GIS MODEL FOR AIR QUALITY CONSIDERATION IN THE STRATEGIC DESIGN AND EVALUATION OF BICYCLE INFRASTRUCTURE: CASE STUDY IN BOGOTA

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ABSTRACT

Particulate matter smaller than 10 microns (PM_{10}) is a major air pollutant in cities, particularly in the developing world where maximum levels recommended by the World Health Organization (WHO) are frequently exceeded. Pedestrians and cyclists are likely to be more exposed to PM_{10} than other road users. Limited work exists today in transforming large area emission information data (commonly available through field work) into concentrations. This paper presents a spatial model developed in geographic information systems (GIS) for the evaluation of bicycle infrastructure based on air quality conditions. The model developed transforms emissions data into differential concentrations of PM_{10} based on distance from the emission sources. The model requires input data for mobile source emissions, which are commonly estimated from a transport model, and emissions from fixed sources (normally obtained thorough field work). With these inputs and the description of the bicycle network, the model identifies critical areas of exposure to PM_{10}. Results for the application of the model in Bogota - Colombia suggest that there are critical areas today where people are encouraged to cycle in high concentrations of PM_{10}. Also, it was found that the model appears to facilitate the assessment of hotspots but it has some limitations for entire

corridors results. Further research is required to include additional variables likely to affect PM_{10} concentration such as wind direction, height of buildings and temperature changes.
Keywords: Urban air quality, GIS modelling, cycling planning and assessment, concentration of PM_{10}

INTRODUCTION

Particulate matter smaller than 10 microns (PM_{10}) is a major air pollutant in cities, particularly in the developing world where maximum levels recommended by the World Health Organization (WHO) are frequently exceeded. Pedestrians and cyclists are likely to be more exposed to PM_{10} than other road users as they are in more direct contact to the air quality environment and have higher respiration rates than motor vehicle passengers (O'Donoghue, Gill, McKevitt, & Broderick, 2007).
Parallel to this, cycling has been promoted as an efficient and effective mode to address sustainability and mobility challenges. However, planning, design and development of these bikeways rarely consider PM concentrations as a strategic variable. Today there are limited tools to determine if cycling infrastructure is being proposed or provided in areas with high concentration of PM_{10} or any other airborne pollutants. The lack of these tools may generate additional health risks when encouraging large number of people to cycle in areas with high PM_{10} concentrations.
Although information about emissions of PM_{10} from fixed and mobile sources are obtainable through fieldwork, limited research exists today to transform these emissions into concentrations with a spatial distribution appropriate for decision-making.
This paper presents a spatial model developed in geographic information systems (GIS) for the evaluation of bicycle infrastructure based on air quality conditions. It is divided into four parts. In the first part we present a literature review of current state-of-the-art for urban air quality related to the evaluation of cycling infrastructure. In the second part we present the description of the model including the methodology used for obtaining results. The third part describes results from the case study in Bogotá Colombia. Finally, conclusions and opportunities for further research are presented.

BICYCLE NETWORK PLANNING AND AIR QUALITY ISSUES

Air quality implications for cycling

In many countries, cycling constitutes an important proportion of the mobility options in the cities. This is due to its low cost for the users and in busy cities it is sometimes the most time efficient mode of transport. However cycling infrastructure varies markedly between countries and even within cities. In some cities, cycling has a very high priority with governments spending considerable funds to provide dedicated cycling infrastructure that maintains separation between cyclists and motorists. In other places, cyclists have to share busy roads with little provision for their safety or comfort. In developed countries cycling may be a worthwhile option for the relatively wealthy inhabitants of the city and inner suburbs, but in developing nations cycling is largely the domain of the poor.

Bogota is a crowded busy city and buses running on high sulphur, low quality diesel produce exhaust gases with heavy particulate loads. Cyclists are particularly vulnerable to pollution both on the road and in road corridors due to their proximity to the mobile pollution sources (buses) and their relatively high respiration rate (when compared with pedestrians and motor vehicle drivers/passengers). The high proportion of buses burning diesel is of particular concern in Bogota as studies have found that the exposure of commuters to particulate matter is affected by the fuel type (Zuurbier, 2010) as well as mode of transport and route selection.

