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An emissions inventory of air pollutants for the city of Bogotá, Colombia

« Master Project 2010, Final Report »

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Abstract

More than 8.5 million people live in the urban area of Bogotá and more than 1.4 million vehicles are taking the road every day. Air pollution is becoming more and more of a problem. Today, air pollution related respiratory diseases are the main cause of death in young children in Bogotá and more than 6000 people die prematurely every year in Colombia from cardiopulmonary diseases or lung cancer related to air pollution.

The creation of a spatially and temporally distributed emission inventory with a relatively high resolution for mobile and stationary sources (i.e. traffic and industries), the subject of this thesis, is part of a bigger project aiming at the development of air quality and meteorological modeling tools for the Secretaría Distrital de Ambiente, Bogotá's environmental agency. Five pollutants – carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter (PM) and volatile organic compounds (VOCs) – are taken into account for the mobile sources, only four of them – CO, SO2, NOx and PM – for the industrial sources. The sources are classified in different categories and their emission factors determined before the calculated emissions are distributed.

For the mobile sources, the emissions were calculated and distributed using the EMISENS model developed jointly at the University of Strasbourg, France, and the Swiss Federal Institute of Technology (EPFL) in Lausanne, Switzerland. A first attempt was made using the program and some rough input parameters. The obtained results and the uncertainty analysis included in the EMISENS model then allowed for a precise focusing of the efforts that needed to be made to improve the results for the second application of the model.

Concerning the stationary sources, the distribution in time was based on operational information obtained from a field survey conducted by Universidad de los Andes and the distribution in space on the street addresses of the manufacturing plant. All this information was then represented graphically in ArcGIS®, enabling the visual analysis of the results.

This study confirms an already known fact: the road traffic is responsible in most cases for more than 90% of the emissions and all abatement strategies should focus on these sources to be effective. The obtained quantities are close to the values given in previous studies and the distribution in space and time showed in the first comparisons good correlations with measured immission data.

Résumé

La population de la zone urbaine de Bogotá a atteint plus de 8.5 millions d'habitants et chaque jour plus de 1.4 millions de véhicules circulent sur les rues de la ville. La pollution de l'air pose de plus en plus de problèmes. Actuellement, les maladies respiratoires liées à la pollution excessive de l'air sont la cause principale de décès chez les jeunes enfants à Bogotá et chaque année plus de 6000 personnes meurent prématurément en Colombie de maladies cardio-pulmonaires ou d'un cancer des poumons en lien avec la pollution de l'air.

La création d'un cadastre d'émissions de polluants atmosphériques à relativement haute résolution incluant les émissions des sources fixes et stationnaires (i.e. du trafic et des industries) achevé dans ce projet fait partie d'un projet fait partie d'un projet plus important visant à développer des outils de modélisation de la qualité de l'air et de la météorologie pour la Secretaría Distrital de Ambiente, le service de l'environnement de Bogotá. Cinq polluants ont été pris en compte pour les sources mobiles, à savoir le monoxyde de carbone (CO), les oxydes d'azote (NO_x), les dioxydes de souffre (SO_2), les particules en suspension (PM) et les composés organiques volatils (COV). Pour les sources industrielles, seuls le CO, les NO_x, le SO_2 et les PM ont été utilisés. Les sources ont ensuite été classifiées dans différentes catégories et leurs facteurs d'émissions déterminés avant de distribuer les émissions ainsi calculées dans la zone modélisée.

Les émissions des sources mobiles ont été déterminées à l'aide d'EMISENS, un modèle de calcul et de distribution des émissions du trafic routier développé conjointement à l'Université de Strasbourg, France, et à l'Ecole Polytechnique Fédérale de Lausanne (EPFL), Suisse. Une première tentative de modélisation basée sur le programme et des paramètres d'entrée très grossiers a été complétée. Sur la base des résultats obtenus et de l'analyse des incertitudes incluse dans EMISENS, la redéfinition des paramètres afin d'améliorer le modèle a pu se faire de manière très ciblée.

En ce qui concerne les sources fixes, la distribution temporelle s'est basée sur des informations opérationnelles trouvées dans une étude de terrain menée par Universidad de los Andes et la distribution spatiale sur les adresses des sites de production. Toutes ces informations ont ensuite été représentées graphiquement dans ArcGIS®, afin de pouvoir visualiser les résultats.

L'étude a confirmé un fait déjà connu : le trafic routier est responsable dans presque tous les cas de plus de 90% des émissions et toutes les stratégies d'abattement devraient donc se focaliser sur ces sources afin d'être effectives. Les résultats obtenus sont proches des valeurs citées dans des études précédentes et la distribution spatiotemporelle montre dans les premières comparaisons une bonne corrélation avec les données d'immissions mesurées.

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1. Introduction

As described in the United States Environmental Agency's (US-EPA) "Handbook for Criteria Pollutant Inventory Development": *an emission inventory is a current comprehensive listing, by source, of the air pollutant emissions, and covers a specific geographic area for a specific time interval*. The same handbook also states: *emission inventories are used for a wide variety of purposes, but are most often developed in response to regulation. Emission inventory data are used to evaluate the status of existing air quality as related to air quality standards, air pollution problems, assess the effectiveness of air pollution policy, and initiate changes as needed. Emission inventories provide the technical foundation for programs designed to improve or maintain ambient air quality. They are used to identify sources and general emission levels, patterns and trends, to develop control strategies and new regulations, and serve as the basis for modeling of predicted pollutant concentrations in ambient air* (EPA-OAQPS, 1999).

One of the big problems related with air pollution are its effects on health and the environment. The pollutants covered by the inventory presented in this report – namely carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter (PM) and volatile organic compounds (VOCs) – are all part of US-EPA's list of criteria pollutants defined by the Clean Air Act (CAA, 2004) or serve as precursors for these pollutants. These pollutants are responsible for the formation of acid rains and ozone, impact aquatic and terrestrial ecosystems and all of them show effects on human health. They can reduce the delivery of oxygen to organs and tissues, irritate the lungs, cause bronchitis and pneumonia, lower the resistance to respiratory infections and increase the likeliness of suffering from cardiopulmonary diseases or lung cancer (EPA-OAQPS, 1999). A broader description of their properties and effects on health can be found in Appendix I.

Bogotá, Colombia's capital and biggest city of the country, is situated on the highest plateau in the Colombian Andes, the Sabana, amidst a mountain formation in the east, the Rio Bogotá in the west and a hillier region in the south. The city's elevation is more than 2600 m above MSL, although further east, to the Llanos, and west, towards the Rio Magdalena, some kilometers away from the city, the altitude decreases rapidly to almost sea level. Bogotá has a subtropical high-mountain climate and an annual average temperature close to 14°C – most of the time between 5°C and 25°C. Along with this very constant temperature, only two seasons coexist: the wet season and the dry season. Most of the rains occur during the months of April, May, September, October and November; the remaining months of the year being rather dry. The capital district is composed of 20 localities of different sizes and different main soil uses. Mainly rural on the outskirts, the commercial activities are concentrated in the eastern part of the city center and most industrial sites are located in the western central part of the city. The poorest areas of the city are situated in the south, where most of the displaced people, fleeing the guerrilla and other armed forces in the rural parts of the country, have settled. It is estimated that in Colombia almost 72% of the population, or 32 million people, live in urban areas (Sánchez-Triana, Kulsum, & Yewande, 2007). In 2009, Bogotá's population had risen to an estimated 7.26 million inhabitants, based on the official projections from the national census 2005 (DANE, 2005), and the estimations for the whole urban area are actually much higher, accounting for more than 8.5 million inhabitants.

One of the major environmental and health related concerns in Bogotá is air pollution, as the amount of engine powered vehicles continues to rise. At present, there are more than 1.4 million cars on the roads every single day. The average age of the vehicle fleet in Bogotá is relatively high. For buses, for example, estimations are, that the average age is close to 15 years and maintenance rather poor (Echeverry, Ibáñez, & Hillón, 2004). Efforts are made to reduce actual and potential impacts. Politicians and the public become more and more aware of the problem, new policies are put in place, public collective transportation systems are developed (« Transmilenio », a rapid mass transport system using buses circulating in their own lanes; a subway is projected) and circulation restrictions (« Pico y Placa ») apply to privately owned vehicles used for individual or collective transportation (SDM, 2010). The recent quality increase of diesel combustibles used in Bogotá – a progressive reduction of the sulfur concentration from 1200 ppm to 50 ppm – is yet another factor reducing significantly harmful emissions (SDA, 2010). Still, according to the World Bank's world development indicators, Bogotá's air counts among the 50 most polluted in the world (World Bank, 2007), but the situation is improving. The quality of life in Bogotá, as measured by the consulting firm Mercer, which includes air quality as a parameter, has improved compared to the earlier measurements. In the actual ranking, Bogotá is situated at the 132nd place out of 221 investigated cities, two places better than the previous year (Mercer, 2010).

The relations between air pollution and respiratory diseases have been evaluated in several studies conducted in Bogotá. In a risk assessment, it has been established that annually approximately 2'300 premature deaths due to cardiopulmonary diseases and lung cancer can be attributed to long term $PM_{2.5}$ exposure and close to 1400 premature deaths to short term PM_{10} exposure in Bogotá alone (Llorente Carreño, 2009). The same study also found that a reduction of PM_{10} concentrations by 30%, as it might be induced by an extension of the Transmilenio network, would result in an annual avoidance of close to 400 premature deaths in Bogotá. The reduction of the sulfur content in diesel fuels is yet another possibility studied in this report, which suggests that a reduction of the sulfur content from 1000 to 500 ppm would avoid annually more than 750 premature deaths. As stated above, in Bogotá, the sulfur content just was reduced to a maximum of 50 ppm (SDA, 2010).

Emission inventories have been realized at various times for the city of Bogotá. One of the first studies on this subject was done by the Japan International Cooperation Agency between 1990 and 1992 (JICA, 1992), followed several years later by studies financed by the Departamento Técnico Administrativo del Medio Ambiente (DAMA), which later became the Secretaría Distrital de Ambiente (SDA) – Bogotá's environmental agency. These informations were included in the "Plan de gestión del aire para el Distrito Capital 2000-2009", published by the DAMA in 2001. In 2002, in one of the latest attempts in this subject, Universidad de los Andes (UniAndes) applied the AIREMIS model (ACRI-ST, 2002) for the city of Bogotá (Zárate, Belalcázar, Clappier, Manzi, & Van den Bergh, 2007).

Standards for the determination of emission inventories for traffic are numerous. In Europe, mainly two methodologies coexist: the HBEFA, the Handbook of Emission Factors, developed jointly by Germany, Switzerland and Austria (HBEFA, 2010) and the European COPERT IV methodology (COPERT IV, 2010) used in the EMEP/CORINAIR Emission Inventory Guidebook (EMEP/CORINAIR, 2009). European projects, like ARTEMIS (André, Keller, Sjödin, Gadrat, & Mc Crae, 2008) try to unify these different methodologies in a single tool to model all traffic related emissions.

The project presented in this report is part of a research mandate for the SDA and Ecopetrol, Colombia's principal petroleum company, at the Universidad Nacional de Colombia in Bogotá (UNAL). It follows earlier investigations led by UniAndes, who determined emission factors for key pollutants of the car fleet (CIIA, 2008b) as well as the major industries (CIIA, 2008a) in the capital city Bogotá and produced an updated emissions inventory based on these factors, but without a focus on spatial and temporal distribution.

The main objective of the present project was to produce an air pollutants emissions inventory which does specifically include a distribution in time and space for the mobile and stationary sources (e.g. traffic and industries) based on the EMISENS model. This tool was developed jointly by and is still in development at the University of Strasbourg and the Swiss Federal Institute of Technology in Lausanne, EPFL (LIVE, 2010). Additionally, the usability of the tools as well as the quality of the available data needed to be evaluated and missing data identified for future applications of the model. A second objective, but not less important, was the capacity building in Colombia. A great part of the knowledge had to be transmitted to the partners in this project, thus enabling them to be autonomous for future applications based on the tools and theories used. In this project, pollutant transport or reactions are not considered, only emissions.

The research mandate ultimately aims at an actualization of the meteorology and air quality models for Bogotá, which will not only model the different emissions, but also transport and reactions of the contaminants, to help support political decision making in the next years and tackle effectively the air pollution problem of the city.

2. Methodology

Some useful definitions for a better understanding of the methodology and theory used in this project are presented in the following section. A reader who is familiar with the subject of this report may directly jump to chapter 2.2.

2.1. Definitions

Stationary sources

Stationary sources are emission sources, mainly caused by industrial or artisanal activities. They are often called point sources, because their emission can be quantified and allocated to a single point of emissions, for example the stack of an industrial installation.

Mobile sources

The mobile sources include all traffic related emissions, i.e. the emissions produced by the vehicles circulating in the area that is studied.

Hot emissions

Hot emissions are the emissions produced by the combustion while the equipment is already at normal working temperature, meaning the functioning is already stabilized (Kennesaw State University, 2006).

Cold emissions

Cold emissions are the amount of additional emissions that are emitted while the equipment is not yet at the normal working temperature. Emissions for some pollutants are higher if the temperature of the equipment and mainly its emissions control equipment is lower than its optimal operating temperature (Kennesaw State University, 2006).

Evaporative emissions

These emissions concern mainly the volatile organic compounds (VOCs) emissions. They occur in four different ways: "running losses", meaning the amount of fuel evaporated while the engine is running; "hot soak", or evaporation while the engine is off but still warm; "diurnal emissions", occurring while the car is parked and the engine is cool due to the external temperature; and finally "refueling", losses occurring while the tank of the vehicle is being filled (Kennesaw State University, 2006).

