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Urban Particulate Pollution Source Apportionment

Part 2. Applications, Results, and Policy Implications

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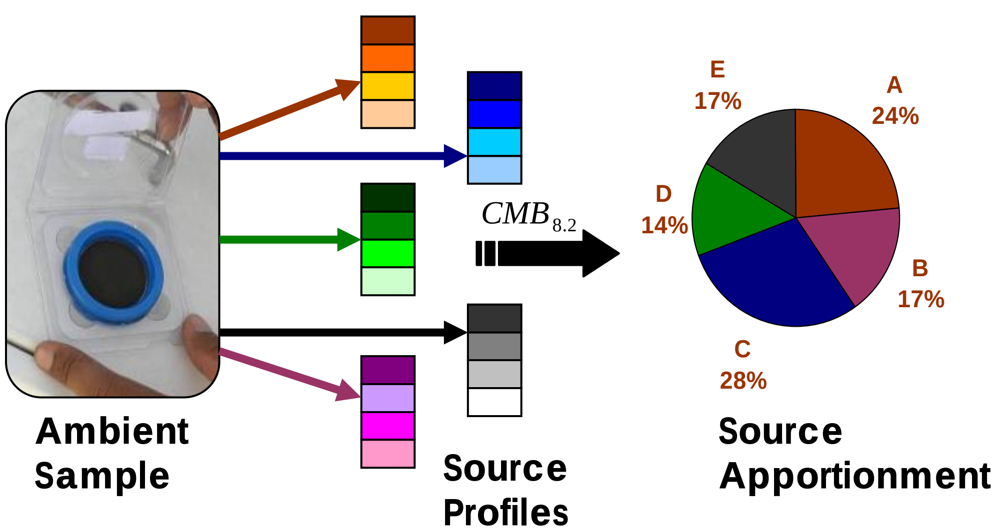

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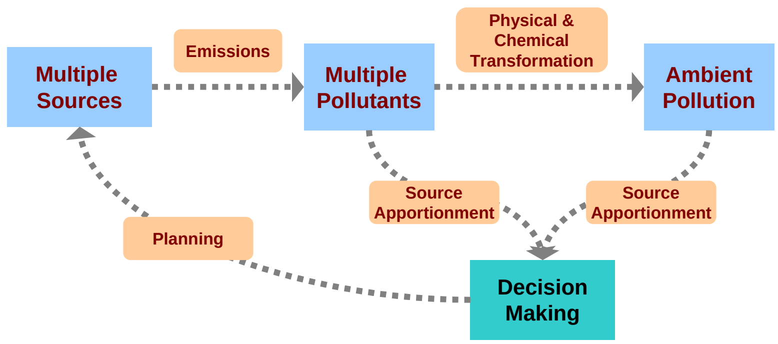
Part 2. Applications, Results, & Policy Implications

The particulate pollution source apportionment methodology, presented in **Figure 1** and described in the earlier papers[1], was reviewed and applied in a number of cities around the world, with varying degrees of adaptations at each stage.

Figure 1: Cycle of particulate pollution source apportionment



The main objective of the particulate (PM) pollution source apportionment is to identify the potential contribution of various sources to the ambient pollution levels (indicators), which can be utilized for effective informed decision making (planning). Though the methodology focuses primarily on the PM pollution, it includes the contribution of other pollutants in the secondary form. While discussing the source apportionment methodology, it is important to note that the contribution of the sources to the emission totals is different from their contribution to the ambient pollution. In the later, the cumulative contributions (via physical and chemical transformation) are rolled into one form (e.g. PM pollution) and can provide information on an indicator directly responsible for the public health concerns.

The physical transformation includes advection of the emissions from area to area, which also varies for sources. The ground level sources, such as vehicle exhaust and road dust, tend to contribute more to the local pollution, whereas the stacked emissions from industries also contribute to areas away from the source. The chemical transformation includes, for example, the contribution of pollutants like sulfur dioxide (SO_2) and nitrogen oxides (NO_x) to the secondary PM in the form of sulfates and nitrates.

This paper presents a summary of the source apportionment applications (for emissions and ambient pollution) and policy implications[2].

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[1] SIM-10-2008, "What is Particulate Matter – Composition and Science?" and
SIM-16-2009, "Urban Particulate Pollution Source Apportionment. Part 1. Definition & Methodology" @ http://urbanemissions.info/simair/simseries.html

[2] Sections of this working paper are part of the "Handbook on Particulate Pollution Source Apportionment", (published by the World Bank). Details are available @ www.urbanemissions.info/pmsa

Emission Sources in Asian Megacities

An emission inventory for Asian cities is presented in **Table 1**, for city-specific emission estimates in 2000[3]. Of the total anthropogenic emissions in Asia, megacities account for ~10-15% of the primary pollutant emissions (SO_2, NO_x, carbon monoxide, volatile organic carbons, PM, black carbon, and organic carbon), while concentrated into ~2% of the land area, leading to a very high emission density. Furthermore, 30% of the Asian population resides in these cities; thus megacity emissions project a disproportionate impact on human health.