Epidemiological studies have demonstrated links between long term exposure to fine particulate matter in the air and adverse health outcomes (Pope III CA, 2006). A study in the Netherlands of the effects of fine (PM_{10}) and ultrafine particles (smaller than PM_{10}) demonstrated a link between elevated particulate exposure to cyclists and lung function six hours after exposure (Strak M, 2010). Another study in the Netherlands links chronic exposure to particulates with increased mortality and morbidity across the population as a whole (Brunekreef B, 2009). It is therefore desirable to reduce the impact of particulates on cyclists and the population generally.

Modelling the particulate emissions may enable the selection of better transit routes for cyclists and might better inform planning of future cycling infrastructure. Further, the modelling may also lead to an estimate of the health implications and public health costs of different transport planning strategies for all transport system users and not just cyclists.

Air quality modelling

In order to estimate the concentrations a Gauss Plume dispersion model was applied. This model allowed the estimation of concentrations at ground level without having high computational demands, instead of a messo scale atmospheric model that would not give the local detail needed. Concentrations were estimated using the following equation:

$$c = \frac{Q}{2u\pi \bullet \sigma_y \sigma_z} \bullet \exp - \left[\left(\frac{y^2}{2\sigma_y^2} \right) + \left(\frac{z^2}{2\sigma_z^2} \right) \right]$$

$$\sigma_y = 213.\, x^{0,894}$$

$$\sigma_z = 440{,}8.\, x^{1,941} + 9{,}3$$

Where c is the concentration of particulates, Q represents the total emissions, u is the wind velocity, σy and σx are the vertical and horizontal dispersion coefficients and y and z are the displacements on the y and z axis from the source to any given point in the direction of the dispersion.

Emissions:

In order to estimate the total emissions for different sources in Bogota, PM_{10} sources were divided in two: fixed sources and mobile sources. Other possible particulate sources such as area and natural sources were not considered in the model. The formation of secondary PM was also neglected due to the lack of local data in this subject.

Mobile sources:

Total emissions from mobile sources were estimated for the morning peak hour using the transport model of the city developed in Visum by the Urban and Regional Sustainability Group at Universidad de los Andes. This is a four-stage model based on the local O/D matrices according to citywide surveys and calibrated using several vehicle counts in different areas. The model estimates geo-referenced vehicle counts for the entire city divided into different categories such as public transport, private transport and freight transport. Emissions for each link in the city's network are estimated using the following equation:

$$E_i = l_i \cdot \sum_{j=1}^{n} Fe_j \cdot N_{j,i}$$

Where l_i is the length of link *i*, Fe is the emission factor for a given vehicle category *j* and $N_{j,i}$ is the number of vehicles in category *j* in link *i*. Emission factors for the different categories were obtained from the city's Air Quality Management Plan (Behrentz, 2010).
Once the emissions for every link were estimated, each link was divided in ArcGis in 10-meter cells so the total emissions were divided accordingly. The Gauss model will also require an emission height for mobile sources. This was defined as 3 meters for every cell in order to allow the dispersion of the tailpipe emissions and consider each cell as a homogeneous emission source.

Fixed sources

The emissions from fixed sources were estimated using a results form (Fandiño, 2009). The authors produced a geo-referenced database of fixed sources in the entire city using isokinetic measures in selected sources. Using the results from their measures, an extrapolation was done for all other fixed sources identified according to their categories and fuel types. Their work included a correction factor for fixed sources that are not registered in the local authority's database; considering that about 20% of fixed sources in Bogota are part of the informal sector and thus, are not registered. Unfortunately, the database provided by Fandiño and Behrentz (Fandiño, 2009) does not include the chimneys heights, namely the z-coordinate in the Gauss model. These were estimated by assuming that all chimneys in the city comply with the national norm of minimum chimney height according to emissions volume and temperature. According to the national standards, minimum chimney heights should be calculated using Figure 1:

