Designing cities as a nodes of a system: challenges on air quality issues and policy analysis

Jorge E. Pachón, Carlos R. Costa
Universidad de La Salle, Facultad de Ingeniería, Bogotá, Colombia
E-mail: Jpachon@unisalle.edu.co, Phone +571 3417900 Fax +571 3362840

Abstract

A model to estimate air quality in Colombian cities based on population, industrial and vehicle activity is built for Bogota and Bucaramanga as examples of large and intermediate cities in the country. The model is built on a linear relationship between ambient air concentrations and emissions of PM_{10}, NO_x, SO_2 and CO. Results are used to estimate future air quality under different emission reduction scenarios, and to develop policy recommendations for the central government in order to guide and support the development of an environmentally sustainable system of cities. If no emission controls are implemented in the nodes of cities in the future, cities will reach harmful level of pollutants. Controls in mobile sources (implementation of DFP in buses and trucks) and point sources (replacement of coal with natural gas in boilers and heaters) were found effective to reduce levels of particulate matter in big and intermediate cities. Strategies associated with a low-carbon development policy in the country can also be effective to abate air pollution in cities.

Introduction

The rapid urbanization processes in emerging economy countries in the world is causing environmental deterioration and lose of life quality. The atmosphere is one of the most affected components of the environment due to the lack of urban planning and flexibility of emissions standards. Urban planning should be oriented towards ensuring environmental sustainability of cities and minimizing the urban footprint.

In Colombia, the traditional approach that regards cities as independent entities is beginning to be replaced by an approach in which cities and their metropolitan areas are nodes of a system. Under this approach, cities can satisfy their needs with the help of other cities in the system in a more sustainable manner. The system proposed in this approach implies challenges in the environmental management.

A model to estimate air quality in Colombian cities based on population, industrial and vehicle activity is built for Bogota and Bucaramanga as examples of large and intermediate cities in the country. The model is built on a linear relationship between ambient air concentrations and emissions of PM_{10}, NO_x, SO_2 and CO. Results are used to estimate future air quality under different emission reduction scenarios, and to develop policy recommendations for the central government in order to guide and support the development of an environmentally sustainable system of cities.

Methods

The development of this method is summarized in the following activities (Figure 1):

i. *Ambient air concentration records*. Ambient air concentrations of PM_{10}, NO_2, SO_2 and CO were collected in Bogota and Bucaramanga from the city air quality networks. For Bogota, we used an average concentration from the 14 monitoring stations to represent air quality in the city. For Bucaramanga, we used the downtown monitoring station given the availability of air quality records at that site.

ii. *Emission inventories consolidation and update*. Emission inventories for mobile and point sources in Bogota were available for 2008. For Bucaramanga, only point sources were accounted in 2010. The mobile source emission inventory was updated to 2011 considering the increase in the vehicular fleet, the fleet renovation and changes in driving patterns as a result of car restriction programs. The point source emission inventory was updated according with the change in Colombia´s GDP during 2008-2011.

iii. *Association between emission and ambient air concentrations*. We adjusted a linear regression model between emissions and ambient concentrations of PM_{10}, NO_2, SO_2, CO in Bogota and Bucaramanga in the period 2008-2011. From this model, we obtained a slope K_i ($\Delta C_i/\Delta E_i$) that represents the change in ambient concentrations due to the change in emissions. Each regression is evaluated for its statistical significance based on the correlation coefficient (R^2) and the p-value.

iv. *Assessment of emission changing scenarios*. Emission inventories were projected to 2035 under different scenarios: business as usual, fuel conversion in point sources (coal replaced with natural gas in industries), implementation of diesel particle filters (DPF) in buses and trucks, relocation of industry outside the city, and low-carbon development strategies.

v. *Estimation of change in ambient air concentrations due to change in emissions*. Using the slope K_i from the linear regression model, we estimate the ambient air concentrations in 2035 under the proposed emission changing scenarios (ΔE_i).

vi. *Assessment of impact on public health*. Infant mortality due to respiratory diseases was the selected outcome for the assessment of air quality impacts on public health. Epidemiological information (Risk Ratios) was obtained from the World Health Organization (WHO) to assess the change in health under the different emission scenarios.

