The Effect of Metro Rail on Air Pollution in Delhi

Deepti Goel*and Sonam Gupta†

1 Introduction

The Delhi Metro (DM) is an intra-city electric rail system serving the National Capital Region (NCR) of India.[1] Here we examine whether operation of this mode of public transportation, first introduced in 2002, has had an impact on air quality in Delhi.

The motivation for this study comes from existing evidence on the adverse health effects of air pollution. Block et al. (2012) define air pollution as a complex mixture that includes carbon monoxide, sulfur oxides, nitrogen oxides, particulate matter (PM), ozone, methane and other gases, volatile organic compounds (e.g., benzene, toluene, and xylene), and metals (e.g., lead, manganese, vanadium, iron). They provide an excellent review of the state of epidemiological research on the health effects of air pollution and cite several studies that link damage of the central nervous system to air pollution, leading to decreased cognitive function, low test scores in children, increased risk of autism and neurodegenerative diseases such as Parkinson's and Alzheimer's. They also document research that shows that air pollution causes cardiovascular disease (Brook et al., 2010) and can worsen asthma (Auerbach and Hernandez, 2012). Turning to recent research in economics, Currie and Walker (2011) identify the health effects of exposure to motor vehicle emissions using the introduction of electronic toll collection and the consequent drop in emission levels in the vicinity of the toll sites. They conclude that exposure to motor vehicle emissions increases the likelihood of pre-mature births, and also causes low birth weight. Moretti and Neidell (2011) use daily boat traffic in the

*Department of Economics, Delhi School of Economics, Delhi 110007, India; email: dgoel@econdse.org

†Food and Resource Economics Department, University of Florida, P.O. Box 110240 IFAS, Gainesville, FL 32611, U.S.A.; email: sonam.gupta@ufl.edu

[1]The NCR covers an area of about 33,578 sq kms. It comprises of the National Capital Territory of Delhi at it core, nine districts in Haryana, five in Uttar Pradesh, and one in Rajasthan. At present, the DM serves Delhi, Gurgaon in Haryana, and Noida and Ghaziabad in Uttar Pradesh.

Los Angeles port as an instrument for ozone levels, and find that at least $44 million in annual costs in Los Angeles are due to hospitalizations attributable to ozone related respiratory ailments. Some other recent studies that examine the health consequences of air pollution include Kenneth and Greenstone, 2003; Neidell, 2004; Currie and Neidell, 2005; Currie, Neidell and Schmieder, 2009; and Lleras-Muney, 2010. Thus, there is substantiative evidence showing that air pollution is harmful for human health.

Delhi has been documented to have high levels of air pollution. In its report on the 'National Ambient Air Quality status in 2008,' the Central Pollution Control Board (CPCB) notes that the city recorded critical levels of respiratory suspended particulate matter (RSPM/PM_{10}). Observed annual mean concentrations of RSPM were more than 1.5 times the acceptable standard for residential areas (CPCB, 2009). Using revised national ambient air quality standards notified in 2009, the 'State of the Environment Report for Delhi, 2010,' documents that annual average levels of RSPM exceeded the national standard (60 $\mu g/m^3$) in the period between 1999 and 2008. This was also the case for nitrogen dioxide (national standard being 40 $\mu g/m^3$) during the period from 2003 onwards, for recorded values till 2008. The report also notes that carbon monoxide concentrations in ITO (a major traffic intersection in Delhi), exceeded the national standard (2000 $\mu g/m^3$) between 1996 to 2008, though there is a declining trend in recent years (DEF, 2010). Such high levels of pollution raise concerns for the health of the city's inhabitants.[2] Studies by the CPCB find that high pollution levels in Delhi are positively associated with lung function deficits and with respiratory ailments (CPCB, 2008a and CPCB, 2008b). Guttikunda and Apte (2009) conduct a monitoring experiment in 2009, and estimate that, every year, approximately 10,900 premature deaths in Delhi occur due to ambient PM pollution.

In light of the above, it would be useful to study whether the DM has had any significant impact on the city's air pollution. Theoretical research from transport economics predicts that the final impact on pollution could go in either direction (Vickery, 1969 and Mohring, 1972). The gist of the argument is that introduction of a new mode of public transport has two

[2] According to the latest Indian Census of 2011, the population of the Nation Capital Territory of Delhi is 16.8 million, with a density of 11,300 persons per square kilometer, making it one of the most densely populated regions of the world.

potential effects: traffic creation and traffic diversion. Improvement in the means of intra-city transportation could lead to an increase in economic activity, and this could in turn generate new demand for intra-city trips. It could also lead to residential relocation, away from the city center to adjoining suburbs, resulting in longer commute distances to work. This is the traffic creation effect, which presumably would increase pollution. On the other hand, commuters who earlier relied on private means of transport may now switch to the new mode.[3] This traffic diversion effect would reduce pollution. Besides these two effects, one would also need to take into account any pollution arising from the generation of electricity used to run the DM. The DM draws electricity from three sources, namely, the Northern Grid, Indraprastha Gas Turbine Plant and the Main Line Railway. Some of this maybe generated in coal based power plants located within the city. Thus, the sign and magnitude of the net impact needs to be determined empirically.

This paper seeks to quantify the causal effect of operation of the DM on air pollution using secondary data from several sources, including hourly levels of 'criteria' pollutants. 'Criteria air pollutants' is a term used to describe air pollutants that are being regulated within a country and are used as indicators of air quality. The standards used to regulate the levels of these pollutants are based on criteria that relate to health and/or environmental effects of each pollutant. The criteria pollutants that we consider here are, nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3) and sulphur dioxide (SO_2).

To be able to attribute changes in pollutant measures to the DM, we need to address concerns about endogeneity. An Ordinary Least Squares (OLS) regression of a pollutant measure on metro ridership over time does not take care of endogeneity. This is because, typically, the intensity of utilization of different modes of transportation are positively correlated: periods of relatively high ridership on the metro coincide with periods of high automobile usage. Furthermore, pollution levels also tend to be higher during periods of high demand for transportation. Consequently, OLS estimates would be biased upwards. We use regression discontinuity to overcome endogeneity (Lee and Lemieux, 2010). We exploit the sharp discontinuities in metro ridership resulting from each extension of the rail network, and examine

[3] According to a report by the Delhi Metro Rail Corporation (DMRC, 2008), the DM has already taken the share of 40,000 vehicles.

whether they coincide with corresponding discontinuities in pollutant measures. The identifying assumption is that, in the absence of the extension there would have been a smooth transition in air quality over time. This assumption would breakdown if other events, that also have a discontinuous effect on air quality, happen simultaneously. For example, if a city wide strike is called on the same day as the extension of the metro line, we would not be able to disentangle the two effects. To address this issue, we study the chronology of events in the city and do not find any such occurrences.

Our identification strategy is similar to that used by Chen and Whalley (2012). They look at the effect of the *introduction* of the Taipei Metro on air quality. While they use the discontinuity arising from the *opening* of the metro system, we exploit the discontinuities arising from each *extension* of the network. We cannot use the first opening of the metro line for two reasons. First, we do not have high frequency pollution data that dates back to the period when the metro was introduced. Second, even if we did have this data, it would be incorrect to use opening ridership discontinuity for Delhi, because there was an unprecedented transitory jump in metro ridership when it was first introduced (DMRC, 2008).[4] By using discontinuities in ridership that occur several years after the metro first started, we believe that to a large extent we avoid capturing effects arising from one time joy rides and the impact that we measure is the steady state effect. In addition, an additional benefit of using discontinuities at each extension allows us to get at a range of estimates. In implementing the estimations, we are constrained by a large number of missing observations for hourly pollution data. The details of how we deal with this are explained in the empirical strategy section below.

From our analysis we find evidence to conclude that the DM has led to a reduction in NO_2 and CO levels for Delhi. Looking at each extension of the rail network as a separate event, we find that it results in a 3 to 47 percent reduction in NO_2 concentration, and a 31 to 100 percent reduction in CO concentration. The estimates vary depending on the particular extension and monitoring station being considered. Evidence using multiple extensions, suggests a

[4]On the first day itself, about 1.2 million people turned up to experience this modern transport system. As the initial section was designed to handle only 0.2 million commuters, long queues of the eager commuters wishing a ride formed at all the six stations . . . Delhi Metro was forced to issue a public appeal in the newspapers asking commuters to defer joy rides as Metro would be there on a permanent basis (DMRC, 2008).

cumulative impact of a 35 percent reduction in CO levels for the region around ITO (a major traffic intersection in Delhi). Both NO_2 and CO are important constituents of vehicular emissions and our findings are suggestive of the traffic diversion effect of the DM. Guttikundu (2010) presents probable scenarios of shifts in traffic patterns in Delhi due to the DM. Based on these, he estimates vehicular emission reductions that range from 20 to 54 percent. Our identification relies on *observed* changes in metro ridership, and we consider overall changes in criteria pollutants and not just changes in vehicular emissions. This might be a reason why our estimates differ from his.