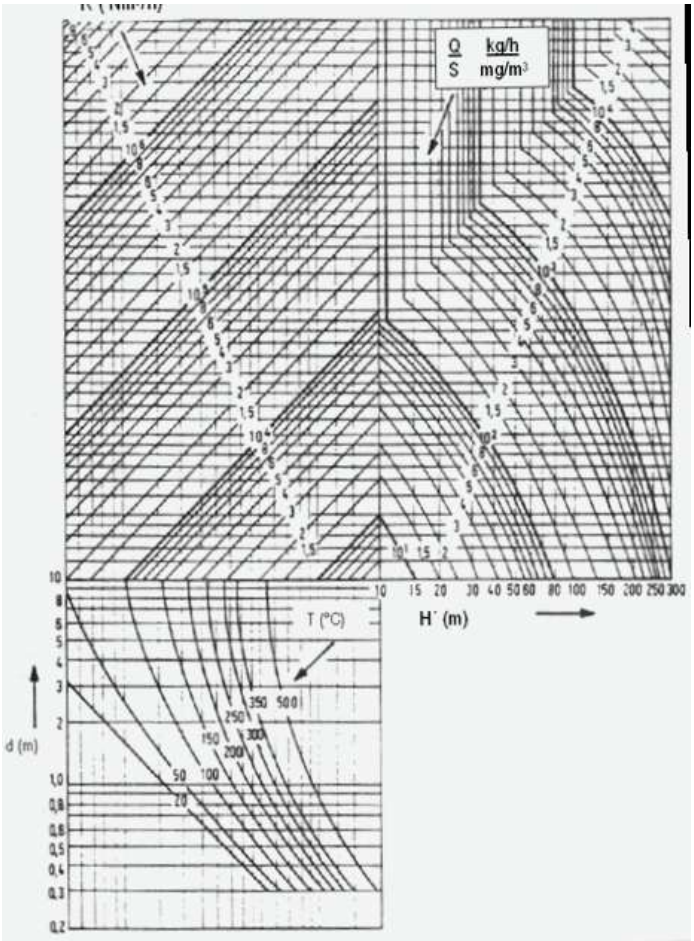


Figure 1 - Estimation of chimney heights in Bogota according to emission rates and operating temperatures.

Other variables

Wind speed was estimated using average results from the city's meteorological stations for the morning peak hour for the period 2008-2009. Although there is enough information to determine not only a general wind speed for the entire city but also wind direction and different speeds for different zones, this was left for future exercises. The selected wind speed was 2m/s and concentrations were estimated for all possible wind directions.

Vertical and horizontal dispersion coefficients where determined using Figure 2. During the morning peak hour in a typical workday in Bogota, there are low wind speeds and strong solar radiation, so a stability category type A was assumed.

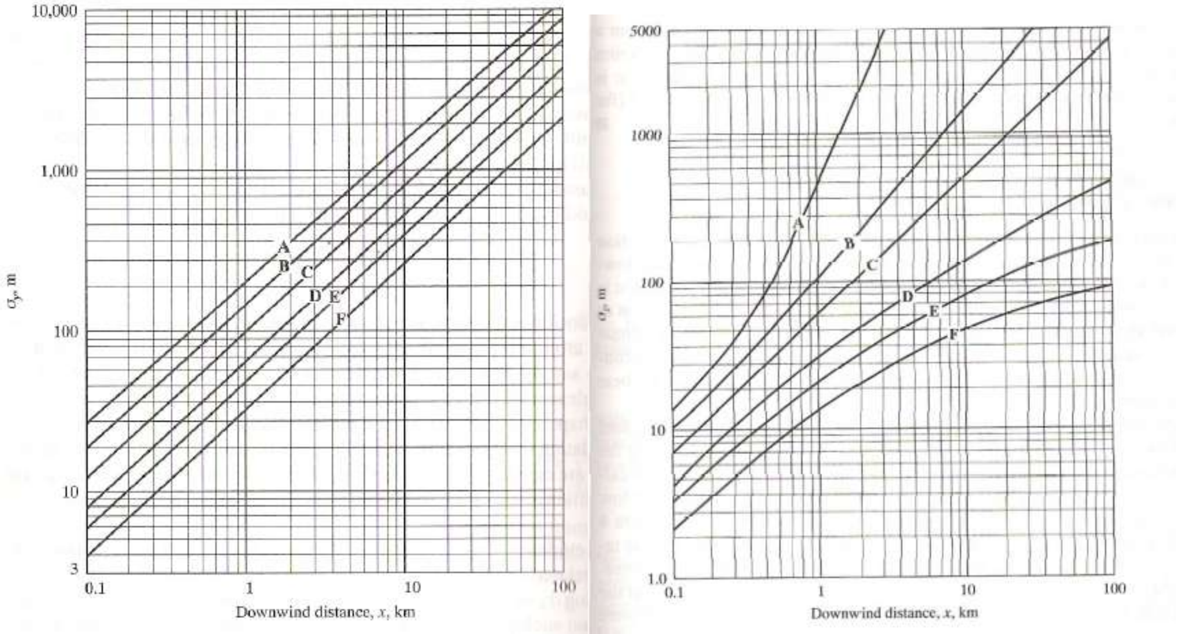


Figure 2 - Charts for the definition of vertical and horizontal dispersion coefficients (From Wang et al. 2004)