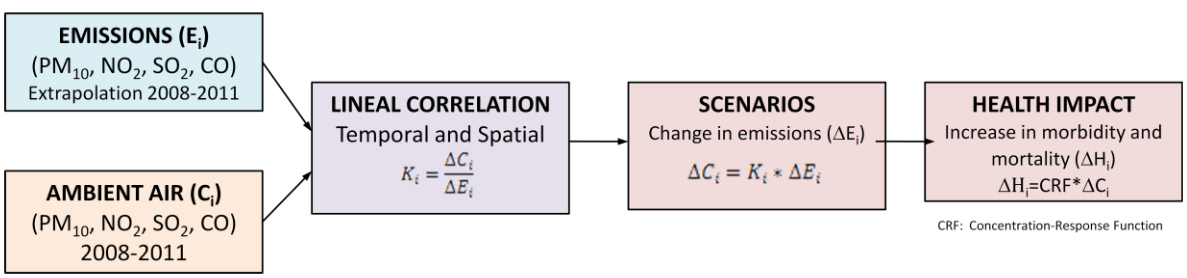

Figure 1 Summary of the method for estimating future air quality in Colombia

Results

i. Air quality in Bogota and Bucaramanga

In Bogota, particulate matter (PM) is the pollutant of most concern. Annual average concentrations of PM10 from 2007-2011 ranged 53.1-59.2 ug/m^3, above the air quality standard of 50 ug/m^3 (MAVDT, 2010). Reduction in PM10 concentrations during that period was around 14% due to several factors: diesel quality improvement (from 450 ppm of sulfur before 2008 to 50 ppm of sulfur after 2008), replacement of coal by natural gas in industrial heaters and boilers, private and public vehicle restriction of circulation based on the last number of the license plate, rapid private fleet renovation, among other factors. Other pollutants (NOx, CO, SO_2) are in general below the standards, with a decreasing trend for CO (40% reduction due to private fleet renovation) and increasing trend for NO_x (15% increase due to conversion of taxi fleet to natural gas).

In Bucaramanga, PM10 concentrations exceed the national standard at the downtown air quality station with annual averages ranging from 71.3 ug/m^3 in 2007 to 53.5 ug/m^3 in 2011. PM in the downtown area is originated mainly from mobile sources and chicken boilers. NO_x concentrations show an increasing trend (45% increase from 2006 to 2011) while SO_2 and CO show a decreasing trend.

ii. Emission inventory consolidation for Bogota and Bucaramanga

In Bogota and Bucaramanga, emissions of CO, NO_x and SO_2 are dominated by mobiles sources. Emissions of PM are approximately 50% from mobile sources and 50% from point sources in Bogota, while in Bucaramanga PM from mobile sources constitute 62% of the emissions (Table 1). In Bogota, private vehicles emit 75% of CO and 76% of SO_2 while buses and trucks emit 76% of PM to the atmosphere. In Bucaramanga, a similar distribution is expected, with most of the PM emitted by heavy-duty vehicles.

Table 1 Emission inventories in Bogotá and Bucaramanga (2008)

City	Ton/year	**PM**	**SO_2**	**NOx**	**CO**
Bogotá	Point sources	1.017	1.742	2.088	507
	Mobile sources	1.386	13.840	58.073	642.411
	Total	2.403	15.581	60.161	642.918
Bucaramanga	Point sources	83,4	203	86,4	42,6
	Mobile sources	135	1 458	4 501	66.568
	Total	218,5	1 661	4 587	66 610

*For Bogotá, emission inventories from (Rodríguez y Behrentz, 2009; Fandiño y Behrentz, 2009; Rojas y Peñaloza, 2010). For Bucaramanga, emission inventories from (Rangel y Tami, 2010; Núñez y Sarmiento, 2011).