Emission factor

The emissions of the different sources can be measured and transformed in emission factors for each pollutant, meaning the amount of the considered pollutant emitted every kilometer for the mobile sources or every hour for the stationary sources. Those factors are, for example, speed and temperature dependent for the mobile sources.

Vehicle type

Vehicles presenting similar engine technologies and using the same fuel type are grouped as being the same type of vehicles. Thus, the emission factors are the same for all the vehicles of one given type.

Vehicle category

Vehicle types presenting the same behavior on the road are grouped in a single category. Each category then contains vehicles of different types and thus different emission factors. Even though, single emission factors can be derived for each category by using the number of vehicles in each type and the total amount of vehicles in the respective category to aggregate the type emission factors weighted by their relative importance. This can be expressed by the equation 1:

$$F_c = \sum_{t=1}^{j} \frac{n_t}{n_c} F_t \qquad (1)$$

Where F is the emission factor for the category c or the type of vehicle t, n_c the amount of vehicles in the considered category, n_t the amount of cars for each type and j the number of different vehicle types in category c.

Road category

The entire road network is divided in categories based on a similar vehicle velocity and traffic load, for example. Roads classified in the same category are grouped together and treated in the same way for the calculations with EMISENS.

Activity

For the mobile sources, e.g. the road traffic, the activity represents the hourly distance covered by all the vehicles in a same vehicle category and on the same road category in [veh*km/h]. The activity of the stationary sources is equivalent to the fuel consumption, i.e. an amount of fuel in kg, l or m^3 burned during a defined interval of time, in our case every hour.

Grid and Cells

The grid represents a subdivision of the square sized area to be modeled in individual equal sized cells. It is a "rasterization" of the actual area in order to simplify the calculations.

2.2. Modeled area and pollutants

The inventory produced in this project is a spatial and temporal distribution of the emissions calculated for the city of Bogotá for a typical day. The emissions are thus distributed over a grid of 55 km by 55 km centered over the city area of Bogotá and with a spatial resolution of 1 square kilometer. Values are calculated for every cell and hour of the day (i.e. 55 x 55 = 3025 cells and 24 hours).

Two categories of emission sources are taken into account for this project: mobile sources, meaning the road traffic; and stationary sources – mainly industrial boilers and ovens. These sources represent the lion part of the anthropogenic emissions for the contaminants considered in this report: carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter (PM), and – for the mobile sources only – the volatile organic compounds (VOCs).

2.3. EMISENS

The emissions produced by the mobile sources are calculated and distributed in space and time using the EMISENS model. The EMISENS model is developed to address main difficulties developing countries face while trying to confront the ever increasing air pollution problem coupled with their strong economic growth. These difficulties include the complexity of the data needed for the classic traffic emission models and the computing power needed to obtain the results based on road segment modeling. Sufficient data is not always available to use models like CIRCUL'AIR, in use in several French departments and developed by the ASPA, the "Association pour la Surveillance et l'Étude de la Pollution Atmosphérique en Alsace", and which requires very detailed input information (Schillinger, 2008) or AIREMIS (ACRI-ST, 2002), which has been used in Bogotá earlier (Guéguen, Zarate, Mangin, Clappier, & Sanchez, 2003). Moreover, powerful computers, which enable dealing with the great amount of calculations involved in the elaboration of emission inventories using other programs in a reasonable time frame, are only available at mostly prohibitive costs for local institutions in developing countries.

Another limiting factor is that most of these models do not integrate uncertainties computation. EMISENS is able to produce results without the need for very complex information. Instead of differentiating each road segment and the associated vehicles and emission factors, this information is aggregated in larger categories and average values are used for the relevant parameters. This "grouping" of information produces a very important gain in the amount of calculations needed to obtain the results and allows for uncertainty analysis of the results with respect to the input parameters and their respective error values using the Monte Carlo methodology. This enables the user to identify the parameters that should be revised with priority in order to obtain a significant improvement of the results (LIVE, 2010).

EMISENS can be used within a wide range of levels of complexity. The calculations can be done using solely "hot emissions", meaning the emissions produced while the engine is already warm/hot. It is possible to determine the "cold emissions" or "over emissions", produced while the engine is still cold during a certain period after the initial ignition. Even the "evaporative emissions", emissions not caused by the combustion itself, are planned to be included in a near future. As well as many other programs used to elaborate emission inventories, EMISENS is based on the COPERT IV methodology to estimate emission factors for the different car categories and types of emissions. As already stated, the main difference with other emission inventory elaboration techniques lies in the grouping of the different types of vehicles in categories of similar behavior and roads in categories based on speed and traffic charge.

Another important difference with most of the other programs is the bottom-up and top-down consistency achieved with EMISENS. Mostly, the results obtained using these two approaches differ in a more or less significant way from each other. The top-down approach first estimates a global value without considerations for the single entities before refining the results by distributing them over the area to be modeled. The bottom-up approach looks at the problem the other way round and considers first the single emissions to finally combine them in the last step and obtain the global emissions. Typical input parameters for the two approaches are found in Figure 1.

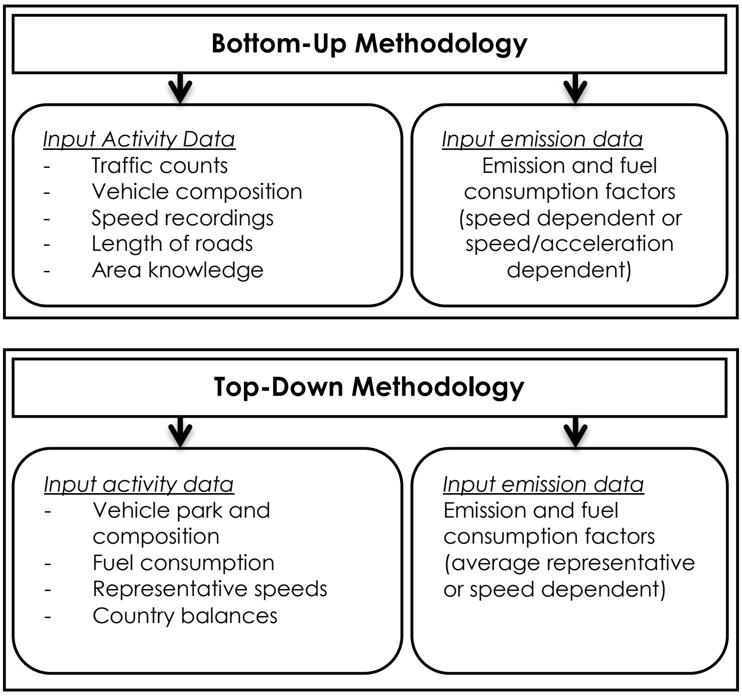

Figure 1: Typical inputs for Bottom-Up and Top-Down methodology adapted from (Ntziachristos, Samaras, & al., 2009)

EMISENS is able to combine favorably both approaches. It has the ability to calculate in a first step the global emissions in the studied area using a top-down approach and then, using a bottom-up methodology, distribute these emissions in space and time. The consistency between the two approaches is ensured by the formulation of the emissions in EMISENS, based on equation 2:

$$E = \sum F \cdot A \tag{2}$$

Where E are the emissions in [gr/h], F the emission factors for the different sources in [gr/unit] and A their respective activities in [unit/h]. The emission factors are average values and mostly derived using a top-down methodology, whereas the activities are local values often based on a bottom-up approach. If the emission factors used are constant in space and time, the total emissions obtained by the top-down approach or the bottom up approach will be the same and thus insure the coherence between the two methods.

EMISENS is usually used in three distinct phases. The first step consists in an estimation of the total emissions based on the least input parameters needed, meaning the emission factors and the activities for each road and car category. The second step takes into account the error values for these input parameters to compute their relative influence on the uncertainties of the results. Finally, the third step needs some extra information, like road network and traffic charges for every cell and every hour of the model's domain, to be able to distribute the emissions in space and time.

The EMISENS tool has been validated by comparing its results with the results produced by the CIRCUL'AIR tool, based on a bottom-up methodology, over the city of Strasbourg, France. The differences between the two models were relatively small. This test also proved the ability of EMISENS to produce valid results not only for developing countries, where the focus is a little less on precision than on the ability to obtain results, but also for countries which expect a much higher resolution or precision of the results (Ho, 2010).

2.4. ArcGIS®

The principal software used in this project to prepare the input data for EMISENS and represent graphically the results was ESRI®'s ArcGIS® in its ArcInfo® version, which includes the most complete set of functionalities and tools available. ArcGIS® was used to produce the grid, calculate the lengths of the road segments of each road category and for every cell of the grid. The data tables associated with the different data sets were used to produce the input data needed for the EMISENS model. Finally, ArcGIS® was also used to produce the graphical illustrations of the emissions calculated with EMISENS for every hour of the day and other maps of the modeled area around Bogotá presented in this report.

2.5. Data sources and preparation

For this project, the input data used was obtained from different sources. The emission factors were mainly found in the two final reports of the project led by UniAndes ((CIIA, 2008a) and (CIIA, 2008b)) and complemented by COPERT IV values (COPERT IV, 2010) if no data was available for the mobile sources or EPA/AP-42 data for the stationary sources (EPA, 2010). The different vehicle categories, number of vehicles in each category, as well as the daily distances covered by the different vehicles were found in the same reports and complemented by data from the company operating the Transmilenio system (Transmilenio SA). The data for the primary and secondary road network was obtained through the SDA, as well as the soil use classification and the limits of the different localities. The Transmilenio network data was provided by the Research Program in Traffic and Transport (Programa de Investigación en Transito y Transporte – PIT) of the UNAL. The data for the stationary sources was obtained from the SDA as files produced by UniAndes for their inventory elaboration. The traffic survey data for the primary roads was obtained from the Secretaría Distrital de Movilidad (SDM). Finally, the rural roads – meaning the roads that are not in the Bogotá district, which is more or less equivalent to the urban area – were obtained from the MapInfo® files used in the preceding project led by UniAndes.

Following a closer examination of the different datasets, it appeared that some needed to be reworked, before they could be used as input data for the project. Some data sets did not include a correct geo-reference and thus needed to be geo-localized beforehand; others were not useable directly due to faulty data or included data that was out of range, as described in the following paragraphs.

The stationary sources data, for instance, required a very detailed manual verification, because most of the sources needed to be correctly re-located. The average distance between the same locations in the old and in the corrected versions was about 600 meters, but some sources were found to be located almost 10 kilometers away from their correct location.

The secondary road network needed some preliminary treatment as well. The two files received included one specifically for the primary roads and a second file which represented the whole road network of Bogotá. In order to be able to use these files, the duplicate primary roads needed to be removed from the file representing the complete road network, so that only secondary roads remained in this file.

The primary roads network received included some road segments that were only planned and not yet constructed at the moment of the project and which had to be removed. Additionally, some existing primary roads were missing in this file and had to be added manually.

The MapInfo® files did cover an area much larger than the modeled area in this project and included some primary roads as well. The roads out of the modeled area as well as the ones located within the Bogotá district area had thus to be removed in order to keep only the roads out of the district boundaries but still inside of the considered area.

The preparatory phase included also the construction of the model grid in order to be able to calculate values for the different elements that are considered for every cell of the grid. The grid was prepared using the "Fishnet" tool available in ArcGIS®. This tool requires the entry of the coordinates of the lower-left and upper-right corner of the area to be covered by the grid, the size of the cells (1km x 1km) and the number of rows (55) and columns (55) to be produced. The option to produce numbered labels for every cell was used to obtain a sequence of numbers (numbering the cells row by row from the bottom-left cell, number 0, to the top-right cell, number 3024) which was then converted to X and Y coordinates as used in EMISENS (ranging each from 1 to 55, the origin being the lower-left corner). This transformation was done using the following mathematical formulas (equation 3 and 4) and the "calculate values" tool in ArcGIS®.

$$X = (Id)mod(55) + 1 \qquad (3)$$

$$Y = (Id)\backslash(55) + 1 \qquad (4)$$

Where X and Y are the coordinates to be determined, Id is the number of the cell label, 55 the number of cells in each row, mod the modulo operator and "\" the integer division as used in Visual Basic (VBA).

2.6. An iterative approach

Regarding the mobile sources, the input parameters were defined twice. The first set of parameters used many estimated values and a very rough subdivision of the road networks, whereas the input parameters were substantially refined for the second set, according to the first results. This iterative approach was chosen mainly for two reasons: 1) the necessary level of detail for the input parameters needed in order to obtain satisfactory results was unknown; and 2) due to the unavailability of some of the input parameters it was necessary to estimate them. The validation of the values chosen for those parameters was done based on the results of the different applications of the model.

The main objective of the first application of the model was to verify that all the tools needed were working correctly and to evaluate which parameters had the biggest influence on the emission results, what needed to be evaluated more precisely and what information was missing and needed to be obtained. Since not all the data were yet available at the time, some input parameters were based on estimations done by people having sufficient local knowledge (e.g. living in the neighborhood, etc.). The results produced by this first modeling attempt were then represented graphically and summarily analyzed.

Following the analysis of the results of the first attempt, new input data were prepared for a second application of the model, using newly available and more precise data, where possible. By focusing the improvement efforts on the factors, which the uncertainty analysis included in EMISENS had indicated as having the greatest influence on the final result, the execution of the ensuing steps was quite straightforward.

In a third step, the emissions of the stationary sources, i.e. the industrial emissions, were calculated. These sources included industrial ovens and boilers running on fuels as diverse as natural gas, liquefied petroleum gas, coal, diesel or used vegetal oil. The emissions were calculated for every single source and, in a subsequent step, all the emissions from sources located in the same cell added to produce similar results than for the mobile sources: emissions distributed over a grid of 3025 distinct cells of 1km^2 and every of the 24 hours of a day.

