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The Impact of Delhi's CNG Program on Air Quality

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The Impact of Delhi's CNG Program on Air Quality

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Abstract

This paper estimates the impact on Delhi's air quality of a number of policy measures recently implemented in the city to curb air pollution using monthly time-series data from 1990 to 2005. The best known of these measures is the court-mandated conversion of all commercial passenger vehicles—buses, three-wheelers, and taxis—to compressed natural gas (CNG). Broadly, the results point to the success of a number of policies implemented in Delhi but also to a number of areas of growing concern. For example, the results suggest that the conversion of buses from diesel to CNG has helped to reduce PM_{10}, CO, and SO_2 concentrations in the city and has not, contrary to conventional wisdom, led to the recent increase in NO_2. At the same time, however, the conversion of three-wheelers from petrol to CNG has not had the same benefit, possibly because of poor technology. Another policy measure that appears to have had a positive impact on air quality is the reduction in the sulfur content of diesel and petrol. This has led to a decrease in SO_2 levels and, because of conversion of SO_2 to sulfates (a fine particle), a decrease in PM_{10} concentrations. Some of these gains from fuel switching and fuel-quality improvements are, however, being negated by the increase in the proportion of diesel-fueled cars, which is leading to an increase in PM_{10} and NO_2 levels, and by the sheer increase in the number of vehicles.

Key Words: air pollution, compressed natural gas, low-sulfur diesel, diesel-fueled cars, Delhi

JEL Classification Numbers: Q53, R41, R48

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The Impact of Delhi's CNG Program on Air Quality

Urvashi Narain and Alan Krupnick*

Introduction

Countries the world over, especially in the developing world, are experiencing rapid urbanization. The share of the world's population living in cities is reported to have grown from about 35 percent in 1970 to almost 50 percent in 2001, and this number is expected to increase to more than 60 percent by 2030 (UN-HABITAT 2001). One of the many consequences of the increased economic activity that accompanies urbanization—particularly increased vehicle use, electricity generation, and industrial production—is the deterioration of air quality (Molina 2004). Concentrations of conventional air pollutants, including sulfur dioxide (SO_2), particulates (PM_{10} and $PM_{2.5}$), ozone (O_3), nitrogen dioxide (NO_2), carbon monoxide (CO), and air toxics, are rising in many cities and are in many cases already well above the World Health Organization's guidelines for ambient air-quality standards. Moreover, even with mounting evidence of the negative health effects of air pollution (HEI 2004), these cities largely have been unable to stem the rising tide.

Yet Delhi, India, once ranked among the world's most polluted megacities (Richmond 1994), has proven to be an exception. Under close supervision from the Indian Supreme Court, Delhi has implemented a wide array of policies that are reputed to have improved its air quality (World Bank 2005).[1] As a direct result of court orders, between 1996 and 2001 the sulfur content of diesel and petrol was progressively reduced from 1 percent for diesel and 0.2 percent for petrol to 0.05 percent for both fuels (see Table 1). Starting in late 1996, industries categorized as being hazardous or noxious under the Delhi Master Plan, the so-called H-category of industries, were forced to shut down. A total of 1,328 units

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[1] Because of these recent improvements in air quality, Delhi was awarded the Clean Cities International Award by the Clean Cities Program of the U.S. Department of Energy in 2003 (DOE 2006). Also, see Appendix A for more information on the policies implemented in Delhi.

were closed.[2] Also, premixed lubricating oil and petrol replaced loose supply of these fuels for two-stroke engines by December 1998.[3] In the same year, the court ordered the retirement of commercial vehicles older than 15 years and passed its now-famous judgment ordering the conversion of all commercial passenger vehicles—buses, taxis, and three-wheelers—to compressed natural gas (CNG). The number of buses in Delhi also was increased from 6,000, to 10,000. Finally, some time between 1999 and 2000, Delhi's thermal power stations began to use beneficiated coal, with an ash content of less than 34 percent, versus coal with an ash content of 40 percent (Delhi Pollution Control Committee n.d.), to increase the efficiency of electrostatic precipitators (ESP), and a high-efficiency ESP was installed in unit five of the Indraprastha power station (Kandikar and Ramaandran 2000).

This period also saw three initiatives from the state. The first was the notification of the first set of emissions standards for Indian vehicles; in 1993, new vehicles were required to achieve progressively stricter standards by 1996 and 2000. These standards were further tightened in 2000 (see Table 2). Second, beginning in 1995, all new passenger vehicles were required to be equipped with catalytic converters to further reduce emissions. Finally, a mass rapid transit system, known as the Metro, was introduced in 2000.

Many believe that these various interventions, especially the conversion to CNG, have improved Delhi's air quality. A number of recent studies have tried to analyze whether this is, in fact, the case. The most relevant among these for our analysis are the following: Chelani and Devotta (2005), Kathuria (2005), Kumar and Foster (2007), and Ravindra et al. (2005).

Chelani and Devotta (2005) and Ravindra et al. (2005) look at trends in air quality measures before and after 2002, when the conversion of commercial vehicles to CNG took place, and attribute any observed improvements, or for that matter any observed deteriorations, to the conversion to CNG, without controlling for other confounding factors. For example, Chelani and Devotta (2005), upon finding no changes in PM_{10} levels, conclude that CNG has, in fact, not helped to improve air quality in Delhi. Similarly, Ravindra et al. (2005) attribute declines in CO and SO_2 concentrations after the implementation

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[2] Information obtained from Ms. Jaiseelan, then Secretary of Environment for the Delhi Government.

[3] This measure was instituted because although it is possible to reduce emissions from two-stroke engines by up to two-thirds by mixing lubricating oil with petrol in the right proportions, approximately 1 part in 50 (Kojima, Brandon, and Shah 2000), for various reasons operators of two-stroke engines were using excessive amounts of lubricating oil and, in turn, causing excessive amounts of pollution.

of the CNG order to the conversion to CNG without controlling for other factors. An increase in NO_2 levels during this period also is attributed to CNG for the same reason.[4]

On the other hand, by regressing measures of air quality on some of the determinants of air quality, Kathuria (2005) and Kumar and Foster (2007) attempt to control for the impact of a subset of confounding factors. Kathuria (2005), for example, regresses daily measures of air quality on its lagged values, on weather and climate variables, and on a shift parameter that takes the value one from the date when the CNG order was fully implemented (December 1, 2002). The author finds no statistical link between the shift parameter and suspended particulate matter (SPM), PM_{10}, and NO_2 levels and a negative and significant link between the shift parameter and levels of CO and concludes that the CNG program has helped only to reduce CO concentrations and has had no impact on the levels of other pollutants.

Similarly, using spatially distributed primary data on $PM_{2.5}$ from 113 sites across Delhi and its neighboring states collected between July and December of 2003, Kumar and Foster (2007) analyze the impact of two major policies: the conversion of vehicles to CNG and the industrial relocation policy of early 2000 (see Appendix A for a description of this policy). Like Kathuria (2005), Kumar and Foster (2007) control for a subset of covariates, namely proximity to major roads and industrial clusters and the frequency of buses and trucks on roads closest to the air-quality data collection sites. A negative and significant coefficient between bus frequency and $PM_{2.5}$ levels leads the authors to conclude that the CNG conversion policy has improved Delhi's air quality.[5]

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[4] Goyal et al. (2006) similarly look at changes in average air-quality measures between the pre-implementation period (1989–1996), the implementation period (1997–2000), and the post-implementation period (2001–2003), but do not try to attribute any observed change to specific policy measures. Observed declines in SO_2 and CO between the pre- and post-implementation periods are attributed to all policies implemented between 1997 and 2000 and not to any specific policy.

[5] Two other studies consider the gamut of measures implemented to reduce air pollution but analyze the impact on vehicle emission loads rather than on measures of air quality (*Down to Earth* 2002; CRRI 2002). According to a study by the Centre for Science and Environment (CSE), by 2002 the different measures implemented by order of the Supreme Court had reduce particulate matter, $NO_{x,}$ CO, and hydrocarbons loads attributable to mobile sources, by 38 percent, 31 percent, 15 percent, and 11 percent, respectively (*Down to Earth* 2002). The CSE study did not, however, separate out the impact of individual measures and based its conclusions on projected, rather than actual, changes in vehicle populations. A study by the Central Road Research Institute, on the other hand, estimated the reduction in particulate matter loads attributable to changes in fuel and vehicle technology and to the conversion to CNG. Based again on projections of numbers of vehicles, the study found that improvements in fuel and vehicle technology reduced particulate matter load nine times more than the conversion to CNG (CRRI 2002).

In this paper we build on the studies by Kathuria (2005) and Kumar and Foster (2007) by similarly analyzing data on measures of air quality and its determinants to isolate the impact of different policy interventions. But unlike these other studies, because of our access to a fairly rich data set we are able to account for the majority of pollution sources in Delhi and thereby analyze the effect of different policy interventions while controlling for other confounding factors. Our analysis points to the success of a number of interventions but also to a number of areas of growing concern. For example, our results suggest that while the conversion of buses from diesel to CNG has helped to reduce PM_{10}, CO, and SO_2, no such gains are being realized from the conversion of three-wheelers from petrol to CNG, possibly because of poor technology. Another policy that appears to have helped PM_{10} and SO_2 levels is the reduction in the sulfur content of diesel and petrol. Some of these gains from fuel switching and fuel-quality improvements, however, are being negated by the increase in the proportion of diesel-fueled cars, which is leading to an increase in PM_{10} and NO_2 levels, and by the sheer increase in number of vehicles in Delhi.

The rest of the paper is organized as follows. The following section presents air-quality trends for Delhi to examine whether air quality has in fact improved in the city in recent times. This is followed, in Section 3, by a discussion of the method we used to examine the effect of different policy interventions on air quality. Section 4 discusses the various sources of pollution in Delhi and the data used to capture the impact of these sources. Section 5 presents the econometric methodology and results of the econometric analysis, and section 6 concludes with some policy recommendations.

Air Quality Trends

In 1984, the Central Pollution Control Board (CPCB) of the Indian Ministry of Environment and Forests instituted the National Ambient Air Quality Monitoring network, later renamed the National Air Monitoring Program, to monitor ambient air quality in a number of Indian cities. Under this network, the CPCB maintains seven air-quality monitoring stations in different parts of Delhi (see Figure 1 for their locations).[6] Six, other than the monitoring station at I.T.O., were established in the late 1980s to monitor

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[6] In addition to the seven monitoring stations maintained by the CPCB, three other air-quality monitors are maintained in Delhi by the National Environmental Engineering Research Institute (NEERI). Their locations are the ESI Dispensary, Najafgarh, NY School, Sarojini Nagar, and Town Hall. Because NEERI uses different monitoring equipment and a different methodology to monitor air quality and because we do not have as complete data for the NEERI-run monitors, we decided not to use the NEERI data. These data have been analyzed in a World Bank (2005) report.

levels of three conventional pollutants—SO_2, NO_2,[7] and SPM. The monitoring station at ITO, also known as the Bahadur Shah Zafar Marg monitor, was established in the late 1990s at a heavy traffic intersection to monitor not only the three pollutants being monitored at the other six stations but also levels of respirable suspended particulate matter (RSPM or PM_{10}), CO and O_3. The other six stations also began monitoring PM_{10} from mid-2000.[8]

Figure 2(a) shows the trend in the average monthly concentration of SO_2 for monitoring stations other than the one at ITO for the period of 1990 to 2005. Figure 3(a), on the other hand, shows the trend in the monthly concentration of SO_2 for the ITO monitoring station and, thus, for the more limited period of 1997 to 2005. While Figure 3(a) suggests that SO_2 levels began to decline in Delhi from at least 1997, Figure 2(a), with a turning point of September of 1996, suggests that the decline began a few months prior and that levels of SO_2 increased up to September of 1996. Throughout this period, however, and therefore even at its peak, SO_2 concentrations remained well below the national annual standard of 60 micrograms per cubic meter (see Table 3 for a comparison of Indian, World Health Organization, and United States ambient air quality standards).

Similarly, levels of CO as registered at the ITO monitoring station have shown a steady decline between 1997 and 2005 (see Figure 3(b)). These levels fell from a high of 5 milligrams per cubic meter to the 1-hour national ambient air-quality standard of 2 milligrams per cubic meter in sensitive areas by 2005, though not the 8-hour standard.

In contrast to the recent improvements in SO_2 and CO levels, however, levels of NO_2 have been increasing in Delhi. As shown in Figure 2(b), NO_2 levels at the non-ITO stations increased from 1990 to about 1995, and then decreased slightly until mid-2000, only to increase again. Furthermore, despite the decrease between 1995 and 2000, the trend between 1990 and 2005 was an overall increase, with average levels surpassing the national ambient air-quality standard of 60 $\mu g/m^3$ for residential areas in late 2005. On the other hand, and as shown in Figure 3(c), NO_2 levels at the ITO monitoring station decreased slightly between 1997 and 1998 and then increased rapidly until late 2004, but declined thereafter. Levels

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[7] Note that NO_2 is a more specific measure of nitrogen oxides (NO_x) and therefore we sometimes use these terms interchangeably.

[8] Note that PM_{10} is monitored every 8 hours and SO_2, CO, and NO_2 every 4 hours for 24 hours. Daily average concentrations are then calculated from three observations for PM_{10} and from six observations for SO_2, CO, and NO_2. Monitoring is done twice a week at all stations other than the one at ITO, were pollutants are monitored from Monday to Friday (CPCB 2006a).

at this station crossed the national annual standard by late 2002 and remain above the standard, despite the recent decline.