Vehicle fleet has substantially increased in Bogota and Bucarmanga in the last years, especially motorcycles (92%) and private vehicles and pickups (35%). On the other side, public buses in Bogota have shown a slight decrease due to oversupply control policies from the local government. In point sources, the most consumed fuels are coal, natural gas, and to a lesser extent oil, fuel oil and LPG. Burning of coal is responsible of 84% of PM and SO_2 emissions, while burning of natural gas accounts for 70% of NO_x emissions.

The mobile source emission inventory was updated to 2011 considering the increase in the vehicular fleet, the fleet renovation and changes in driving patterns as a result of car restriction programs. The point source emission inventory was updated according with the change in Colombia´s GDP during 2008-2011. Emissions from mobile and point sources were added to estimate total emissions (Table 2).

Table 2 Projection in Bogota´s emissions from 2008-2011

Emissions (ton/yr)	**2008**	**2009**	**2010**	**2011**
CO	642918	608211	650269	722532
NO_x	60161	57832	59850	61727
MP	2403	2395	2437	2478
SO_2	15581	14555	15559	16539

iii. Relationship between emissions and concentrations for 2008-2011

Based on a liner regression model, we obtained relations between emissions and concentrations for mobile and point sources independently. We evaluated these relationships for statistical significance (R^2 and p-value) and found the following significant relations (Table 3):

- The increase of 1,000 tons / year of NO_x from mobile sources is reflected in an increase of 0.58±0.38 ppb of NO_x in the atmosphere
- A reduction in PM concentrations of 100 ton/year in point or mobile sources (buses and trucks) corresponds to a reduction of approximately 5.0±4.5 ug/m^3 in the atmosphere.
- The reduction of 100 tons / year of SO_2 from mobile sources (buses and trucks) correspond to a reduction of approximately 7.0±1.7ppb of SO_2 in the atmosphere, while the reduction of 100 tons / year of SO_2 from point sources correspond to a reduction of 4.5±2.0 ppb of SO_2.
- For CO, no significant association was found.

Table 3 Relations between emissions and concentrations for Bogota (highlighted are relationships used as indicators for this study)

POLLUTANT	**MOBILE SOURCES**	**POINT SOURCES**
NO_x	$\frac{0.58 \pm 0.38ppb}{1.000ton/yr}$	$\frac{2.34 \pm 0.23ppb}{100ton/yr}$
MP	$\frac{4.6 \pm 4.6\mu g/m^3}{100ton/yr}$ Only applies for the category B+MB+C	$\frac{5.5 \pm 5.4\mu g/m^3}{100ton/yr}$
SO_2	$\frac{6.9 \pm 1.7ppb}{100ton/yr}$ Only applies for the category B+MB+C	$\frac{4.5 \pm 1.98ppb}{100ton/yr}$

For Bucaramanga, a similar approach to Bogota was conducted, yielding the following relations (Table 4):

- The increase of 1000 ton/year of CO from mobile sources is reflected in an increase of 0.0091±0.0041 ppm of CO in the atmosphere
- The increase of 1 ton / year of NO_x from mobile sources is reflected in an increase of 0.035±0.028 ppb of NO_x in the atmosphere
- A reduction in PM concentrations of 1 ton/year from mobile sources corresponds to a reduction of approximately 0.20±0.08 ug/m^3 in the atmosphere.

Table 4 Relations between emissions and concentrations for Bucaramanga (highlighted are relationships used as indicators for this study)

POLLUTANT	MOBILE SOURCES
CO	$\frac{0.0091 \pm 0.0041 ppm}{1000 ton/yr}$
NO_x	$\frac{0.035 \pm 0.028\, ppb}{1 ton/yr}$
MP	$\frac{0.19 \pm 0.08 \mu g/m^3}{1 ton/yr}$

iv. Assessment of emission changing scenarios

Mobile source emissions were projected to 2035 according to the expected growth of the vehicle fleet, according with the expression: $Emis_{2035}$= $Emis_{2010}$/Number of $vehicles_{2010}$ * Number of $vehicles_{2035.}$ Emissions from point sources were projected to 2035 considering Colombia´s GDP growth (5.7% for 2015, 5.6% in 2020, 5.6% for 2035).

