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Urban Air Pollution

South Asia Urban Air Quality Management Briefing Note No. 14

What is Causing Particulate Air Pollution? Evidence from Delhi, Kolkata, and Mumbai

Very little information is available on sources of fine particulate air pollution in South Asia. This study represents one of the first detailed fine particulate matter source apportionment studies carried out in the region. The results indicate that there is no single dominant source, but sources differ by location and season among the three Indian cities examined. This finding would suggest that vigorously pursuing control measures in one sector, while leaving other sectors largely untouched, is less likely to result in a marked improvement in urban air quality than if a multi-pronged approach addressing a number of sources and sectors is adopted.

Identifying what air pollution sources are major contributors to elevated ambient concentrations of critical pollutants is the first step toward designing an effective policy package for air quality management. In South Asia, this question is especially relevant for sources of airborne $PM_{2.5}$ (particles smaller than 2.5 microns, also called fine particulate matter) which is a major health concern. The Georgia Institute of Technology, United States, in collaboration with the National Physical Laboratory, the Indian Institute of Technology (Mumbai), and the National Environmental Engineering Research Institute carried out an analysis of ambient $PM_{2.5}$ in Delhi, Kolkata, and Mumbai using a technique called chemical mass balance receptor modeling (See [1] for more details and references).

Chemical Mass Balance Receptor Modeling

Receptor modeling has been widely used as a technique in air pollution source apportionment studies [2]. Chemical mass balance receptor models analyze the chemical compositions of $PM_{2.5}$ samples and compare them to "source profiles," the chemical compositions of emissions from different sources such as vehicles, road dust resuspension, and wood burning. The comparison allows estimation of the contributions of different sources to the collected ambient $PM_{2.5}$ samples.

This study used compounds found in the organic carbon fraction of $PM_{2.5}$ as molecular markers for several key sources. Molecular markers can be highly specific for different sources and there exists a good understanding of organic tracers for a wide range of sources in industrial countries. However, detailed compositions of local sources are expensive to generate and this study relied on data from countries outside of South Asia. Markers are sufficiently specific to different sources and are not expected to vary from region to region. However, the precise compositions of sources have been shown to vary with the mode of operation (for example, speed and frequency of stopping and starting in the case of vehicle operation), location (especially for road dust), weather conditions, and other parameters. Therefore, chemical mass balance receptor modeling, as with other source apportionment modeling, should be regarded as a tool that provides a *semi-quantitative* understanding of the importance of different sources. More detailed information on sources of uncertainties are given in [1].

Sampling Sites

One urban residential site was selected in each city. Care was taken to avoid undue influence from heavy city-traffic or industrial emissions.

Mumbai, the largest city in India, is located on the Arabian Sea. Because ocean air is typically cleaner than continental air, proximity to the ocean and the influence of diurnal land and sea breezes aid the dilution of $PM_{2.5}$ concentration. In contrast, Delhi is located inland. Analysis of wind trajectories from 1995 to 1999 shows that 62 percent of all trajectories arriving in Delhi during that period experienced stagnation [1]. Air stagnation keeps particles suspended over the city for an extended period of time and worsens air quality. In addition, lower temperatures in the winter months lead to atmospheric inversion which traps pollutants close to the ground, and

this, combined with low rainfall, increases $PM_{2.5}$ concentrations further.

The weather conditions differ markedly among the three cities [3]. Delhi has a moderate monsoon season between July and September and has the least rainfall of the three cities. Kolkata has a longer monsoon season, lasting from May to October, and much more rainfall. Mumbai has a severe monsoon season with the heaviest rainfall of the three. These differences in the weather and geographical conditions partially explain much higher $PM_{2.5}$ concentrations in Delhi than in other cities.

Sampling of $PM_{2.5}$

$PM_{2.5}$ samples were collected over consecutive 24-hour periods between March 2001 and January 2002. The total number of days yielding useful results was 21 in Delhi, 20 in Kolkata, and 25 in Mumbai. The days on which $PM_{2.5}$ samples were collected are shown in Table 1.

Table 1 Schedule of Dates for Sample Collection

Season	Month	Delhi	Kolkata	Mumbai
Spring	Mar-01	4, 10, 16, 22, 28	16, 22, 28	4, 10, 16, 19, 22, 28
	Apr-01		3, 9	
Summer	Jun-01	8, 14, 20, 26	8, 14, 20, 26	8, 14, 20, 26
	Jul-01	2, 8, 14	2	2
Autumn	Oct-01	5, 11, 17	11, 17, 23, 29	5, 11, 17, 23, 29
	Nov-01		4	4, 10
Winter	Dec-01	17, 23, 29	5, 11, 17, 23, 29	5, 11, 17, 23, 29
	Jan-02		4, 10, 16	4, 10

Chemical Analysis

Detailed analysis of particles typically involves chemical analysis of sulfates (SO_4^{2-}), nitrates (NO_3^-), ammonium (NH_4^+), and other water-soluble inorganic compounds; determination of elemental carbon (EC) and organic carbon (OC) as well as total carbon (the sum of EC and OC) by weight; and chemical analysis of the organic compounds.