Levels of PM_{10}, recorded at the ITO monitoring station since early 1998, have, on the other hand, shown a slight, though by no means consistent, upward trend (see Figure 3(d)). The annual average level of PM_{10} decreased between 1999 and 2001 but then increased sharply in 2002. Thereafter, levels decreased until 2004, only to increase again in 2005. Levels have, however, consistently remained substantially above the national ambient air-quality standard of 60 $\mu g/m^3$ for residential areas. On the other hand, and as shown in Figure 2(c), PM_{10} levels recorded at the other monitoring stations from mid-2000 have shown no consistent trend, leading some to conclude that PM_{10} levels have been stabilized in Delhi. As with the levels at the ITO monitoring stations, levels across the city remain well above the national ambient air-quality standard.[9]

Methodology

Two methods typically are used to estimate the impact of various air-quality regulations on levels of conventional pollutants such as SO_2, CO, NO_2, and PM_{10}. The first, which we will refer to as the "top-down" approach, uses actual data on air quality and its determinants and builds a regression model to explain observed changes in air quality. Under this approach, a given measure of air quality, y_t, is regressed on a vector of covariates, x_t,

$$y_t = \beta_0 + \beta_1 x_t + u_t .$$

Apart from meteorological factors that affect how emissions get transformed into conventional air pollutants, covariates include variables that represent levels of various pollution-causing economic activities, such as miles driven by vehicle type, and variables that represent major policy shifts, such as changes in the sulfur content of diesel and petrol.[10]

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[9] Although all CPCB monitoring stations collect information on the levels of SPM and some stations collect information on O_3, we have chosen not to analyze these pollutants for the following reasons: Unlike PM_{10} measurements, SPM measurements include coarse dust particulates that are neither affected by most pollution-control measures listed above nor are as harmful to health as the smaller particulates included in PM_{10}. Similarly, monitoring to date for O_3 is fairly poor in Delhi and the limited data that exist shows O_3 not to be a pollutant of concern (Roychowdhury et al. 2006). Also, although the CPCB began monitoring levels of $PM_{2.5}$ at its ITO station in 2002, there isn't as yet a sufficient time series to analyze changes in the levels of this pollutant.

[10] See Henderson (1996), Slini et al.(2002), Auffhammer et al. (2005), and Davis (2006) for other variants of the top-down approach.

The second model, the “bottom-up approach,” instead first estimates changes in the emissions load caused by a particular policy and then converts these changes to likely shifts in concentration levels using a relevant air-dispersion model. To estimate, for example, the impact of the conversion of buses to CNG under this approach, one would first estimate the emissions load of CNG buses, which, in turn, is given by the emissions factor for CNG buses—the amount of pollutant released (in grams) per kilometer driven—times the total kilometers driven by CNG buses. This would then be compared to what emissions would have been had the buses not been converted to CNG and were running on diesel instead. The difference would give the change in the emissions load attributable to the CNG policy, holding all else constant. Finally, an air-dispersion model for Delhi would then have to be applied to convert the estimated change in emissions load to a predicted change in ambient air quality. This approach, minus the air-dispersion model, has been used by Takeuchi et al. (2007), for example, to estimate the impact of the conversion of buses to CNG in the city of Mumbai.

Both approaches have their advantages and disadvantages. One advantage of the top-down approach is that it provides estimates of the actual effect of policies, such as the CNG conversion, on air quality—not just the predicted impact, as is the case with the bottom-up approach. To the extent that enforcement is poor or implementation is slow, these hard-to-quantify factors will be reflected in the data for the top-down approach but will be missed by the bottom-up approach. Further the bottom-up approach depends on getting the emissions factors right. For some technologies this may be easy, such as in developing factors for the sulfur emitted from burning a gallon of gasoline. But for others, such as tailpipe emissions when the maintenance condition of an entire fleet is at issue, emissions factors will be very difficult to estimate with any precision. Nevertheless, because air quality is affected by a large number of different factors and because these factors usually change slowly over a long period of time and some factors are difficult to measure, statistical models of air quality often have poor predictive powers (NCHRP 1997).

We have chosen to use the top-down approach for two main reasons. First, while it is usually difficult to attribute changes in air quality to specific policies, because a number of the policies in Delhi, such as the reduction in the sulfur content of fuel and the conversion of all commercial passenger vehicles to CNG, were implemented quickly and represent a dramatic change in fuel quality and fuel mix, an econometric model of air quality in Delhi is less likely to suffer from poor predictive powers. Second, the bottom-up approach requires estimates of emissions factors for Indian vehicles by vehicle type and fuel type and for various Indian industries. These factors, however, are not extensively available. Furthermore, given differences in vehicular technology, especially differences in the pollution-control equipment used, differences in vehicular maintenance practices, in average traffic speeds, and in the quality of fuel, emissions factors developed by the U.S. Environmental Protection Agency for U.S. conditions are not likely to be applicable to Delhi (Kandlikar and Ramachandran 2000).[11]

Data on Covariates

To use the top-down approach, then, we first need to identify the list of variables that affect air quality in Delhi. For this, in turn, we need to identify Delhi's main pollution sources. Unfortunately, there are few source-apportionment studies or emissions inventories for Delhi that can help to identify a complete set of pollution sources and their relative contributions to Delhi's emissions load.

Two source apportionment studies for Delhi—Balachandran et al. (2000) and ESMAP (2004)—use chemical analysis of particles to identify chemically distinct sources of pollution. These studies come to fairly similar conclusions about major pollution sources. Using data collected from three different representative sites in Delhi from February to May 1998, Balachandran et al. (2000) identify vehicular emissions, industrial emissions, and soil re-suspension as the three major sources of PM_{10} in Delhi. Similarly, ESMAP (2004), using data collected during the months of March, June, October, and December of 2001, identifies diesel exhaust, gasoline exhaust, road dust, coal combustion, and biomass combustion as the primary source contributors to $PM_{2.5}$ in Delhi. Another set of estimates, which are the ones cited most often, come from the CPCB (MoEF n.d.). According to these estimates, in 2000, vehicles were responsible for about 72 percent of Delhi's pollution, industry for another 20 percent, and the domestic sector for the remaining 8 percent.[12] Within the industrial sector, about half of the pollution is said to be caused by the three coal-based power plants situated on the outskirts of Delhi.[13]

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[11] The CPCB is in the process of developing Delhi-specific emissions factors (Sengupta 2006), and, once these estimates become publicly available, we hope to estimate the bottom-up model as well.

[12] According to numbers provided by the CPCB, the contribution of vehicles, industrial units, and domestic sources to Delhi's pollution load has changed dramatically over time. In 1970, vehicles were responsible for only about 23 percent of the total pollution. This share increased to 42 percent by 1980 and further to 64 percent by 1990. On the other hand, the contribution of industry to total pollution has decreased over time from 56 percent in 1970, to 40 percent in 1980, to 29 percent by 1990. The domestic sector's share similarly has declined from 21 percent to 7 percent between 1970 and 1990 (DPCC n.d.). Though these numbers often are cited, little is known about the studies that they are based on.

[13] Although long-range transport of pollutants into Delhi from neighboring states is of some concern (Chelani and Devotta 2005), the CPCB estimates do not quantify the relative importance of this source. Due to data constraints, we are unable to take the impact of long-range pollution sources into account.

In summary, these studies suggest then that Delhi's main pollution sources are vehicles, power plants and other industrial units, and domestic units that use fuels such as firewood or kerosene for cooking.[14] Below, we examine these sources in detail to devise variables to capture their emissions.

Vehicular Emissions

To analyze the impact of Delhi's vehicle fleet on air quality, emissions generated by these vehicles must be estimated. The total number of kilometers driven by vehicle type and fuel type[15] can serve as a reasonable proxy for total vehicular emissions in Delhi. Unfortunately, there are no estimates of the actual numbers of vehicles regularly traveling on Delhi's roads. Although the Delhi State Transport Authority (STA) maintains data on the number of vehicles that are registered in Delhi by vehicle type and fuel type, they do not keep track of decommissioned vehicles. Consequently, the number of vehicles registered in Delhi is a gross overestimate of the actual number of vehicles on the road.

For this study, we have converted the vehicle registration data into the actual number of vehicles on the road using information provided by the STA[16] and by incorporating changes to the vehicle fleet that were driven by the various policies implemented in Delhi.[17] Based on the suggestions of the STA, for example, we have assumed that approximately 50 percent of the vehicles registered in Delhi up to 1990 were actually on the road in 1990. Similarly, we have accounted for the retirement of old commercial vehicles—buses, taxis, three-wheelers, and trucks—on the dates when the Supreme Court order for these came into force and also accounted for the conversion of commercial passenger vehicles—buses, taxis,

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[14] A report on the recent air quality improvements issued by the Department of Environment, Government of the National Capital Territory of Delhi, and the Delhi Pollution Control Committee lists vehicles, thermal power plants, large- and small-scale industrial units, and domestic sources as the major sources of pollution. No data, however, are provided as the basis of this statement (DPCC n.d.).

[15] Note that apart from vehicle-type and fuel-type, age of the vehicle also can be an important determinant of vehicular emissions, as older vehicles tend to have higher emissions. Due to difficulties in estimating the age of the Delhi vehicle fleet, we are unable to take this additional factor into account.

[16] Two officers in particular, Mr. Vikas Jain and Mr. Anuj Gupta, provided valuable information. Both officers have been with the STA since 1987 and work in the Pollution Control Department.

[17] One of the main issues that arises with using registration data to estimate actual numbers of vehicles on the road concerns traffic coming into and out of Delhi. Unfortunately, very little is known about the flow of traffic into and out of the city and, therefore, we are unable to make any adjustments for this type of traffic. One study conducted by the Central Road Research Institute suggests that such an omission may not be too problematic. According to this study, conducted in early 2002, approximately the same number of vehicles, about 0.25 million, entered and left the city on an average working day (CRRI 2002).

and three-wheelers—to CNG over the period when this conversion took place. Details on the assumptions used for each type of vehicle are provided in Appendix B.[18]

Numbers by Vehicle Type and Fuel Type

Figures 4 through 7 show the resultant number and composition of vehicles on the roads of Delhi between 1990 and 2005. One of the most telling trends is the dramatic increase in the total number of vehicles in Delhi. Vehicle numbers increased about threefold between 1990 and 2005, from less than a million to close to three million (see Figure 4(a)).[19] The bulk of these vehicles are petrol-fueled, with CNG-fueled vehicles making an appearance starting in the late 1990s.[20] In terms of vehicle type, the bulk of these vehicles, about 58 percent, are privately held two-wheelers, with private cars making up another 36 percent. Buses, three-wheelers, taxis, and trucks make up the remaining 6 percent of vehicles on the road.[21]

Buses. Figure 5(a) shows the trend in the number of petrol-, diesel-, and CNG-fueled public and private buses on Delhi's roads. In the early 1990s, up until mid-1993, Delhi only had diesel-fueled buses. However, starting in mid-1993, a few CNG-fueled buses were introduced. Between mid-2001 and late 2002, though, on account of the Supreme Court order, Delhi's buses switched rapidly from diesel to

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[18] A study of the current vehicle population in Delhi conducted by the CRRI (2002) also voiced doubts about using vehicle registration data as an estimate of the number of vehicles on the road by concluding that "the current vehicle population is significantly different from the registered vehicle population." This study estimates that about 55 percent of registered vehicles are in use on an average day in Delhi. Our analysis suggests a similar magnitude for the percentage of registered vehicles in use; according to our calculations, this percentage varied between 57 percent and 63 percent over the course of 1990 and 2005, but was 57 percent in 2002.

[19] Interestingly, according to Government of India estimates, about 30 percent of all vehicles in India are in Delhi. Two of India's other large metropolitan cities, Mumbai and Kolkata, have 12 percent and 8 percent, respectively (Kandlikar and Ramachandran 2000).

[20] Even though petrol-fueled vehicles far outnumber diesel-fueled vehicles in Delhi, on average between 1990 and 2005 twice as much diesel fuel was sold in Delhi as compared to petrol fuel (our calculations are based on information provided by the Petroleum Planning and Analysis Cell of the Indian Ministry of Petroleum and Natural Gas). These ratios are not surprising given that diesel primarily is used by buses, trucks, taxis, and other commercial vehicles, all of which consume larger quantities of fuel per road kilometer and also constitute a larger share of road kilometers traveled.

[21] These fractions have changed a fair amount since 1990, when the fraction of private cars was significantly lower. In 1990, the relative shares were 70 percent for two-wheelers, only 20 percent for cars, and 10 percent for buses, three-wheelers, taxis, and trucks (our calculations are based on STA registration data). Kandlikar and Ramachandran (2000) suggest that the introduction of the relatively inexpensive Maruti car and the government's liberalization program of the early 1990s, which encouraged car production by multinationals in India, led to this dramatic increase in the share of cars.

CNG, with diesel buses making almost a complete exit by late 2002. Also due to the Supreme Court order, the total number of buses increased from just below 10,000 in 1990 to just below 20,000 in 2005. The upward trend in the total number of buses was interrupted temporarily in the late 1990s when the Supreme Court order on the retirement of older commercial vehicles was implemented.

Three-wheelers. Figure 5(b) shows the trend in the number of petrol-, and CNG-fueled three-wheelers in Delhi. As with buses, and again on account of the Supreme Court order, petrol three-wheelers converted to CNG between July of 1998 and July of 2002. As for their total number, this increased from about 35,000 in 1990 to 50,000 in the mid-1990s, possibly because of increased demand for public transport, and has remained at that level since.

Taxis. As with most types of vehicles, the number of taxis in Delhi has increased from about 4,000 in 1990 to about 20,000 in 2005 (see Figure 6(a)). However, the retirement of old taxis, as ordered by the Supreme Court in the late 1990s, resulted in a sharp, though temporary, dip in their numbers between 1998 and 2002. As for fuel type, despite the increase in the number of CNG-fueled taxis, Delhi still has a significant number of diesel-fueled taxis, as taxis with permits to travel outside Delhi, the so-called all-India-permit taxi, have been exempt by the court from having to convert to CNG.

Trucks. As shown in Figure 6(b), the decline in number is the most striking trend for trucks—from around 80,000 in mid-1998 to about 60,000 in 2005. This decline was caused in part by the policy that called for the retirement of old commercial vehicles. However, part of the decline probably was caused by a shift in registrations away from Delhi caused by the requirement that trucks registered in Delhi meet stricter emissions standards (EPCA 2004a). To the extent that this outside-Delhi registration is on-the-books only, the registration data underestimates the number of trucks in Delhi. Unfortunately, we have no additional information that can correct for this shortcoming in the data.