Both results – from the second application of EMISENS for the mobile sources and the results for the stationary sources – were finally combined in ArcGIS® to produce a cadaster for all the emissions considered in this project. This was done by adding the values pollutant by pollutant in order to obtain the total emissions for each cell of the grid (Equation 5).

$$E_{tot,p}(i,j) = E_{mov,p}(i,j) + E_{fix,p}(i,j) \qquad (5)$$

Where p is the pollutant considered, E_{mov} are the mobile sources emissions in cell (i,j), E_{fix} the stationary sources emissions in cell (i,j) and E_{tot} represents the total emissions in cell (i,j).

As a last step, these results were compared to existing measurement data in order to validate or not the results of this project. This comparison was done mostly qualitatively, based on the PM emissions evaluated with the model and the immissions measured by the air quality monitoring network of Bogotá.

3. Results and procedures

The respective results for the mobile sources are presented in separate chapters (3.1 and 3.2). Another chapter (3.3) presents the results for the stationary sources emissions and, finally, the last chapter (3.4) the combined emissions of both types of sources. In all these chapters, the techniques applied to define the input parameters used in the different steps of the modeling procedure are explained in separate subchapters. At the end of each chapter, the results are evaluated based on the spatial and temporal distribution that was produced. The analysis of the final results is presented as a separate chapter (chapter **Error! Reference source not found.**).

The images of the emissions cadaster presented in this report will only be for hours where peak emissions take place. This is mainly due to the huge amount of graphical material that was produced – more than 500 different images, representing the emissions of the mobile sources, the stationary sources and both sources combined for each of the 24 hours of a day and every one of the 5 pollutant considered in this report. The complete set of graphical representations of the results, the different numerical results, as well as some animations of the results are included on a CD-ROM attached to this report.

3.1. The mobile sources: first attempt

During this attempt, the functioning of all the used tools was verified and the needed parameters defined as a first approximation. The values chosen for the different input parameters and how they were obtained are explained in the following subchapters.

3.1.1. Vehicle categories

The vehicle fleet in Bogotá was already completely characterized during the project led by UniAndes (CIIA, 2008b). The vehicles were subdivided into different categories based on the type of vehicle, their engine technology and capacity. This resulted in a total of 23 different categories: 4 for cars, 4 for four wheel drive vehicles (4x4) and small vans, 2 for the taxis, 2 for the buses, 1 for the micro-buses, 1 for the school and touristic buses, 3 for the trucks, 1 for the articulated Transmilenio buses, 1 for the simple Transmilenio buses, and 4 for the motorcycles. This is the same number of categories than in the EMEP/CORINAIR methodology, but the categories used are not the same (Ntziachristos, Samaras, & al., 2009). This classification was based on criteria illustrated by a diagram shown in Appendix II.

To simplify the calculations and follow the spirit of EMISENS, these 23 categories were grouped for this project in 8 larger categories of vehicles with similar driving behavior:

- Passenger vehicles and light vehicles, including 4x4 and small vans (VP_CC)
- Taxis (T)
- Buses and micro-buses (B_MB)
- Trucks (C)
- School and touristic buses (ET)
- Transmilenio articulated buses (TM-Art)
- Transmilenio simple buses (TM-Alim)
- Motorcycles (M)

Differentiating the Transmilenio buses as separate categories was done because the engine technology used in these buses is by far newer than in other buses in Bogotá and their routes are very well defined. Articulated buses are operated in separate lanes on different routes along the city. The simple buses are used to cruise in the neighborhoods around the final stations of the articulated bus system on predefined routes and bring the people to the interface stations between the two systems.

3.1.2. Road categories

For the first application of the model, the roads were split in five categories based mainly on their size and average velocity: main or principal roads (PRINC), secondary roads (SEC), rural roads (RUR), Transmilenio articulated bus roads (TM_Tronc) and Transmilenio simple bus roads (TM_Alim). This classification was based directly on the different road data files that were available at the beginning of the project. Except the treatments described in chapter 2.5, no other work had been done on these files. The total lengths of the road segments in each category for this classification are shown in Table 1.

Table 1: Total length of the road segments in the different road categories, first attempt

Category	PRINC	SEC	RUR	TM_Tronc	TM_Alim
Long tot [km]	626	8'735	283	78	422

The complexity of the road network can be seen on the following image (Figure 2), representing the main (red), the secondary (grey) and Transmilenio articulated bus roads (green), as well as the modeling grid used in this project (black).

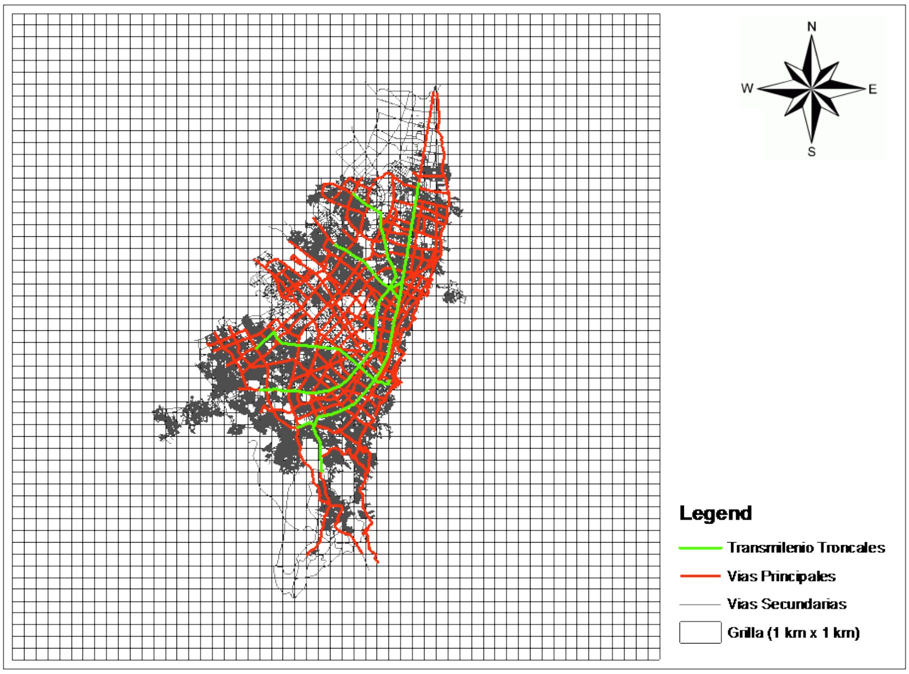

Figure 2: Some of the road networks used in the first application of the model, the grid has a spatial resolution of 1km²

Once the roads were correctly classified and separate layers produced in ArcGIS® for each road category, the road segments were split at the intersections with the cell borders, obtaining only segments fully included in a cell. For each category, the lengths of the road segments were then added for every cell and this value combined with the coordinates for the cells, producing a table containing four columns: an identifying number for each cell, the coordinates X and Y of the cell and the total length of the segments of the considered road category in the cell. To be used in EMISENS, the length of all the road segments of the considered road category in the cell was divided by the total length of all the road segments in this category in the whole modeled area to obtain the fraction of the total length in each cell. This was done for each road category and the resulting fractions, the relative road lengths, served as input data for EMISENS.

3.1.3. Velocities

Since vehicular emissions are speed dependent, the average velocities for each road category had to be determined. In the first attempt, this data was mainly based on local experience, since no real data was available at that time, except for Transmilenio (provided by Transmilenio SA). The velocities were set to the values described in Table 2.

Table 2: Estimated vehicle speeds on the different road categories, first attempt (except for Transmilenio, average velocity)

Road Category	PRINC	SEC	RUR	TM_Art	TM_Alim
Vel [km/h]	35	20	60	27	13

3.1.4. Activities

For each vehicle category, the number of vehicles in the category and the average distance covered by each vehicle during one day were obtained from the different sources ((CIIA, 2008b) and Transmilenio SA data). The activity was then determined based on this information. The results are presented in Table 3.

Table 3: Vehicle categories data (sources – (CIIA, 2008b), except the italic values provided by Transmilenio S.A., all have been regrouped and the activities determined in this project)

Category	Vehicles	Distance [km/d]	Activity [veh*km/h]
VP_CC	889’577	37.8	1’401’084
T	51’953	*231*	*500’048*
B_MB	18’974	*211*	*166’813*
C	24’997	85	88’531
ET	368	172.5	2’645
TM-Art	1’070	*300*	*13’375*
TM-Alim	449	*200*	*37’412*
M	128’860	68.5	367’788

The activities then needed to be split among the different road categories. Since no data for the distance covered on each road category could be found or made available during this project for Bogotá, this partition has been made using estimations based on experienced driving patterns by people having sufficient local knowledge. This consultation led to the values for the first run of the model presented in Table 4.

Table 4: Percentage of total daily covered distance on the different road categories, first application of the model

Vehicle Category	PRINC	SEC	RUR	TM_Art	TM_Alim
VP_CC	50%	48%	2%	0%	0%
T	40%	58%	2%	0%	0%
B_MB	73%	25%	2%	0%	0%
C	70%	25%	5%	0%	0%
ET	40%	55%	5%	0%	0%
TM_Art	0%	0%	0%	100%	0%
TM_Ali	0%	0%	0%	0%	100%
M	50%	48%	2%	0%	0%

Using the activities presented in Table 3, this resulted in the following hourly street mileages (i.e. the distance covered by all the vehicles in the same vehicle category on one given road category in an hour) for every vehicle categories and road categories used in the first application of the model (Table 5).

Table 5: Activities of the mobile sources distributed among the different road categories of the first attempt in [veh*km/h]

Vehicle Category	PRINC	SEC	RUR	TM_Art	TM_Alim
VP_CC	7’005’412	672’520	28’022	0	0
T	200’019	290’028	10’001	0	0
B_MB	121’774	41’703	3’336	0	0
C	61’972	22’133	4’427	0	0
ET	1’058	1’455	132	0	0
TM_Art	0	0	0	13’375	0
TM_Ali	0	0	0	0	3’742
M	183’894	176’538	7’356	0	0

3.1.5. Emission Factors

Once the velocities are defined for all the road categories and the vehicles classified in types and categories, it is possible to determine the emission factors to be used in the model. Most emission factors used in this project were based on the measuring campaign described in (CIIA, 2008b). If no value was available in this report or the values were notably lesser than standard values, while all other values were much higher, it was replaced by data from additional sources. For the mobile sources, the COPERT IV values and methodology (COPERT IV, 2010) were used in this project. The results of this process as well as the sources for the individual emission factors can be found in Appendix III.

The measurements for the mobile sources were made by UniAndes using different vehicles in real driving conditions (i.e. not on a test bench). Unfortunately, the resulting emission values were only available as average values for an average velocity and thus needed to be adapted to include the usually observed speed dependency (see Figure 3 for an illustration).

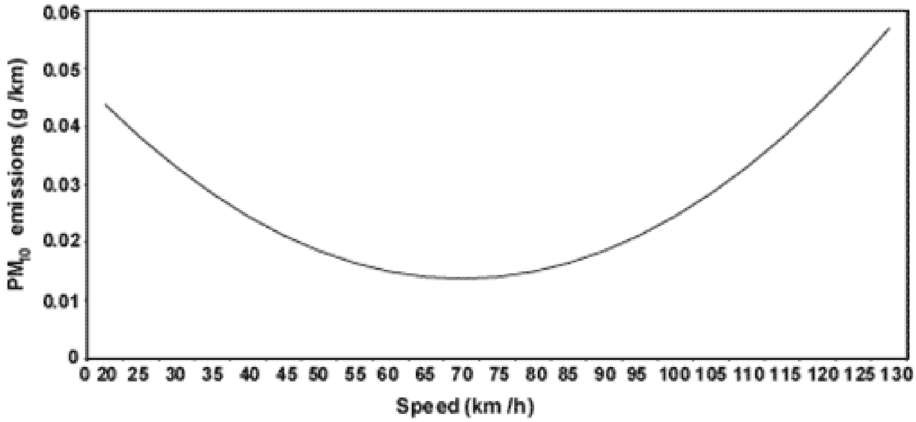

Figure 3: Speed dependency of vehicular PM_{10} emissions for a EURO II Diesel car (DFT-UK, 2010)

This adaptation was done using the closest COPERT IV emission value at the same speed and extrapolating the values for the other speeds using a simple transformation of the COPERT IV values. Mathematically, this was done using calculations as shown in equation 6.

$$E_{B,Vi} = |E_{B,V0} - E_{C,V0}| + E_{C,Vi} \quad (6)$$

Where E_B are emission factors for Bogotá; E_C, the emission factors based on the COPERT IV methodology; v_0, the average speed the values from UniAndes were based on; and v_i, the desired speed value.

The tables containing the different values based on these calculations can be found in Appendix IV. These values served as input data for the EMISENS model to calculate the mobile sources emissions.

3.1.6. Uncertainties

Since EMISENS is able to compute the relative influence on the final result of the standard deviations defined for each input parameter in order to evaluate which parameters are the most problematic ones, the following values were used in this project, based on an analysis of the different available input values (Table 6).

Table 6: Standard deviation of the different parameters in percent

Value	Hourly Street Mileage	NO_x	CO	SO_2	VOC	PM
S.D. [%]	30	47.1	37.93	34.39	35.22	68.29

The standard deviation for the hourly street mileage was calculated by comparing the two sets of values that were available for the average daily distance covered by the vehicles in the different vehicle categories ((CIIA, 2008b) and Transmilenio SA data). The average of the individual differences, expressed as percent of the value finally used, gave the 30% shown in Table 6. The values for the emission factors for the different pollutants were all directly derived from the error values given in the report from UniAndes (CIIA, 2008b), using the average value of all the measurements that were available for each pollutant.

3.1.7. Distribution of the emissions in space and time

In order to be able to distribute the emissions in space and time using EMISENS, one needs to prepare input files for every vehicle category on every road category. These files contain a distribution in time of the hourly street mileage, followed by a distribution in space of the relative road lengths for each cell. The preparation of these input files was done in ArcGIS®. A short description of the methodology followed in this project for the preparation of the road length information has already been given in the chapter 3.1.2.