In addition to the concentrations associated to the Gauss Plume dispersion modeling, Bogota's background concentration was determined using reports from the air quality monitoring network. The city's network includes two stations that have been traditionally used for background concentrations of PM_{10}, namely *El Bosque* and *Escuela.* Average concentrations from those stations in the period 2007-2009 were determined in order to estimate the background concentration. According to the available data, this concentration was defined as 37.5µg m^{-3}.

METHODOLOGY AND MODEL DESCRIPTION

The evaluation of cycling infrastructure under air-quality parameters requires assessing the location (existing and/or proposed) of the infrastructure and the levels of concentration of PM_{10}.

To do this, the model developed is divided in two parts. The first part uses emission information to produce a general map of the concentrations for the whole city. Then, in the second part, the model identifies areas of the city in which high concentrations occur in close proximity to cycling infrastructure.

Map constituted by cells which values and colors are representing the PM10 concentration superposed with the map representing the bicycle infrastructure (paths).

Identification (in red) of bicycle paths pieces passing by high PM10 concentrations.

Figure 3 – Explanation of the two parts of the methodology

Modelling Part 1: Development of a PM_{10} citywide concentration map

The aim of this part is to visualize PM_{10} concentrations in the whole city of Bogotá. The key question addressed is where PM_{10} concentrations exceed the international and national recommendations for health.

Data collection

PM_{10} are particles emitted by motorized vehicles and industrial chimneys. Sources of PM_{10} are divided into two: fixed sources (chimneys) and mobile (vehicles). To apply the plume model, various characteristics of these sources are needed in a spatial form including:

- For fixed sources:
  - Location
  - Emissions per time unit
  - Height of the chimney
- For mobile sources:
  - Location and length of the major transport links
  - Traffic volumes per type of vehicles in each link

Model logic

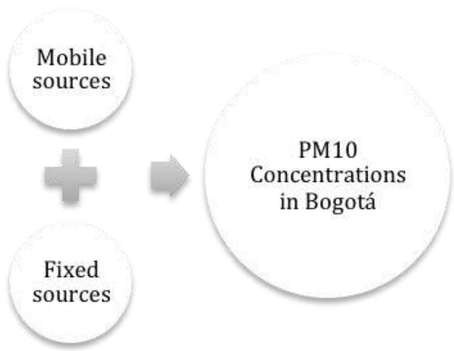


Figure 4 - General emission inputs for the model

Variables of the Gauss equation such as height and emission are proper to each source and this implies to calculate links and chimneys concentrations distribution one by one. To achieve this, ArcGIS ModelBuilder was used to calculate for each source an individual concentration effect that will be then aggregated at the citywide level. The model developed selects another source for each round and calculates its concentration and spatial distribution.

The following equation shows how individual concentrations were calculated for fixed sources as detailed in the precedent part:

$$C = \frac{Q}{2\, u\, \pi\, \sigma_y \sigma_z} \exp(-\left[\left(\frac{y^2}{2{\sigma_y}^2}\right) + \left(\frac{z^2}{2{\sigma_z}^2}\right)\right]$$

The equation was applied to each source using the “raster calculator” tool and the attributes of the initial layer. The distance x is the one obtained using “Euclidian Distance” tool. At the end, fixed sources where summed up together as well as mobile sources. And a final map was obtained summing both source types.