Cars. The total number of privately owned cars, as shown in Figure 7(a), has increased five-fold, from about 200,000 in 1990 to about 1 million in 2005. Furthermore, though petrol-fueled cars remain the dominant type, the proportion of diesel-fueled cars has been increasing in recent years, from about 9 percent in 1990 to 13 percent in 2005. This trend can in part be explained by the fact that the retail price of a liter of diesel fuel is substantially lower than that of a liter of petrol and that car manufacturers often price petrol and diesel versions of their cars at the same level (Roychowdhury 2006).

Two-wheelers. As previously mentioned, two-wheelers make up the majority of vehicles on Delhi's roads. Their number has risen sharply as well, from about 600,000 in 1990 to more than 1.6 million in 2005. Another interesting trend for these vehicles has been the increase in the proportion of four-stroke two-wheelers. The number of four-stroke two-wheelers has increased consistently from the early 1990s, reaching approximately 70 percent of the total number of two-wheelers on the road in 2005 (*Down to Earth* 2002).

Conversion from Numbers to Kilometers Driven

We now need to further convert the number of vehicles to the number of kilometers driven by these vehicles. Here again we are faced with significant data constraints; there are very few studies that estimate the kilometers driven by different vehicles or how these numbers have changed over time. One recent study, and the one we use, was conducted by the Central Road Research Institute (CRRI) of New Delhi (CRRI 2002) (see Table 4). On the basis of the CRRI estimates, Figure 4(b) shows the number of kilometers driven by petrol-, diesel-, and CNG-fueled vehicles. Note that even though the share of CNG-fueled vehicles in the total number of vehicles is low (see Figure 4(a)), their share in terms of total vehicle kilometers driven is higher. This follows directly from the fact that commercial passenger vehicles, and therefore the vehicles that travel more kilometers per day, were the ones targeted for conversion by the Supreme Court order.

To test the validity of our estimates of the actual number of kilometers driven by vehicles on Delhi’s roads, we estimated the correlation between the number of kilometers driven by all vehicles of a particular fuel type and the total consumption of that particular fuel in the city. For both CNG and petrol, the correlation between kilometers driven and fuel consumption is 0.97, and for diesel it is 0.77, which suggests that our estimates for kilometers driven are fairly reasonable.[22]

Major Policy Initiatives

Our estimates of the actual numbers of vehicles on the road reflect three major policy initiatives: the retirement of old commercial vehicles; the conversion of all commercial passenger vehicles to CNG; and the mandated increase in the number of buses. In addition, we have constructed variables to capture the impact of the reduction in the sulfur content of diesel and petrol fuel, the introduction of pre-mixed fuel for two-stroke engines, the tightening of emissions standards, the introduction of catalytic converters, and the commissioning of the Delhi Metro.

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[22] As discussed below, diesel also is used in Delhi to power generators sets. This may explain the lower correlation between diesel fuel and diesel kilometers driven.

For catalytic converters and pre-mixed fuel, we have constructed dummies for the dates on which these initiatives came into effect, namely, January 1995 for catalytic converters and December 1998 for pre-mixed fuel. As for the policy that led to the reduction in the sulfur content of fuel, we began by constructing two separate variables: one for the change in the sulfur content of diesel and another for the change in the sulfur content of petrol (see Table 1). The variable for diesel was assigned values between 1 and 0.05 to represent the reduction in the sulfur content of diesel from 1 percent to 0.05 percent between April 1996 and June 2001. Similarly, the variable for petrol was assigned values between 0.2 and 0.05 to represent the reduction from 0.2 percent to 0.05 percent between March 1997 and June 2001. We then constructed a single variable for the sulfur-reduction policy as the quantity weighted average of the variables for petrol and diesel. Similarly, for the policy that led to the tightening of emissions standards, we first constructed separate variables for CO, NO_2, and PM by vehicle type and fuel type to represent the changes in the vehicle emissions standards for each of these pollutants between 1990 and 2005 (see Table 2). Fuel-specific and vehicle-specific standards were then collapsed into a single variable using fuel consumed or kilometers driven as the weights. Finally, the variable representing the impact of the Delhi Metro was assigned values between 0.5 and 2 over the course of December 2002 to July 2005 to represent the gradual commissioning of two lines of the Delhi Metro.

Power Plant and Industrial Emissions

Power Plants

Delhi has three coal-fired power plants within its city limits—the 247-megawatt (MW) Indraprastha Power Station, the 135-MW Rajghat Power House, and the 705-MW Badarpur Thermal Power Station. Until recently, the Delhi Pollution Control Committee (DPCC) did not collect data on a regular basis on emissions generated by these power plants;[23] therefore, we had to use the total monthly power generated by these three power plants as a proxy for their emissions. Figure 8(a) shows the trends in the quantity of power generated by these three power plants.[24] Note that the output from all three power stations shows a fair amount of month-to-month variation but only the output from the Badarpur

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[23] A report issued by the Delhi government contains some information on the annual average emissions from coal-based and gas-based power plants in Delhi (DPCC n.d.). However, its annual estimates are based on very few readings, especially for the period from the early to late 1990s (Kumar, 2006). We have chosen not to use these data.

[24] Despite repeated attempts to acquire more complete data, we were only able to get yearly data for the Badarpur Thermal Power station from 1991 to 1994. No data were available for 1990 for this station. We have converted the yearly data into monthly data by dividing the annual amount by 12.

Thermal Power Station shows any consistent increase. In addition to the data on power-plant output, we have included a dummy variable to capture the impact of the switch to beneficiated coal in early 2000 and the investment in new ESPs.

Other Industrial Units

Even though a Supreme Court order led to the closure of some industrial units in the late 1990s, Delhi still has a significant number of industrial units operating within its boundaries. According to the Delhi government’s Department of Industry, the number of industrial units in Delhi grew to 126,000, by 1996 from approximately 8,000 in 1951 (Government of NCT of Delhi 2004). Little is known, however, about the amount of air pollution caused by these units, or, for that matter, the type or quantity of output being generated. Yet, it is important to control for the impact of these industrial units on Delhi’s air quality.[25] In the absence of other information, we proxy this effect by the amount of the two main fuels—light diesel oil and fuel oil—supplied to these units in Delhi (see Figure 8(b)).[26]

Finally, as mentioned in the introduction, one of the earliest orders of the Supreme Court pertained to the closure of category-H industries in Delhi, of which a total of 1,328 units were closed; 168 of these were closed in November 1996, another 513 in January 1997, followed by 43 hot-mix plants the next month, and 21 arc or induction furnaces in March 1997. Finally, 246 brick kilns and 337 other category-H units were closed in June 1997 (Jaiseelan 2006). We have constructed a proportion-of-units-closed-per-month weighted dummy to capture the impact of this policy measure. Note that because category-F units were simply relocated in 2000, we have not included these units in our dummy variable list.

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[25] Kandlikar and Ramachandaran (2000) make the point that a large fraction of the industrial units in Delhi are small-scale operations that are unlikely to be able to afford pollution-abatement technologies. Also, their large number makes them a monitoring and enforcement challenge. For both these reasons, these units are likely to be significant contributors to air pollution.

[26] According to the CPCB, small boilers used in industrial units have reduced coal usage in favor of light diesel oil in Delhi (Sengupta 2003). Despite repeated attempts, we were unable to get coal-consumption data for Delhi’s industrial units and therefore were unable to include coal as another fuel type used by industry in Delhi.

Other Variables

The third major source of pollution in Delhi is fuel consumption by domestic sources. Biomass, coal, kerosene, and liquefied petroleum gas are the main fuels used for domestic uses such as cooking and heating. There is, however, little information available about the quantities of these fuels used, especially monthly estimates. We were able to gather information on the amount of kerosene consumed and have included it in our list of right-hand-side variables.

The final class of variables included in the covariates is meteorological. The specific variables included are monthly averages of the daily maximum and minimum temperature, average monthly rainfall, and average monthly wind speed. As the numbers in Table 5 suggest, Delhi has a tropical, semi-arid climate with hot summers and cold winters and an average annual rainfall of about 750 millimeters, falling mostly over the months of July and August. These meteorological characteristics have a significant effect on Delhi's ambient air quality. Rain washes away pollutants and high wind speeds disperse them, lowering concentrations. Further, low wind speeds, along with winter thermal inversion (where cold air is trapped under warm air), also tend to decrease air quality in the winter months (Goyal 2002).

Finally, we include a time trend to capture the emissions effect of macroeconomic changes such as population growth and income growth. According to the Census of India, Delhi's population has grown from 9.42 million in 1991 to 13.78 million in 2001, registering a decadal growth of 46.3 percent against the national growth rate of 21.3 percent (DPCC n.d.). Apart from its impact on emissions caused by vehicles, which is captured by the increase in the number of vehicles, this rapid population growth also is likely to lead to an increase in domestic emissions, the impact of which is only partially captured by the change in the consumption of kerosene. In the absence of other data, we rely on the time trend to capture the effect of this and other effects of population growth on air quality. Similarly, economic growth in Delhi has led to an increase in demand for energy, which is only partially met by the total power supplied to Delhi. The rest of the demand largely is being met through the use of small, diesel power generators. There is, however, no information available on the number of diesel generators in use in Delhi. We therefore rely on the time trend to capture this effect, at least partially.[27]

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[27] One other variable that may have an impact on Delhi's air quality is the construction of flyovers, or overpasses, in the city. By one estimate, 19 flyovers were under construction in Delhi between 1998 and 2003. While the construction activity may have contributed to an increase in particulate matter, once constructed, the flyovers likely improve traffic management and thereby lead to a decrease in emissions (World Bank 2005). However, there is no easy way to capture the negative and positive effects of flyovers in our regression analysis.

Econometric Analysis

To estimate the effect of the various policy measures to curb air pollution in Delhi, we run time-series regressions for each of the four conventional pollutants monitored regularly: PM_{10}, NO_2, CO, and SO_2. Monthly estimates of air quality are regressed on monthly estimates of the different determinants of air quality. Because the monitoring station at ITO was commissioned later than the other six stations, and because this station monitors more pollutants than the other stations, we run separate regressions for the ITO station and for all other stations combined.[28]

Methodology

For each pollutant, we estimate the following static time series model:

$$y_t = \beta_0 + \beta_1 x_t + u_t ,$$

where, y_t denotes the level of the air pollutant, x_t the vector of independent variables including a time trend, and u_t the error term.

Three issues commonly arise when estimating such static time-series models. The first concerns the relationship between the independent variables and the error term, the second the nature of the stochastic process underlying the dependent and the independent variables, and the third the nature of the error term itself.

In addition to the usual concerns about contemporaneous correlation between the independent variables and the error term (related to omitted variables, measurement errors, or functional form misspecifications), we are concerned about this correlation over time. Independent variables that have no relationship with the error term in all time periods are called strictly exogenous. An independent variable, however, will not be strictly exogenous if there is feedback from the dependent variable on future values of the independent variable. Because the policy that led to the conversion of all commercial passenger

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[28] An assessment of the policies to improve air quality undertaken by the CPCB also considers the ITO monitoring station separately because this station is said to best reflect traffic-related emissions (CPCB 2001). For the same reason, in his paper on Delhi's air quality, Kathuria (2005) only analyzes the data from the ITO monitor. Also note that our regressions for the ITO station do not include estimates of industrial activity—consumption of fuel oil and light diesel oil, and closure of category-H units—because there is no significant industrial activity in the vicinity of the ITO monitor. We do, however, include the output produced by the power plants, as these are situated close to the ITO monitor. Also, because the ITO monitor became operational in 1997, we do not include the dummy for the introduction of catalytic converters in the regressions for this monitor. Finally, taxis are not considered as a separate category because of their small number and small share of total kilometers traveled.

vehicles to CNG was implemented because of concern with past levels of air pollutants, such a feedback mechanism exists in our model. To the extent, however, that once the policies were announced there were no further adjustments made to the number of commercial passenger vehicles that converted to CNG, the feedback was limited to the pre-announcement period.

Given these facts, we can deal with the issue of endogenous variables in one of two ways. First, we can limit our analysis to the post-announcement period; that is, the period post-1998. This, however, would force us to discard too much data. The second approach is to rely on large sample properties of OLS instead, which allows us to relax the requirement of strictly exogenous variables for the requirement that the variables be weakly dependent.

This issue of weakly dependent time-series processes, or non-persistent time series, also arises in the context of “spurious correlations” in time-series analysis and brings us to the second issue in such estimations. It is now well established that a simple regression involving two highly persistent, but independent, time series often can find a significant relationship between the variables when there is obviously none.

We examined the variables in our regressions to find if they are, in fact, weakly dependent and, if not, to transform the variables to make them so. Applying the augmented Dickey-Fuller test (Wooldridge 2006) with 12 lags (as is common for monthly data) to our dependent and independent variables, we fail to reject the null hypothesis of weak dependence for all but two variables: the log of average monthly precipitation and SO_2 levels at non-ITO stations. This suggests that the variables in our analysis are not highly persistent, in which case it is appropriate to use OLS, which will be consistent, if not BLUE.

Finally, as regards the nature of the error term, it is common in such models for the error terms to be serially correlated. We therefore need to test for such serial, or auto, correlation and to correct for it where it arises. In each of our regressions, we tested for serial correlation under conditions of strictly exogenous and weakly dependent variables. These tests reject the null of no serial correlation for the NO_2 and SO_2 non-ITO regressions and for the CO ITO regression. In each of these cases, we report results for OLS alone; OLS with heteroskedasticity and autocorrelation consistent, or HAC, standard errors; and for feasible generalized least squares (FGLS) estimated using the Prais-Winsten method (Wooldridge 2006).

Testable Hypothesis

Before turning to the results of the regression analysis, we provide some basis for the types of relationships one would expect to find between the different pollutants and the various independent variables discussed in Section 4. Some of these relationships are straightforward: an increase in the level of any pollution-causing activity, be it the use of vehicles, power generation, or industrial production, should increase concentration levels of all pollutants, with increases in the number of kilometers driven by different types of vehicles especially leading to an increase in levels of NO_2. Furthermore, the coefficients on the dummies for the introduction of beneficiated coal, pre-mixed fuel and catalytic converter are expected to be negative in the regressions. We would be surprised, however, if these coefficients, especially on the dummy for catalytic converters, are significant, as it takes a long time for a new technology to diffuse into an existing vehicle stock. Similarly, policies that led to the closure of category-H industries and the introduction of the Delhi Metro are expected to reduce pollution, while the policy of stricter emissions standards for vehicles is expected to reduce CO, NO_2, and PM_{10} concentrations, and the policy that led to the reduction in the sulfur content of fuel to reductions in SO_2 concentrations.