1.1 Genesis and Expansion of the Delhi Metro

The history of the making of the DM, right from envisioning a mass rapid transit network for Delhi way back in 1969, to the operation of the first segment in 2002, is well documented in DMRC, 2003 and DMRC, 2008. In May of 1995, The Delhi Metro Rail Corporation Limited (DMRC) was set up by the Government of India and the Government of the National Capital Territory of Delhi, to take over the construction and subsequent operation of the DM. Construction finally began in October 1998. The first trial train run was conducted on September 17, 2002, and the first commercial run between Shahdara and Tis Hazari took place on December 25, 2002, marking the beginning of operations of the Delhi Metro. The phasing out of the metro rail network in the NCR was primarily a response to the expected demand for transportation from different localities within the NCR. The rail lines were first laid in areas with a high population density, and where it was felt that the metro would benefit the largest number of people. Subsequent extensions were similarly motivated. Figure 1 shows the map of the DM rail network. The network is characterized by several lines, identified by different colors, that traverse the length and breadth of the NCR.

The DMRC has been awarded several international certifications for being environment friendly: ISO 14001 Environmental Management System during the construction phase, ISO 14001 EMS and OHSAS 18001. It is the first railway project in the world to earn Certified Emission Reductions (CER) for its regenerative breaking system that routes the kinetic energy released when a train brakes to the overhead electrification lines. DMRC can claim 400,000

CERs for a ten year crediting period beginning December 2007, translating to a gain of Rs. 1.2 crore per year (DMRC, 2008).

2 Empirical Strategy

We identify the effect of DM using Regression Discontinuity (RD) framework. Due to availability of data, we restrict our study period to $2004 - 2006$. Table 1 shows the phase wise extension of the metro network in this period. As shown, the DM rail network was extended six times during this time. These extensions identify the potential discontinuities in metro ridership and are the basis of our RD estimation. For each extension listed in Table 1, we estimate the following equation:

$$y_t = \theta_0 + \theta_1 DM_t + \theta_2^{'} \mathbf{x}_t + \theta_3 \mathbf{P}(t) + u_t \tag{1}$$

Here, y_t is hourly pollutant level in logs at time t. y_t could either be the level of the pollutant at one of the three monitoring stations, or it could be the average of levels at two or more stations. DM_t is the discontinuity dummy characterized by each extension. It takes the value one for all periods after an extension, and it is zero for periods before that.[5] t extends for an equal length of time on either side of the extension (typically, a one month on either side, making it a 60 day window). Also, the equation is estimated only if there are no other extensions within the length of time being considered. The vector of covariates, $\mathbf{x}_t$, includes current and 1-hour lags of quartics of humidity, rainfall, temperature, and wind speed. In addition, $\mathbf{x}_t$ includes controls for hour of the day, day of the week (weekend or working day), and interactions between hour and day of the week. $\mathbf{P}(t)$ stands for the third-order polynomial in time. It controls for the smooth variation in pollutant levels in the absence of the metro extension.[6] θ_1 is the coefficient of interest. It measures the percentage change in pollutant

[5] We exclude the 24 hour data on the day of the extension because we do not know the exact hour that the new line became operational.

[6] Air quality can also be affected by government regulations aimed at reducing pollution. To the best of our knowledge we do not know of any regulation that was implemented during our study period $(2004 - 2006)$ and that would have a discontinuous effect on pollution. The mass conversion of diesel buses to compressed natural gas (CNG) happened earlier in 2001.

level due to the particular extension of the DM.

As mentioned in the introduction, our assumption is that within the period of estimation, pollutant levels would have changed smoothly in the absence of the DM extension. After controlling for weather and any other non-linearities using the polynomial time trend, any observed change in pollutant levels around the extension may be attributed to the extension itself.

One of our main challenges in estimating equation 1, is the lack of good quality hourly data on pollutants. Our estimation strategy is severely constrained by the presence of contiguous segments of missing observations in the pollution series. We restrict our analysis to only those extensions for which there is at least a one month period on either side of the extension, in which missing observations do not exceed 20 percent of maximum potential observations for that month.[7] We treat each metro extension as a separate event and analyze the metro effect on each pollutant in its unique continuous time window. We start the analysis using a 60 day window around the extension, and later, we conduct robustness checks by extending the window length wherever the data permits us to do so. As before, in determining the longer window lengths as well, we extend the window by a month only if at least 80 percent of the maximum potential observations are non missing. We intend to check the robustness of our results by increasing this cut-off from 80 percent to 90 and 95 percent.

Missing data constrains us to study only five out of six extensions defined in Table 1. The second extension of the red line is therefore excluded from our analysis. Table 2 summarizes the extensions and the corresponding window lengths that we can consider, given the patterns of missing pollution data. For instance, for ITO, we can examine the effect of opening of the yellow line on only two pollutants (CO, SO_2) out of four. Here, data allow us to extend the 60 day (2 months) window to a maximum of 180 days (6 months) for CO, and 300 days (10 months) for SO_2. Table 2 shows that ITO has the best data with least missing observations.

Table 2 shows that for ITO, we have a fairly long series of good quality (in terms of missing observations) data spanning from September 2004 to October 2005 for CO, and from October 2004 to March 2006 for SO_2. We use this longer series to study the cumulative effect of DM

[7]The maximum potential hourly observations for a month is 720 (=24*30).

using the following equation:.

$$y_t = \delta_0 + \delta_1^{'}\mathbf{x}_t + \delta_2\mathbf{P}(t) + \sum_{i=3}^{K}\delta_i(DMi)_t + \varepsilon_t \tag{2}$$

The variables and coefficients are similarly defined as in equation 1. However, now the time period extends over the longest possible contiguous segment of reasonably good quality data, and accordingly includes K contiguous extensions. The cumulative effect of the DM would then be given by $\sum_{i=3}^{K}\delta_i$.

Other specifications: We re-estimate equation 1 with 1, 2, 3, and 4 hour lags of outcome pollutant. We have picked 4 lags after taking into account Henderson's observation that ozone persists in air for four hours in the US (Henderson, 1996). Inclusion of lags allows us to examine the effect taking into account the persistence of pollutant concentrations in the air.

Our identification strategy relies on the crucial assumption that any discontinuous change in air quality that is observed anytime a new segment of the network starts is due to the particular extension. We include weather related variables in our models to capture changes in weather conditions that might influence concentrations of pollutants in the air. Polynomial time trend captures any smooth variation in pollution, demand for travel, and any other non-linearities that might affect pollutant levels. Our identifying assumption could break down if any unobservable factors lead to a discontinuous change in the air quality on the day of the opening of Metro rail. One big threat to our empirical strategy could be the construction activity undertaken to build Delhi Metro. One would expect this activity to slow down in a continuous fashion just before the metro line becomes operational. Effect of this would therefore we captured by the time polynomial. Second, our estimates might under- or over-estimate the effect of opening of any of Delhi Metro lines if DMRC officials manipulated the date of extensions. To us this seems highly unlikely. Given the enthusiasm of Delhi's inhabitants for the metro and the recognition of economies of scale in its operation, officials were always in a hurry to open a new line.

3 Data and Descriptive Statistics

All our data comes from secondary sources. The National Data Center of the India Meteorological Department, provided hourly data for Delhi on four weather related variables, namely, temperature, wind speed, rainfall, and relative humidity, for the period $2004 - 2006$. The Central Pollution Control Board (CPCB) of India collects air quality data for the National Capital Territory (NCT) of Delhi as part of the National Air Quality Monitoring Program (NAMP). The NAMP network consists of 342 monitoring stations all over the country, out of which 11 stations are located in the NCT. Of these 11 stations, only 3 measure high frequency hourly pollutant data. These are located at ITO (a traffic intersection in central Delhi), Siri Fort (a residential area in south Delhi), and Delhi College of Engineering (DCE, in north Delhi adjoining industrial areas). The criteria pollutants monitored by these stations are nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3), sulphur dioxide (SO_2), and two types of particulate matter (PM_{10} and $PM_{2.5}$).[8] The CPCB provided us with this hourly data for the time period $2004 - 2010$. [9] Any analysis of pollution should control for atmospheric conditions, and since we do not have weather data beyond 2006, we restrict our study period to the years 2004 to 2006. At this stage, we focus on only four pollutants, namely, NO_2, CO, O_3, and SO_2. We omit particulate matter because data on it is very sparse. For our study period, about 63 percent of all observations for PM_{10} and 43 percent for $PM_{2.5}$ are missing. Finally, line wise monthly ridership data was obtained from the Delhi Metro Rail Corporation (DMRC).

Table 1 provides information about the phase wise extension of the metro network. It shows that during the period 2004-2006, the red line was extended for the second time from *Inderlok* to *Rithala*, yellow and blue lines were introduced and extended. The yellow line was extended once, and the blue line was extended twice in this period.