Baseline scenario was defined as "business as usual", that is, the increase in emissions from the vehicle fleet and the industrial activity without taking any control measures in the following years. Under a "business as usual" scenario, PM10 concentrations in Bogota and Bucaramanga remain above the normative value and tend to increase to harmful concentrations to human health (Figure 2).

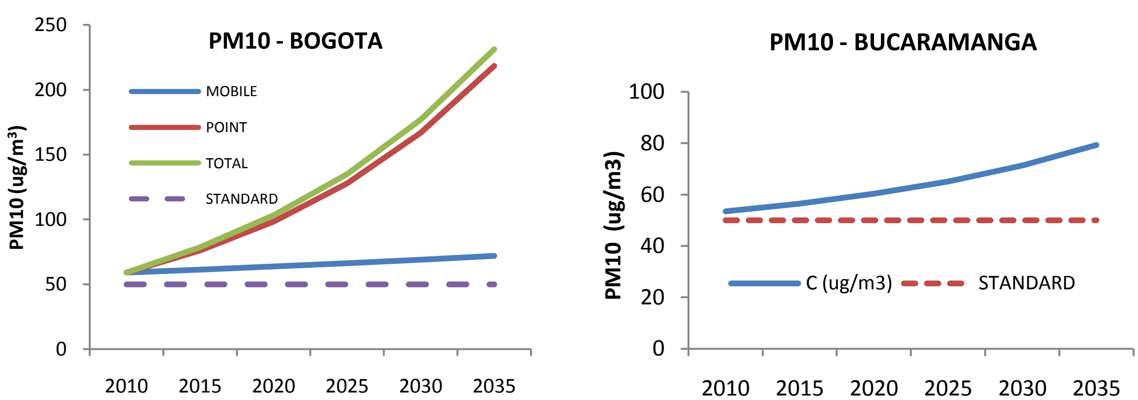

Figure 2 PM10 projections for Bogota and Bucaramanga on a "business as usual" scenario

v. *Estimation of change in ambient air concentrations due to change in emissions*

The application of strategies to control PM10 in point and mobile sources generate a significant improvement of air quality, especially in Bogotá (Figure 30).

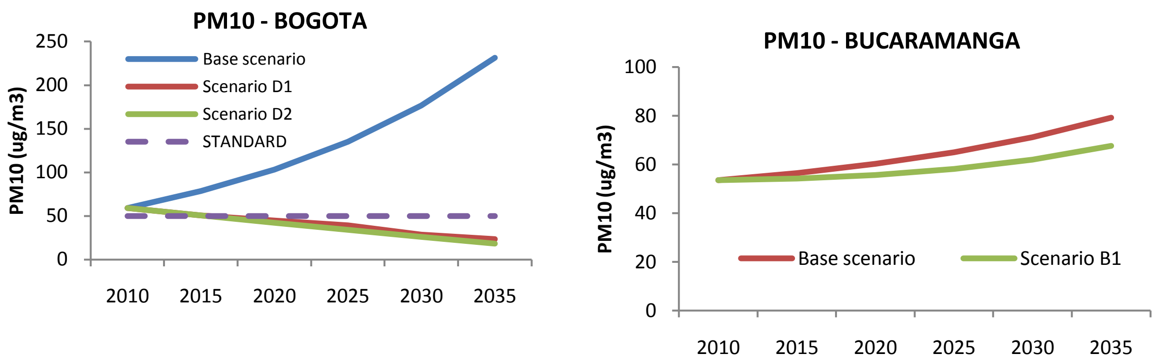

Figure 3 PM10 projection for Bogota and Bucaramanga under different scenarios. In Bogotá, baseline scenario was evaluated as 'business as usual'; Scenario D1: industry is gradually relocated out of the city (20% by 2015, 50% in 2025, 90% by 2035). Scenario D2: gradual replacement of coal-fired boilers to natural gas (20% by 2015, 30% in 2020, 50% by 2030) and gradual installation of particulate diesel filters on buses and trucks (20% by 2015, 30% in 2020, 50% by 2035). For Bucaramanga, baseline scenario is 'business as usual' scenario and D1 is the gradual installation of particulate filters on buses and trucks (10% by 2015, 50% by 2035).