It is more difficult to predict the impact on air quality from a change in the proportion of vehicles by fuel type. For example, it is not obvious what the effect of the conversion of all commercial vehicles to CNG or the increase in the proportion of diesel cars will be on levels of NO_2, as both types of vehicles emit NO_2. To develop some testable hypotheses on the relationship between changes in fuel types and levels of air pollutants, we turn to Table 10, which lists emissions factors for the relevant vehicle types. As noted above, emissions factors for vehicles in Delhi are unreliable (which argues against the use of a bottom-up approach to explaining air quality effects). Still, as a ballpark for hypothesis creation, this is a reasonable place to start.

According to these emissions factors, an increase in the proportion of CNG versus diesel buses and in the proportion of CNG versus petrol three-wheelers is expected to lead to a decrease in CO and PM_{10} levels. Furthermore, while the conversion of buses to CNG also is expected to reduce NO_2 levels, the conversion of three-wheelers is expected to increase it. Similarly, an increase in the proportion of four-stoke two-wheelers, while leading to a reduction in PM_{10} and CO, also is expected to increase NO_2 levels, and an increase in the proportion of diesel versus petrol cars is expected to increase NO_2 and PM_{10} but also to reduce CO levels.

Results

We now present the results of the regressions for each of the four pollutants. Note that in addition to correcting for serial correlation where this is an issue, we have used partial residuals plots extensively to specify functional relationships and to determine which variables need to be logged.

PM_{10}

Table 6 shows the results of the regression for PM_{10} concentrations registered at the ITO monitoring station. As previously noted, there is no significant trend in PM_{10} levels registered at the other monitoring stations, making it impossible to run regressions on these data.

The results for the ITO station suggest that two policies, namely the conversion of buses from diesel to CNG and the reduction in the sulfur content of diesel and petrol, have helped to reduce PM_{10} emissions in Delhi. As shown in Table 6, PM_{10} levels decreased at an increasing rate as the proportion of CNG to diesel buses increased. This finding supports our conjecture based on emissions factors reported in Table 10. Further, the positive coefficient on sulfur content and the negative coefficient on its square suggest that a decrease in the sulfur content of fuel also has helped to decrease PM_{10} concentrations at an increasing rate. Because sulfur dioxide converts into sulfate particulates, a form of $PM_{2.5}$ particles, any reduction in the sulfur content of fuel is expected to reduce the quantity of particulates in the atmosphere.

Unlike the conversion of buses to CNG, and contrary to our hypothesis based on emissions factors, the conversion of three-wheelers to CNG does not appear to have helped reduce PM_{10} levels. Rather, the regression results suggest that an increase in the proportion of CNG- to petrol-fueled three-wheelers has led to an increase in PM_{10} concentrations. One possible reason for this may be poor CNG three-wheeler technology, at least for the first generations of CNG three-wheelers introduced in Delhi. A report issued by the Environment Pollution Prevention and Control Authority for Delhi[29] in 2004 provides some basis for such a conjecture. After lengthy discussions with CNG three-wheeler manufactures and operators, the report concluded that the poor quality of piston rings, as well as the improper maintenance of air filters, which was causing abnormally high wear-and-tear of the piston rings, was allowing lubricating oil to leak from the oil sump to the combustion chamber and generate white, visible smoke (EPCA 2004b). This smoke may well be what is causing the increase in PM_{10} levels from

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[29] This agency was established in 1998 by the Ministry of Environment and Forests at the behest of the Indian Supreme Court to help develop and monitor the progress of policies to curb air pollution in Delhi (Bell 2004).

CNG three-wheelers, as suggested by the regression. This possibility also points to the limitation of bottom-up approaches that are not based on accurate emissions factors.

Additionally, and as conjectured, the recent increase in the proportion of diesel cars also appears to be increasing PM_{10} levels in Delhi. Finally, for similar reasons, an increase in the proportion of diesel light trucks also appears to increase PM_{10} concentrations.

NO_2

The results of the regressions for NO_2 levels registered at the ITO monitoring station are shown in column 1 of Table 7, while columns 2 to 4 of this table show the results of the OLS, FGLS, and OLS with HAC errors for the levels registered at all other monitoring stations.[30]

The regression results suggest that increases in the proportions of diesel-fueled cars and four-stroke two-wheelers have led to an increase in NO_2 concentrations in Delhi. As previously mentioned, both results can be explained in terms of the differences in the NO_x emissions factors of these two categories of vehicles. Similarly, the coefficient on the proportion of diesel light and medium trucks is positive and significant for similar reasons.

Interestingly, and in contradiction to the received wisdom in Delhi (see e.g., Goyal 2006 and Roychowdhury et al. 2006), the regressions suggest that the conversion of buses to CNG is not leading to an increase in NO_2 concentrations. The decrease in NO_2 concentrations predicted by the emissions factors also is not being seen. CNG three-wheelers are, however, and as conjectured by the analysis of emissions factors, leading to some of the increase. Furthermore, the regressions also suggest that irrespective of the type of fuel being used, be it diesel or petrol or CNG, the sheer increase in the number of kilometers traveled by vehicles of all fuel types also is one of the causes of the recent increase in NO_2 concentrations in Delhi. The coefficients on total three-wheeler kilometers, bus kilometers, and those of cars and two-wheelers are all positive and significant. Additionally, the regressions suggest that some blame for the increase in NO_2 levels also lies with Delhi's power plants. Finally, the introduction of the catalytic converter appears to have helped reduce NO_2 concentrations.

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[30] Note that the variable representing the sulfur content of fuel was not included in these regressions as it is not expected to affect the level of NO_2 in the atmosphere.

CO

Table 8 presents the results for the change in the ambient concentrations of CO measured at the ITO monitoring station.[31] The negative and significant coefficients on the proportion of CNG buses and on the proportion of diesel cars suggest that it is an increase in the proportions of both these types of vehicles that has helped to reduce CO concentrations in Delhi. Again, and as mentioned previously, these results are best explained in terms of the differences in the CO emissions factors for different types of vehicles. Improvements in the emissions standards for CO also appear to have had a positive impact on reducing CO levels. However, the results also suggest that some of the gains made from fuel switching and technology improvements are being lost from the sheer increase in the number of kilometers being driven by different vehicles. The coefficients on total three-wheeler kilometers (in the relevant range) and total car and two-wheeler kilometers are positive and significant in the regression. Finally, and somewhat surprisingly, the introduction of beneficiated coal has not led to an improvement in CO levels. Because the effect of the change to beneficiated coal is being captured by a dummy variable that takes on the value one after January 2000, it may well be the case that this dummy is capturing some other change.

SO_2

Finally, Table 9 presents the results of the regressions for SO_2 concentrations. Column 1 of the table presents the results for the ITO monitoring station, while columns 2 to 4 present the results for the other monitoring stations.

The regressions suggest, as is to be expected,[32] that the reduction in SO_2 levels in Delhi is related to the reduction in the sulfur content of fuel—the coefficient on the sulfur content of fuel being positive and significant in both regressions. Additionally, the regressions suggest that an increase in the proportion of diesel cars also has contributed to a decline in SO_2 concentrations, as these cars are now running on cleaner diesel. Furthermore, the coefficients on the proportion of CNG three-wheelers and CNG buses are negative and significant, while those on their squares are positive and significant. This suggests that switching away from fuels that contain sulfur (e.g., away from petrol in the case of three-wheelers and away from diesel in the case of buses) also appears to have helped reduce SO_2 concentrations at an

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[31] The variable representing the sulfur content of fuel also is left out of the regression for CO because this variable is not expected to influence CO concentrations.

[32] Sulfur oxides are emitted in various quantities by vehicles largely in proportion to the sulfur content of fuel (Kandlikar and Ramachandran 2000).

increasing rate. Finally, one pollution source that appears to be increasing SO_2 concentrations is the use of coal by the power plants.

Weather

The pollutants appear to be affected similarly by meteorological variables. For three of the four pollutants—NO_2, CO, SO_2—the regression results suggest that wind speed decreases pollutant concentrations in the atmosphere. For SO_2, this confirms findings by Goyal (2002), whose analysis of the impact of winds on SO_2 concentrations in Delhi suggests that an increase in wind speed leads to a decrease in SO_2 concentrations. As for particulate matter, the regression results suggest that faster wind speed leads to a decrease in particulate matter but only at relatively low wind speeds. Concentrations of all four pollutants, however, appear to increase with temperature; the coefficient on maximum temperature is positive, while that on minimum temperature is negative in the regressions for each of the four pollutants.

Conclusion

Broadly speaking, the regression results point to the success of a number of policies implemented in Delhi but also to a number of areas of growing concern.

The policy that led to the conversion of all buses to CNG, for example, appears to have helped reduce PM_{10}, CO, and SO_2 concentrations, and, contrary to the common wisdom, has not contributed to the emerging threat of NO_2 in Delhi. Targeting buses for conversion to CNG has been effective in part because these buses, due to the number of kilometers they travel, contribute more to the pollution load than other vehicles. Similarly, the policy that led to the reduction in the sulfur content of fuel appears to have helped reduce air pollution by reducing PM_{10} and SO_2 concentrations. At the same time, the CNG-switching gains, which are apparent in the case of buses, are not being seen in the case of three-wheelers. Possibly because of poorer technology, CNG three-wheelers are leading to an increase, rather than a decrease, in levels of PM_{10}. CNG three-wheelers also are leading to an increase in NO_2. Though not necessarily policy-driven, the recent trend in Delhi toward an increase in the proportion of diesel-fueled cars also appears to be having somewhat of a mixed impact on air quality. While diesel-fueled cars have helped to reduce CO and SO_2, the latter because these cars are running on cleaner diesel, diesel cars also appear to be leading to an increase in PM_{10} and NO_2. Finally, our results suggest that a number of the gains that have been made from fuel switching and other improvements in fuel quality and vehicle technology are being negated to some extent by the sheer increase in the number of vehicles in Delhi. Though the increase in the proportion of CNG- to diesel-fueled buses has helped to reduce CO and SO_2, for example, the increase in total bus kilometers traveled is leading to an increase in these pollutants. Similarly, the dramatic increase in the kilometers traveled by cars and two-wheelers also is contributing to a decrease in air quality.

These findings point to lessons that can be learned for other cities, especially those looking to replicate Delhi's experience, and to the need for further policy interventions in Delhi.

First and foremost, air-pollution regulators in other cities should consider the gains that can be made from fuel switching—moving away from diesel or petrol to CNG—as this single intervention, if targeted at gross polluters, can have a significant impact on air quality. It is important to note, however, that these gains will only be realized if the technology being used in CNG vehicles is sufficiently advanced and therefore sufficiently clean. Delhi, for example, has not been able to realize all the gains from its CNG-conversion policy in part because of poor technology in the case of CNG three-wheelers. This suggests the need for regulators in Delhi to seek ways to improve the current three-wheeler CNG technology. Another policy intervention needed in Delhi concerns the rampant increase in the number of diesel-fueled cars. Our results suggest that some of the gains from the introduction of cleaner diesel are being negated because of the increase in the number of diesel-operated cars, which, in turn, is adding to the emerging threat of NO_2 and the continued threat of PM_{10}. This suggests a need for stricter emissions standards for diesel cars. Finally and most importantly, our results suggest that the gains from the large number of interventions made in Delhi could well be lost if the kilometers traveled by all vehicle types continue to rise. Since it's not reasonable to place restrictions on people's mobility, this argues for increased public transportation in Delhi. With the introduction of the Delhi Metro and the recent efforts to introduce high-capacity buses, Delhi is making some strides toward increasing public transportation. There is, however, a clear need for Delhi to promote public transportation more aggressively, especially given the plans to introduce the very affordable Rs.100,000 car, which is likely to cause the vehicle population in Delhi to explode further (*The Hindu* 2007).

Appendix A: Policies Implemented in Delhi

The Delhi story began in 1985 when, concerned with the rising levels of pollution, M.C. Mehta, a public-interest lawyer, filed a "public interest litigation" before the Indian Supreme Court asking the court to direct the central and Delhi governments to take measures to curb pollution. Faced with Mehta's petition, the court asked both governments to report on what measures had been implemented to arrest pollution. In the mid-1990s, when the executive branches reported back with little in the way of policies, the court pushed them to develop new policies to tackle the growing problem of air pollution. Despite developing comprehensive policies, and even going so far as announcing specific policy initiatives, the executive branches did little to implement these policies. Faced with this inaction and the continuing problem of air pollution, the court began to pass orders to force implementation (Bell et al. 2004; Narain and Bell 2006).

Some of the earliest orders of the Supreme Court, announced in the mid-1990s, pertained to the quality of fuels being used in Delhi, the closure of hazardous industries, and the retirement of old commercial vehicles (for information on these and other policies implemented in Delhi see World Bank 2005; Roychowdhury et al. 2006; Narain and Bell 2006; Kathuria 2002; and Resources for the Future 2006). As a direct result of court orders, between 1996 and 2001, the sulfur content of diesel and petrol was progressively reduced from 1 percent for diesel and 0.2 percent for petrol down to 0.05 percent for both fuels (see Table 1). Also, premixed lubricating oil and petrol replaced loose supply of these fuels for two-stroke engines by December 1998. This measure was instituted because although it is possible to reduce emissions from two-stroke engines by up to two-thirds by mixing lubricating oil with petrol in the right proportions (approximately 1 part in 50 [Kojima et al. 2000]), for various reasons operators of two-stroke engines were found to be using excessive amounts of lubricating oil, and, in turn, causing excessive amounts of pollution.

Starting in late 1996, industries categorized as being hazardous or noxious under the Delhi Master Plan, the so-called H-category of industries, were forced to shut down. A total of 1,328 units were closed (Jaiseelan 2006). Interestingly, these H-category industries had been operating in Delhi in direct violation of the 1990 revised Delhi Master Plan, which, like its 1962 predecessor, had called for the immediate closure of these units. It was only after the Supreme Court's intervention that these units were finally closed.