Table 1: Primary Emission Estimates (ktons) for Asian Cities in 2000[4]

	SO_2	NO_x	VOC	CO	BC	OC	PM_{10}	$PM_{2.5}$
East Asia								
Beijing	238.0	118.1	225.6	1237.0	8.6	13.1	83.2	42.7
Taiyuan	178.3	52.1	55.5	329.6	4.0	3.8	28.5	11.0
Tianjin	200.7	152.6	198.8	973.1	8.1	12.8	70.4	35.7
Shanghai	250.8	222.4	348.3	1716.1	7.6	11.8	79.9	42.6
Qingdao	23.9	17.1	27.8	148.9	1.2	3.9	11.5	9.5
Guangzhou	97.2	63.3	120.0	390.6	2.7	7.5	29.6	20.9
Wuhan	93.9	56.3	115.8	594.9	10.3	30.4	95.2	73.7
Chongqing	150.5	31.9	83.3	463.4	7.8	24.4	71.4	58.1
Hong Kong	36.1	99.8	133.1	270.5	1.3	2.5	17.2	12.1
Seoul	309.9	400.9	282.1	254.1	7.0	9.0	46.9	24.0
Pusan	55.7	97.3	183.0	133.6	1.0	0.8	13.3	6.6
Tokyo	112.3	276.2	414.5	461.1	5.7	6.5	31.7	18.3
Osaka	83.1	176.7	197.6	330.2	4.1	4.7	24.3	14.9
S.E Asia								
Bangkok	162.4	58.2	235.6	213.2	3.9	15.5	67.5	55.5
Singapore	188.7	213.7	153.7	158.2	3.9	5.1	266.0	165.4
Jakarta	97.4	66.6	671.3	1210.1	21.2	102.8	298.4	281.6
Manila	113.4	26.0	123.7	59.0	2.9	12.0	39.5	35.8
Kuala Lumpur	54.3	48.2	157.6	101.9	1.8	5.8	30.0	20.4
South Asia								
Calcutta	65.2	61.6	233.0	631.3	16.1	76.7	345.3	273.0
New Delhi	69.7	64.6	181.8	598.8	7.4	32.4	223.2	152.3
Bombay	46.3	24.8	61.0	113.4	3.0	12.8	59.5	43.5
Karachi	155.1	25.0	40.7	47.9	4.4	18.5	95.2	72.1
Lahore	93.2	32.4	88.8	254.3	6.4	28.4	155.5	117.3
Dhaka	20.3	14.1	73.5	380.5	6.3	30.9	118.3	100.2

The group of cities selected in this presentation range from cities dominated by transport related emissions (e.g., Tokyo, Seoul, Shanghai) to cities with coal based technologies (e.g.,

[3] A detailed analysis of the emissions inventories and their contribution to the particulate pollution in Asia is presented in SIM-20-2009, "PM Pollution in Asia - Part 1" @ http://urbanemissions.info/simair/simseries.html
[4] For approximate representation, the city totals are extracted from the gridded emission fields including the grid cells in which the city resides and the neighboring eight grid cells at 0.25 degree resolution.

Beijing and Dhaka). **Figure 2** presents the sectoral contribution to various pollutant emissions.

- For SO_2, industry (IND) and power generation (PG) account for ~80% of the emissions. Tokyo, Osaka and Pusan are the exceptions. Pusan is the only city with >40% of the SO_2 emissions originating from the transport sector (TRAN). This is primarily due to the use of high sulfur diesel for shipping and road transport. Otherwise, TRAN contributes less than 5% to the SO_2 emission inventory in Asian cities.
- For NO_x, IND, PG and TRAN dominate the inventory, with the transport sector accounting for as much as 60% in Pusan, Tokyo and Singapore.
- For carbon monoxide (CO), IND and TRAN dominate the inventory, with domestic bio-fuels (DOMB) contributing significantly in the rural areas of Southeast and South Asia. Here the domestic sector consists of residential fuel usage and is divided into two parts – emissions due to bio-fuel usage (DOMB) and fossil fuel usage (DOMF). While most of the East Asian cities have >50% of their CO emissions originating from TRAN, Hong Kong and Singapore have them approaching 100%.
- For the carbonaceous particles, domestic fossil (DOMF) for the black carbon (BC), and DOMB for organic carbon (OC), are dominant sources. TRAN is important in the Northeast Asian cities and IND is important in China.
- For the non-methane volatile organic carbons (NMVOC) emissions, IND and TRAN are important sources in the cities of China, and IND, TRAN and DOMF are important in the Northeast Asian Cities. Besides industrial activity and evaporative sources, domestic coal and bio-fuel combustion contribute to NMVOC emissions in many Asian cities.
- On a broader perspective, biomass burning contributes between 10-20% of the primary trace gas and carbonaceous emissions in Asia megacities.

Differences in the primary energy mix in Asia cities are partially explained by the endowment of energy resources. Asia has 33 percent of world coal reserves, sufficient for more than 50 years of consumption and these reserves are highly concentrated in China, India and Indonesia[5]. Hence, the high dependency on coal as a primary energy source in the power, industrial and domestic sectors[6]. Use of locally available high sulfur coal for domestic cooking and heating, small scale industrial boilers and power sector is the main reason why the SO_2 to NO_x emission ratios are high in cities in China, Southeast Asia, and the Indian Subcontinent[7]. This wide range of values reflects cities with energy reforms in transition and a breadth of sulfur and PM control programs[8].