The distribution in time was done based on flux information that was available in the road survey data from the SDM for all the vehicle categories excepting Transmilenio. The Transmilenio buses were not included in the survey and the relevant data was not available publicly. Although a lot of data concerning Transmilenio is freely available the frequency of the different bus lines is not part of the public information. An official request for this data was made to Transmilenio SA, unfortunately without success during the time spent on this project. Thus the data for Transmilenio has been constructed based on user comments and operational hours indicated on the official webpage[1].

Concerning the other vehicle categories, the different survey points were analyzed and average values calculated for every hour of the day based on all the data available for this hour; this was done for every vehicle category considered in this model. Dividing the individual values obtained from this analysis by the daily total for each category produced the quantities needed as input data for the distribution in time in EMISENS. The resulting values can be found in the tables of Appendix V.

3.1.8. Results from the first application of the model

The main objective of this first run, the evaluation of the tools used in this project was completed successfully. The preparation of the data using ArcGIS® and spreadsheets turned out to be a relatively easy way of producing the input files and the different runs completed with EMISENS showed no greater difficulties, once that all the input data were in the correct format.

Even though the functioning of the tools was satisfactory, this was not the case with the spatial distribution of the results. The main problem encountered with the results of the application of the model is illustrated quite vividly by Figure 4.

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[1] http://www.transmilenio.gov.co

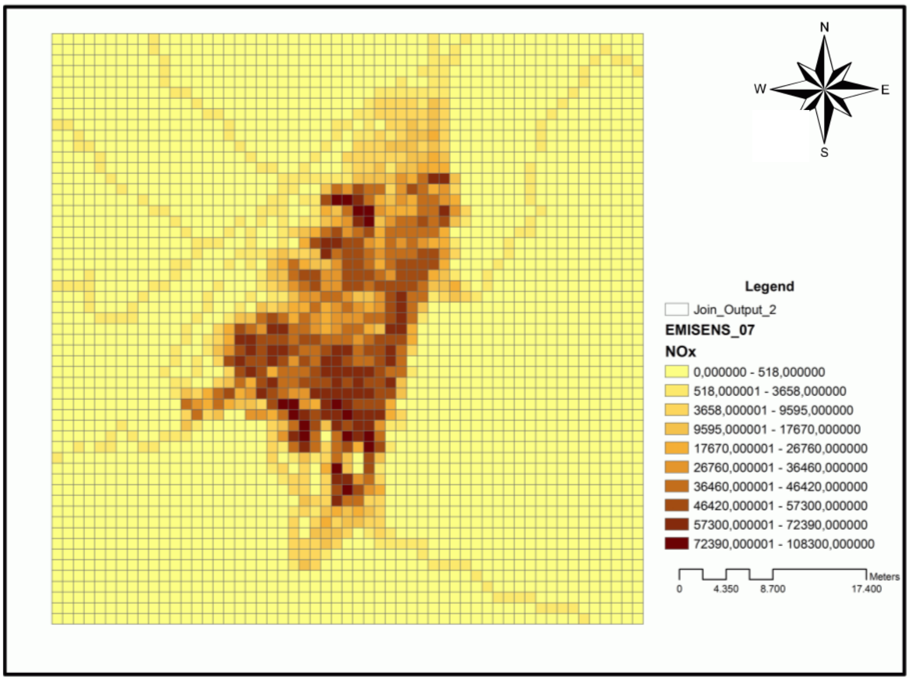

Figure 4: NO_x Emissions at 07h00 calculated by the first application of the model, the distribution in space shows some inconsistencies with local reality

In this model, the main emissions take place in the southern part of the city, as well as in the north-west, whereas the industrial zone, close to the center of the map shows only little emissions compared to the rest of the city. These high emissions areas in this model correspond to the localities of Ciudad Bolivar, Usme and Suba, the poorer parts of the city (as already stated in the introduction, most of the displaced people are settling in the south of the city; a map representing the 20 localities of Bogotá can be found in Appendix VI for orientation purposes). The amount of vehicles with combustion engines is rather low in these areas and thus is the traffic. The greater amount of emissions shown in this model is mainly due to the higher road density in these parts of the city, where the housing blocks are smaller, as people cannot afford to build bigger houses (compared to the richer parts of Bogotá).

Taking a closer look at the road density distribution, it appeared that the denser the secondary road network, the poorer the area, except for the historical parts of the city, where the road density was also higher. At the opposite, the less dense the secondary road network out of the non-constructed areas (e.g. green zones, parks, lakes, non-constructed land, etc.), the more likely it was, that the area was either of industrial or of official use (e.g. military installations, governmental buildings, airport, etc.).

Since no distinction was made during this attempt for the traffic charge – except for the difference between main and secondary roads – the denser the road network in a given area, the higher the emissions in this area. This showed clearly the need for a much finer definition of the road categories based on the traffic charge.

Compared to the values of previous studies, notably the one which served as basis for most of the entry values (CIIA, 2008b), the results seemed to be by far too high, as illustrated in Table 7. This indicates as well an overestimation of the emissions in this first application of the model and the need for a redefinition of some input parameters.

Table 7: The results of the first application of the model exceed by far the results of (CIIA, 2008b)

Values [tons/year]	CO	NO_x	SO_2	PM	VOC
First Attempt	3341940	136744	55635	2020	463141
CIIA 2008b	450000	30000	NA	1100	60000

Finally, the information provided by the uncertainties analysis included in EMISENS was helpful to identify the flawed inputs. The influence of the uncertainties introduced as input data for the different parameters (see Table 6) on the final results was very high for mainly two parameters: the emission factor as well as the hourly street mileage for private vehicles, light vans and 4x4 (VP_CC) on the secondary roads (SEC). The values for both are presented in Table 8.

Table 8: Standard deviation values in percent for the emission factors and hourly street mileage for vehicle category VP_CC and road category SEC for the five pollutants considered for the mobile sources

VP_CC_SEC	CO	NO_x	SO_2	PM	VOC
Emission Factor	34.69 %	30.49 %	30.07 %	19.15 %	31.34 %
Hourly Street	27.44 %	19.51 %	26.22 %	15.15 %	26.70 %

These values are actually close to the initial uncertainties introduced as input data and exceeded what seemed acceptable to the members of the Grupo Interuniversitario de Calidad del Aire. In order to reduce these values, the corresponding input data had to be refined accordingly. Since no possibility existed for a refinement of the emission factor, due to the absence of better data, the hourly street mileage and thus the street categories needed to be defined more precisely (mainly for the vehicle category VP_CC and the secondary roads (SEC)). The five road categories considered in this attempt (main roads, secondary roads, rural roads, Transmilenio articulated and Transmilenio simple bus roads) were simply not sufficient to model correctly the situation in Bogotá.

All the images produced based on the results of this first attempt can be found in the "Version_1" folder on the CD coming with this report.

3.2. The mobile sources: improvement of the model

For this new attempt, the vehicle categories remained unchanged; the other modifications are explained in the following subchapters.

3.2.1. Road Categories

The classification was refined for the second application of the model to include traffic charge information where available or deducible from other relevant information. Traffic surveys, provided by the SDM, were available for the main roads in 24 locations of the city with hourly data for 24 hours for most of them. The information was used to classify the main roads in 4 distinct categories: low, medium, high and very high traffic. This classification was made using the maximum values in each location for each vehicle category considered in the survey (light vehicles, public collective transport vehicles, trucks and total traffic). Each category was classified in the same four categories (low, medium, high and very high) and finally an "average" value was calculated for each location (presented as Appendix VII and Appendix VIII). The point data of the surveys was then converted in areas using a Thiessen polygon algorithm available in ArcGIS's Toolbox® (a short illustration of the concept can be found in Appendix IX).

Since no survey data was available for the secondary road network, the traffic charge data on these roads was determined for each of the 20 localities using the soil use classification provided by the SDA. Each of the 8 soil use categories had been attributed a traffic charge index ranging from 0 for no traffic to 3 for high traffic (industrial = 3, residential = 2, commercial = 3, soil extraction = 1, official = 2, green areas and swamps = 0, historical zone = 2, water = 0). Based on the surface of each category and the total surface where the soil use had been defined (soil use was only defined in the urban area of Bogotá but not in the whole district), the traffic charge index for each locality was calculated as follows (equation 7):

$$T_L = \frac{\sum T_i \times A_{i,L}}{\sum A_{i,L}} \qquad (7)$$

Where T_L is the traffic index for the locality L, T_i the traffic index for the soil use category i and $A_{i,L}$ the area of soil use i in locality L.

This weighing produces a final index varying between approximately 1 and 2.5. All localities having an index ranging from ~1 to 1.5 are classified as low, localities with an index between 1.5 and 2 as medium and between 2 and 2.5 as high traffic areas.

Finally, this process resulted in the following classification (Table 9), where the main roads are divided in four traffic charge related subcategories (low = PRINC_B, medium = PRINC_M, high = PRINC_A and very high = PRINC_MA), the secondary roads in three (low = SEC_B, medium = SEC_M, high = SEC_A) and the other< roads are not subdivided compared to the first run (rural = RUR, Transmilenio articulated bus roads = TM_Tronc and Transmilenio simple bus roads = TM_Alim).

Table 9: Total length of the road segments in the different road categories and subcategories, second attempt

Main roads	PRINC_B	PRINC_M	PRINC_A	PRINC_MA
Length [km]	35	319	226	46
Sec. roads	SEC_B	SEC_M	SEC_A	
Length [km]	2'300	5'351	1'084	
Other roads	RUR	TM_TRONC	TM_ALIM	
Length [km]	283	78	422	

3.2.2. Velocities

For the second attempt, the velocities were redefined, as new data became available. No subdivision was made according to the traffic charges, as no direct correlation could be found between the amount of traffic and the velocity only, probably because the road configuration, for example the amount of lanes on each road, was not taken into account for the classification. However, a subdivision by vehicle categories was made to take into account more precisely the differences in driving behavior.

A report by the SDM about the effect of "Pico y Placa" – the number plate based driving prohibition – contained averaged velocities for some high traffic roads thus allowing the determination of an average value for the main roads category based on objective data (SDM, 2009). This average velocity of 25 [km/h] was used for all the vehicles circulating on the main roads (e.g. cars, taxis, 4x4, small vans, school or touristic buses and motorcycles), except for public transport buses and trucks. The velocity for these last two categories, 20 [km/h], was based on the 2009 statistics of the Secretaría de Planeación (SDP, 2010).

Since the velocity on the main roads was substantially lower than in the first estimation (10 [km/h] less), the velocity on the secondary roads needed to be adapted consequently. For cars, taxis, 4x4, small vans, school or touristic buses and motorcycles the velocity was set to be 20 [km/h], but lacking objective data, this value is only an estimation. For public transport buses and trucks, the velocity taken as average, 13 [km/h] is equivalent to the velocity obtained from Transmilenio SA for their simple buses, which are mainly circulating on secondary roads. The velocity for the articulated Transmilenio buses was not changed for the second run, since the velocity was already based on measurements done by Transmilenio SA. Velocities on the rural roads were also lowered accordingly: all vehicles, except the public transport buses and trucks, for whom the average velocity was set to 35 [km/h], were supposed to be circulating at an average velocity of 47 [km/h].

Table 10 gives a summarized overview of the speeds on the different road categories.

Table 10: Average velocities on the different road categories for the second application of the model, no distinction is made according to the traffic charge, thus all main road (PRINC) and secondary road (SEC) categories have the same velocity values and are not presented separately. A velocity of 0 [km/h] means that this vehicle category is not present on the roads of this category.

Velocity in [km/h]	PRINC	SEC	RUR	TM_TRONC	TM_ALIM
VP_CC	25	20	47	0	0
T	25	20	47	0	0
B_MB	20	13	35	0	0
C	20	13	35	0	0
ET	25	20	47	0	0
TM-Art	0	0	0	27	0
TM-Alim	0	0	0	0	13
M	25	20	47	0	0

3.2.3. Activities

For the second application of the model, the main and secondary roads activities were distributed among the newly created subcategories based on the actual traffic charge derived from the SDM survey for the main roads and on an estimated partition coefficient concerning the secondary road network (again, no objective data was available at the time of the project).

For the main roads, this traffic charge based distribution was done by calculating the maximum traffic value for all the vehicle categories and all the survey points classified in the same traffic category (see chapter 3.2.1, Appendix VII and Appendix VIII for the categories and survey point classification). Table 11 shows the maxima used for this classification.

Table 11: Maximum traffic values (number of vehicles in one hour) for each vehicle category and on each main road subcategory. The last row represents the total of the maxima for each vehicle category.

Value [veh/h]	VP_CC + T	B_MB	C	M	ET
PRINC_B	1073	446	301	347	76
PRINC_M	3327	809	217	665	191
PRINC_A	7887	743	773	1319	549
PRINC_MA	11607	1317	933	2704	708
TOTAL	23894	3315	2224	5035	1524

These maximum values served as starting point for the determination of the fraction driven on the main roads. This was done by dividing each maximum by the sum of all the maxima in the same vehicle category (i.e. the last row of Table 11). The values in percent are shown in Table 12 below.

Table 12: Percentage driven on each main road category and for each vehicle category

Fraction [%]	VP_CC + T	B_MB	C	M	ET
PRINC_B	4.49	13.45	13.53	6.89	4.98
PRINC_M	13.92	24.39	9.77	13.20	12.56
PRINC_A	33.01	22.43	34.74	26.20	36.02
PRINC_MA	48.58	39.73	41.96	53.71	46.44

The average hourly street mileage for the main roads calculated during the first application of the model was then distributed among the different traffic charge related categories by multiplying the initial value by the factors of Table 12.