Yet another Supreme Court order forced the retirement of old commercial vehicles. Although the Delhi government had issued a notification in October of 1997 to phase-out these vehicles, with elections looming and widespread protests from owners of commercial vehicles, the government withdrew its notification in February of 1998, stating that it would "take an objective decision later" (*Down to Earth* 1998). Nothing happened, however, until the Supreme Court stepped in and once again ordered the implementation of this previously announced policy. In 1998, in accordance with the Supreme Court's order, commercial vehicles older than 20 years were forced to retire starting in October of that year, those older than 17 years in November, and those older than 15 years in December.

This period also saw two initiatives from the state. The first was the notification of the first set of emissions standards for Indian vehicles; in 1993, new vehicles were required to achieve progressively stricter standards by 1996 and 2000 (see Table 2). Second, beginning in 1995, all new passenger vehicles were required to be equipped with catalytic converters to further reduce emissions.

Despite these interventions, however, Delhi's air quality continued to deteriorate. This led the Supreme Court to pass its now-famous judgment of July 28, 1998, ordering the conversion of all commercial passenger vehicles—buses, taxis, and three-wheelers—to CNG. The number of buses in Delhi also was increased from 6,000, to 10,000. Though this order proved to be the most controversial, and led to widespread protests, it was eventually implemented by late 2002. Consequently, Delhi today boasts of one of the world's largest fleets of CNG vehicles, with approximately 90,000 CNG buses, taxis, and three-wheelers.

Early 2000 saw further tightening of vehicle emissions standards and the introduction of a mass rapid transit system known as the Metro. Sometime between 1999 and 2000, Delhi's thermal power stations began to use beneficiated coal, with an ash content of less than 34 percent, versus coal with an ash content of 40 percent (DPCC n.d.). This measure was implemented in part to make the ESPs installed in these power plants more efficient at abating emissions. Also, a high-efficiency ESP was installed in Unit 5 of the Indraprastha power station during this time (Kandlikar and Ramachandran 2000). Finally, in July 2000, by order of the Supreme Court, category-F polluting units in areas of Delhi not designated to be industrial parks were shut down. According to estimates from the DPCC, 2,783 units were shut down between December 2000 and January 2001, another 1,419 units were shut down between February and March of 2001, and a final 786 units were closed between April 2001 and December 2005 (DPCC n.d.). To the best of our knowledge, these units were relocated to Delhi's 28 industrial parks, leading only to a spatial redistribution of pollution and not to any reduction in citywide emissions.[33]

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[33] The index of industrial production in Delhi decreased during the period when category-H industries were closed by order of the Supreme Court. However, no such reduction in production took place during the period when the category-F units were relocated from non-conforming areas to industrial parks (Government of NCT New Delhi 2004). This suggests that category-F units were relocated and not closed permanently.

Appendix B: Vehicle Registration Data

Vehicle registration data were obtained from the Delhi STA. The data covered 3,432,698 vehicle registrations in 230 different categories from January 1990 to December 2005, broken down by month. To facilitate our analysis, we generated six major vehicle categories that covered 99.4 percent of all registrations, leaving out categories such as ambulances, tractors, invalids, and others and unknowns. See Table A-1 for the different categories.

To convert registration data into the actual number of vehicles on the road, we needed an estimate of the number of vehicles on the road in 1990 and an estimate for the monthly vehicle attrition due to factors such as retirement, crashes, and mechanical malfunction. Unfortunately, there are no studies on vehicle attrition factors for Delhi. We choose modest rates of attrition and higher rates for commercial vehicles that are likely to be subject to higher wear-and-tear (see Table A-2). To determine the number of vehicles on the road in 1990, we began with yearly registration data from 1978–1989 from the Center for Science and Environment’s Anil Agarwal Vehicular Emissions Model (AAVEM) (*Down to Earth* 2002). We then applied the monthly vehicle attrition factor to determine the number of yearly registrations on the road and finally summed these yearly estimates to estimate the number on the road in 1990. Using this method, approximately 50 percent of vehicles registered up until 1990 were found to be in use in 1990. We then assumed that for each particular category of vehicle, the share by fuel type in 1990 was equal to the share by fuel type of registrations of that particular category during 1990 and 1991. For example, according to the 1990–1991 truck registration data, about 12 percent of all truck registrations during this period were for petrol-fueled trucks and the rest for diesel-fueled trucks. Based on these data, we assumed that 12 percent of the total number of trucks on the road in 1990 were petrol-fueled and the rest were diesel-fueled.

From 1990 onward, we calculated the number of vehicles on the road in each month by adding the number of registered vehicles for the month to the total number of vehicles on the road in 1990, allowing for monthly attrition. We then made adjustments to these totals to allow for the impact of the policy that called for the retirement of older commercial vehicles: buses, three-wheelers, taxis, and trucks. According to published reports, commercial vehicles older than 20 years were forced to retire in October 1998, those older than 17 years in November 1998 and, finally, those above 15 years in December 1998 (Bell et al. 2004) Using estimates from AAVEM, we assumed that commercial vehicles registered in 1978 were retired in October 1998, commercial vehicles registered in 1979–1981 were retired in November 1998, and commercial vehicles registered in 1982–1983 were retired in December 1998. Furthermore, using the same estimates for the number of commercial vehicles registered in 1984–1985, we proceeded to subtract a portion from each subsequent month, assuming that during 1999, commercial vehicles that reached the 15-year mark were retired. This continued until April 2000, at which point a ban on buses over eight-years-old was enacted. To account for this, we subtracted out the number of buses on the road in April 1992.We continued subtracting out the number of buses registered eight years ago from that month on.

Next, we made adjustments for the impact of the policy that led to the conversion of all commercial passenger vehicles to CNG. For buses, using data obtained from the STA, we accounted for the permit transfers that took place between April and November 2002, when a number of diesel buses traded in their permits for CNG bus permits but were not decommissioned. Similarly, we accounted for the fact that a number of petrol three-wheelers traded in their permits for CNG three-wheeler permits but were still on the registration records as operating and on petrol. In the absence of other information, and in order to gradually reduce the number of petrol three-wheelers to zero by June of 2002, we assumed that approximately 83 percent of CNG registrations during 1998 and 2002 were transfers from petrol to CNG. We therefore decommissioned a comparable number of petrol three-wheelers for this period, which effectively reduced the number of petrol three-wheelers on the road to zero by June 2002. We made a similar adjustment for local diesel taxis based on information from the STA.

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Tables and Figures

Table 1. Sulfur Content of Vehicle Fuel in Delhi

	Diesel	Petrol
April 1996	Lowered from 1% to .5%	
March 1997		Lowered from .2% to .15%
August 1997	Lowered from .5% to .25%	
April 2000	.05% diesel introduced	Lowered to .1% and .05% introduced
June 2001	.05% diesel available only	.05% petrol available only

Source: CPCB 2001; CPCB 2006b.

Table 2. Emissions Standards for Vehicles in Delhi

	1991	1996	2000		2001	2005	2010
Petrol vehicles: Passenger cars			India 2000 (Euro 1)		Bharat II (Euro 2)	Bharat III (Euro 3)	Bharat IV (Euro 4)
CO (g/km)	14.3-27.1	4.5	2.72		2.2	2.3	1.0
HC (g/km)	2.0-2.9	-	-		-	0.2	0.1
HC + NOx (g/km)	-	3.00-4.36	0.97		0.5	-	-
NOx (g/km)	-	-	-		-	0.15	0.08
Diesel truck and bus engines			Euro I		Euro II	Euro III	
CO (g/km)	17.3-32.6	11.2	4.5		4.0	2.1	-
HC (g/km)	2.7-3.7	2.4	1.1		1.1	0.66	-
NOx (g/km)	-	14.4	8.0		7.0	5.0	-
PM (g/km)	-	-	0.36		0.15	0.1	-
2-wheelers			TA	COP			
CO (g/km)	12-30	4.5	2.0	2.4	-	1.5	1.0*
HC (g/km)	8-12	-	-	-	-	-	-
HC + NOx (g/km)	-	3.6	2.0	2.4	-	1.5	1.0*
3-wheelers: Petrol			TA	COP			
CO (g/km)	12-30	6.75	4.0	4.8	-	2.25	1.25*
HC (g/km)	8-12	-	-	-	-	-	-
HC + NOx (g/km)		3.6	2.0	2.4	-	2.0	1.25*
3-wheelers: diesel			TA	COP			
CO (g/km)	12-30	5.0	2.72	3.16	-	1.0	0.5*
HC (g/km)	8-12	-	-	-	-	-	-
HC + NOx (g/km)	-	2	0.97	1.13	-	0.85	0.5
PM (g/km)	-	-	0.14	0.18	-	0.1	0.05*

*Proposed; COP = conformity of production; TA = type-approval
Source: CPCB 2001; Agarwal et al. 1996.

Table 3. National Ambient Air Quality Standards

		India[†]				
Pollutant	**Time-weighted average**	***Industrial Areas***	***Residential, Rural & other Areas***	***Sensitive Areas***	**WHO[‡]**	**US[§]**
Sulfur Dioxide (SO_2)	Annual Average	80 μg/m^3	60 μg/m^3	15 μg/m^3	-	78.6 μg/m^3
	24 hours	120 μg/m^3	80 μg/m^3	30 μg/m^3	20 μg/m^3	370 μg/m^3
Nitrogen Dioxide (NO_2)	Annual Average	80 μg/m^3	60 μg/m^3	15 μg/m^3	40 μg/m^3	100 μg/m^3
	24 hours	120 μg/m^3	80 μg/m^3	30 μg/m^3	-	-
Respirable Suspended Particulate Matter (RSPM) or PM_{10}	Annual Average	120 μg/m^3	60 μg/m^3	50 μg/m^3	20 μg/m^3	Revoked*
	24 hours	150 μg/m^3	100 μg/m^3	75 μg/m^3	50 μg/m^3	150 μg/m^3
$PM_{2.5}$	Annual Average	-	-	-	10 μg/m^3	15 μg/m^3
	24 hours	-	-	-	25 μg/m^3	35 μg/m^3
Carbon Monoxide (CO)	8 hours	5 mg/m^3	2 mg/m^3	1 mg/m^3	-	10 mg/m^3
	1 hour	10 mg/m^3	4 mg/m^3	2 mg/m^3	-	40 mg/m^3

[†]CPCB 2007; [‡]WHO 2007; [§]U.S. EPA n.d.

*The U.S. EPA revoked this standard as of Dec 17, 2006, citing a lack of evidence linking long-term exposure to coarse particle pollution and health problems.

Table 4. Average Kilometers Traveled Per Day by Vehicles in Delhi

Bus	157.2 (km/d)
Three-wheeler	66.5 (km/d)
Taxis	45.1 (km/d)
Cars	36.6 (km/d)
Trucks	39.7 (km/d)
Two-Wheelers	36.4 (km/d)

Source: CRRI 2002.

Table 5. Summary Statistics for Weather Variables

Variable	Mean	Std. Dev.	Min	Max
Temp (Monthly Avg. of Daily High)	88.08	11.47	62	107
Temp (Monthly Avg. of Daily Low)	66.78	13.40	43	88
Wind speed (Monthly Avg. of Daily Avg.)	3.25	1.18	0.84	6.03
Precipitation (Monthly Average)	0.08	0.13	0	0.78

Source: National Climate Data Center n.d..

Table 6: Regression Results for PM_{10}

Control Variables		Results (ITO)
Three-wheelers	Total Three-wheeler KM	-0.042***
	Proportion of CNG Three-wheeler	5.729*
Bus	Total Bus KM	-0.011
	Proportion of CNG Bus	-10.506*
	Proportion of CNG Bus^2	7.114*
Cars and Two-wheelers	Total Two-wheeler and Car KM	-0.001
	Proportion of Diesel Cars	70.586**
	Proportion of 4-Stroke Two-wheelers	1.516
Trucks	Total Heavy Truck KM	-0.004
	Total Medium and Light Truck KM	-0.114
	Total Medium and Light Truck KM^2	0
	Proportion of Diesel Light and Medium Trucks	7.596*
Metro	Metro	-0.305
Policy Interventions	Pre-mixed Fuel	-0.492
	Sulfur Content in Fuel	27.227***
	Sulfur Content in $Fuel^2$	-45.956***
	Emissions Standard for Particulates	-1.718
Industry and Domestic	Total Power Output	-0.008
	Total Power $Output^2$	0
	Beneficiated Coal	-0.48
	Kerosene	0.039
Weather	Temperature (Daily High)	-0.111**
	$Temperature^2$ (Daily High)	0.001***
	Temperature (Daily Low)	-0.046***
	Wind speed	-0.355***
	Wind $speed^2$	0.044**
	Log of Precipitation	0.002
	Time trend	0.07***
	Constant	24.364***
		N = 89; R^2 = .887