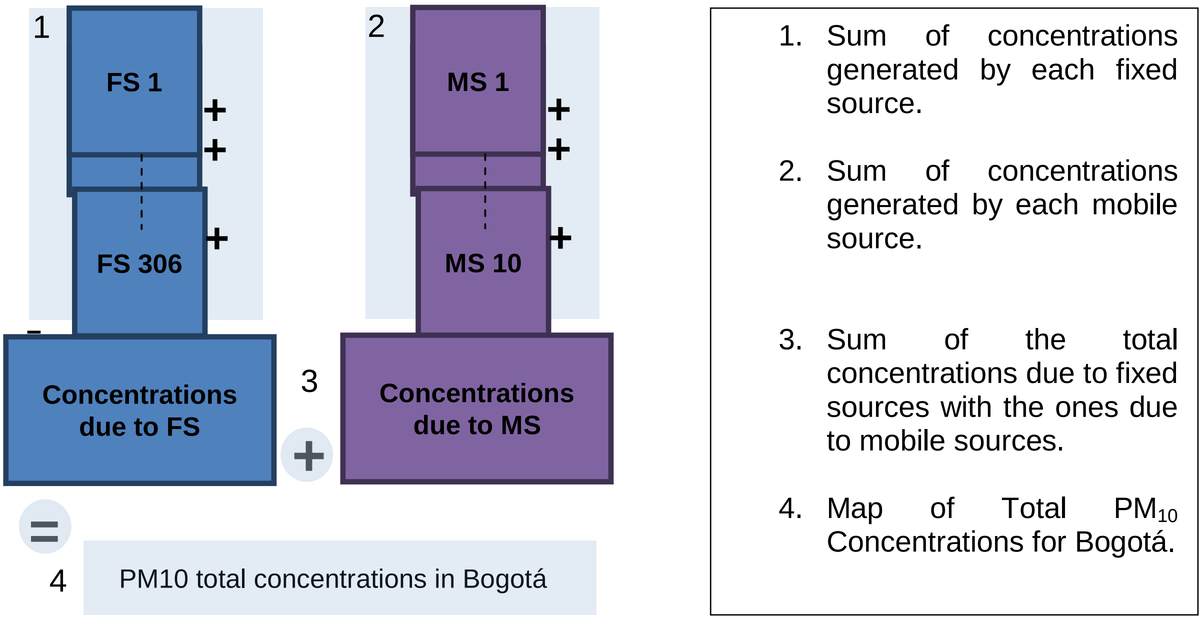


Figure 5 - Modelling part 1 scheme

For mobile sources, traffic flows for the two directions of each link were summed. Then, ten groups of these sources were created corresponding to different ranges of emissions. The average emission (according to the range) was assigned to each group.

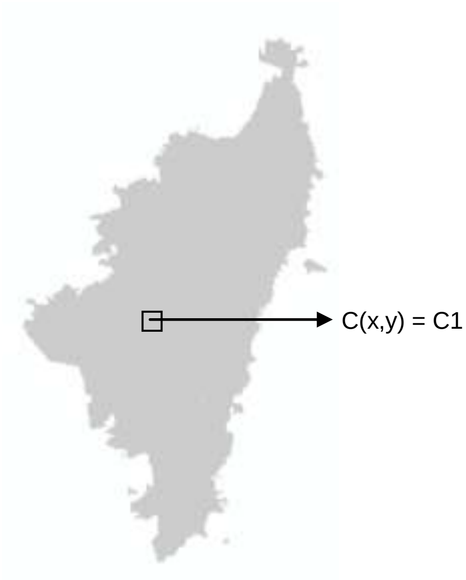
Figure 6 - Sum of the two directions to form one source, one link

Considerations in the logic of the model

The Fixed sources are modelled as point sources with an influence over a 1000m radius. This is the maximum distance value when running the Euclidian Distance tool.
The Mobile sources are modelled lines (links). The influence distance of these links is about 100m. A rectangular geometry of 100m of width was created on both sides of each link to take into account this distance.
For the mobile sources another issue appeared: how to treat link intersections. For this study we considered that concentrations are the sum of the concentrations caused by each link at the intersection but it is not the case in the reality as chemical reactions occur. So, after applying the model to one group level, we selected the intersections of the rectangular areas surrounding each link of the group. With GIS tools, the number of original rectangles constituting the intersection can be obtained. The value of the cells included in these intersections is multiplied by this number (x times the initial concentration).