Concerning the secondary roads, the distribution of the average hourly street mileage was based on the total road length in each subcategory, since no traffic related data was available for this category. The percentage of road length was modified for the low and high traffic subcategories in order to take into account the difference in flux. Arbitrarily it was decided to change the values by 5 percent, resulting in a reduction of the low traffic charge by 50% and an increase of the high traffic charge by 30% compared to the medium value. The total lengths in each category the relative percentage they represent and the percentage finally taken into account by modulating the low and high traffic values are given in Table 13 below.

Table 13: Secondary road classification factors based on the road length

Road Category	Length [km]	Length [%]	Fraction [%]
SEC_B	648	10%	5%
SEC_M	5351	75%	75%
SEC_A	1084	15%	20%

Since no subdivision was carried out for the rural roads and the Transmilenio networks, the average hourly street mileage stayed unchanged for these road categories. The new values for the hourly street mileage on the traffic charge related subcategories for the main and secondary road networks are shown in the last table of this chapter (Table 14).

Table 14: Average hourly street mileage, values for the newly created subcategories on main and secondary roads

Mileage [km]	VP+CC	T	B+MB	C	ET	M
PRINC_B	31457.2	8981.7	16379.4	8385.3	52.7	12671.7
PRINC_M	97549.1	27852.3	29699.3	6053.8	132.9	24278.8
PRINC_A	231238.1	66023.2	27309.7	21527.3	381.1	48180.8
PRINC_MA	340297.5	97161.9	48385.3	26005.4	491.3	98762.7
SEC_B	33626.0	14501.4	2085.2	1106.6	72.7	8826.9
SEC_M	504390.2	217520.7	31277.5	16599.6	1091.1	132403.7
SEC_A	134504.0	58005.5	8340.7	4426.6	291.0	35307.6

3.2.4. Emission factors

Since the velocities were redefined for this second application of the EMISENS model, the emission factor values needed to be modified accordingly. The methodology followed was the same as in chapter 3.1.5 and the results for all the road and vehicle categories are presented as Appendix X.

3.2.5. Uncertainties

The uncertainties taken into account for the different input parameters of this second application were not changed compared to the first attempt. Table 15 below is given as a reminder of the standard deviation values used.

Table 15: Standard deviation for the different parameters, in percent

Value	Hourly Street Mileage	NO_x	CO	SO_2	VOC	PM
S.D. [%]	30	47.1	37.93	34.39	35.22	68.29

Even the uncertainty for the hourly street mileage stayed unchanged, though the values were distributed more finely. The distribution in the different road categories was simply done using more subcategories, but not based on better input data.

3.2.6. Distribution of the emissions in space and time

The distribution in space of the results required the preparation of new layers in ArcGIS® containing the road segments for the newly created subcategories. Based on these files, the new input data was prepared following the same steps as described in chapter 3.1.2.

Concerning the distribution in time, the preparation of the required input data was done following the methodology already used in the first attempt (see chapter 3.1.7). Unfortunately not all the main road categories contained data for the 24 hours of the day. Missing data was thus complemented based on the average values for all the main road categories, which also served as distribution factor for the hourly street mileage on the secondary roads, since, as in the first attempt, no specific data was available. The resulting distribution in time for the average main road values can be seen in Figure 5.

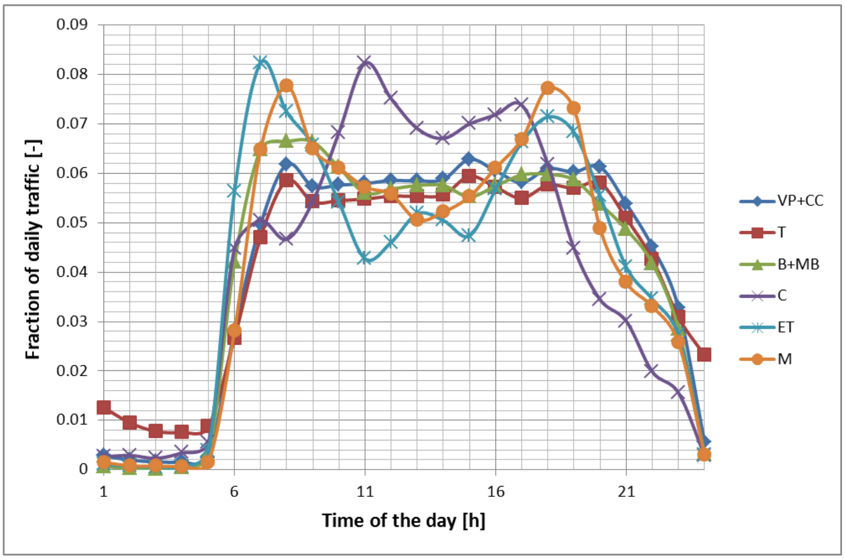

Figure 5: Graphical representation of the fraction of daily traffic for every hour and vehicle category, average value for the main roads

The traffic peaks for the different vehicle categories are clearly visible in the morning (at about 07h00) and in the early evening (at about 18h00). Only trucks show a very different behavior, since they almost never circulate during the classic peak hours. Their morning peak, for example, occurs much later (at about 11h00). Taxis (T) and light vehicles (VP_CC) exhibit almost no peak at all. The activity for those two categories remains relatively constant. The complete graphical analysis for the different main road subcategories can be found in Appendix XI.

The data for Transmilenio SA remained unchanged compared to the first application of the model, as the requested data remained unavailable to improve the information and make use of objective sources instead of constructed and subjective data.

3.2.7. Results of the improved version

Analyzing the emissions for the five pollutants calculated with EMISENS, it appeared that for this second application of the model they were still higher than the emissions calculated by UniAndes (CIIA, 2008b). A summarized overview of the results and comparison with previous studies can be found in Table 16.

Table 16: Comparison of the results of the second application of the model with the results from previous studies, adapted from (CIIA, 2008b)

Values [tons/year]	CO	NO_x	SO_2	PM	VOC
This Study (2nd Attempt)	706932	57658	13009	1594	108011
CIIA 2008b	450000	30000	NA	1100	60000
Bogotá (2003)	306162	13651	NA	1643	NA
Bogotá (2005a)	230000	12000	NA	NA	25000
Bogotá (2005b)	900000	55000	NA	2200	NA
Average (previous studies)	471540	27663	NA	1648	42500
Min (previous studies)	230000	12000	NA	1100	25000
Max (previous studies)	900000	55000	NA	2200	60000

Nevertheless, the results of this second application of the model seem reasonable, if one considers that UniAndes values only include light vehicles (i.e. categories VP_CC and T) for all the pollutants except PM, and concerning this last pollutant, only $PM_{2.5}$ emissions from heavy vehicles.

Moreover, values for CO and PM are in the interval defined by the maximum and minimum values of the previous studies. On the other hand, NO_x and VOC values are higher than the maximum value obtained from previous studies – only little for NO_x, but substantially for VOCs. These differences probably derive from the use in this study of COPERT IV values for vehicle categories, where no locally defined values were available, instead of ignoring the category in the inventory and extrapolating the data later, as it was done for instance in the UniAndes report.

The distribution in space resulting from this second attempt is shown in Figure 6, keeping the same pollutant (NO_x) and the same time (07h00) as in the example for the previous attempt.

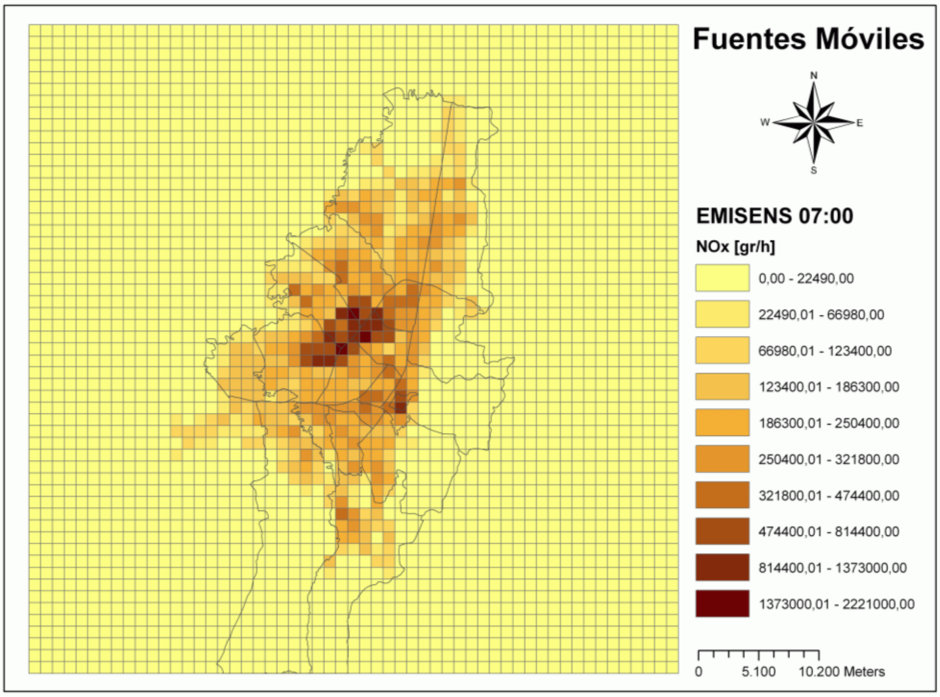

Figure 6: NOx Emissions at 07h00 calculated by the second application of the model

The main emission center is now situated in the areas showing the highest amount of traffic, i.e. the industrial zone situated close to the center of the map and the city center a little more to the south-east. This relationship is also shown on the next image (Figure 7).

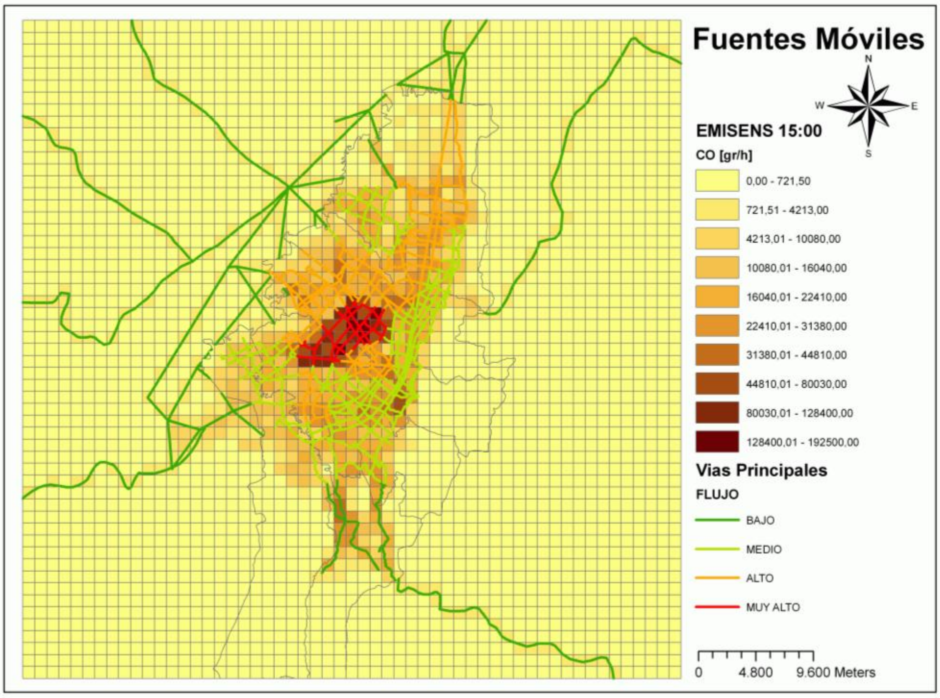

Figure 7: Comparison between the emissions (CO at 15h00) calculated by EMISENS and the traffic charge defined on the main roads. The traffic charge is symbolized in dark green for low traffic, light green for medium traffic, orange for high traffic and red for the very high traffic.

All the images produced with the results of this second application of the model can be found on the CD accompanying this report in the folders having names starting with "EMISIONES_MOVILES" contained in the folder "version_2".

3.3. The stationary sources: a third step

3.3.1. Industrial Categories

In a similar manner than for the vehicle categories, the industrial sources were received already classified by UniAndes (CIIA, 2008a) in categories according to their equipment and technology. An overview of the classification criteria can be found in Appendix XII.

The following map (Figure 8) shows the localization of the 1478 sources considered in this inventory as well as the limits of the different localities (see Appendix VI for the names).