Under a low-carbon development scenario, air quality significantly improves and the city meets the PM10 standard (Figure 4). However, the renewal of diesel trucks should be maintained in the years and the low-carbon strategy should be applied to private vehicles as well, to maintain a good air quality in the city.

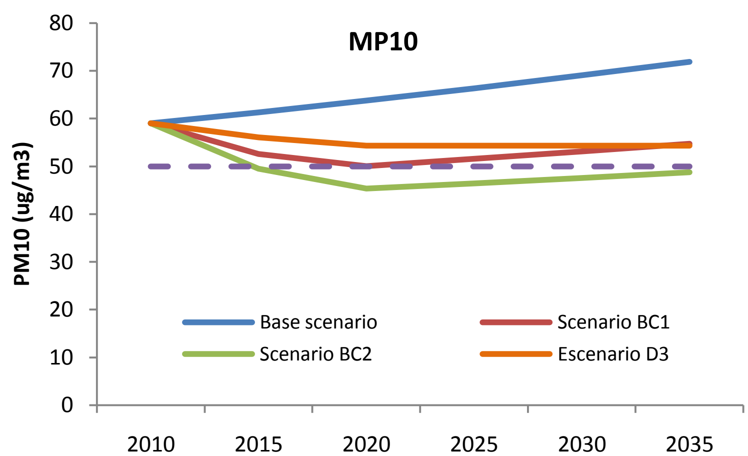

Figure 4 PM10 projections in Bogota under low-carbon development scenarios. Scenario D3: Bogota reduces 20,000 to 12,000 the number of diesel buses; Scenario BC1: 60% of the diesel fleet is converted to hybrid and electric buses; Scenario BC2: renewal 60% of trucks in the city, others are scrapped.

In evaluating the renewal of 20% of the city private vehicles by electric cars, this strategy shows that the air quality benefits are few, since private vehicles do not emit significant amounts of particulate matter to the environment, as buses and trucks do. There are more benefits in the reduction of CO_2 to the atmosphere by this strategy.

vi. Assessment of impacts on public health

To assess the impact on human health, infant mortality due to respiratory diseases was chosen as base indicator. The incidence of mortality due to the increase in PM10 concentration with respect to the base concentration is estimated as: $E = AFxBxP$, where AF = impact fraction for respiratory disease and is related to the risk ratio. This model implies a liner relationship between PM10 and infant mortality cases. As PM10 concentrations increases, more cases of death due to respiratory diseases are expected (Figure 5).

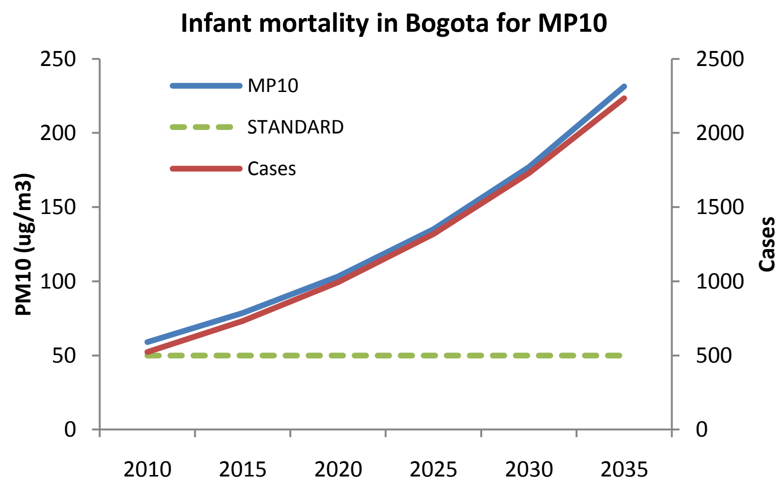

Figure 5 Infant mortality due to increase in the concentration of PM10 in Bogota under a "business as usual" scenario.