[5] Coal use around the world, International Energy Agency (IEA) @ http://www.iea.org/Textbase/subjectqueries/keyresult.asp?KEYWORD_ID=4101

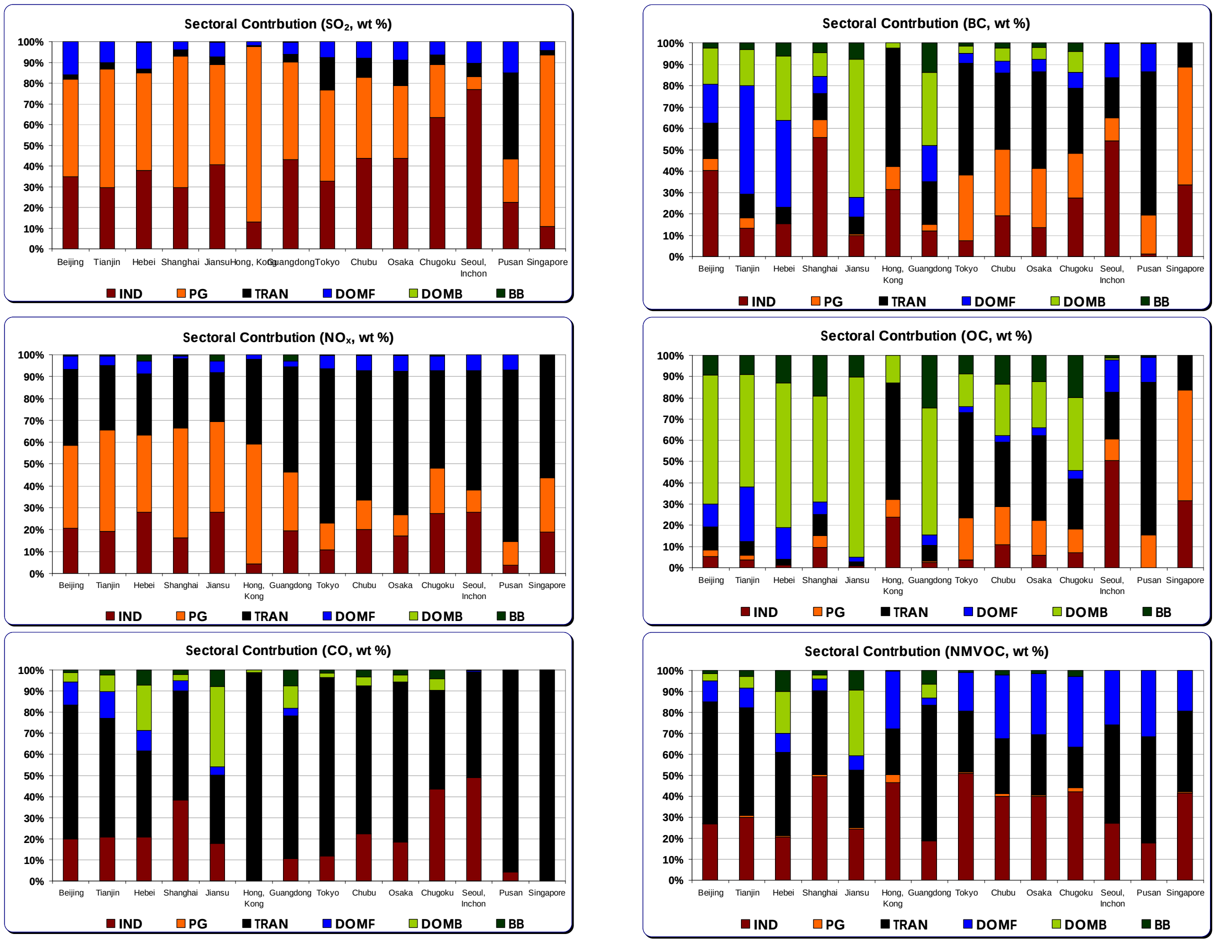
[6] Scientific American, August 8th, 2008, "Can Coal and Clean Air Coexist in China?" @ http://www.scientificamerican.com/article.cfm?id=can-coal-and-clean-air-coexist-china

[7] New York Times, June 11th, 2006, "Pollution From Chinese Coal Casts a Global Shadow" @ http://www.nytimes.com/2006/06/11/business/worldbusiness/11chinacoal.html

New York Times, May 9th, 2009, "China Outpaces U.S. in Cleaner Coal-Fired Plants" @ http://www.nytimes.com/2009/05/11/world/asia/11coal.html

[8] Database of clean coal technologies @ http://www.iea-coal.org.uk/site/ieacoal/databases/clean-coal-technologies

Figure 2: Sectoral Contribution to Urban Primary Emission Inventory for 2000



IND = Industry; DOMB = Domestic Biofuels; DOMF = Domestic Fossils; TRAN = Transportation; PG = Power Generation; BB = Biomass Burning

An aggressive shift in the energy mix from coal to oil and gas in South Korea and Japan[9], implementation of strict sulfur control technologies, and a relatively higher level of vehicular emissions (especially NO_x), cities in these countries have a lower SO_2 to NO_x emission ratio (~0.5) (**Figure 3**). In the future, rapidly motorizing cities in China and the Indian Subcontinent are expected to see their SO_2 to NO_x emission ratios decrease and expected follow the trends observed in the Japan and South Korea.