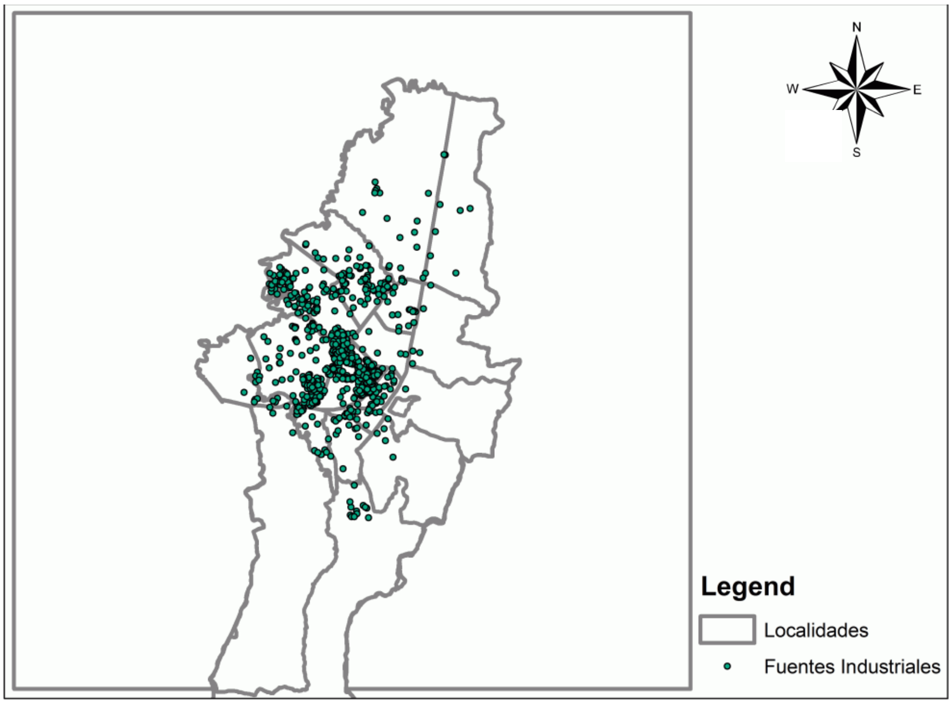

Figure 8: Localization of the different industrial sources and limits of the localities forming the northern part of the Bogotá district

3.3.2. Emission factors

The emission factors for the stationary sources available in the report from UniAndes (CIIA, 2008a) were complemented with data from other sources, which included the AP-42 Emission factors inventory from US-EPA (EPA, 2010) and a policy of the Department of Environmental Quality of the Commonwealth of Virginia (DEQ-Virginia, 2008). The emission coefficients used for the stationary sources can be found in Table 17. Error data were available for the values determined by UniAndes. These values were rather high, ranging approximately from 30 to 100 percent of the value of the emission factor.

Table 17: Emission factors grouped by category (gas fired boilers CG1, CG2 and CG3; gas fired ovens HG; coal fired boilers CC1 and CC2; coal fired ovens HC; coal fired brick burning kilns HL; equipment using liquefied petroleum gas GPL, diesel D, or used vegetal oil AU).

Industrial Category	Unit	Emission Factors									
		CO	NO_x			PM			SO_2		
CG1	[g/m³]	1,344	6,5	+/-	5	0,6	+/-	0,5	0,02	+/-	0,015
CG2	[g/m³]	1,344	0,8	+/-	0,6	0,25	+/-	0,2	0,0005	+/-	0,0004
CG3	[g/m³]	1,334	1	+/-	0,9	0,05	+/-	0,02	0,005	+/-	0,005
HG	[g/m³]	1,334	1,2	+/-	1	0,2	+/-	0,19	0,07	+/-	0,07
CC1	[g/kg]	0,3	8	+/-	5	6	+/-	4	22	+/-	18
CC2	[g/kg]	0,3	5	+/-	2	10	+/-	8	12	+/-	4
HC	[g/kg]	0,3	5	+/-	3	12	+/-	8	12	+/-	10
HL	[g/kg]	0,3	5	+/-	3	12	+/-	8	12	+/-	10
GPL	[g/L]	1,008	1,8			0,096			0,018		
D	[g/L]	0,6	6,6			2,0406			28,26		
AU	[g/L]	0,288	3,72			1,2			0,12		
Sources:	CIIA, 2008a										
	EPA, 2010										
	DEQ VIRGINIA, 2008										

3.3.3. Distribution of the emissions in space and time

The information collected by UniAndes (CIIA, 2008a) included the number of hours per day, days per week and weeks per year that each source was operating, but no information at all regarding the time of the day the processes take place. Thus, the operational hours of the different sources were defined using a randomized but partly directed distribution, programmed as a VBA macro. The sources were divided in 5 groups and the start of the operations set for each source randomly in the corresponding timespan:

- From 1 to 12 hours of daily operation, starting between 06h00 and 12h00
- From 12 to 16 hours of daily operation, starting between 02h00 and 08h00
- From 16 to 20 hours of daily operation, starting between 01h00 and 04h00
- From 20 to 22 hours of daily operation, starting between 01h00 and 02h00
- From 22 to 24 hours of daily operation, starting at 01h00

The functioning was then supposed to be continuous for the number of hours the equipment was indicated to operate every day.

The fuel consumption as well was part of the information collected by UniAndes (CIIA, 2008a). This information was transformed into an hourly value based on the operational information described and then multiplied by the corresponding emission factor to obtain the hourly emissions for every single source.

The random distribution described above resulted in the numbers of sources active at the same time represented graphically in Figure 9. The classification method used for the distribution in time of the sources based on the activity information contained in the received database produced a peak amount of active sources at noon.

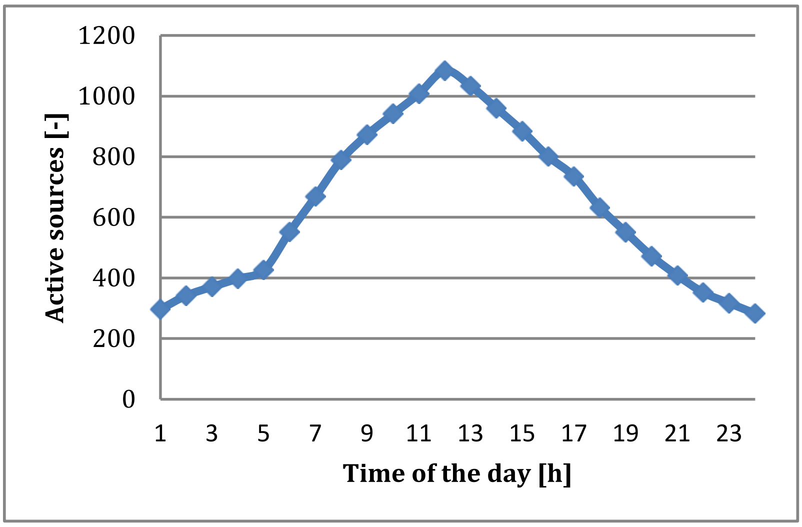

Figure 9: Graphical representation of the number of industrial sources active at the same time

The distribution in space was then done based on the input file for ArcGIS® containing all the geo-localized sources. The problems encountered with this file were already described in chapter 2.5.

The hourly emissions calculated earlier were then added to the data table in ArcGIS®, and the sum of the hourly emissions from all the sources located in a same cell was finally computed to obtain the total emissions of the stationary sources for each hour and cell.

3.3.4. Results of the industrial emissions

The annual emissions originating in industrial sources for the whole modeled area are shown in Table 18 below. Graphics representing the emissions for every hour of the day and each pollutant considered can be found in Appendix XIII.

Table 18: Annual emissions calculated for the industrial sources; the extrapolated values try to take into account the sources presenting insufficient data (242 sources out of 1478, i.e. 16.37 %) and comparison with values presented in (CIIA, 2008a)

Emissions [tons/year]	CO	NOx	SO2	PM
Calculated	508	2088	1741	1017
Extrapolated	607	2497	2082	1216
CIIA 2008a	NA	2600	2200	1400

Bearing in mind the huge error values for the emission factors (30-100%, see chapter 3.3.2) and the fact that UniAndes made an extrapolation for allegedly all the industrial sources of Bogotá, the values are relatively close. The estimation made by UniAndes thus seems rather low, considering that with "only" 1478 sources taken into account in this project, the difference is less than 200 [tons/year] or between 5 and 15 percent.

The correct spatial distribution of the stationary sources' emissions with a resolution of 1 km^2 is completely new information if compared to the previous report, where the spatial distribution was only secondary information (CIIA, 2008a). Actually, the resolution is much higher, since all the sources are located with errors mostly less than 100 meters compared to the corrected addresses indicated in the database. The following maps represent the daily emissions for CO (Figure 10) and PM (Figure 11).

The industrial areas of the city are still clearly visible, but the peak values are not located in the same localities for these two pollutants.

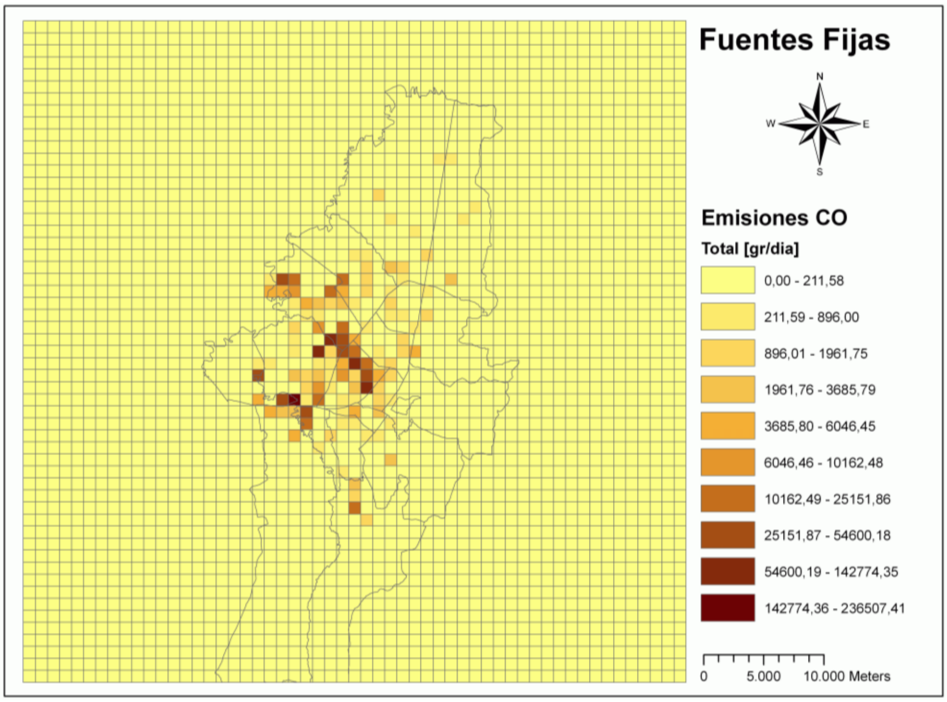

Figure 10: Daily emissions of CO by the stationary sources considered in this report

CO emissions are highest in the localities of Puente Aranda, Fontibón and Kennedy, in the central western part of the city (see Appendix VI). This area has the greatest amount of industrial sources in Bogotá, as already shown on Figure 8. CO is mainly emitted by the industrial sources burning natural gas or GPL, who on the other hand have the lowest PM emissions (see also Table 17 for the emission factors).

The spatial distribution of PM emissions is a little different. High emissions can still be found in the industrial area formed by the localities of Puente Aranda, Fontibón and Kennedy, but high emissions are also present in the southern part of the city, in the locality named Usme (see Appendix VI). This area corresponds to the brick production zone of Bogotá and presents a high density of coal fired brick burning kilns. PM emissions are particularly high for sources using coal as fuel, as can be clearly seen in Figure 12.

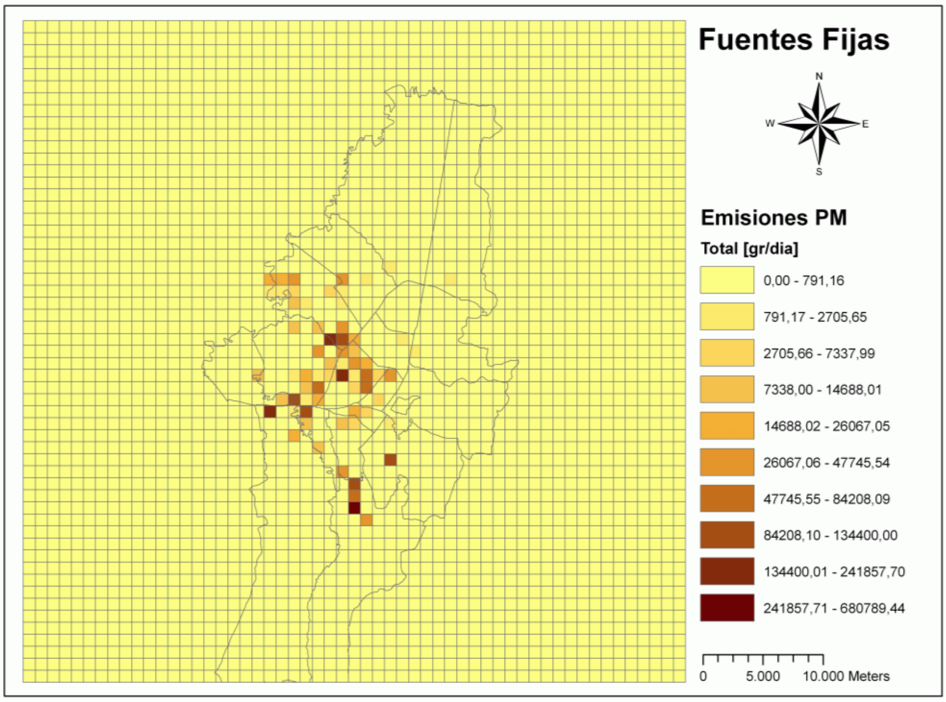

Figure 11: Daily emissions of PM by the stationary sources considered in this report

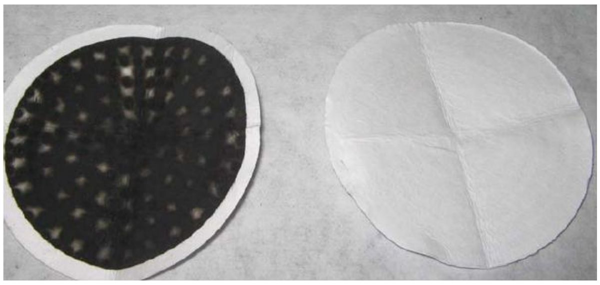

Figure 12: Filters used to measure PM emissions; on the left, a filter used in a coal fired plant, on the right, a filter from a natural gas fired plant (CIIA, 2008a)

The complete set of images and animations for the stationary sources can be found on the CD attached to this report in the folders having a name starting with "EMISIONES_FIJAS" located in the "version_2" folder.