Carbon in particulate matter comes from combustion processes and it is relatively straightforward to determine the total amount. Differentiation between EC and OC is more complex. Fine particles found in diesel engine exhaust and fuel oil and coal combustion products tend to have a high EC-to-OC ratio, while emissions from gasoline cars not equipped with catalytic converters, biomass combustion products, and road dust tend to have a low ratio. It is important to emphasize that the definition of EC and OC is procedural. There are at least 15 internationally accepted procedures for EC and OC determination, and the ratio of EC to OC differs for any given sample depending on the procedure, although all of them should give the same total carbon content.

The molecular markers used in this study included:

- Hopanes and steranes, present in lubricating oil and consequently in the exhaust emissions of gasoline and diesel-powered motor vehicles
- Levoglucosan, a major component of particulate matter from wood combustion
- Picene, a marker for coal combustion
- Silicon and aluminum, markers for road dust and the only markers that were not based on OC.

Twenty source profiles were tested in the chemical mass balance model. The modeling did not find significant levels of combustion products of fuel oil. This is consistent with very low consumption of fuel oil compared to diesel and gasoline in Delhi. After extensive analysis, five source profiles were retained: gasoline, diesel, road dust, coal, and biomass. Of the five source profiles retained, regional source profiles—Bangladesh in this case—were available only for biomass: coconut leaves, rice straw, cow dung, biomass briquette, and jackfruit branches. The source profiles used for gasoline, diesel, and road dust were from the United States, and that for coal was from Beijing. The absence of local source profiles is one source of modeling uncertainties.

The profiles for gasoline, diesel, and coal indicate the fuel used but not how or in which sector the fuel is combusted. In the case of gasoline, virtually all gasoline can be safely attributed to vehicles. But it is not possible to distinguish between diesel burned in vehicles and diesel burned in stationary sources (such as small diesel power generators frequently used by shops and small industrial establishments in India). That said, stationary sources are known to emit much less particulate matter per unit of fuel burned than vehicle engines so that a significant fraction of what is identified as diesel here is probably from diesel vehicle exhaust. In this study diesel actually includes kerosene used in conjunction with lubricating oil, most notably kerosene added to automotive diesel, but not kerosene used in cooking. Biomass and coal burned by households are indistinguishable from those burned in bakeries and cottage industries. Some portions of $PM_{2.5}$ classified as road dust may be fugitive emissions from industry. It is also not possible to trace secondary sulfates, nitrates, and ammonium to different sources.

Results

A summary of the total concentrations of $PM_{2.5}$, EC, and OC in micrograms per cubic meter (µg/m³), and carbon (EC+OC) as a percentage by weight (wt%) of $PM_{2.5}$ is given in Table 2. The high carbon contents measured indicate the importance of fossil-fuel and biomass contributions to fine particulate air pollution.

Table 2 Seasonal Average Concentrations of $PM_{2.5}$ and Carbon

Season	Component	Units	Delhi	Kolkata	Mumbai
Spring	$PM_{2.5}$	µg/m³	114	55	36
	EC	µg/m³	9.1	6.1	3.7
	OC	µg/m³	38	19	9.5
	Total carbon	wt%	41	44	37
Summer	$PM_{2.5}$	µg/m³	49	26	21
	EC	µg/m³	4	6.6	1.1
	OC	µg/m³	16	7.8	1.6
	Total carbon	wt%	40	55	13
Autumn	$PM_{2.5}$	µg/m³	159	45	64
	EC	µg/m³	11	9.1	5.6
	OC	µg/m³	57	18	20
	Total carbon	wt%	44	62	38
Winter	$PM_{2.5}$	µg/m³	231	305	89
	EC	µg/m³	17	27	8.2
	OC	µg/m³	96	147	34
	Total carbon	wt%	46	57	48

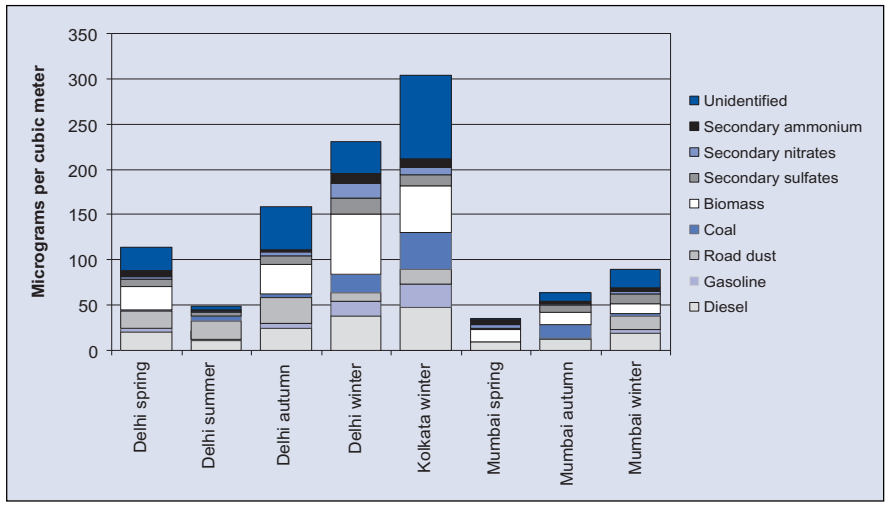
Samples in each city were combined by season for organic marker analysis, giving a total of 12 combined samples for source apportionment determination. Of the 12 samples, one (summer in Mumbai) could not be used because it gave OC that was below the detection limit for identifying organic markers, leaving a total of 11.