Figure 2 and Figure 3 show the time series of monthly DM ridership and percentage change in the DM monthly ridership for all lines in the time period $2004 - 2006$. Both these graphs show sharp discontinuities at red line extension 2, yellow line extension, blue line introduction,

[8] Only DCE provides data on PM_{10} and only ITO provides data on $PM_{2.5}$.
[9] Data from DCE starts from 2005.

and blue line extension 2.

Figures 3 to 7 display average monthly levels of concentrations of pollutants recorded at each monitoring station, and average over the three monitoring stations. These graphs inform us about a few distinctive features of the data. First, each monitoring station witnessed different trends in concentrations of each pollutant. Compared to the other two stations, ITO reported higher concentration of all pollutants, except O_3. Second, one can observe that we do not have complete time series for pollutant data for the entire study period. Hence, we cannot average criteria pollutant data over all monitoring stations as done by Chen and Whalley (2012). Although we do not have contiguous time series for the study period, figures show clearly that we do have sufficient data to examine the effects of DM in shorter time windows. We have exploited this fact in our empirical strategy. Third, we do observe a sharp change in pollutant levels when the metro line is introduced/extended, although this is not seen for all instances. In Tables 3 and 4, we report the descriptive statistics for the four pollutants and weather related variables. In both the tables, first column shows the discontinuity being studied.[10] Second column reports the full sample mean, standard deviation, and sample size for each discontinuity, followed by pre-discontinuity and post-discontinuity mean, standard deviation, and sample size. Last column reports the difference between pre and post means along with p-value (in parenthesis) of t-test that compares pre and post DM means of criteria pollutants. These tables reveal a number of patterns. First, with few exceptions, levels of concentrations of all the four pollutants are lower in the post-Metro period as compared to the pre-Metro period. We also find that these differences are statistically significant in most cases. Second, data from all three pollution monitoring stations shows that blue line second extension from *Barakhamba - Indraprastha* led to statistically significant lower levels of carbon monoxide post DM. Third, pollutant data from ITO and Siri Fort stations provides consistent evidence that levels of concentration of SO_2 and O_3 were lower after the extension of yellow line. Fourth, there are significant differences in all weather related variables in pre and post DM values. Differences in weather related variables before and after the introduction

[10] We have only reported those discontinuities for each monitoring station that we examine in this paper. Both for weather related variables and pollutants we have only reported summary statistics calculated within 60 day window.

or extension of almost all Metro lines, make it imperative that we control for atmospheric conditions. Our empirical approach is discussed in detail in the previous section.

4 Results

Tables 5 to 7 report estimates from equation 1 for the effect of DM on criteria pollutant levels around a 60 day window for each of the three monitoring stations. Each column displays the estimates obtained by fitting equations for a particular pollutant, and each cell reports the results from a separate regression. For each regression, we report the coefficient on the discontinuity dummy, its standard error, and the number of observations (N).[11]

From these tables we make the following observations. First, data from ITO (Table 5) and Siri Fort (Table 6) indicates that DM had a negative effect on levels of NO_2. For ITO, each extension of the metro network resulted in a decrease in NO_2. The estimates range from 3.2 percent (yellow line extension) to 38.6 percent (introduction of the blue line). Except for the first extension of the blue line, all estimates are statistically significant at the 1 percent level. We observe the same pattern for Siri Fort, though the magnitude of reduction is higher. For both the extensions for Siri Fort, we find about a 47 percent reduction in NO_2 emissions. Again, these estimates are statistically significant at the 1 percent level. For DCE, we find positive coefficient values. However, in one case the estimate is marginally significant at the 10 percent level, and in the other it is not statistically significant at conventional levels.

Second, for both ITO and Siri Fort, we find that DM has reduced CO concentrations. For ITO, the estimates range from 33 to 99.9 percent and for Siri Fort, it is 31.4 percent. All estimates are significant at the 1 percent level. For DCE, we do not find statistically significant results.

Third, we do not observe any consistent pattern across the three stations for SO_2 emissions. ITO shows significant increases, Siri Fort shows significant reductions, and for DCE the results are insignificant. SO_2 is mainly a non-transportation based pollutant and is an important

[11] In each regression, the sample size is determined by the number of non-missing observations for a particular pollutant, in the 60 day window around a particular extension (one of the six discontinuities listed in Table 1). Thus, sample sizes may differ across regressions. As stated earlier, we estimate a regression only if at least 80 percent of the maximum possible observations (approximately 1440) are non-missing.

constituent of industrial emissions. It could be affected by localized activity such as the location of coal based power plants within the city. This could be an explanation for lack of consistent results across all monitoring stations.

Finally, for O_3, our results are a bit puzzling at this stage as there is no consistent pattern even when we look at estimates for each station separately (results for ITO in particular). Ozone is a secondary pollutant formed in the atmosphere by reaction between oxides of nitrogen and volatile organic compounds (VOCs) in the presence of sunlight. Peak O_3 levels generally occur during the summer when temperatures are higher. At this stage, our results for O_3 are perplexing and we need to investigate possible explanations for them.

Overall, we find evidence to conclude that the DM has led to a reduction in NO_2 and CO. Both these pollutants are an important constituents of vehicular emissions. This suggests that one explanation for our results for these tailpipe emissions could be the traffic diversion effect mentioned earlier. It is suggestive that the DM is encouraging more people to switch from private to public means of transport.

We account for persistence of pollutants in the atmosphere by including up to 4 lags of outcome pollutant as controls. Results for estimations with lagged pollutants are displayed in Tables 8 to 10. As expected the magnitude of point estimates is much smaller in these specifications as compared to the previous ones without lagged variables. The broad patterns however, remain the same.

Next, we consider specifications longer than the 60 day window. Conceptually, it makes sense to choose a shorter time period around the observed discontinuity. However, a longer period gives more precise estimates due to increased sample size. The trade-off is that with a longer window there is a greater possibility of having discontinuities arising from events other than the metro extension. If such events do occur within the larger time span, then they would distort our earlier results. In Tables 11 and 12 we report the results from re-estimating most of the earlier regressions in with longer time series, and find that for NO_2 and CO, whenever the results were significant in the 60 day estimations, either the direction of the effect remains the same (though magnitudes are smaller in the longer period estimations) or the estimate loses significance.[12] Ideally, increase in window length should only increase precision and not

[12]Window lengths differ for each regression depending on the pattern of missing observations for a particular

change magnitudes or signs of coefficients. These results require closer scrutiny. They may be an indication of other discontinuities occurring within the longer window.

Table 13 reports results obtained after averaging hourly data across two or more monitoring stations. These regressions give us an estimate of effect of DM on overall pollution levels for the city as a whole. These estimates show that DM improved overall air quality of Delhi by reducing levels of NO_2 by 22.7 percent and of CO by 23 percent. These results are significant at 1percent level.

We use ITO data on CO from October 2004 to March 2006 to estimate the regressions reported in Table 14, and ITO data on SO_2 from September 2004 to October 2005 for Table 15.[13] The specification used is shown in equation 2 and is different from estimations presented so far because we include multiple discontinuities. This enables us to estimate the cumulative effect of the DM over time. Introduction of the yellow line resulted in a 22.2 percent decline in CO levels, followed by a further decline of 12.8 percent when that line was extended. This is a cumulative effect of a 35 percent reduction in CO levels. The introduction and extension of the yellow line also led to a decline of 123.7 percent in SO_2, though the introduction of the blue line resulted in an increase of 29.3 percent. Thus, the cumulative effect of the DM on SO_2 is a decline of 94.4 percent.

We plan on conducting several robustness checks to test the validity of our estimates. We intend to include details on industrial activity and traffic patterns in our analysis to help us interpret the results better. Also, given that some of our results changed when we extended the window length, we would like to re-estimate our regressions using a 30 day window, to see if that makes a difference. Lastly, this paper could benefit by obtaining data from another city to conduct a difference-in-difference analysis.

pollutant around the discontinuity being considered. Table 2 gives information on the exact window length used for each regression. As is seen from this table the longest window length is 10 months.

[13]Similar estimations for other monitoring stations and other criteria pollutants could not be carried out because a long continuous series of non-missing data for these was not available.

5 Summary and Conclusions

The Delhi Metro is an electric based public transit system serving the National Capital Region of India. It was first introduced in Delhi in 2002. We quantify the effect of the DM on air pollution in the city. We use hourly data on four criteria pollutants for the years 2004 through 2006. To identify causal effects, we use Regression Discontinuity framework. We exploit jumps in metro ridership that are observed each time the rail network is extended, and look for concomitant changes in pollutant levels. Controlling for weather conditions, hour and weekday fixed effects, and a third order time polynomial, we attribute any discontinuous change in pollutant levels around the extension date to the DM.