Modelling Part 2: identification of areas with high PM_{10} concentration and the presence of cycling infrastructure

The preceding part explained the first step of the method. With this methodology a map representing total PM_{10} concentrations for Bogotá was developed. This study aims to evaluate the bicycle infrastructure in terms of air quality. Thus, the next step is to analyze where the bike paths go occur on the PM_{10} concentration map.
To realize this analysis, characteristics of bicycle paths were needed. A GIS file including length and location of the links constituting the bicycle paths was used. This bicycle paths layer was converted into Raster with cells of 10mx10m. The GIS tools attributed to each raster cell of this layer, the PM_{10} concentration equal to the value of the cell located with the same coordinates in the concentrations map of Bogotá.



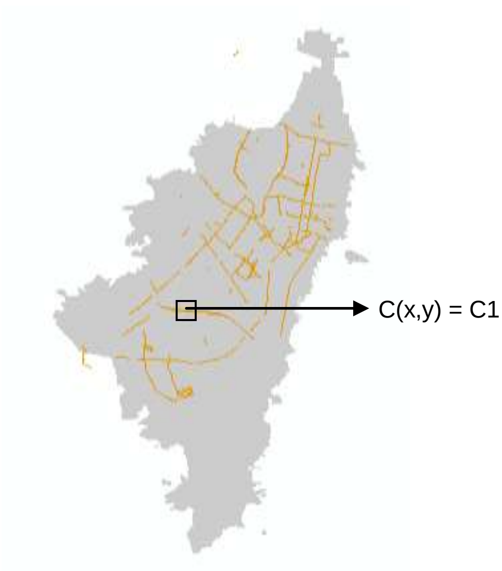


Figure 7 - Illustration of bike paths cells' value assignation

This method generates a map of bike paths compounded by cells whose value is the PM_{10} concentration at this point. Statistics can be obtained counting the percentage of cells that present a concentration included in a determined range.

CASE STUDY - BOGOTA

The model developed was tested in the city of Bogotá – Colombia. Bogota has more than 350 km of segregated bikeways along the city's main road and water corridors developed for the last 15 years. These bike paths, as commonly happens, were developed where available space existed rather than using a strategic plan to serve main destinations of the city. This means that large roads with some available space were the primary target for cycling infrastructure.

However, it was not considered during these developments that large roads carry significant traffic volumes and are, therefore, a source of high concentration of PM_{10} to cyclists. Similarly, locations of fixed sources of PM_{10} were not considered.

Applying the methodology developed before, a GIS analysis was performed in order to visualize and evaluate PM_{10} concentrations in Bogotá.

This section presents several maps of PM_{10} concentrations in Bogotá highlighting the spatial location of bike paths to examine whether or not they pass through high PM_{10} concentrations. These maps are accompanied by analysis of the air pollution level comparing it to international and national recommendations.

At the city-wide scale, some places are highlighted as zones of major exposure for cyclists.

Background concentration

The background concentration of PM_{10} particles for Bogotá is of 37,5 µg/m^3 while the annual average recommended by the World Health Organization is of 20 µg/m3, (WHO, 2005).

The following conclusion of a WHO's study justifies this recommendation: "The WHO Air quality guidelines indicate that by reducing particulate matter (PM_{10}) pollution from 70 to 20 micrograms per cubic metre, we can cut air quality related deaths by around 15%." (WHO, 2005).

Thus, Bogotá already exceeds the recommended value for PM_{10} concentrations for the background concentration, exposing its inhabitants to increased risk of respiratory and cardiovascular diseases.

Results for mobile sources

Concentrations calculated on the basis of the mobile sources emissions reach almost 20 µg/m^3. Adding the background concentration, it goes up to 57,5 µg/m^3. Figure 8 presents the concentrations due to motorized vehicles with the links of the road network considered as the sources. Figure 9 shows the consequences of the modelling methodology at the street level.