3.4. Total Emissions

Generally, the main source for the emissions in the modeled area is the traffic, but locally, some industrial sources produce very high emissions. A comparison between the results for the whole modeled area regarding these two sources and all the pollutants considered in this report can be found in Table 19.

The only pollutant, which is somehow influenced by the industrial sources, is SO_2. The industrial emissions represent close to 14% of the total emissions of this pollutant.

Table 19: Influence of the different sources on the final result

Values	CO	NO_x	SO_2	PM	VOC
Mobile [tons/year]	706932	57658	13009	107973	108011
Stationary [tons/year]	607	2497	2082	1216	NA
Total [tons/year]	707539	60155	15091	109189	108011
Mobile	99.9%	95.8%	86.2%	98.9%	100.0%
Stationary	0.1%	4.2%	13.8%	1.1%	NA

The following maps represent the emissions of the different pollutants (i.e. CO, NO_x, SO_2 and PM) from both sources, mobile and stationary, at 08h00 in the morning. The map representing VOC emissions only includes the mobile sources, since the emissions for this pollutant from the industrial ovens and boilers were not calculated during this project.

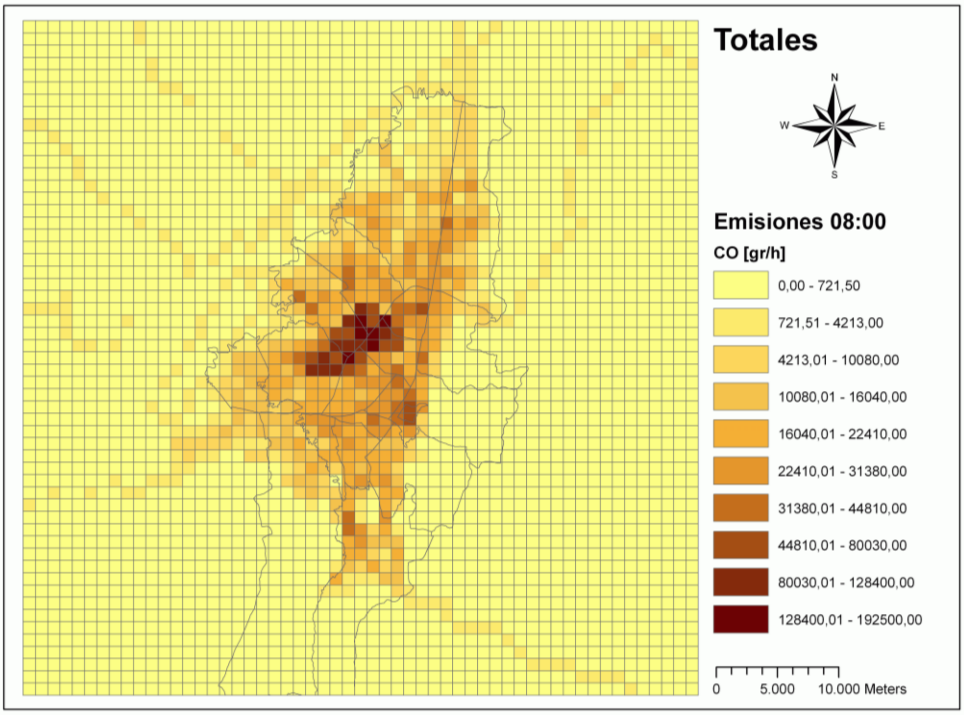

Figure 13: Total CO emissions at 08h00, combining emissions from mobile and stationary sources

Concerning the CO emissions illustrated in Figure 13, the influence of the industrial sources is almost insignificant. As already seen in Table 19, they represent less than 1% of the total emissions calculated in this project. This might be due to the fact that no locally valid CO emission factors were available and AP-42 emission factors used instead (see Table 17). It seems thus possible, that the industrial CO emissions are actually higher than the results presented here. Even though, the difference between the two values is such that the main influence will probably always be due to the mobile sources, i.e. the traffic.

NO_x emissions factors considered for the industrial sources were all based on local values. Still, the influence on the total emissions is very small (close to 5%). According to these results, only traffic related emission reductions would be effective. The hourly emissions at 08h00 for the NO_x are illustrated by Figure 14.

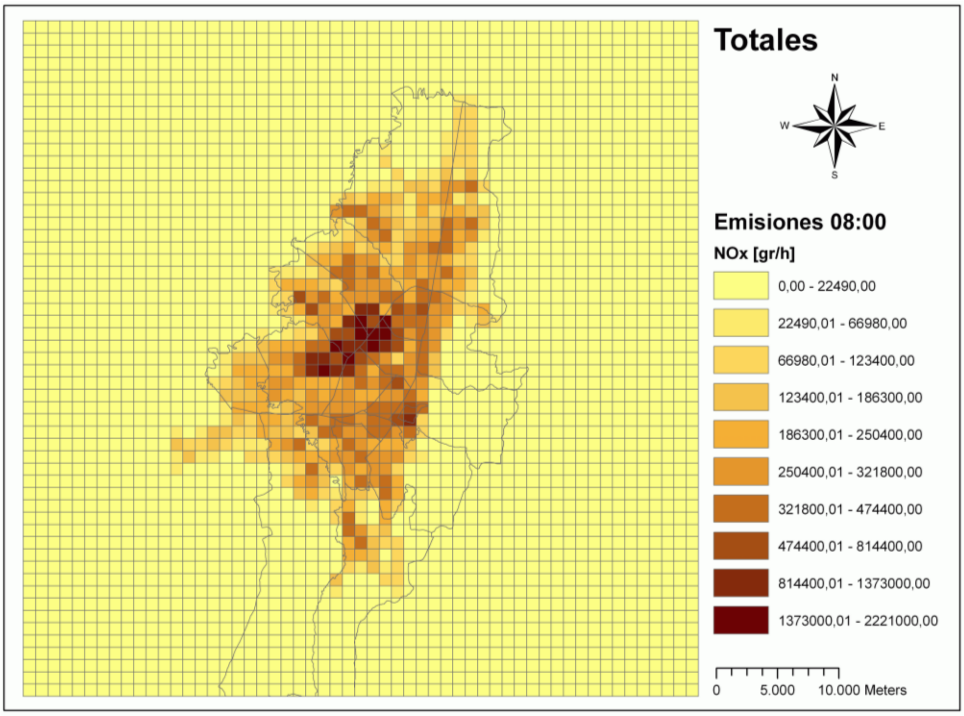

Figure 14: Total NO_x emissions at 08h00, combining emissions from mobile and stationary sources

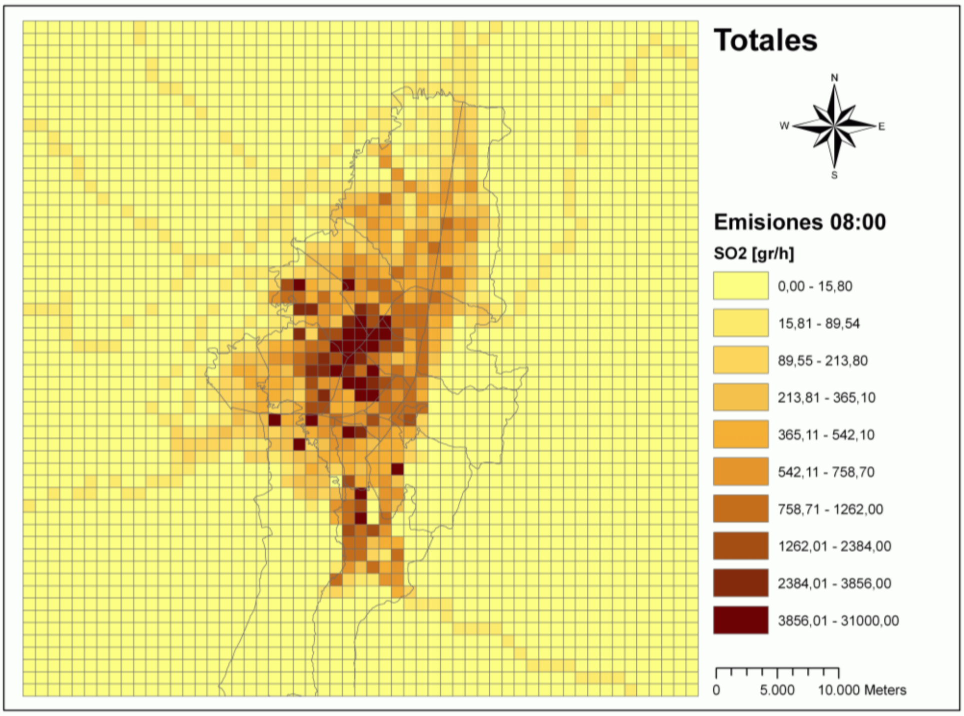

Figure 15: Total SO_2 emissions at 08h00, combining emissions from mobile and stationary sources

Figure 15 is interesting, because of the differences in SO_2 emissions that can be seen if compared with the result for the mobile sources (shown as Appendix XIV). The influence of the industrial sources is visible by the higher amount of dark-brown squares and a maximum SO_2 emission value close to 31 [kg/h*km²] – impressive if compared to the little more than 6 [kg/h*km²] maximum produced by the mobile sources only. Most of the sources presenting high SO_2 emissions are coal fired; its sulfur content is still relatively high in Colombia. As a result, even though the industrial emissions represent in the whole modeled area only close to 14% of the total SO_2 emissions, their local influence can be extremely higher.

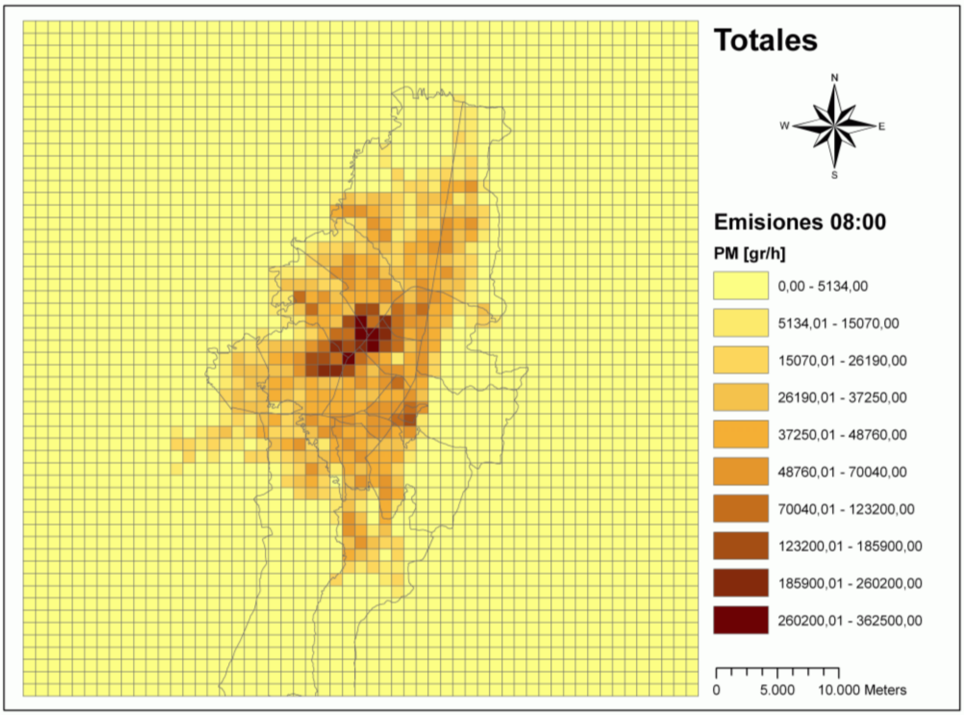

Figure 16: Total PM emissions at 08h00, combining emissions from mobile and stationary sources

PM emissions, as shown in Figure 16, are mainly traffic related (99% produced by mobile sources in this model), this is also the conclusion of previous studies indicating that PM is the priority pollutant to be targeted by future rules and regulations (Vargas & Rojas, 2009). The same study concludes that more than 50% of the PM_{10} in Bogotá is due to combustion processes, i.e. produced mainly by traffic and industries. This would mean that, in order to obtain the total PM emissions, i.e. not only due to the sources considered in this project, the amounts calculated could be almost doubled.

VOC emissions were only calculated for mobile sources, due to the lack of emission factors for the industrial categories considered in this report. The spatial distribution can be found in Figure 17. As for all the other pollutants, the highest emissions occur in the localities of Puente Aranda, Fontibón and Kennedy, corresponding to the sector, where very high traffic main roads are located.

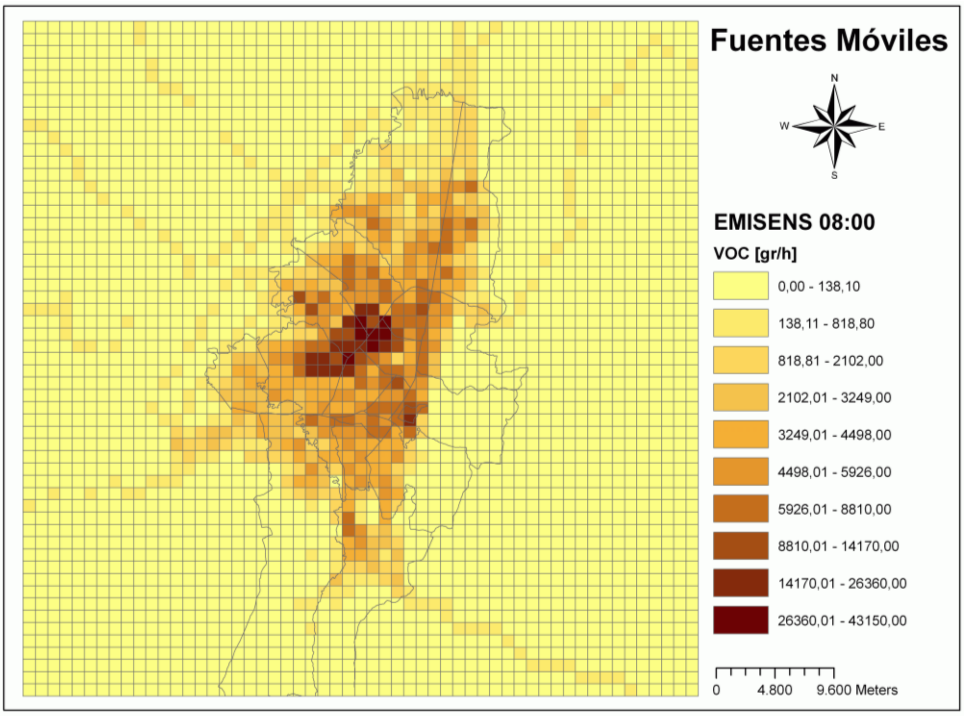

Figure 17: VOC emissions from the mobile sources only, no emissions calculated for the stationary sources

As for the previous models, the complete set of images and animations produced during this project concerning the total emissions can be found on the CD coming with this report in folders having names starting with "EMISIONES_TOTALES" in the "Version_2" folder.