Our estimates show that each extension of the metro rail resulted in a decline in nitrogen dioxide and carbon monoxide in Delhi. The estimates for nitrogen dioxide reductions range from 3 to 47 percent, while those for carbon monoxide range from 31 to 100 percent. For ITO, a major traffic intersection in Delhi, we find that the cumulative effect of multiple extensions, is a net decline in carbon monoxide of 35 percent. Given that both nitrogen dioxide and carbon monoxide are important tailpipe emissions, our findings suggest that the DM has encouraged people to switch from private to public mode of travel resulting in positive externalities for air quality in the city.

Given the huge health costs associated with high levels of air pollution, these indirect health benefits should be taken into account when urban policy makers contemplate the setting up large scale intra-city transportation systems. Our paper provides a rationale for subsidizing these mass transit systems even when the direct accounting costs do not show a net profit. The municipalities of many other tier I and tier II cities in India are planning to build metro systems in their respective cities. Evidence of positive effect on air quality for Delhi's metro could provide a rationale for encouraging metro expansion in other cities that face similar challenges in terms of vehicular congestion and health costs due to pollution.

References

Auerbach, Amya and Michelle L. Hernandez (2012) "The Effect of Environmental Oxidative Stress on Airway Inflammation," Current Opinion in Allergy and Clinical Immunology, 12 (2): 133-139.

Block, Michelle L., Alison Elder, Richard L. Auten, Staci D. Bilbo, Honglei Chen, et al. (2012) "The outdoor air pollution and brain health workshop", NeuroToxicology, forthcoming.

Brook, Robert D., Sanjay Rajagopalan, C. Arden Pope - III, Jeffrey R. Brook, Aruni Bhatnagar, Ana V. Diez-Roux, et al. (2010) "Particulate Matter Air Pollution and Cardiovascular Disease : An Update to the Scientific Statement From the American Heart Association," Circulation, 121: 2331-2378.

Chay, Kenneth Y. and Michael Greenstone (2003) "The Impact of Air Pollution on Infant Mortality: Evidence from Geographic Variation in Pollution Shocks Induced by a Recession," The Quarterly Journal of Economics, 118 (3): 1121-1167.

Chen, Yihsu and Alexander Whalley (2012) "Green Infrastructure: The Effects of Urban Rail Transit on Air Quality," American Economic Journal: Economic Policy, 4 (1): 58-97.

CPCB (2008a) "Epidemiological Study on Effect of Air Pollution on Human Health (Adults) Delhi," Environmental Health Series 1.

CPCB (2008b) "Study on Ambient Air Quality, Respiratory Symptoms and Lung Function of Children in Delhi," Environmental Health Series 2.

CPCB (2009) "National Ambient Air Quality Status 2008," National Ambient Air Quality Monitoring Series, NAAQMS/2/2009-10.

Currie, Janet, and Matthew Neidell (2005) "Air Pollution and Infant Health: What Can We Learn from California's Recent Experience?," Quarterly Journal of Economics, 120 (3): 1003-1030.

Currie, Janet, Matthew Neidell, and Schmieder, Johannes F. (2009) "Air Pollution and Infant Health: Lessons from New Jersey," Journal of Health Economics, 28(3): 688-703.

Currie, Janet and Reed Walker (2011) "Traffic Congestion and Infant Health: Evidence from E-ZPass," American Economic Journal: Applied Economics, 3 (1): 65-90.

DEF (2010) "State of Environment Report for Delhi-2010," Department of Environment and Forests, Government of NCT of Delhi.

DMRC (2003) “A Dream Revisited: An Archival Journey into the making of the Delhi Metro Rail,” Public Relations Department, Delhi Metro Rail Corporation Ltd, New Delhi, India.

DMRC (2008) “A Journey to Remember,” Public Relations Department, Delhi Metro Rail Corporation Ltd, New Delhi, India.

Guttikunda, Sarath (2010) “Estimated Air Pollution and Health Benefits of Metro System in Delhi,” SIM-air Working Paper Series, 32.

Guttikunda, Sarath and Joshua Apte (2009) ”Monitoring & Mapping Urban Air Pollution: A One Day Experiment in Delhi, India,” SIM-air Working Paper Series, 29.

Henderson, Vernon (1996) “Effects of Air Quality Regulation,” American Economic Review, 86(4): 789-813.

Lee, David, and Thomas Lemieux (2019) “Regression Discontinuity Designs in Economics,” Journal of Economic Literature, 48: 281-355. Lleras-Muney, Adriana (2010) “The Needs of the Army: Using Compulsory Relocation in the Military to Estimate the Effect of Air Pollutants on Children’s Health,” Journal of Human Resources, 45 (3): 549-590.

Mohring, Herbert (1972) “Optimization and Scale Economies in Urban Bus Transportation,” American Economic Review, 62 (4): 591-604.

Moretti, Enrico and Matthew J. Neidell (2011) “Pollution, Health, and Avoidance Behavior: Evidence from the Ports of Los Angeles,” Journal of Human Resources, 46 (1): 154-175.

Neidell, Matthew J. (2004) “Air Pollution, Health, and Socio-Economic Status: The Effect of Outdoor Air Quality on Childhood Asthma,” Journal of Health Economics, 23(6): 1209-1236.

Vickery, William (1969) “Congestion Theory and Transport Investment,” American Economic Review, 59(2): 251-60.

Table 1: Phase wise extension of the Delhi Metro during 2004-2006

Metro Line	**New Rail Segment**	**Opening Date**
Red Line Extension 2	*Inderlok* - *Rithala*	1 April 2004
Yellow Line Introduction	*Vishwavidyalaya* - *Kashmere Gate*	20 December 2004
Yellow Line Extension 1	*Kashmere Gate* - *Central Secretariat*	3 July 2005
Blue Line Introduction	*Barakhamba* - *Dwarka*	31 December 2005
Blue Line Extension 1	*Dwarka* - *Dwarka Sector* 9	1 April 2006
Blue Line Extension 2	*Barakhamba* - *Indraprastha*	11 November 2006

Source: Delhi Metro Rail Corporation

Table 2: Discontinuities Studied During 2004-2006

Delhi Metro Rail Line (Start Date)	NO_2	CO	SO_2	O_3
	Pollution Monitoring Station: ITO			
Yellow Line Introduction (20^{th} December 2004)		2-6 months	2-10 months	
Yellow Line Extension (3^{rd} July 2005)	2 months	2-10 months	2-10 months	2 months
Blue Line Introduction (31^{st} December 2005)	2-4 months		2-4 months	2-4 months
Blue Line Extension 1 (1^{st} April 2006)	2-4 months			2-4 months
Blue Line Extension 2 (11^{th} November 2006)	2 months	2-4 months		2-4 months
	Pollution Monitoring Station: Siri Fort			
Yellow Line Introduction (20^{th} December 2004)	2 months		2-4 months	2-4 months
Yellow Line Extension (3^{rd} July 2005)			2 months	
Blue Line Extension 1 (1^{st} April 2006)			2 months	
Blue Line Extension 2 (11^{th} November 2006)	2-4 months	2-4 months	2-4 months	
	Pollution Monitoring Station: DCE			
Blue Line Extension 1 (1^{st} April 2006)	2 months	2 months	2 months	2 months
Blue Line Extension 2 (11^{th} November 2006)	2 months	2 months	2 months	2 months
	Mean Across Three Monitoring Stations			
Blue Line Extension 2 (11^{th} November 2006)	2 months	2 months		
	Mean Across Two Monitoring Stations			
	ITO + DCE			
Blue Line Extension 1 (1^{st} April 2006)	2 months			2 months
Blue Line Extension 2 (11^{th} November 2006)				2 months
	ITO + Siri Fort			
Yellow Line Introduction (20^{th} December 2004)			2 months	
Yellow Line Extension (3^{rd} July 2005)			2 months	
Blue Line Extension 2 (11^{th} November 2006)		2 months		

Table 3: Summary Statistics for Criteria Pollutants During 2004-2006

Delhi Metro Rail Line	Full Sample	Pre	Post	Difference (Pre-Post)
	Pollution Monitoring Station: ITO			
	Pollutant: Nitrogen Dioxide			
Yellow Line Extension	4.25	4.30	4.23	0.072*
	(0.51)	(0.48)	(0.54)	(0.099)
N	1305	614	619	
Blue Line Introduction	5.29	5.40	5.18	0.220***
	(0.61)	(0.64)	(0.57)	(0.000)
N	1399	679	720	
Blue Line Extension 1	4.85	4.82	4.87	-0.042
	(0.49)	(0.50)	(0.48)	(0.119)
N	1302	616	686	
Blue Line Extension 2	4.99	5.00	4.99	0.005
	(0.46)	(0.50)	(0.42)	(0.844)
N	1415	719	696	
	Pollutant: Carbon Monoxide			
Yellow Line Introduction	7.37	7.49	7.25	0.241
	(1.09)	(1.25)	(0.88)	(0.000)
N	1319	677	642	
Yellow Line Extension	7.39	7.45	7.32	0.130***
	(0.72)	(0.52)	(0.87)	(0.000)
N	1344	653	691	
Blue Line Extension 2	7.92	8.05	7.78	0.269***
	(0.63)	(0.63)	(0.61)	(0.000)
N	1415	719	696	
	Pollutant: Sulphur Dioxide			
Yellow Line Introduction	2.36	2.44	2.27	0.17***
	(0.88)	(0.84)	(0.90)	(0.000)
N	1387	668	719	
Yellow Line Extension	1.29	1.69	0.90	0.795***
	(0.94)	(1.10)	(0.50)	(0.000)
N	1316	651	665	
Blue Line Introduction	2.98	2.50	3.43	-2.98***
	(1.03)	(0.98)	(0.86)	(0.000)
N	1383	667	716	
	Pollutant: Ozone			
Yellow Line Extension	2.60	2.77	2.42	0.07***
	(1.25)	(1.34)	(1.11)	(0.00)
N	1233	645	588	
Blue Line Introduction	2.43	2.59	2.28	0.306***
	(0.97)	(0.76)	(1.11)	(0.000)
N	1372	664	708	
Blue Line Extension 1	2.23	2.12	2.34	-0.219**