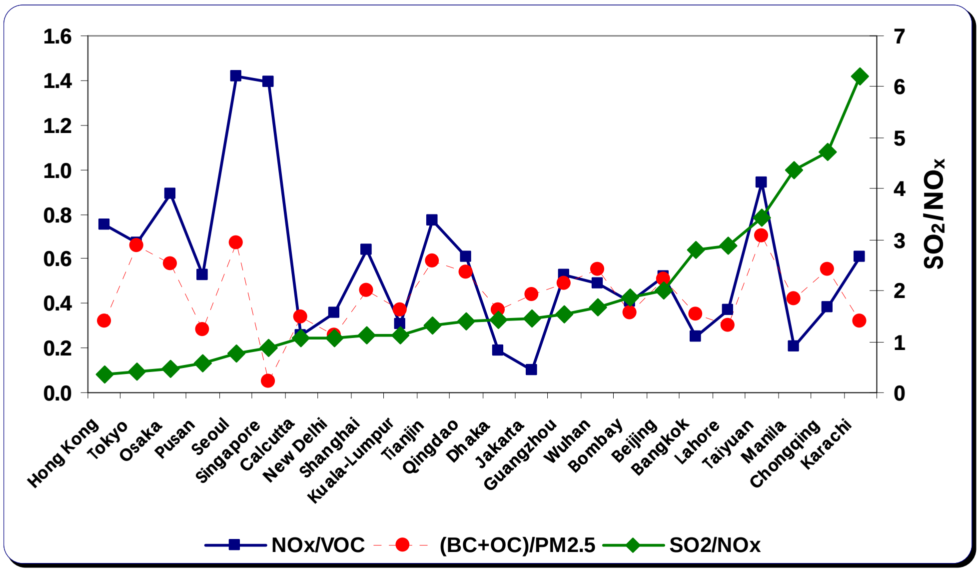
The high average CO to VOC emission ratios in the cities of China (~4.7) and the Indian Subcontinent (~2.8) compared to the cities in the rest of East Asia and Southeast Asia (~1.1 and ~0.9 respectively), reflect the diverse energy splits between coal, oil and natural gas.

The VOC to NO_x emission ratios (mass based) range from ~10 in Jakarta to ~0.7 in Seoul. The highly motorized cities like Seoul, Tokyo, Singapore and cities in the emerging markets regions in China have a higher VOC to NO_x ratios. Major anthropogenic sources of VOC's

[9] Our World, May, 2009, "Japan, waking up to peak oil?" @ http://ourworld.unu.edu/en/2009/05/05/japan-and-peak-oil/

include motor vehicle exhaust, use of solvents, and the chemical and petroleum industries. NO_x emission sources, mainly from the combustion of fossil fuels include motor vehicles and electricity generating stations. This ratio has serious implications to the ozone formation at the ground level, whose ambient levels are growing to the level of health concerns and agricultural yields[10].

Figure 3: Ratio of primary emissions in the urban centers in 2000



Carbonaceous particles (BC and OC) account for a significant fraction of $PM_{2.5}$ in the megacities of Asia. The fractions of carbonaceous particles range from >50% in the South and Southeast Asia to <50% in East Asia. The large fraction of carbonaceous particulates reflects in part the inefficient combustion of fossil- and bio-fuels in South and Southeast Asia[11].

While the source contributions to the emissions provide necessary information on the energy mix, the contributions of the sources to the ambient pollution provide the necessary indicators to support the decision making process and development of effective control strategies, depending on the criteria pollutant, e.g. PM or ozone.

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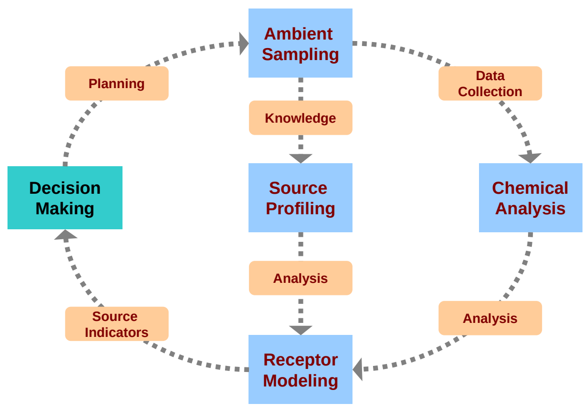
[10] Environmental Science and Technology, February, 2009, "East China Plains: A "Basin" of Ozone Pollution" @ http://pubs.acs.org/doi/abs/10.1021/es8027764
"Science Daily, June, 2009, "Lower Crop Yields Due To Ozone A Factor In World Food Crisis" @ http://www.sciencedaily.com/releases/2008/06/080603183309.htm
[11] Science Daily, March, 2008, "Black Carbon pollution emerges as major player in global warming" @ http://www.sciencedaily.com/releases/2008/03/080323210225.htm
Bond et al., 2004, Journal of Geophysical Research, "A technology-based global inventory of black and organic carbon emissions from combustion" @ http://www.agu.org/pubs/crossref/2004/2003JD003697.shtml

Source Contributions to Ambient Air Pollution

While the contribution of the sources to the emissions is estimated based on the bottom up energy use and emission factors, the contribution of the same sources to the ambient air pollution (especially PM) is estimated following the four steps presented in **Figure 4**. An important step in this process is the ambient sampling, which is conducted on a routine basis for most of the cities. The samples collected in the process are chemically analyzed and the results are regressed against known source profiles for specific signatures identifying specific sources. The end results provide an indicative analysis of source contributions to ambient pollution, which can be used for targeting the most polluting source and better air quality.

Figure 4: Cycle of ambient particulate pollution source apportionment



The initial review of the source apportionment studies was conducted as part of the World Bank review. The case studies presented in the **Table 2** do not include cities from Europe or United States. The only study conducted during the review is for the city of Hyderabad, India. Otherwise, all the case studies from Africa, Asia, and Latin America are based on the published material[12]. Not all studies are conducted using the same methodology. Each of the stages involved in the case studies were adapted to the local institutional and financial needs. The **Table 2** presents the shares of four categories to the measured PM pollution – transport, road dust, industries, biomass, and others.