Table 7. Regression Results for Nitrogen Dioxide

		Results (ITO)	Results (CPCB)		
	Control Variables	**OLS**	**OLS**	**FGLS**	**OLS with HAC**
Three-wheelers	Total Three-wheeler KM	0.116	0.006***	0.006**	0.006***
	Total Three-wheeler KM^2	0			
	Proportion of CNG three-wheeler	2.673*	-0.058	0.01	-0.058
Bus	Total Bus KM	-0.048	0.002***	0.002	0.002**
	Total Bus KM^2	0			
	Proportion of CNG Bus	2.661	-0.008	-0.05	-0.008
	Proportion of CNG Bus^2	-1.811			
Cars and Two-wheelers	Total Two-wheeler and Car KM	0.013**	0***	0	0
	Total Two-wheeler and Car KM^2	0**			
	Proportion of Diesel Cars	76.172***	11.47	11.284**	11.47***
	Proportion of 4-Stroke Two-wheelers	-1.123	2.086	1.976*	2.086**
Trucks	Total Heavy Truck KM	0.073	-0.002***	-0.001	-0.002
	Total Heavy Truck KM^2	0			
	Total Medium and Light Truck KM	0.014	0.001***	0	0.001
	Proportion of Diesel Light and Medium Trucks	95.147	7.596*	7.596*	7.596*
	Proportion of Diesel Light and Medium Trucks^2	-75.696			
Metro	Metro	0.089	-0.309	-0.231	-0.309*
	Metro^2	0.028	0.138*	0.084	0.138
Policy Interventions	Pre-mixed Fuel	0.012	-0.07	-0.064	-0.07
	Emissions Standard for NO_2	0.476	-0.029*	-0.068	-0.029
	Emissions Standard for NO_2^2	-0.195			
	Catalytic Converter		-0.073**	-0.087	-0.073*
	Closure of Category-H Industries		0.087*	0.079	0.087
Industry	Total Power Output	0.001*	0***	0	0
	Beneficiated Coal	-1.693	-0.1	-0.235	-0.1
	Kerosene	0.015	-0.004***	-0.002	-0.004
	Log of Fuel Oil		-0.002***	-0.001	-0.002
	Light Diesel Oil		0.001***	0	0.001
Weather	Temperature (Daily High)	0.051*	-0.016**	-0.013	-0.016
	Temperature^2 (Daily High)	0	0***	0**	0**
	Temperature (Daily Low)	-0.014**	-0.005***	-0.006***	-0.005**
	Wind speed	-0.215**	0.058**	0.045	0.058**
	Wind speed^2	0.016	-0.01***	-0.007	-0.01**
	Log of Precipitation	0.126**	-0.003***	-0.002	-0.003
	Log of Precipitation^2	-0.01			
	Time trend	-0.163**	-0.008***	-0.008	-0.008
	Constant	-78.705	7.469	7.197***	7.197***
		N=103; R^2=.818	N=172; R^2=.729	N=172; R^2=.809	N=172;

Table 8. Regression Results for Carbon Monoxide

		Results (ITO)		
	Control Variables	**OLS**	**FGLS**	**OLS with HAC**
Three-wheelers	Total Three-wheeler KM	-1.669	-1.16	-1.669*
	Total Three-wheeler KM^2	0.002***	0.002	0.002*
	Proportion of CNG three-wheeler	0.876	0.232	0.876
Bus	Total Bus KM	0.008***	0.008	0.008
	Proportion of CNG Bus	-2.454	-2.164**	-2.454**
Cars and Two-wheelers	Total Two-wheeler and Car KM	0.007***	0.005**	0.007***
	Proportion of Diesel Cars	-58.129	-45.807	-58.129*
	Proportion of 4-Stroke Two-wheelers	2.788	0.066	2.788
Trucks	Total Heavy Truck KM	-0.001**	0.003	-0.001
	Total Medium and Light Truck KM	-0.032**	-0.033*	-0.032**
	Proportion of Diesel Light and Medium Trucks	3.653	3.691	3.653
Metro	Metro	0.846	0.446	0.846
	Metro^2	-0.292	-0.144	-0.292
Policy Interventions	Pre-mixed Fuel	-0.196	-0.264	-0.196
	Emissions Standard for CO	0.775	0.789*	0.775**
Industry and Domestic	Total Power Output	-0.001***	0.003	-0.001
	Total Power Output^2	0***	0	0
	Beneficiated Coal	2.706	2.769*	2.706**
	Kerosene	-0.026**	-0.028	-0.026
Weather	Temperature (Daily High)	0.012***	0.014	0.012
	Temperature (Daily Low)	-0.015***	-0.018*	-0.015
	Wind speed	-0.166**	-0.144***	-0.166***
	Log of Precipitation	0.029**	0.029	0.029
	Time trend	-0.235	-0.17	-0.235**
	Constant	283.672	194.54	283.672*
		N = 103; R^2 = .795	N=103; R^2=.797	N=103;

Table 9. Regression Results for Sulfur Dioxide

		Results (ITO)	Results (CPCB)		
	Control Variables	**OLS**	**OLS**	**FGLS**	**OLS with HAC**
Three-wheelers	Total Three-wheeler KM	-0.013	0.006**	0.006**	0.006**
	Proportion of CNG Three-wheeler	-0.529	-2.49***	-2.377***	-2.49***
	Proportion of CNG Three-wheeler^2		2.844***	2.704***	2.844***
Bus	Total Bus KM	-0.039	-0.004***	-0.004**	-0.004***
	Total Bus KM^2	0			
	Proportion of CNG Bus	0.061	-5.188**	-5.035**	-5.188**
	Proportion of CNG Bus^2		3.504**	3.421**	3.504**
Cars and Two-wheelers	Total Two-wheeler and Car KM	0.002	0	0	0
	Proportion of Diesel Cars	-72.789***	-43.747***	-42.198***	-43.747***
	Proportion of 4-Stroke Two-wheelers	-2.327	0.341	0.163	0.341
Trucks	Total Heavy Truck KM	0.012	0.004	0.004	0.004
	Total Medium and Light Truck KM	0.004	-0.005*	-0.006*	-0.005*
	Proportion of Diesel Light and Medium Trucks	-0.349	1.83	1.773	1.83
Metro	Metro	-0.187	0.008	-0.02	0.008
Policy Interventions	Pre-mixed Fuel	-0.181	-0.224*	-0.205*	-0.224**
	Sulfur Content in Fuel	3.958***	1.812**	1.874*	
	Sulfur Content in Fuel^2		-1.038	-1.107	-1.038*
	Catalytic Converter		-0.029	-0.044	-0.029
	Closure of Category-H Industries		-0.095	-0.093	-0.095
Industry and Domestic	Total Power Output	0.001*	0	0	0
	Beneficiated Coal	-0.223	0.08	0.068	0.08
	Kerosene	-0.058	-0.01	-0.009	-0.01
	Log of Fuel Oil		0.019*	0.017	0.019
	Diesel Light		0.003	0	0.003
Weather	Temperature (Daily High)	0.017**	-0.025**	-0.021*	-0.025**
	Temperature^2 (Daily High)		0**	0**	0***
	Temperature (Daily Low)	-0.016**	-0.002	-0.002	-0.002
	Wind speed	-0.273**	-0.024**	-0.022**	-0.024**
	Wind speed^2	0.027			
	Log of Precipitation	0.135	-0.006	-0.006	-0.006
	Log of Precipitation^2	-0.013*			
	Time trend	0.002	0.035***	0.034***	0.035***
	Constant	12.43**	7.389***	7.129***	7.389***
		N=103; R^2=.873	N=172; R^2=.908	N=172; R^2=.881	N=172;

Table 10. Emissions Factors for Pollution Weighting

BUS (diesel/petrol)

	CO	HC	NO_x	PM
1986-1990	5.5	1.78	19	3
1991-1995	5.5	1.78	19	3
1996-2000	4.5	1.21	16.8	1.6
2001-2005	3.6	0.87	12	0.56

BUS (CNG)

	CO	HC	NO_x	PM
1986-1990	5.6	8.92	2.2	0.032
1991-1995	5.6	8.92	2.2	0.032
1996-2000	5.6	8.92	2.2	0.032
2001-2005	1.46	1.958	6.68	0.02

Three-Wheeler (diesel/petrol)

	CO	HC	NO_x	PM
1986-1990	14	8.3	0.05	0.35
1991-1995	14	8.3	0.05	0.35
1996-2000	8.6	7	0.09	0.15
2001-2005	4.3	2.05	0.11	0.08

Three-Wheeler (CNG)

	CO	HC	NO_x	PM
1986-1990	0.1	2.07	0.25	0.02
1991-1995	0.1	2.07	0.25	0.02
1996-2000	0.1	2.07	0.25	0.02
2001-2005	0.1	2.07	0.25	0.02

Two-Wheeler (2-stroke)

	CO	HC	NO_x	PM
1986-1990	6.5	3.9	0.03	0.23
1991-1995	6.5	3.9	0.03	0.23
1996-2000	4	3.3	0.06	0.1
2001-2005	2.2	2.13	0.07	0.05

Two-Wheeler (4-stroke)

	CO	HC	NO_x	PM
1986-1990	3	0.8	0.31	0.07
1991-1995	3	0.8	0.31	0.07
1996-2000	2.6	0.7	0.3	0.06
2001-2005	2.2	0.7	0.3	0.05

Trucks (Diesel/Petrol)

	CO	HC	NO_x	PM
1986-1990	5.5	1.78	9.5	1.5
1991-1995	5.5	1.78	8.4	0.8
1996-2000	4.5	1.21	6.3	0.28
2001-2005	3.6	0.87	5.5	0.12

Trucks (CNG)

	CO	HC	NO_x	PM
1986-1990	5.6	8.92	2.2	0.032
1991-1995	5.6	8.92	2.2	0.032
1996-2000	5.6	8.92	2.2	0.032
2001-2005	1.46	1.958	6.68	0.02

Car (Diesel)

	CO	HC	NO_x	PM
1986-1990	7.3	0.37	2.77	0.84
1991-1995	7.3	0.37	2.77	0.84
1996-2000	1.2	0.37	0.69	0.42
2001-2005	0.9	0.13	0.5	0.07

Car (CNG)

	CO	HC	NO_x	PM
1986-1990	3.85	1.19	0.71	0.02
1991-1995	3.85	1.19	0.71	0.02
1996-2000	0.786	1.55	0.92	0.02
2001-2005	0.786	1.55	0.92	0.02

Car (Petrol)

	CO	HC	NO_x	PM
1986-1990	9.8	1.7	1.8	0.06
1991-1995	9.8	1.7	1.8	0.06
1996-2000	3.9	0.8	1.1	0.05
2001-2005	1.98	0.25	0.2	0.03

All Emission Factors are in gm/km; Source: CRRI 2002, A-13/14.

Table A-1. Categorization of Vehicles

Vehicle Category	Fuel-Type	Number of Registrations	Included categories
Buses	CNG	14,678	Bus, Light Passenger Vehicles
	Diesel	16,293	
	Petrol	1,264	
Three-wheeler	CNG	55,350	TSR
	Diesel	30,492	
	Petrol	127	
Taxis	CNG	5,543	Cab, Local Taxi, Maxi Cab, Radio Taxi, Tourist Taxi
	Diesel	3,898	
	Petrol	12,031	
Two-wheelers	CNG	86	Moped, Motorcycle, Phat-Phat, Scooter
	Diesel	2,025,264	
	Petrol	525	
Cars and Jeeps	CNG	6,370	Light Motor Vehicles: Car, Jeep, Imported, Van
	Diesel	1,002,160	
	Petrol	149,460	
Trucks	CNG	9,900	Heavy, Medium and Light Goods Vehicles
	Diesel	14,996	
	Petrol	64,013	

Table A-2: Monthly Retirement Factors for Each Vehicle Type

Bus Depreciation Rate	0.5%
Three-Wheeler Depreciation Rate	0.5%
Taxi Depreciation Rate	0.1%
Two-Wheeler Depreciation Rate	0.5%
Car Depreciation Rate	0.1%
Truck Depreciation Rate	0.2%