	(1.43)	(1.41)	(1.43)	(0.004)
N	1363	695	668	
Blue Line Extension 2	2.65	2.79	2.52	0.260***
	(0.79)	(0.81)	(0.73)	(0.000)
N	1407	713	694	
	Pollution Monitoring Station: Siri Fort			
	Pollutant: Nitrogen Dioxide			
Yellow Line Introduction	3.94	4.04	3.84	0.205***
	(0.48)	(0.48)	(0.46)	(0.000)
N	1366	682	684	
Blue Line Extension 2	4.06	3.79	4.34	-0.556
	(0.81)	(0.48)	(0.81)	(0.000)
N	1409	715	694	
	Pollutant: Carbon Monoxide			
Blue Line Extension 2	7.02	7.08	6.95	0.269**
	(1.05)	(1.08)	(1.02)	(0.029)
N	1342	680	662	
	Pollutant: Sulphur Dioxide			
Yellow Line Introduction	1.17	1.13	1.23	-0.095
	(1.01)	(1.19)	(1.00)	(0.108)
N	1380	696	684	
Yellow Line Extension	1.27	1.38	1.18	0.200***
	(0.51)	(0.57)	(0.42)	(0.000)
N	1225	598	627	
Blue Line Extension 1	1.68	1.56	1.81	-0.249***
	(0.65)	(0.68)	(0.59)	(0.000)
N	1353	679	674	
Blue Line Extension 2	2.37	2.52	2.23	0.285***
	(0.66)	(0.74)	(0.54)	(0.000)
N	1369	695	674	
	Pollutant: Ozone			
Yellow Line Introduction	2.60	2.77	2.42	0.07***
	(1.25)	(1.34)	(1.11)	(0.00)
N	1233	645	588	
	Pollution Monitoring Station: DCE			
	Pollutant: Nitrogen Dioxide			
Blue Line Extension 1	3.32	3.36	3.27	0.090*
	(0.86)	(0.74)	(0.96)	(0.058)
N	1333	705	628	
Blue Line Extension 2	2.93	2.09	3.81	-1.717***
	(1.37)	(1.33)	(0.71)	(0.000)
N	1369	693	676	
	Pollutant: Carbon Monoxide			
Blue Line Extension 1	7.24	7.27	7.23	0.043***
	(0.27)	(0.27)	(0.28)	(0.002)
N	1411	718	693	

Blue Line Extension 2	7.36	7.50	7.23	0.272***
	(0.43)	(0.38)	(0.44)	(0.000)
N	1375	698	677	
	Pollutant: Sulphur Dioxide			
Blue Line Extension 1	1.99	1.17	2.85	-1.680***
	(1.79)	(1.73)	(1.42)	(0.000)
N	1400	716	684	
Blue Line Extension 2	1.68	1.87	1.50	0.368***
	(0.95)	(0.87)	(0.98)	(0.000)
N	1370	694	674	
	Pollutant: Ozone			
Blue Line Extension 1	5.46	5.35	5.58	-0.227***
	(0.41)	(0.33)	(0.44)	(0.000)
N	1410	718	692	
Blue Line Extension 2	2.91	3.21	2.71	0.411***
	(1.19)	(1.17)	(1.18)	(0.000)
N	1367	696	674	

Notes: In columns 2-4, in each cell the first entry is the mean of the log pollutant (measured in $\mu g/m^3$), below it in parenthesis is standard deviation, and the third entry is the number of observations. In the last column, p-values are reported in the parenthesis. Each cell entry pertains to a 60 day window around the corresponding extension. ***, **, * show statistical significance at the 1%, 5% and 10% levels respectively.

Table 4: Summary Statistics for Weather Related Variables

Delhi Metro Rail Line	**Full Sample**	**Pre**	**Post**	**Difference** (Pre-Post)
	Relative Humidity (%)			
Yellow Line Introduction	72.17	72.47	71.87	0.609
	(17.86)	(18.10)	(17.64)	(0.5217)
N	1416	696	720	
Yellow Line Extension	63.85	49.68	77.53	-27.85***
	(21.75)	(20.73)	(11.56)	(0.000)
N	1416	696	720	
Blue Line Introduction	64.88	65.71	64.05	1.67
	(22.33)	(22.43)	(22.21)	(0.1568)
N	1440	720	720	
Blue Line Extension 1	47.01	58.05	35.58	22.47***
	(22.12)	(22.30)	(14.98)	(0.000)
N	1416	720	696	
Blue Line Extension 2	68.14	68.88	67.39	1.49
	(20.17)	(19.82)	(20.55)	(0.165)
N	1416	720	696	
	Rainfall (MM)			
Yellow Line Introduction	**No Rainfall**			
Yellow Line Extension	0.163	0.087	0.236	-0.148**
	(1.43)	(0.027)	(1.88)	(0.049)
N	1405	685	720	
Blue Line Introduction	0.001	0.00	0.001	-0.001
	(0.16)	(0.00)	(0.023)	(0.160)
N	1440	720	720	
Blue Line Extension 1	0.001	0.035	0.003	0.0322***
	(0.16)	(0.245)	(0.060)	(0.000)
N	1416	720	696	
Blue Line Extension 2	0.002	0.004	0.00	0.004*
	(0.044)	(0.062)	(0.00)	(0.071)
N	1416	720	696	
	Temperature (Degree Centigrade)			
Yellow Line Introduction	15.84	17.83	13.93	3.90***
	(4.44)	(4.42)	(3.52)	(0.000)
N	1416	696	720	
Yellow Line Extension	31.70	33.13	30.32	2.81***
	(4.29)	(5.04)	(2.79)	(0.000)
N	1416	696	720	
Blue Line Introduction	14.06	13.72	14.39	-0.67**
	(5.02)	(4.87)	(5.14)	(0.011)
N	1440	720	720	
Blue Line Extension 1	26.28	22.92	30.14	-7.21***
	(6.00)	(4.63)	(4.99)	(0.000)
N	1344	720	624	
Blue Line Extension 2	21.37	24.15	18.49	5.65***

	(5.51)	(4.63)	(4.81)	(0.000)
N	1416	720	696	
	Wind Speed (Km/Hour)			
Yellow Line Introduction	4.18	3.27	5.07	-1.79***
	(5.27)	(5.11)	(5.26)	(0.000)
N	1416	696	720	
Yellow Line Extension	4.74	5.21	4.29	0.92***
	(5.32)	(5.82)	(4.74)	(0.001)
N	1400	696	704	
Blue Line Introduction	5.15	3.86	6.45	-2.59***
	(6.34)	(5.33)	(6.97)	(0.000)
N	1440	720	720	
Blue Line Extension 1	4.94	5.15	4.79	0.366
	(5.85)	(6.05)	(5.11)	(0.289)
N	1205	509	696	
Blue Line Extension 2	1.68	1.01	2.38	-1.369***
	(3.18)	(2.48)	(3.64)	(0.000)
N	1416	720	696	

Notes: In columns 2-4, in each cell the first entry is the mean of the log pollutant (measured in $\mu g/m^3$), below it in parenthesis is standard deviation, and the third entry is the number of observations. In the last column, p-values are reported in the parenthesis. Each cell entry pertains to a 60 day window around the corresponding extension. ***, **, * show statistical significance at the 1%, 5% and 10% levels respectively.