Of the 11 remaining samples, Kolkata in spring, summer, and autumn showed trends that were inconsistent with all other samples. In addition, the sums of contributions of different components (combustion products of gasoline, diesel, and so on) exceeded the measured $PM_{2.5}$ mass in these samples, adding up to 107 (spring), 130 (summer), and 120 (autumn) percent of the measured mass. It is possible, and in fact not uncommon, for the sum to exceed 100 percent using this source apportionment methodology. These observations nevertheless suggest that the results for these samples could contain larger uncertainties than other samples and should be interpreted with greater caution. For the rest of this note, Kolkata spring, summer, and autumn samples are excluded from further consideration for these reasons.

The results of chemical mass balance receptor modeling for the remaining eight samples are shown in Figure 1. The sources shown in the figure include fuels (gasoline, diesel, coal, and biomass), "road dust," particulate matter formed through atmospheric reactions (secondary nitrates and sulfates, which are formed from emissions from various combustion sources, and secondary ammonium, which can be from agricultural sources in addition to combustion sources), and unidentified sources (such as water and unidentified organic compounds). "Unidentified" is the difference between the sum of components accounted for in source apportionment and the measured $PM_{2.5}$ level.

"Road dust" (which may include fugitive industrial emissions) was the largest contributor in three samples, biomass combustion in one, and unidentified sources in the remaining four. Despite large numbers of two-stroke engine gasoline vehicles, known for their high particulate emissions, diesel contribution exceeds that of gasoline in all cases. This is plausible given the high consumption of diesel compared to gasoline in India. This finding would suggest that focusing on diesel vehicles should be given priority in air quality management. However, it is difficult to separate gasoline and diesel contributions accurately, so that the aggregate contribution of gasoline and diesel combustion is likely to be a much more accurate value than the contribution of each fuel.

Figure 1 Receptor Modeling of $PM_{2.5}$ in Delhi, Kolkata, and Mumbai



If all of diesel is attributed to mobile sources, vehicle exhaust becomes the largest contributor in one season: Mumbai in spring at 28 percent. The combined contribution of coal and biomass combustion was greater than that of gasoline and diesel combined in all seasons except summer in Delhi and spring and winter in Mumbai.

Secondary particulate formation comprised approximately one-tenth to one-fifth of $PM_{2.5}$. Secondary sulfates and nitrates arise mostly from combustion processes, so that the actual percentage contributions of biomass, coal, and fossil fuel combustion are higher than those indicated above. In particular, high-sulfur fuels such as fuel oil used in industry may be contributing disproportionately to secondary sulfates.

Conclusions and Policy Implications

The results show that there is no single dominant source but rather a number of sources contribute to $PM_{2.5}$. Broadly, the contributions of different sources vary with season and across the three cities. For example, mobile sources and biomass combustion appear to contribute substantially and in several cases approximately in equal proportions (spring and autumn in Delhi and autumn in Mumbai). The contribution of "road dust" can also be significant (summer in Delhi and spring and autumn in Mumbai). Predictably the combined contribution of biomass and coal is the highest in winter in Delhi and Kolkata, presumably as a result of heating. Contributions from solid fuel combustion are also significant in non-heating seasons: spring and autumn in Delhi and autumn in Mumbai, probably on account of considerable use of solid fuels in small-scale industries and by households for cooking.

Understandably, much policy attention has concentrated on vehicle exhaust to date in the region. However, this source apportionment study highlights the importance of addressing several sources of air pollution in parallel. In particular, solid fuel use in industry and household cooking as well as for heating in winter can become a significant source of to airborne fine particulate matter. This is especially true in cities with cold winters that require heating—mainly in northern India, Nepal, and Pakistan—precisely in the season when ambient concentrations from all sources are elevated on account of thermal inversion. These and other sources would need to be tackled for air quality improvement.

A number of cities in India are currently developing action plans to improve air quality. The results of this study underscore the importance of basing, to the extent possible, strategies on city-specific data on the mix of emission sources and meteorological parameters.

References

1. ESMAP. 2004. *Toward Cleaner Urban Air in South Asia: Tackling Transport Pollution, Understanding Sources*. ESMAP Report 281/04, March. Washington D.C. Available online at <http://www.worldbank.org/sarubanair>.
2. Chow, J.C. and J.G. Watson. 2002. "Review of $PM_{2.5}$ Source Apportionment for Fossil Fuel Combustion and Other Sources by the Chemical Mass Balance Receptor Model." *Energy & Fuels* 16(2): 222-260.
3. World Bank. Forthcoming. "For a Breath of Fresh Air: Ten Years of Progress and Challenges in Urban Air Quality Management in India."

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