Conclusions

A system of nodes of cities is proposed to Colombia in such a way that city´s needs that cannot be satisfied by the city itself are satisfied by other cities increasing the efficiency of the system. This approach implies environmental challenges that can be assessed through the use of environmental indicators. A linear relationship was adjusted between ambient air concentrations and emissions to built indicators that address the change in air quality in the future due to the change in emissions from mobile and point sources. If no emission controls are implemented in the nodes of cities in the future, cities will reach harmful level of pollutants. Controls in mobile sources (implementation of DFP in buses and trucks) and point sources (replacement of coal with natural gas in boilers and heaters) were found effective to reduce levels of particulate matter in big and intermediate cities. Strategies associated with a low-carbon development policy in the country can also be effective to abate air pollution in cities.

While the development and implementation of an air quality model is still in progress in Bogota and most Colombian cities, the approach presented in this study constitutes a simple method to evaluate air quality in the future and can be easily implemented in cities where air quality records and emission inventories are available. However, some limitations are recognized: the effect of meteorology is neglected, which can influence the relationship between emission and concentrations; statistical significance for the linear relationship is based on the amount of data, which for our case was only four years, it is recommended a greater number of years; for this study we focused exclusively on mobile and point sources, but there are other emission sources that can contribute with pollutants to the atmosphere in Colombian cities such as landfills, wildfires, constructions, airports, erosion.

References

Fandiño, M & Behrentz, Eduardo. 2009. Actualización del inventario de emisiones de fuentes fijas para la ciudad de Bogotá, a través de mediciones directas. Disponible en: http://biblioteca.uniandes.edu.co/Tesis_12009_primer_semestre/525.pdf

Ministerio de Ambiente, Vivienda y Desarrollo Territorial. Resolución 610 de 2010, por la cual se establecen niveles máximos permisibles de calidad del aire en el territorio nacional. Avilable at: http://www.minambiente.gov.co/documentos/normativa/ambiente/resolucion/res_0610_240310.pdf

Núñez Herrera, Jorge Armando y Sarmiento Garcés, Diana Sofía. Inventario de emisiones atmosféricas de las fuentes fijas ubicadas en la vía Girón-Bucaramanga desde el puente El Palenque hasta el Colegio La Salle. Corporación Autónoma Regional para la Defensa de la Meseta de Bucaramanga (CDMB), Bucaramanga, 2011.

Rangel Ortiz, Sonia Patricia y Tami Pimiento, Leidy Magaly. Inventario de emisiones atmosféricas de las principales fuentes fijas ubicadas en la zona industrial de Chimita a lo largo de la via entre El Palenque y Café Madrid. Universidad Pontificia Bolivariana, Corporación Autónoma Regional para la Defensa de la Meseta de Bucaramanga (CDMB), Bucaramanga, 2010.

Rodríguez, Paula y Behrentz, Eduardo. 2009. Actualización del inventario de emisiones de fuentes móviles para la ciudad de Bogotá, a través de mediciones directas. Disponible en: http://biblioteca.uniandes.edu.co/Tesis_12009_primer_semestre/524.pdf

Rojas, Néstor y Peñaloza, Eduardo. 2010. Distribución espacial y temporal del inventario de emisiones provenientes de las fuentes móviles y fijas de la ciudad de Bogotá. Convenio 195-08, Fortalecimiento y desarrollo de herramientas de modelación meteorológica y de calidad de aire para Bogotá D.C. Ecopetrol, Secretaría del Ambiente, Universidad Nacional de Colombia.