Figure 1. Locations of CPCB Air Quality Monitoring Stations in Delhi

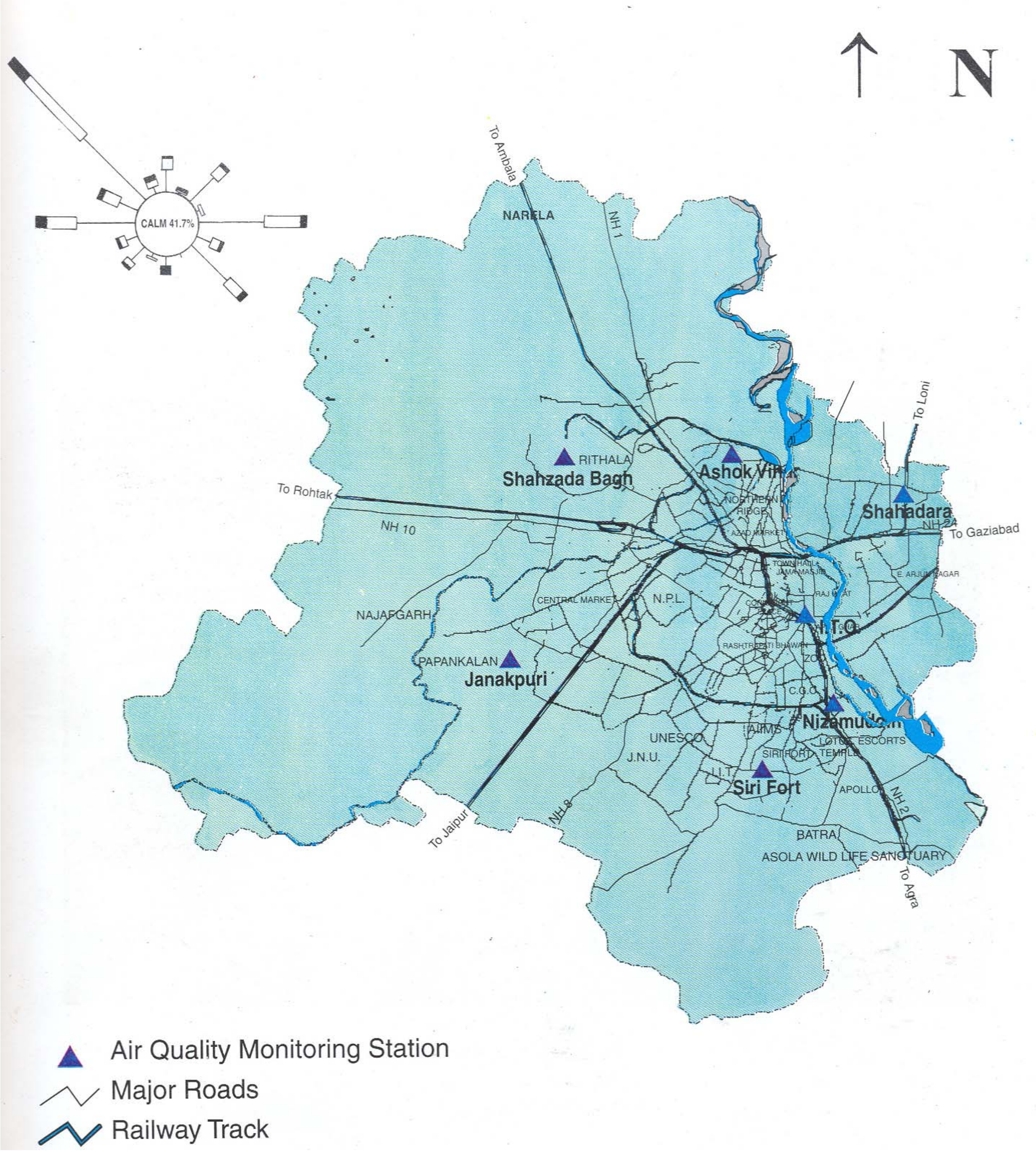
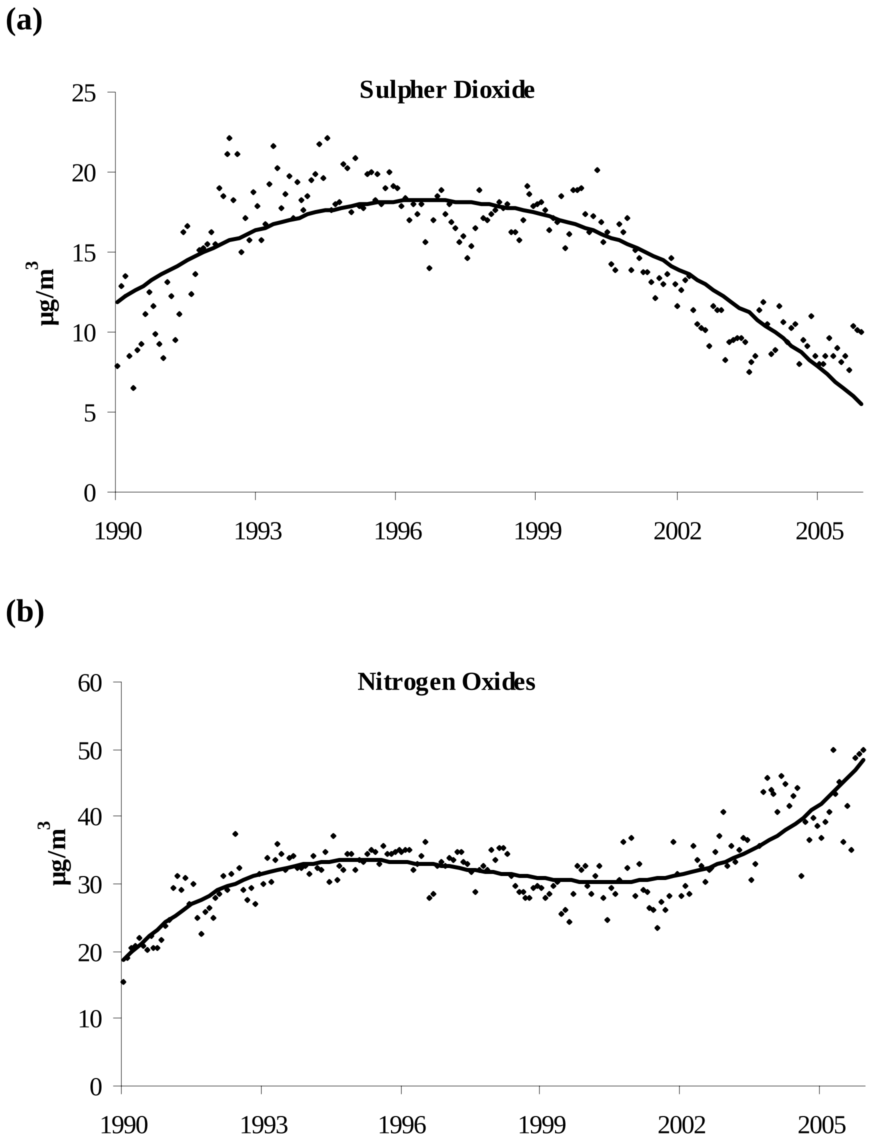


Figure 2. Air Pollutant Levels from Monitoring Stations Other Than ITO



(c)

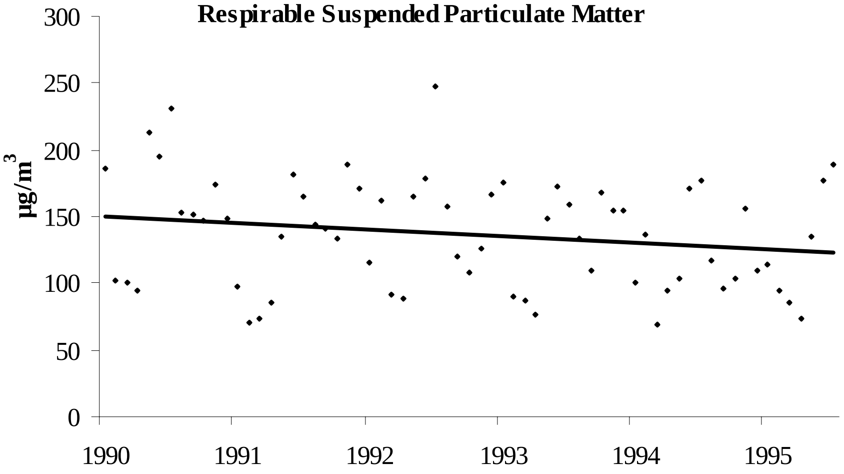
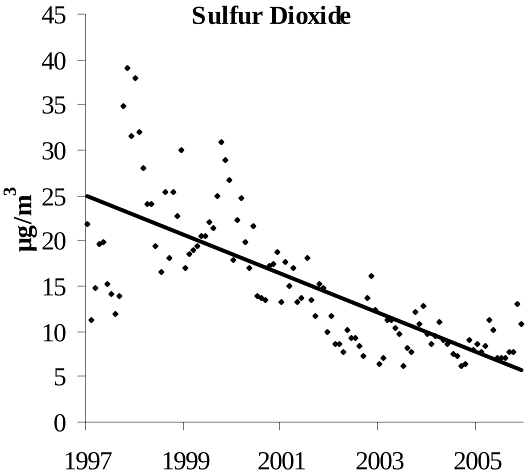
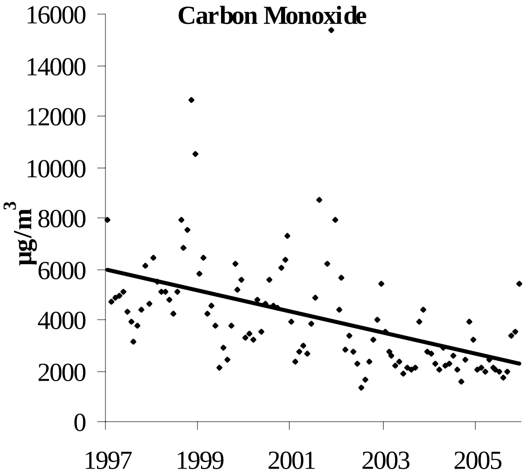

Respirable Suspended Particulate Matter
μg/m^3
300
250
200
150
100
50
0
1990
1991
1992
1993
1994
1995

Figure 3. Air Pollutant Levels from ITO Monitoring Stations

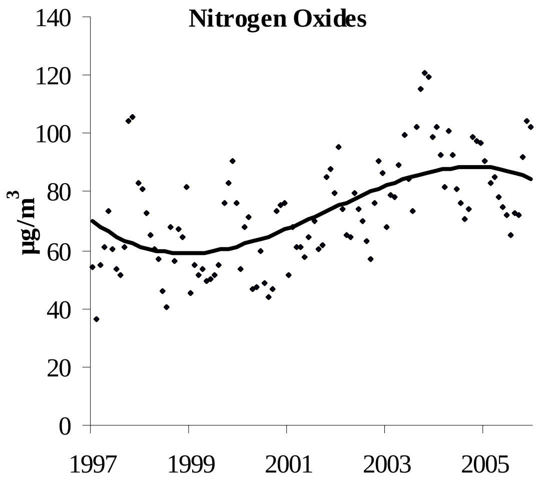
(a)



(b)



(c)


Nitrogen Oxides
140
120
100
80
60
40
20
0
μg/m^3
1997
1999
2001
2003
2005

(d)

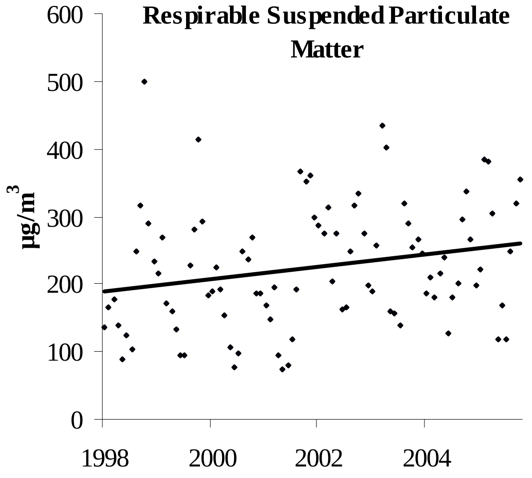
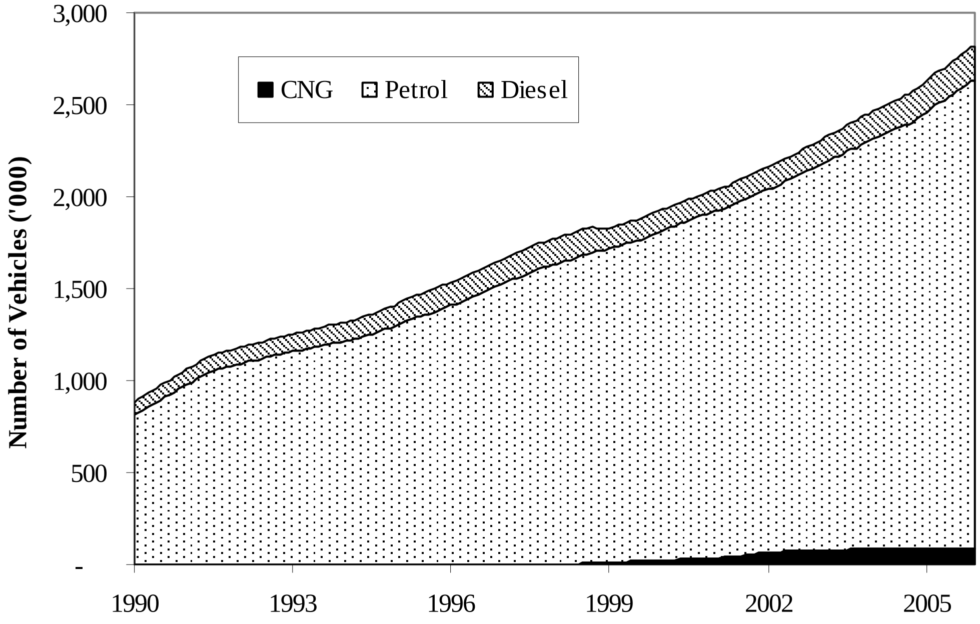

Respirable Suspended Particulate Matter
600
500
400
300
200
100
0
μg/m^3
1998
2000
2002
2004

Figure 4. Number of Vehicles on the Road and the Number of Kilometers Traveled in Delhi, 1990–2005

(a) Number of Vehicles



(b) Kilometers Driven

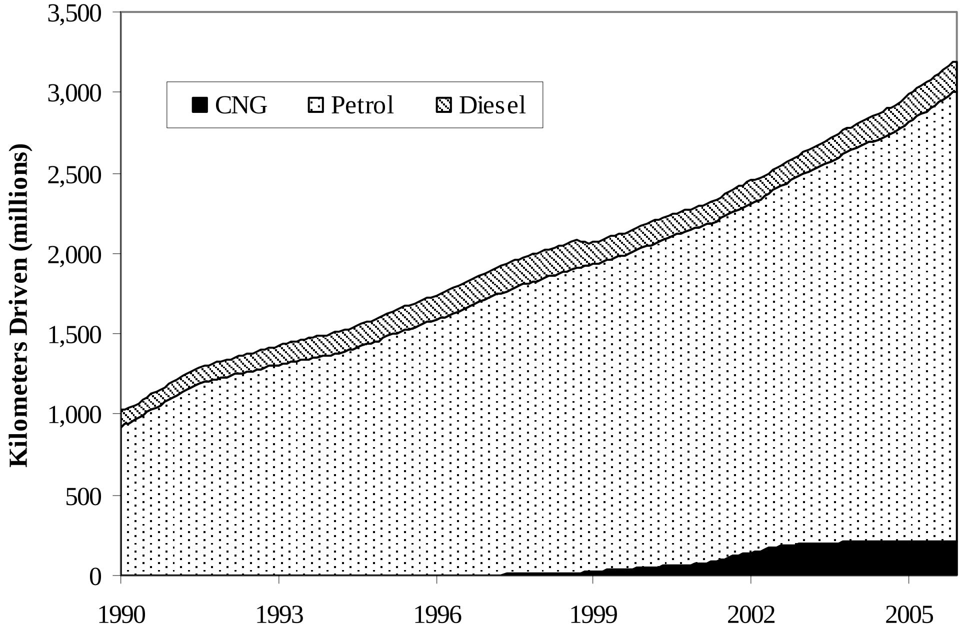
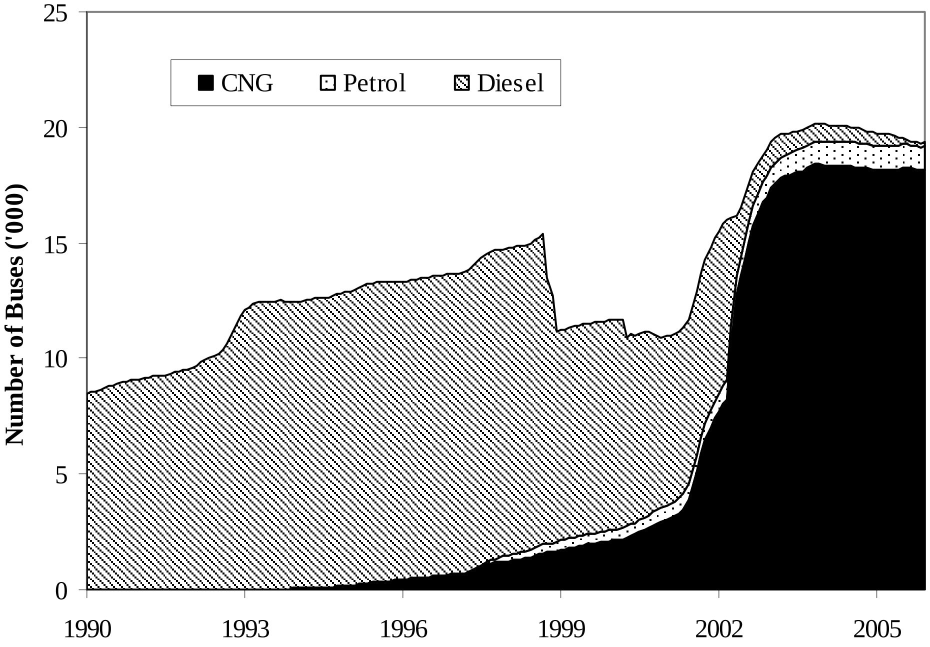