Major Pollution Sources

The analytical techniques for bottom-up (emissions inventories) analysis and top-down (ambient measurements) analysis vary significantly and it is difficult to make direct comparisons of pollution sources across urban areas. However, there are enough commonalities in source categories that an indirect comparison can be made. For each urban area listed in **Table 2**, one of the categories is highlighted as representing the largest contributor to the PM pollution. Also note that some of the categories overlap in their definitions, which points out a lack of uniformity in the studies.

[12] The World Bank, 2009, Washington DC, USA, "Handbook on Particulate Pollution Source Apportionment" (*in press*) Details are available @ www.urbanemissions.info/pmsa

The commonly identified source categories include: coal burning and associated secondary pollutants such as sulfates and nitrates (sometimes over 50 percent of the mass), mobile sources (more than 40 percent of the mass in highly motorized cities), crustal sources (typically due to the resuspension of road dust and construction activities), biomass burning (including biomass fuels used for cooking in the rural areas), industrial activities, smelters and metal processing, power plants (where they are located within the city limits), and marine sources (such as sea salt) in coastal regions.

The most common source identified in all the cases is **dust emissions**. Dust sources include: unpaved roads, construction, demolition, dismantling, renovation activities, and disturbed areas. When dust sources are caused by sporadic or widespread activities due to wind or vehicle travel, it can often be difficult to quantify such emissions. Typically, these emissions while modeling are calculated online depending on the prevailing wind and dust loading in the area, and hence not part of the emissions inventories presented in **Figure 2**. However, a rough estimate based on the number and types of vehicles on roads, conditions of the roads, and entrainment factors, the dust loading on the roads can be estimated[13]. Otherwise, there is no specific emission factor established for dust sources.

Some control measures for dust include: (i) minimizing track-out onto paved roads, (ii) covering materials in trucks, (iii) rapidly cleaning up material spills on roads, (iv) employing street cleaning/sweeping, (v) washing or otherwise treating the exterior of vehicles—personal and public, (vi) keeping roadway access points free of materials that may be carried onto the roadway, (vii) restricting speed limits, (ix) paving unpaved roads, and (x) promoting vegetation of dry areas lacking vegetative cover. Implementation of many of these measures requires capacity at the municipal and city level[14].

In developing countries, **urban clusters of small-scale manufacturers**, such as leather tanneries, brick kilns, smelters, and metalworking shops, can create severe environmental problems. In some of the case studies, where source profiles were available, these were identified as a major source – some are seasonal like the brick kilns in Dhaka and Rajshahi, Bangladesh[15], and some year long like copper smelters in Mexico City. Such polluters are difficult for regulators to identify, much less monitor. However, innovative environmental management strategies can be effective. For example, relocation has proven very successful in the case of reducing Delhi air pollution[16]. Another particularly promising approach is to introduce clean technologies that prevent pollution without unduly raising production costs.

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[13] See **v-dust**, dust resuspension calculator based on the US-AP 42 methodology @ http://www.urbanemissions.info/simair

[14] See "Dust Busters" on Clean Air Initiative for Asian Cities @ http://www.cleanairnet.org/caiasia/1412/article-58207.html

[15] See SIM-21-2009, "Impact of Brick Kiln Emissions on Air Quality in Dhaka, Bangladesh" @ http://www.urbanemissions.info/simair/simseries.html

[16] See SIM-22-2009, "Air Quality Management in Delhi: Then, Now, and Next" @ http://www.urbanemissions.info/simair/simseries.html