Table 5: Effect of Delhi Metro on Air Quality: 60 Day Window (Pollution Monitoring Station: ITO)

Delhi Metro Rail Line	**log(NO_2)**	**log(CO)**	**log(SO_2)**	**log(O_3)**
Yellow Line Introduction		-0.794***	0.330***	
		(0.146)	(0.099)	
N		1319	1387	
Yellow Line Extension	-0.032***	-0.999***	0.926***	-0.460***
	(0.065)	(0.097)	(0.110)	(0.162)
N	1275	1314	1288	1203
Blue Line Introduction	-0.386***		0.545***	-0.456***
	(.072)		(0.123)	(0.104)
N	1399		1383	1372
Blue Line Extension 1	-0.0824			-0.603***
	(0.065)			(0.122)
N	1234			1290
Blue Line Extension 2	-0.220***	-0.331***		0.127**
	(0.049)	(0.066)		(0.062)
N	1415	1415		1407

Notes: Each cell reports the results from a different regression with controls for all weather variables, their quartics, one-hour lags, and third order polynomial time trend. Dependent variable for each regression is listed in the first row. Unit of observation is hour. Blank cell indicates that regression was not estimated due to data constraints. 60 day window refers to 30 days before and after opening of DM. Standard errors are reported in the parenthesis. ***, ** and * indicate that the estimated coefficients are statistically significant at the 1%, 5% and 10% levels respectively.

Table 6: Effect of Delhi Metro on Air Quality: 60 Day Window (Pollution Monitoring Station: Siri Fort)

Delhi Metro Rail Line	**log(NO_2)**	**log(CO)**	**log(SO_2)**	**log(O_3)**
Yellow Line Introduction	-0.474***		-1.811***	0.225**
	(0.048)		(0.123)	(0.094)
N	1366		1380	1381
Yellow Line Extension			-0.130	
			(0.081)	
N			1209	
Blue Line Extension 1			-0.149*	
			(0.083)	
N			1286	
Blue Line Extension 2	-0.465***	-0.314***	-0.265	
	(0.061)	(0.099)	(0.087)	
N	1409	1342	1369	

Notes: Each cell reports the results from a different regression with controls for all weather variables, their quartics, one-hour lags, and third order polynomial time trend. Dependent variable for each regression is listed in the first row. Unit of observation is hour. Blank cell indicates that regression was not estimated due to data constraints. 60 day window refers to 30 days before and after opening of DM. Standard errors are reported in the parenthesis. ***, ** and * indicate that the estimated coefficients are statistically significant at the 1%, 5% and 10% levels respectively.

Table 7: Effect of Delhi Metro on Air Quality: 60 Day Window (Pollution Monitoring Station: DCE)

Delhi Metro Rail Line	**log(NO_2)**	**log(CO)**	**log(SO_2)**	**log(O_3)**
Blue Line Extension 1	0.176*	0.034	-0.007	-0.391***
	(0.093)	(0.030)	(0.203)	(0.037)
N	1272	1338	1331	1337
Blue Line Extension 2	1.778	-0.073	0.165	0.100
	(0.154)	(0.046)	(0.131)	(0.111)
N	1369	1375	1370	1367

Notes: Each cell reports the results from a different regression with controls for all weather variables, their quartics, one-hour lags, and third order polynomial time trend. Dependent variable for each regression is listed in the first row. Unit of observation is hour. Blank cell indicates that regression was not estimated due to data constraints. 60 day window refers to 30 days before and after opening of DM. Standard errors are reported in the parenthesis. ***, ** and * indicate that the estimated coefficients are statistically significant at the 1%, 5% and 10% levels respectively.

Table 8: Effect of Delhi Metro on Air Quality: 60 Day Window Model with Lagged Outcome Variables (Pollution Monitoring Station: ITO)

Delhi Metro Rail Line	**log**(NO_2)	**log**(CO)	**log**(SO_2)	**log**(O_3)
Yellow Line Introduction		-0.106***	0.094	
		(0.070)	(0.069)	
N		1299	1356	
Yellow Line Extension	-0.013	-0.183***	0.272***	-0.099
	(0.049)	(0.056)	(0.087)	(0.115)
N	1228	1290	1208	1117
Blue Line Introduction	-0.047		0.118*	-0.109*
	(.036)		(0.071)	(0.061)
N	1391		1328	1332
Blue Line Extension 1	0.008			-0.173*
	(0.040)			(0.089)
N	1177			1241
Blue Line Extension 2	-0.053**	-0.074**		0.047
	(0.026)	(0.032)		(0.043)
N	1411	1411		1379

Notes: Each cell reports the results from a different regression with controls for all weather variables, their quartics, one-hour lags, and third order polynomial time trend. Regressions reported here also control for all four lags of outcome variable. Dependent variable for each regression is listed in the first row. Unit of observation is hour. Blank cell indicates that regression was not estimated due to data constraints. 60 day window refers to 30 days before and after opening of DM. Standard errors are reported in the parenthesis. ***, ** and * indicate that the estimated coefficients are statistically significant at the 1%, 5% and 10% levels respectively.

Table 9: Effect of Delhi Metro on Air Quality: 60 Day Window Model with Lagged Outcome Variables (Pollution Monitoring Station Data: Siri Fort)

Delhi Metro Rail Line	**log**(NO_2)	**log**(CO)	**log**(SO_2)	**log**(O_3)
Yellow Line Introduction	-0.074***		-0.204***	0.020
	(0.029)		(0.064)	(0.102)
N	1334		1364	1365
Yellow Line Extension			-0.025	
			(0.055)	
N			1133	
Blue Line Extension 1			-0.007	
			(0.054)	
N			1215	
Blue Line Extension 2	-0.065**	-0.075	-0.070	
	(0.028)	(0.055)	(0.048)	
N	1397	1274	1307	

Notes: Each cell reports the results from a different regression with controls for all weather variables, their quartics, one-hour lags, and third order polynomial time trend. Regressions reported here also control for all four lags of outcome variable. Dependent variable for each regression is listed in the first row. Unit of observation is hour. Blank cell indicates that regression was not estimated due to data constraints. 60 day window refers to 30 days before and after opening of DM. Standard errors are reported in the parenthesis. ***, ** and * indicate that the estimated coefficients are statistically significant at the 1%, 5% and 10% levels respectively.

Table 10: Effect of Delhi Metro on Air Quality: 60 Day Window with Lagged Outcome Variables (Pollution Monitoring Station: DCE)

Delhi Metro Rail Line	**log**(NO_2)	**log**(CO)	**log**(SO_2)	**log**(O_3)
Blue Line Extension 1	0.049	0.008	0.027	-0.033
	(0.067)	(0.017)	(0.138)	(0.020)
N	1216	1326	1311	1329
Blue Line Extension 2	0.122*	-0.018	-0.009	0.026
	(0.065)	(0.021)	(0.066)	(0.081)
N	1345	1359	1342	1339

Notes: Each cell reports the results from a different regression with controls for all weather variables, their quartics, one-hour lags, and third order polynomial time trend. Regressions reported here also control for all four lags of outcome variable. Dependent variable for each regression is listed in the first row. Unit of observation is hour. Blank cell indicates that regression was not estimated due to data constraints. 60 day window refers to 30 days before and after opening of DM. Standard errors are reported in the parenthesis. ***, ** and * indicate that the estimated coefficients are statistically significant at the 1%, 5% and 10% levels respectively.

Table 11: Effect of Delhi Metro on Air Quality: Longer Time Window (Pollution Monitoring Station: ITO)

Delhi Metro Rail Line	**log(NO_2)**	**log(CO)**	**log(SO_2)**	**log(O_3)**
Yellow Line Introduction		0.002	-0.611***	
		(0.065)	(0.060)	
N		3965	6840	
Yellow Line Extension		-0.260***	-0.429***	
		(0.064)	(0.062)	
N		6956	6823	
Blue Line Introduction	-0.026		0.883***	-0.508***
	(.052)		(0.089)	(0.077)
N	2544		2732	2715
Blue Line Extension 1	0.187***			-0.490***
	(0.055)			(0.088)
N	2486			2526
Blue Line Extension 2		-0.286***		-0.105**
		(0.048)		(0.048)
N		2349		2260

Notes: Each cell reports the results from a different regression with controls for all weather variables, their quartics, one-hour lags, and third order polynomial time trend. Time windows for each cell differ. This information is provided in Table 2. Dependent variable for each regression is listed in the first row. Unit of observation is hour. Blank cell indicates that regression was not estimated due to data constraints. Standard errors are reported in the parenthesis. ***, ** and * indicate that the estimated coefficients are statistically significant at the 1%, 5% and 10% levels respectively.

Table 12: Effect of Delhi Metro on Air Quality: Longer Time Window (Pollution Monitoring Station: Siri Fort)

Delhi Metro Rail Line	**log(NO_2)**	**log(CO)**	**log(SO_2)**	**log(O_3)**
Yellow Line Introduction			-1.237***	0.062
			(0.081)	(0.065)
N			2856	2747
Blue Line Extension 2	-0.280***	-0.091	-0.601***	
	(0.048)	(0.075)	(0.065)	
N	2344	2267	2292	

Notes: Each cell reports the results from a different regression with controls for all weather variables, their quartics, one-hour lags, and third order polynomial time trend. Time window is two months before and after DM open data for each cell. Dependent variable for each regression is listed in the first row. Unit of observation is hour. Blank cell indicates that regression was not estimated due to data constraints. Standard errors are reported in the parenthesis. ***, ** and * indicate that the estimated coefficients are statistically significant at the 1%, 5% and 10% levels respectively.