Figure 5. Number of Buses and Three-Wheelers in Delhi, 1990–2005

(a) Buses (Public and Private)



(b) Three-Wheelers

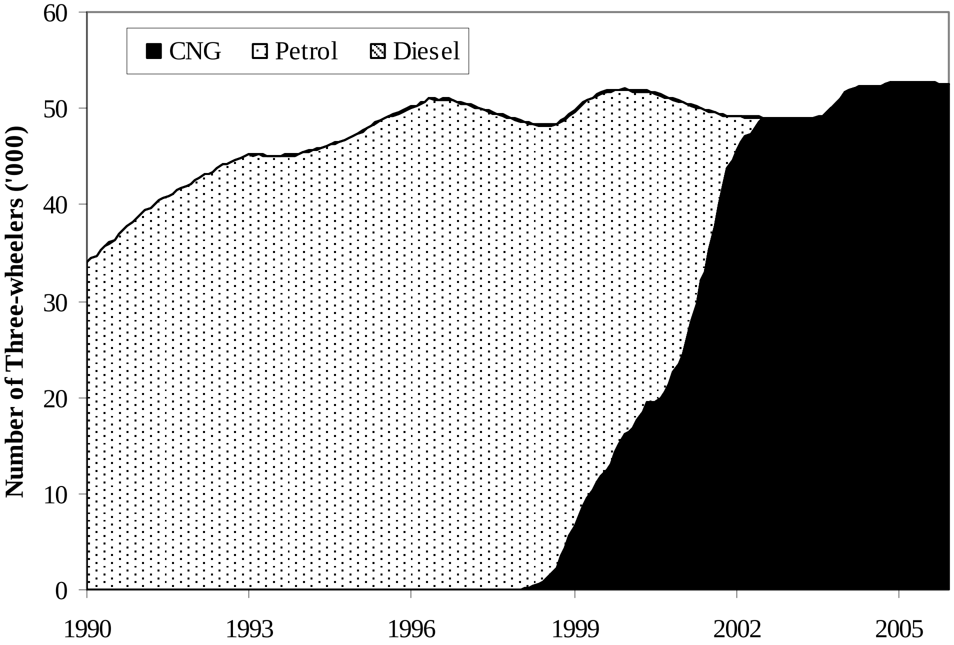
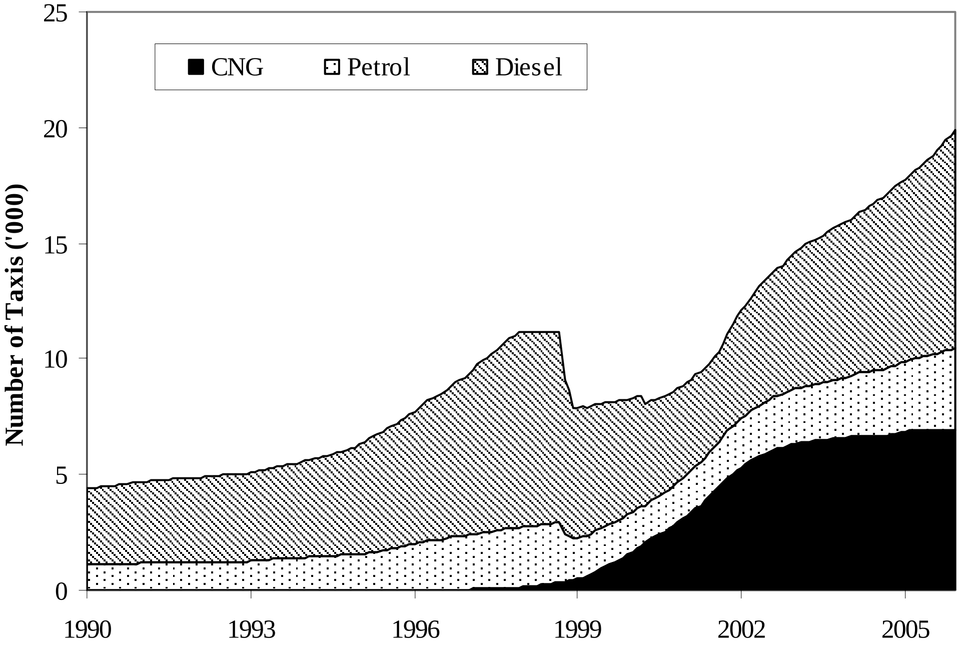


Figure 6. Number of Taxis and Trucks in Delhi, 1990–2005

(a) Taxis



(b) Trucks

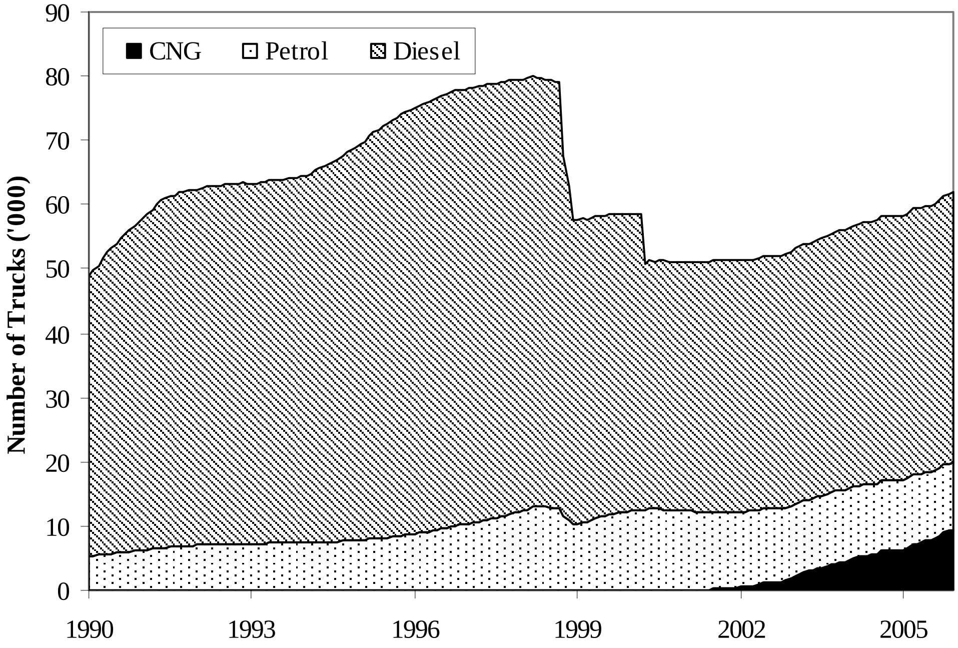
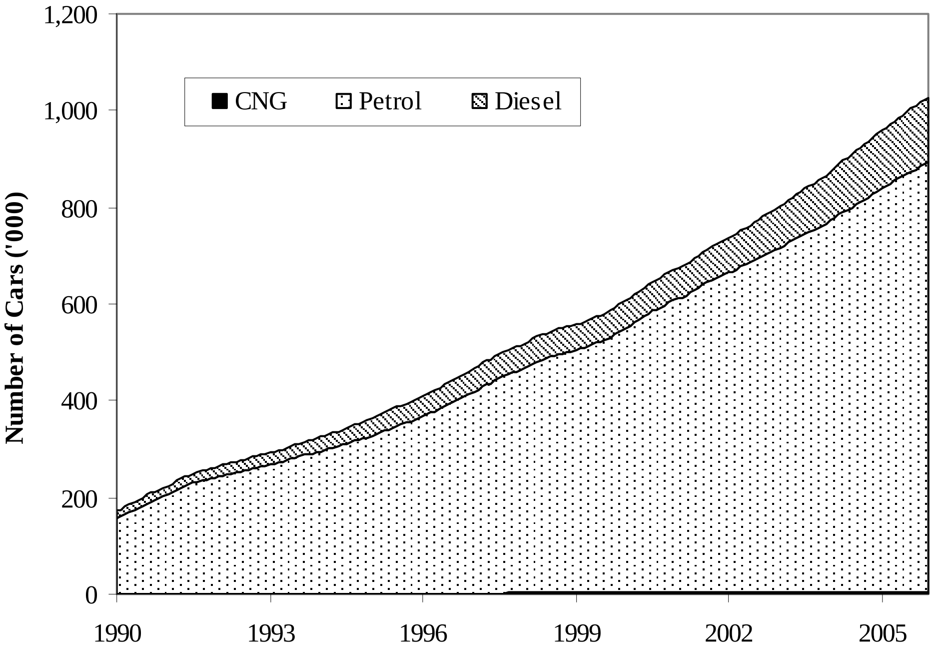


Figure 7. Number of Cars and Two-Wheelers in Delhi, 1990–2005

(a) Cars



(b) Two-Wheelers (petrol only)

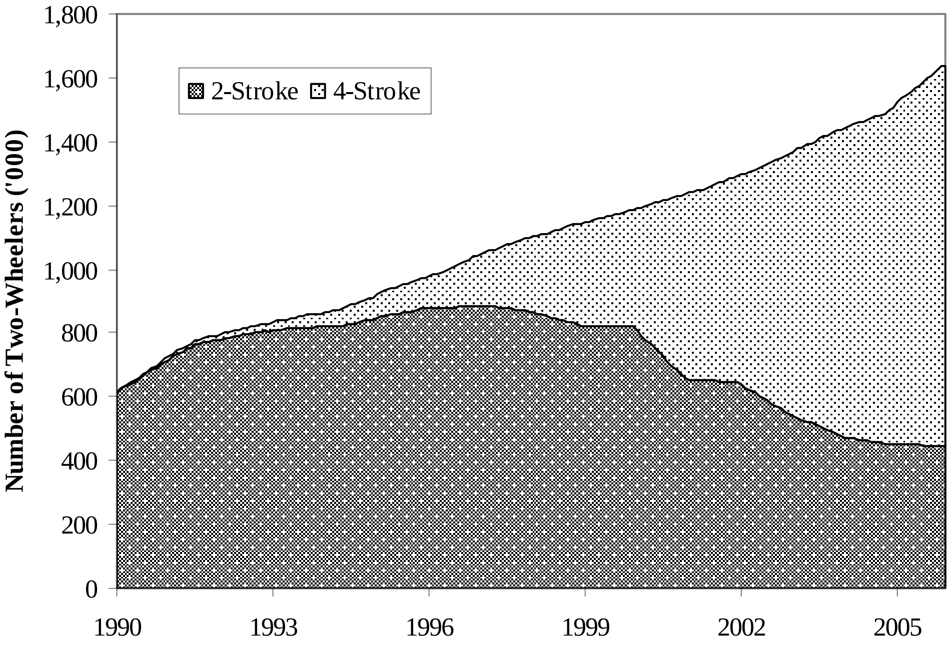
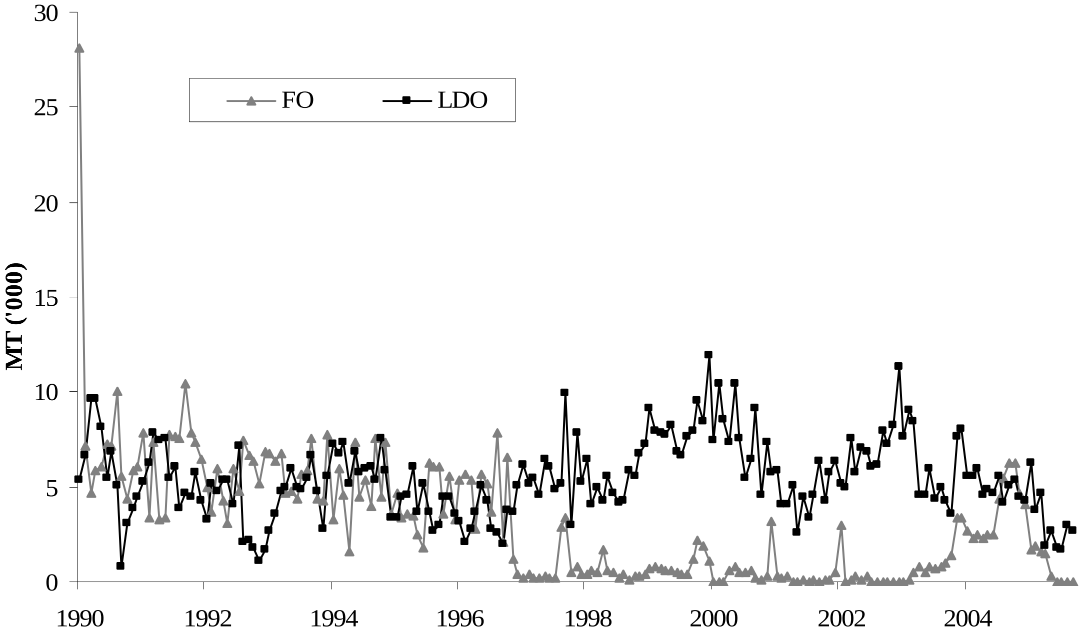


Figure 8. Industrial Fuel and Power Production in Delhi

(a) Industrial Fuel Purchases



(b) Power Production