Table 2: Share of various sources to PM pollution measured around the world

				Dust (%)		Transport (%)			Industry (%)			Non-urban (%)			%	%
City	**Country**	**PM Size**	**Study Period**	**RD**	**OD**	**T**	**D**	**G**	**I**	**CB**	**PP**	**BB**	**LRT**	**MA**	**SA**	**O**
Shanghai	China	PM2.5	Autumn	2		17			29		28			24		
			Winter 2001	2		16			31		24			27		
			Spring 2001	3	1	19			33		23			21		
			Summer 2001	3	2	12			37		15			32		
			Annual	3	1	16			33		22			26		
Beijing	China	PM2.5	Annual 2000	9		8			6	19		11			31	18
Xi'an	China	PM2.5	Fall 2003				23	73				4				
			Winter 2003				3	44		44		9				
Delhi	India	PM2.5	Spring 2001	16			18	4		2		22			16	23
			Summer 2001	41			23	2		1		10			15	9
			Autumn 2001	18			16	3		2		21			10	30
			Winter 2001	4			16	7		9		29			20	15
			Annual	20			18	4		3		20			15	19
Mumbai	India	PM2.5	Spring 2001	38			25	3		0		13			19	2
			Autumn 2001	23			20	2		1		21			17	16
			Winter 2001	16			21	5		4		13			19	22
			Annual	26			22	3		2		16			18	10
Kolkata	India	PM2.5	Spring 2001	28			24	11		4		19			20	
			Summer 2001	21			61	8		1		24			14	
			Autumn 2001	7			43	21		5		32			11	
			Winter 2001	5			15	9		13		17			10	30
			Annual	15			36	12		6		23			14	8
Chandigarh	India	PM2.5	Summer 2001	32			7	17				9			24	10
Dhaka	Bangladesh	PM2.5	2001-02 Univ	19	10	39		9	22					1		
			2001-02 Farmgate		1	43		2	41							13
		PM10	2001-02 Univ	7	44	40		4	1					4		
			2001-02 Farmgate		53	23		13	2					9		
Rajshahi	Bangladesh	PM2.5	2001-02	5	2	29			50					14		
		PM10	2001-02	14	50	23								13		
Cairo	Egypt	PM2.5	Fall 1999		6	16			9			46			23	
			Winter 1999		11	18			27			17		1	26	
			Summer 2002		8	31			12			29		2	18	
		PM10	Fall 1999		31	8			8			39		2	12	
			Winter 1999		29	12			19			22		3	14	
			Summer 2002		44	12			8			24		3	9	
Qalabotjha	S. Africa	PM2.5	1997		62				1			14			9	14
		PM10	1997		54				2			20			8	16
Bangkok	Thailand	PM2.5	Dry 2002-03		5	35			2			26			32	
			Wet 2002-03		12	33			3			33			19	
		PM10	Dry 2002-03		60	11						17		2	9	
			Wet 2002-03		65	5			2			21		1	6	
Hanoi	Vietnam	PM2.5	1999-01		4	5				28			45	8	10	
		PM10	1999-01		32	7				26			2	22	11	
Bandung	Indonesia	PM2.5	Dry 2002-03		25	15			25				15			20
			Wet 2002-03		21	20			22				16			20
		PM10	Dry 2002-03		21	20			21				17			20
			Wet 2002-03		22	20			22				14			21
Sao Paulo	Brazil	PM2.5	Winter 1997	25		28			23						23	
			Summer 1998	30		24			27						17	
Mexico City	Mexico	PM2.5	2003		39				20			8			33	
Santiago	Chile	PM2.5	2000		42	36									11	2

RD = Road Dust; OD = Other Dust (Soil Dust, Resuspension; Fugitive Dust, Construction); T = Transport; D = Diesel; G = Gasoline; CB = Coal Burning; BB = Biomass & Open Burning; PP = Power Plants; I = Industry & Commercial including Oil Burning & Brick Kilns; LRT = Long Range Transport; MA = Marine; SA = Secondary Aerosols; O = Others

While not the highest PM contributor in any of the cases, **coal-fired power plants** can be important contributors to ambient PM and regional haze, mostly by conversion of their SO_2 emissions to sulfates during dispersion. In countries like China, the acid rain and sulfur pollution from coal fired power plants is a major concern[17].

In addition to power plants, large- and small-scale industries are also likely major contributors to local pollution levels. Large-scale sources with tall stacks contribute most to the long-range transport; small-scale sources may have even greater emissions, but they contribute mostly to local ambient concentrations in densely populated areas. Given the economies of scale—both technically and institutionally—regulatory regimes for large emission sources, such as power plants and key specialty industries, can greatly reduce total emissions, long-range transport, and impacts, depending on how close they are to major urban areas.

In the rural areas and in secondary cities, **biomass burning** is one of the major sources of pollution which is poorly characterized and is believed to contribute anywhere from 10-60 percent of the ambient PM levels, depending on where it is being measured. For regions like Africa, the main pollution source is the residential sector where a combination of coal and biomass (wood, field residue, and dung) are most commonly used. The scarcity of firewood often leads to substitutes which have higher emission levels than wood, for example crop residues and dung. Although a transition to electricity, gas, or renewables would be the healthiest solution, the complete transition from biomass fuels in the poorer urban and rural communities will take time, owing to costs and supply.

The **transportation sector** along with the resulting indirect emissions – fugitive dust or resuspension – is a major source of PM pollution in megacities and up-and-coming urban areas. Air pollution from vehicle exhaust can be localized or have trans-boundary and global effects. In dense traffic zones, pollutants are emitted near populations that are potentially exposed whereas other pollutants can travel long distances before they are deposited on the ground (ozone). The emission of greenhouse gases (especially CO_2), of which transportation is one of the main sources, have been identified to lead the global impacts on climate[18].

Field Burning clears fields of plant residue, preparing the soil for planting without the need for tillage. Some farmers believe that burning increases crop yield and helps control weeds and pests[19]. Unfortunately, the small soot particles from field burning and other combustion sources, such as coal-burning power plants, travel across large distances and easily enter buildings. This was one of the major sources identified in Bangkok.

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[17] National Academy Press, 2004, "Urbanization, Energy, and Air Pollution in China" @ http://www.nap.edu/catalog.php?record_id=11192

[18] A detailed review of the impacts of urban transport, control measures, and implications are discussed in "Reducing Air Pollution from Urban Transport", 2004, @ http://www.cleanairnet.org/cai/1403/article-60384.html