Figure 8 – Map: PM_{10} Concentrations in Bogotá due to mobile sources

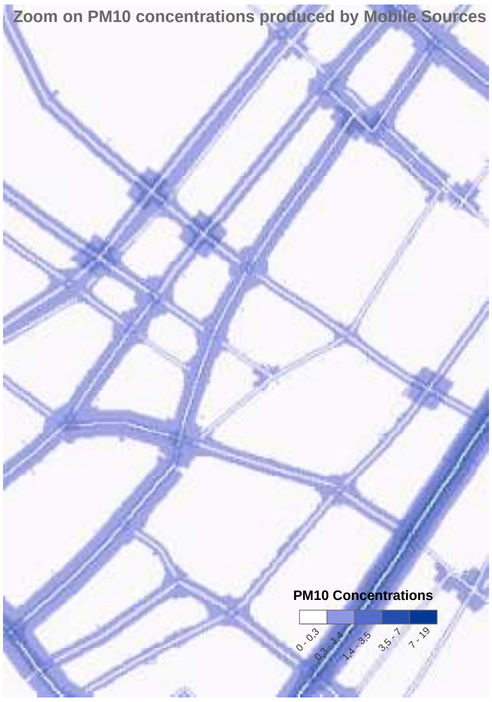


Figure 9 – Map: Model simplifications; Visualization of concentration value at intersections and Gauss distribution around a link.

Results for fixed sources

The highest PM_{10} concentration produced by fixed sources is of 3119 µg/m^3.
Figure 10 shows the total concentrations in Bogotá summing concentrations due to mobile sources, fixed soures and the background concentration.

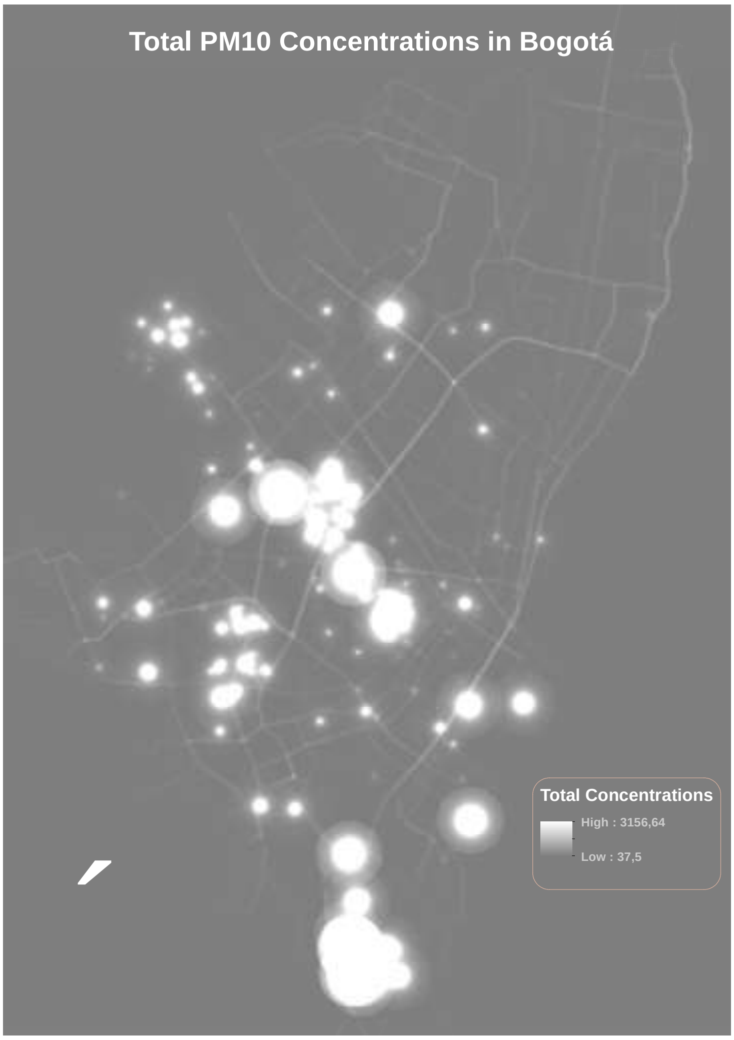


Figure 10 – Map: Total Concentrations

Cyclists' exposure to PM_{10}

The PM_{10} concentration recommended by the WHO is of 20 µg/m3.
The PM_{10} concentration recommended by the Colombian Administration is of 50 µg/m3.
Figure 11 shows the classification of the bike paths using the value recommended by the Colombian Administration, it also presents a relative classification of Bogota's bike paths in terms of PM_{10} concentration.