Table 13: Effect of Delhi Metro on Air Quality: 60 Day Window

Delhi Metro Rail Line	**log(NO_2)**	**log(CO)**	**log(SO_2)**	**log(O_3)**
Average Across All Stations				
Blue Line Extension 2	-0.227***	-0.230***		
	(0.047)	(0.059)		
N	1361	1307		
Average Across ITO and DCE				
Blue Line Extension 1	-0.017			-0.364***
	(0.066)			(0.038)
N	1164			1284
Blue Line Extension 2				0.088
				(0.079)
N				1358
Average Across ITO and Siri Fort				
Yellow Line Introduction			-0.298***	
			(0.087)	
N			1351	
Yellow Line Extension			0.570***	
			(0.086)	
N			1117	
Blue Line Extension 2		-0.347***		
		(0.071)		
N		1341		

Notes: Each cell reports the results from a different regression with controls for all weather variables, their quartics, one-hour lags, and third order polynomial time trend. Dependent variable for each regression is listed in the first row. Unit of observation is hour. Blank cell indicates that regression was not estimated due to data constraints. Standard errors are reported in the parenthesis. ***, ** and * indicate that the estimated coefficients are statistically significant at the 1%, 5% and 10% levels respectively.

Table 14: Effect of Delhi Metro on CO: Longest Time Window (Monitoring Station: ITO)

Delhi Metro Rail Line	**Model with no Lags**	**Model with Lags**
Yellow Line Introduction	-0.222***	0.003
	(0.047)	(0.022)
Yellow Line Extension	-0.128**	0.002
	(0.047)	(0.024)
N	8448	8328

Notes: First column reports the regression run with data from September 2004 to October 2005. It includes both discontinuities that occurred in this time period along with controls for all weather variables, their quartics, one-hour lags, and third order polynomial time trend. Regression results reported in third column, in addition, control for all four lags of outcome variable. Unit of observation is hour. Standard errors are reported in the parenthesis. ***, ** and * indicate that the estimated coefficients are statistically significant at the 1%, 5% and 10% levels respectively.

Table 15: Effect of Delhi Metro on SO_2: Longest Time Window (Pollution Monitoring Station: ITO)

Delhi Metro Rail Line	**Model without Lags**	**Model with Lags**
Yellow Line Introduction	-0.169***	-0.033
	(0.060)	(0.034)
Yellow Line Extension	-1.068***	-0.198***
	(0.055)	(0.032)
Blue Line Introduction	0.293***	0.085***
	(0.063)	(0.035)
N	10,877	10,519

Notes: First column reports the regression run with data from October 2004 to March 2006. It includes all three discontinuities in this time period along with controls for all weather variables, their quartics, one-hour lags, and third order polynomial time trend. Regression results reported in third column, in addition, control for all four lags of outcome variable. Unit of observation is hour. Standard errors are reported in the parenthesis. ***, ** and * indicate that the estimated coefficients are statistically significant at the 1%, 5% and 10% levels respectively.