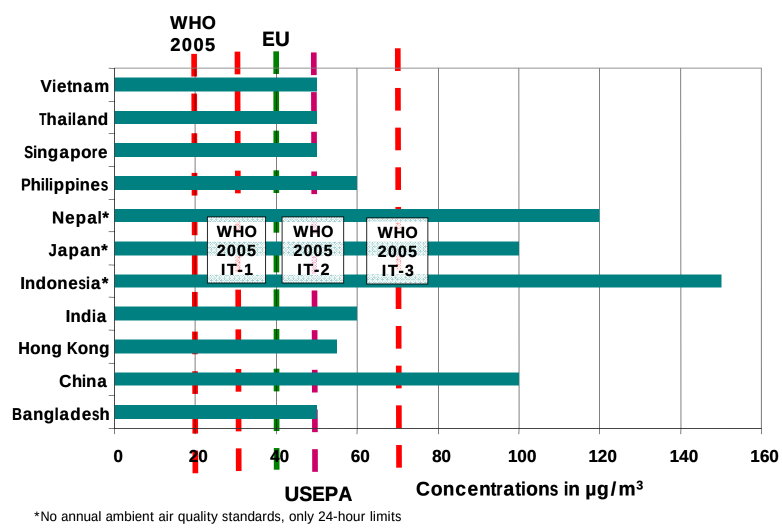
[19] Satellite imagery of dust storms, fires, and haze pollution @ http://urbanemissions.blogspot.com/2009/05/dust-storm-haze-pollution-in-asia.html

Policy Implications & Recommendations

As illustrated in **Figure 4**, the techniques of source apportionment, in particular, top-down, receptor-based analysis is a useful tool for developing countries that have not amassed a detailed, accurate information base of pollution sources and their contributions. By utilizing a first-level analysis with only a few samples, air quality managers can improve their knowledge of potential pollution sources and revise their air quality management strategies (AQMS) to deal more efficiently with air pollution problems.

That is, the implementation of an effective air quality management system in an urban area it is not an all or nothing proposition and source apportionment offers a powerful tool in improving that. For example, an urban area can set an ultimate air quality goal with interim targets to be met along the way. In fact, the World Health Organization provides suggested interim targets for meeting their new PM_{10} and $PM_{2.5}$ guidelines (**Figure 5**). These interim goals allow the governing authority to build their AQMS gradually and gain competency while allowing local polluters time to reduce emissions.

Figure 5: Ambient air quality standards for PM_{10}

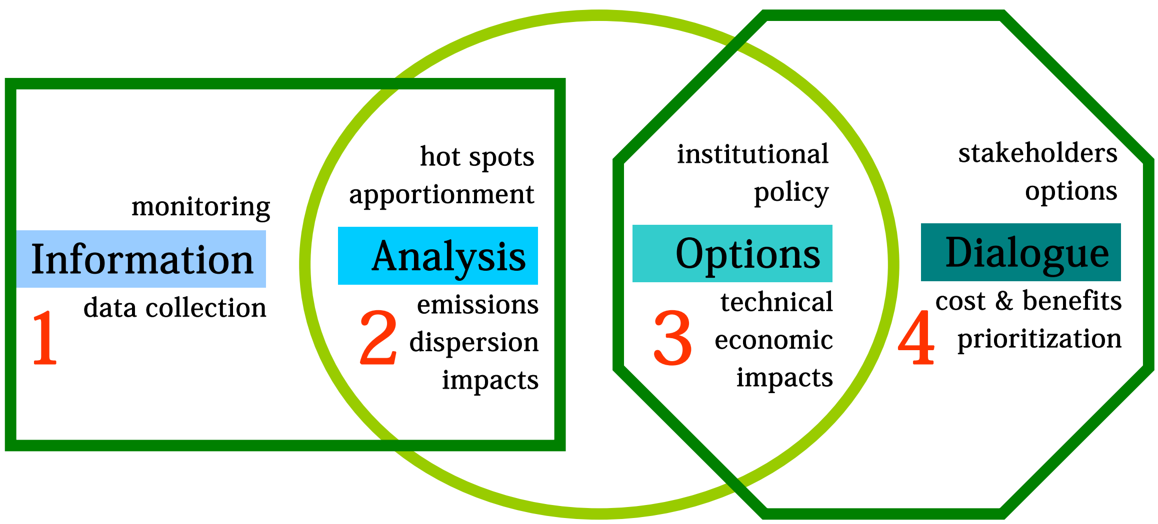


Utilization of top-down techniques can assist in improving the emission inventory, monitoring, control strategies, and air quality modeling portions of the AQMS. It is often observed that early emission inventories may be incomplete and inaccurate. Refinements can be made through building monitoring capacity, continued identification of pollution sources, and utilization of top-down studies. In short, utilizing top-down techniques, in conjunction with bottom-up methods, forms a key element in building and maintaining an effective AQMS; and furthers the local capacity to undertake similar analytical responsibilities.

Additionally, because of the expected long-term growth of energy use, governing authorities may be able to find allies to assist in building an effective AQMS via the source apportionment techniques. An example is partnering with those interested in reducing greenhouse gases, via a **co-benefits framework**[20]. Another example is a policy that reduces automotive air pollution by reducing the reliance on automobiles (e.g. public transport and non-motorized transport). The result could produce collateral benefits of reduced congestion on roads and shorter trip times for drivers. Top-down analysis may help build a case for these partnerships.

Effective AQM includes ensuring thorough and reliable monitoring of ambient concentrations as well as: keeping the authorities and the public informed about the short- and long-term changes in air quality; developing accurate emission inventories; keeping an inventory of sources of various pollutants; analyzing the dispersion of pollutants emitted from various sources; measuring the impacts of pollutant exposure on health; assessing the results of abatement measures; and thereby providing the best abatement strategies possible within the given available resources (**Figure 6**). Such a management system is especially lacking in secondary urban areas of developing countries.

Figure 6: Informed decision making for air quality management



To make the best decisions when developing the strategies, analysts and policymakers need to understand the intensity of local emission sources, the sources that impact the local community the most, and the potential effects of a wide range of abatement measures on the different source sectors involved. Top-down source apportionment helps to provide this knowledge.

