pricing and air pollution

	(1)	(2)
Dependent Variable:	PM10	NO2
CPZ*Trial	-3.961	-1.327
	(0.767)	(0.493)
	{0.000}	{0.112}
	[0.102]	[0.172]
CPZ*in between	-1.766	-0.498
	(0.664)	(0.679)
	{0.009}	{0.474}
	[0.007]	[0.000]
CPZ*Perm	-3.361	-1.580
	(0.838)	(0.473)
	{0.000}	{0.002}
	[0.007]	[0.112]
Observations	2,879	2,669
Adjusted R-squared	0.67	0.90
Mean	20.28	22.64
Clusters	99	58

***Notes*:** Each column is a separate regression. An observation is a monitor and month. Analytical p-values are in curvy brackets and clustered at the monitor level. Permutation-based P-values appear in square brackets. Models also include fixed effects for monitors,

Table 3: Asthma, Predicted Asthma, and Accidents

	(1)	(2)	(3)
Dep. Var.:	Asthma	Predicted Asthma	Accidents
CPZ*Trial	-2.272	0.457	-1.614
	(1.145)	(0.118)	(0.376)
	{0.050}	{0.000}	{0.000}
	[0.007]	[0.000]	[0.677]
CPZ*	-4.849	0.165	1.018
in between	(1.194)	(0.149)	(0.298)
	{0.001}	{0.271}	{0.000}
	[0.007]	[0.000]	[0.458]
CPZ*Perm	-8.731	-0.127	0.966
	(1.860)	(0.257)	(0.337)
	{0.002}	{0.621}	{0.005}
	[0.007]	[0.000]	[0.737]
Obs	7,416	7,416	7,416
Adj R2	0.544	0.999	0.211
Mean	19.06	19.06	8.711
Clusters	103	103	103

Notes: See notes to Table 2. An observation is a municipality and month. Analytical standard errors are clustered at the municipality level. Models also

month*year, region*month, as well as controls for municipality*weather	include fixed effects listed in Table 2 notes, but include fixed effects for municipalities not monitors.