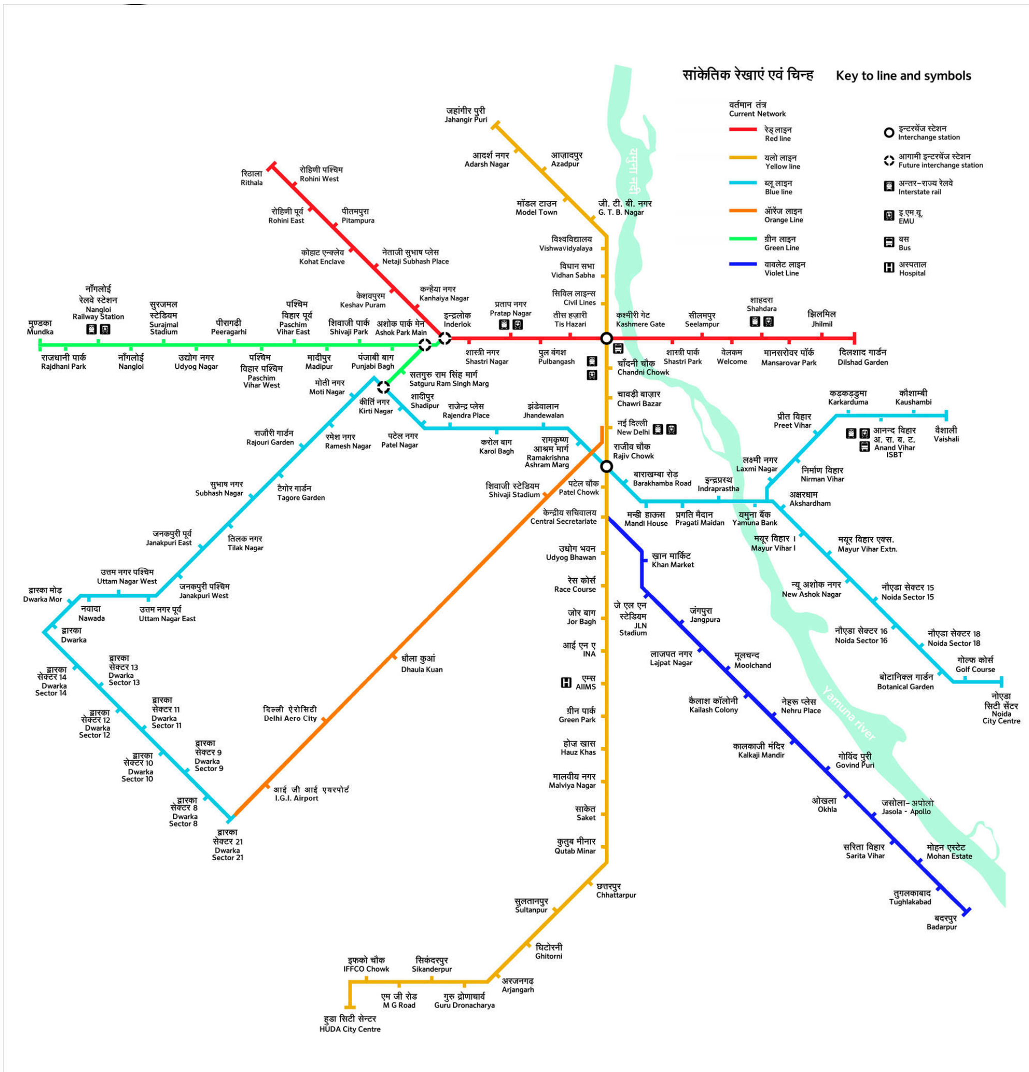

Figure 1: Map of the Delhi Metro

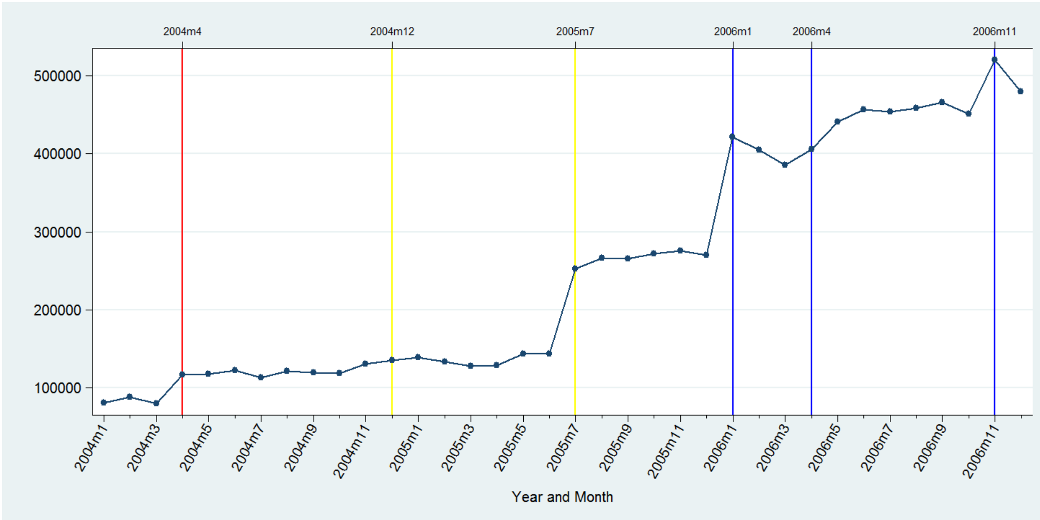

Figure 2: Delhi Metro Ridership During 2004-2006

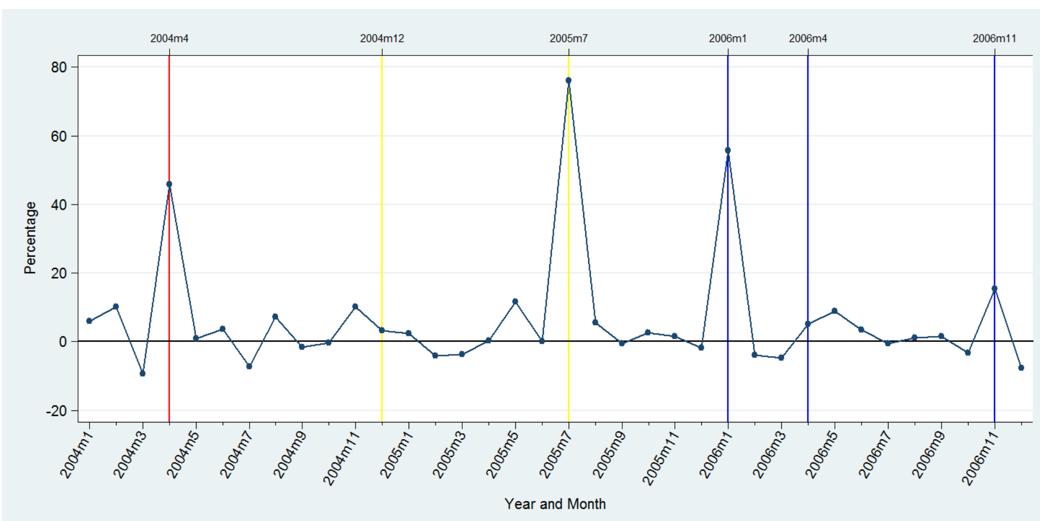

Figure 3: Percentage Change in Delhi Metro Ridership During 2004-2006

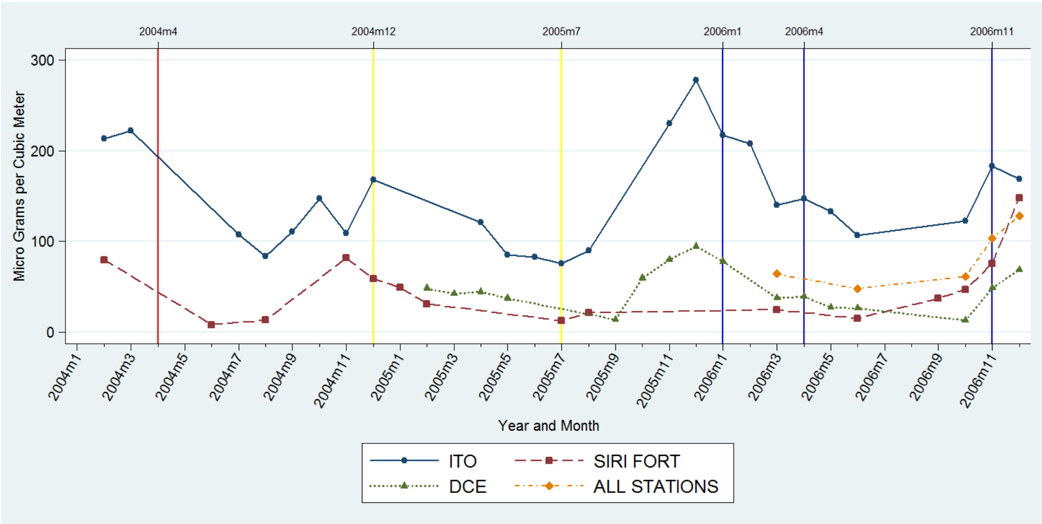

Figure 4: Concentration of Nitrogen Dioxide During 2004-2006

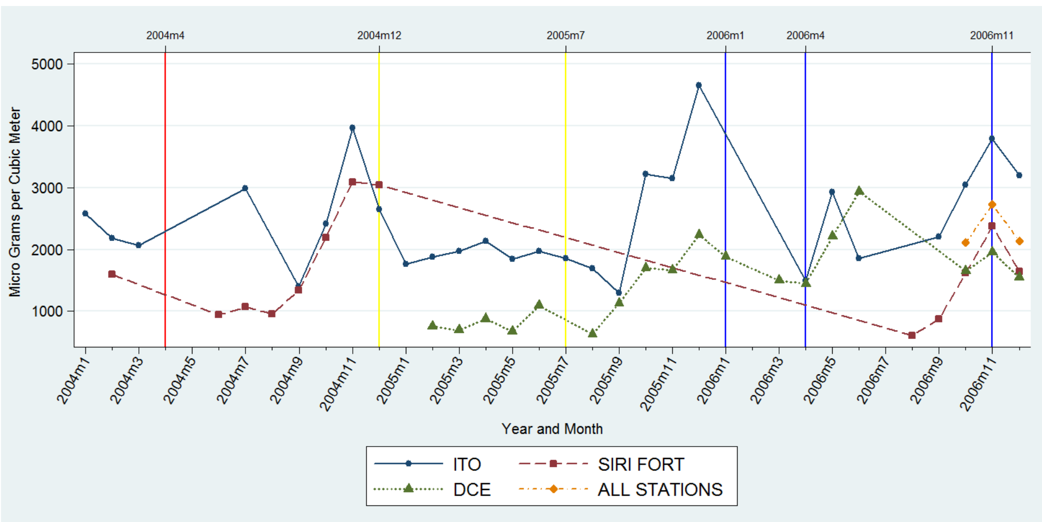

Figure 5: Concentration of Carbon Monoxide During 2004-2006

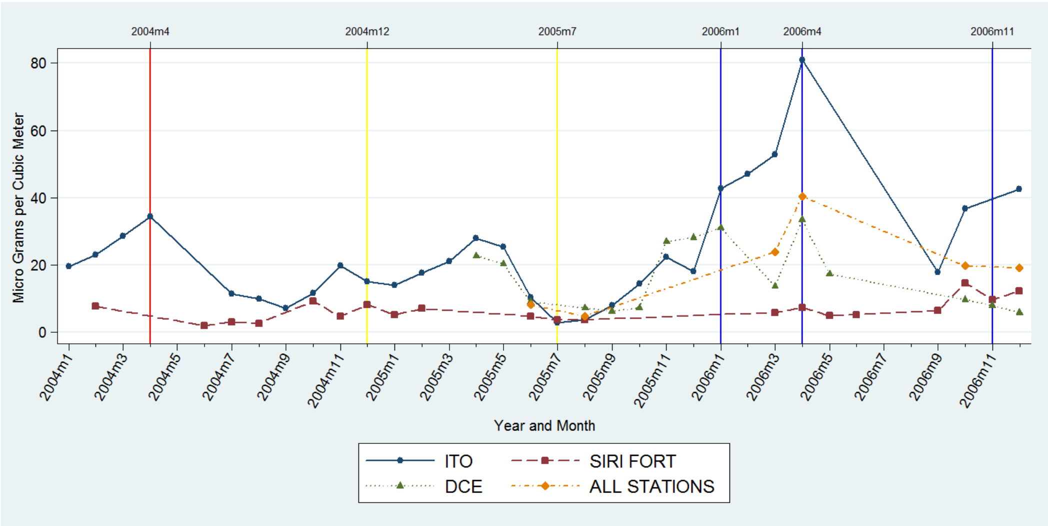

Figure 6: Concentration of Sulphur Dioxide During 2004-2006

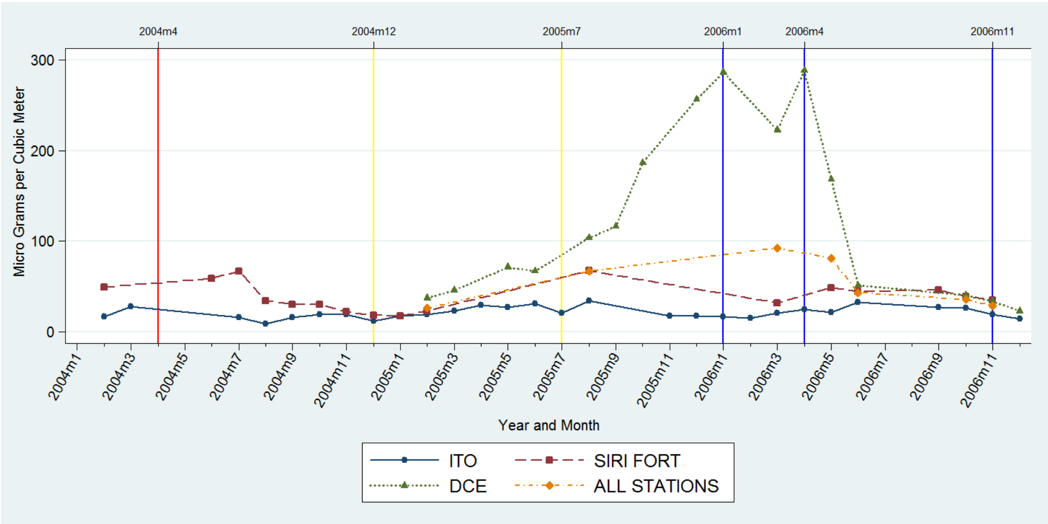

Figure 7: Concentration of Ozone During 2004-2006