Figure 11 – Map: classification of Bogotá's bike paths following National recommendations

A critical situation is demonstrated for the cyclists using some bicycle paths. particularly when they pass near chimneys as shown in figure 12:

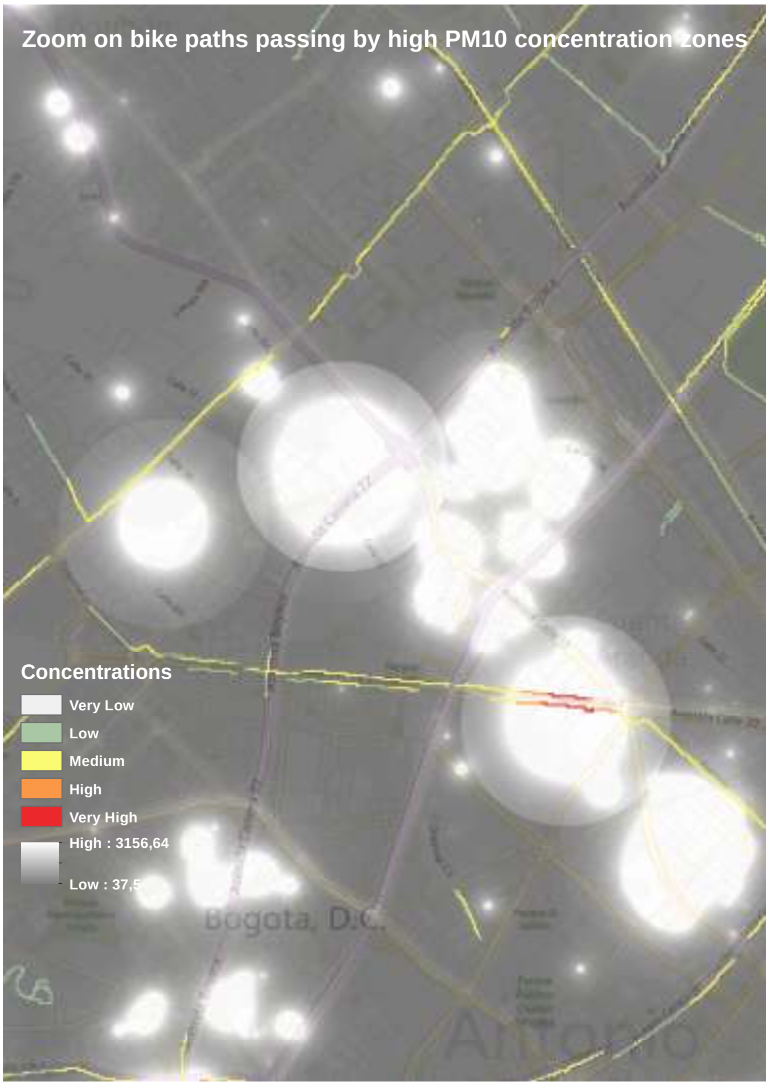


Figure 12 – Map of high PM_{10} concentrations along bicycle paths

These results were summarized into a table to draw up the balance sheet of the study.

Table I – Proportion of bike paths respecting the National recommendation

PM_{10} Concentration Range (in µg/m3)	< 50	50-150	> 150
Bike Paths Percentage passing by these concentrations ranges	0,97	0,026	0,003
Equivalent in kilometers	236,81	6,45	0,8

CONCLUSIONS

The model allowed the transformation of emissions data (which is commonly available or accessible through field work) into differential concentrations of PM_{10} based on distance from the emission source. With this information and the use of spatial analysis, it was possible to identify critical areas of exposure to cyclists in Bogota.
Highest areas of exposures were due to mobile sources, particularly corridors where the old bus system operates. Bikeways developed along watercourses, such as creeks and channels, seemed to offer lower exposure.
The model appears to be adaptable to other cities as long as information about emissions can be georeferenced. Additionally, results from the model require an underlying transport model and they are very sensitive to it. Therefore, it is important to understand the reliability of the transport model being used to determine traffic flows.
Finally, and due to limitations in the input data and the modeling technique, precision of the model does not allow for assessment of bikeways with a length of less than 100 meters.
The model appears to facilitate the assessment of whole corridors, both existing and proposed. Further application of the model is likely to facilitate holistic development of health and urban infrastructure policies. With this, decision makers may develop plans and strategies that promote bicycles and at the same time reduce the risk of exposing cyclists to high levels of air pollutants.

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