In developing effective air quality management systems, overcoming knowledge gaps is critical. Fortunately, a wealth of new data on $PM_{2.5}$ and PM_{10} constituents, pollution trends, main sources, and pollution chemistry, is becoming available on a routine basis as the results of new bottom-up and top-down analyses are published[21]. This new information

[20] The Hyderabad, India case study under the USEPA's Integrated Environmental Strategies program to evaluate the co-benefits of the action plan prepared by the Andhra Pradesh Pollution Control Board, included a source apportionment study to better understand the strengths of various sources to reduce pollution and greenhouse gases. Details @ http://www.epa.gov/ies/india/apportionment_documents.htm

[21] For example: "info pools" of Clean Air Initiative @ http://www.cleanairnet.org/infopool

along with a growing commitment to utilizing scientifically-based analytical techniques offers developing countries the hope to better understand the challenges of the air quality management.

In Conclusion

The technical capacity to conduct both top-down and bottom-up studies in developing countries is still an issue. For the majority of the top-down analyses listed in this paper, a collaborative effort was undertaken with the analysis being conducted outside of the region. On one hand, collaborations like these help develop local capacity, since a local institution is always involved in the process of sample collection, filter management, and final estimation of sources. On the other hand, the capability to conduct a full scale study in the receptor region is desirable.

Now a days, the tools and techniques needed to conduct these studies are becoming more widely available, which facilitates developing countries acquiring the technical capacity to conduct all aspects of source apportionment studies.

There is an acute need for source apportionment analysis in developing countries, and with proper training and capacity development (both technical and financial) source apportionment can make a valuable contribution in attempts to reduce air pollution. Utilization of source apportionment techniques is expanding, especially in Africa and Asia, and these techniques are increasingly aiding environmental compliance and answering policy-relevant questions like what sources to target for pollution abatement efforts, where to target (e.g., suspected hot spots), and how to target.

Annex 1: References for studies listed in Table 2

Abu-Allaban, M., Gertler, A.W., Lowenthal, D.H., 2002. *"A preliminary apportionment of the sources of ambient PM10, PM2.5, and VOCs in Cairo."* Atmospheric Environment 36 (35), 5549-5557

Bell, M. L., D. L. Davis, N. Gouveia, V. H. Borja-Aburto and L. A. Cifuentes, 2006. "*The avoidable health effects of air pollution in three Latin American cities: Santiago, São Paulo, and Mexico City*." Environmental Research, 100, March 2006, 431-440.

Cao, J. J., J. C. Chow, S. C. Lee, Y. Li, S. W. Chen, Z. S. An, K. Fung, J. G. Watson, C. S. Zhu, and S. X. Liu "*Characterization and source apportionment of atmospheric organic and elemental carbon during fall and winter of 2003 in Xian, China*." Atmos. Chem. Phys. Discuss., 5, 3561–3593.

Chow, J.C. (1995). "Critical Review: *Measurement Methods to Determine Compliance of Ambient Air Quality Standards for Suspended Particles.*" J. Air and Waste Management Assoc., 45, 320-385.

Engelbrecht, J.P., Swanepoel, L., Chow, J.C., Watson, J.G., Egami, R.T., 2002. "*The comparison of source contributions from residential coal and low-smoke fuels, using CMB modeling, in South Africa*." Environmental Science & Policy 5 (2), 157-167.

Etyemezian, V.,M. Tesfaye, A. Yimer, J.C. Chow, D. Mesfin, T. Nega, G. Nikolich, J.G. Watson, M. Wondmagegn, 2005. "*Results from a pilot-scale air quality study in Addis Ababa, Ethiopia*." Atmospheric Environment, 39, 7849–7860.

Hien, P. D., V. T. Bac and N. T. H. Thinh, 2004. "*PMF receptor modeling of fine and coarse PM10 in air masses governing monsoon conditions in Hanoi, northern Vietnam*." Atmospheric Environment, 38, 189-201

V. Shutthanandan, 2006. "*Aerosol composition and source apportionment in the Mexico City, Metropolitan Area with PIXE/PESA/STIM and multivariate Analysis*." Atmos. Chem. Phys., 6, 4591–4600.

Oanh, K. N. T. et al., 2006. "Particulate air pollution in six Asian cities: Spatial and temporal distributions, and associated sources." Atmospheric Environment, 40, 3367–3380.

Sharma, Dhruv, A. A. Sawant, R. Uma, D. R. Cocker, III. (2003) *"Preliminary chemical characterization of particle-phase organic compounds in New Delhi, India.´* Atmos. Environ. 37(30):4317-4323.

Song. Y., Y. Zhang, S. Xie, L. Zeng, M. Zheng, L. G. Salmond, M. Shaob, S. Slanina, (2006). "*Source apportionment of PM2.5 in Beijing by positive matrix factorization*" Atmospheric Environment, 40, 1526–1537.

Wang, Y.Q., X.Y. Zhang and R. Arimoto, 2006. "The contribution from distant dust sources to the atmospheric particulate matter loadings at XiAn, China during spring." Science of The Total Environment, 368, 875-883

Zheng, M., L. G. Salmon, J. J. Schauer, L. Zeng, C.S. Kiang, Y. Zhang and G. R. Cass, 2005. "*Seasonal trends in PM2.5 source contributions in Beijing, China.*" Atmospheric Environment, 39, 3967-3976.

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