4. Validation of the model: first insights

These results were compared to actual measurements made by the air quality monitoring network of Bogotá (Red de Monitoreo de Calidad del Aire de Bogotá – RCAB) and in a second attempt to the nonattainment levels for PM_{10} concentrations for the district of Bogotá (Behrentz, 2007). The comparisons made are mainly of qualitative nature.

The results from meteorological and air quality monitoring stations were obtained for two stations located in Kennedy and Fontibón (for the names and locations of the localities see Appendix VI). The results of both stations were actually very similar, which is why only the results for the station in Kennedy are presented in Figure 18.

The peak of the emissions can be clearly seen to occur between 08h00 and 09h00 in the morning. The maximum values for the spatial distribution of the emissions are present a little earlier: between 07h00 and 08h00 the traffic presents its morning peak, during the rush hour (see Figure 5).

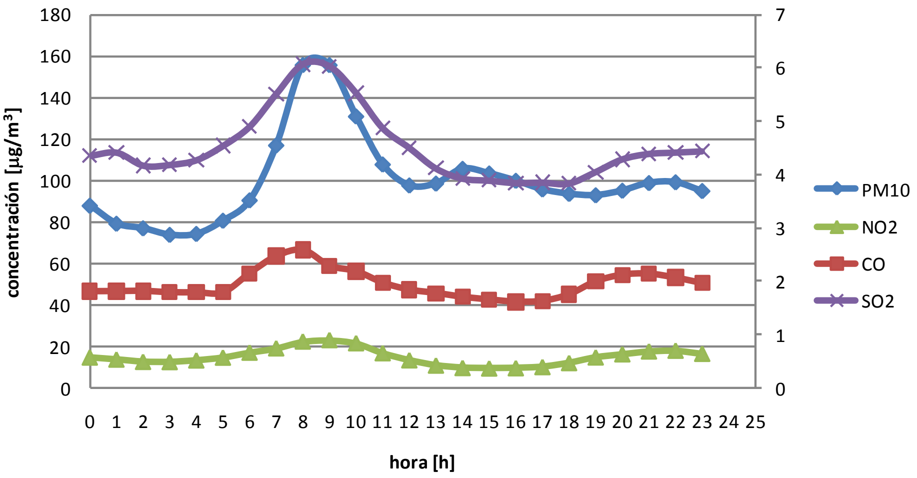

Figure 18: Monitoring results for immissions measured by the RMCAB station in Kennedy, the measures are given in [µg/m³] for every hour

Considering the direction of the wind and the approximate localizations of the measuring stations, as shown in Figure 19, the modeled distribution could well be at the origin of the peak.

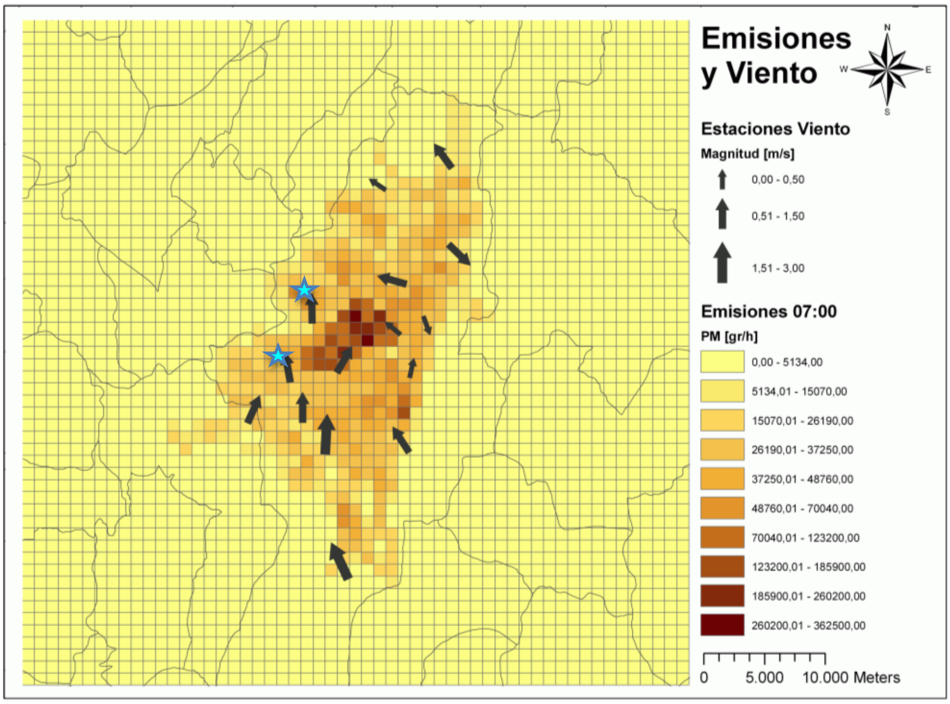

Figure 19: PM emissions and wind direction around 07h00 in the morning ; the stars indicate the approximative localization of the monitoring stations Fontibón (in the north) and Kennedy (in the south)

During the later hours of the day, the wind direction changes and, instead of coming from the south-east, it blows mainly towards the north-east, moving the emitted pollutants away from both stations. This probably leads to the absence of the second traffic peak shown in Figure 5.

The second comparison was done based on the PM_{10} medium value comparison map for the year 2006 (Figure 20), which was again compared to the spatial distribution of PM emissions shown in Figure 19 at 07h00 or Figure 16 at 08h00, the peak emission hours for the results modeled in this project.

As can be seen on the juxtaposition of the two maps shown in Figure 20, the results are very well correlated except maybe for the higher values in the north (locality named Suba). Maybe the traffic values for Suba on the secondary roads based on the land use calculations explained in chapter 3.2.1 were not high enough for this locality or the amount of buses circulating in this area should be higher, since many schools are located in this part of the city. With more traffic, all the pollutants would be emitted at higher rates, whereas by increasing the amount of school buses using diesel fuel, in particular the PM emissions would increase. To correctly identify the source for this discrepancy and find a solution for the modeling, extra studies and investigations would be needed.

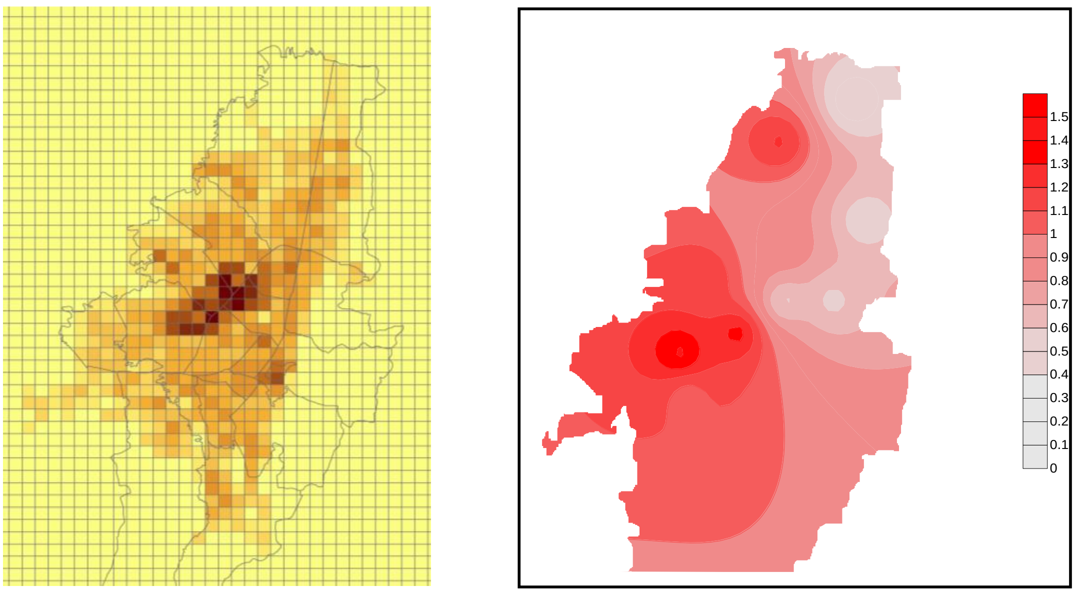

Figure 20: on the right, total PM emissions at 08h00 the darker the color, the higher the emissions (produced for this project); on the left, PM10 yearly average concentrations as compared to the legal limit, white represents lower values and red represents higher values (Behrentz, 2007)

Similar evaluations could be made for the other pollutants considered in this report (i.e. NO_x, CO, SO_2 and VOCs) in order to correctly validate the results or point out necessary further developments. The final objective of this kind of investigations would be the generation of an emissions model that would be completely in accordance with the immissions measured by the air quality monitoring network (RMCAB).

5. Conclusions and Perspectives

The objectives of this project were all successfully attained: the distribution in space and time of the emission inventory produced using EMISENS and ArcGIS® seems to be consistent at a first glance with available measured data and previous inventories; and the newly build capacities of different people at the UNAL allow them to continue the work on this project. Some of the elements of this project are worth to be reminded here: the uncertainty analysis included in EMISENS allowed for an efficient focusing during the redefinition of the input parameters (as explained in chapter 3.1.8). Even though some data was missing, the ability to use derived information which was relatively simple to obtain allowed for an efficient application of the model. The spatial resolution of the model is much higher than what was achieved during previous attempts and seems to be in accordance with actual immission measurements. Still, a more in depth examination of the results of this model is needed in order to validate or improve it according to the conclusions of this analysis.

An interesting observation made based on the results of the first attempt was that, in the case of Bogotá, a direct correlation exists between the road density and the socio-economic status of a residential neighborhood: the higher the density of the secondary road network, the higher the poverty in the area.

During the time spent on this project, some missing data and some possible developments were identified. It is certain, that much more could be done to obtain an even better insight on the air pollution problem in Bogotá, but the intention of the following list is not to be exhaustive. It was mainly compiled to present ways of obtaining data that would allow for a more objective distribution of the emissions and the replacement of the, for now, estimated or deduced parameters. It would for example be possible:

- to conduct a GPS based study to obtain the mileage partitioning among the different road categories and better speed data;
- to execute some road surveys in strategic points on the secondary roads to gain a better understanding of flux data and traffic charge on these roads;
- to request more precise information on operational hours concerning the industrial sources in order to be able to distribute the sources in time based on objective data;
- to determine local emission factors for stationary industrial CO emissions, in order to replace the American AP-42 values used in this study and better take into account the local situation (fuel quality, technologies used, altitude, pressure, temperature, etc.); and
- to include the speciation of VOCs, in order to differentiate and be able to quantify separately methane and other non-methane VOCs that are emitted.

Additional projects are already on track at UNAL evaluating the biogenic emissions; trying to develop a single ArcGIS® based tool allowing for a much easier preparation of the EMISENS input files; or applying meteorological and photo-chemical models to the area around Bogotá in order to obtain a complete set of tools for air quality forecasting and the evaluation of future air quality related policies based on a sound cost-benefit analysis.

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Appendixes

Appendix I: Description of the pollutants and their effects on health

The following descriptions of the pollutants and their effects are all directly cited from or based on the descriptions found in the "Handbook for Criteria Pollutant Inventory Development" (EPA-OAQPS, 1999).

Carbon monoxide (CO)

Carbon monoxide is a colorless, odorless, and poisonous gas produced by incomplete burning of carbon in fuels. The biggest part of the CO emissions comes from transportation sources. Other major CO sources are wood-burning stoves, incinerators, and fuel combustion at industrial sources. When CO is inhaled, it enters the bloodstream, and reduces the delivery of oxygen to organs and tissues.

Nitrogen oxides (NO_x)

Nitrogen oxides are important precursors to both ozone and acid rain, and as a result may affect not only human health, but also both terrestrial and aquatic ecosystems. Nitrogen oxides can interact with other compounds in the air to form PM. Nitrogen oxides form when fuel is burned at high temperatures. The two major emissions sources are motor vehicles and stationary fuel combustion sources such as electric utility and industrial boilers. The major mechanism for the formation of nitrogen dioxide (NO_2) in the atmosphere is the oxidation of the primary air pollutant nitric oxide (NO). When inhaled, nitrogen dioxide can irritate the lungs, cause bronchitis and pneumonia, and lower resistance to respiratory infections.

Sulfur dioxide (SO_2)

Sulfur dioxide is a colorless, pungent gas that is a respiratory irritant and like NO_x, is a precursor to acid rain. SO_2 can also interact with other compounds in the air to form PM. Thus, sulfur compounds in the air contribute to visibility impairment. Ambient SO_2 results largely from stationary sources such as coal and oil combustion, steel mills, refineries, pulp and paper mills, and nonferrous smelters.

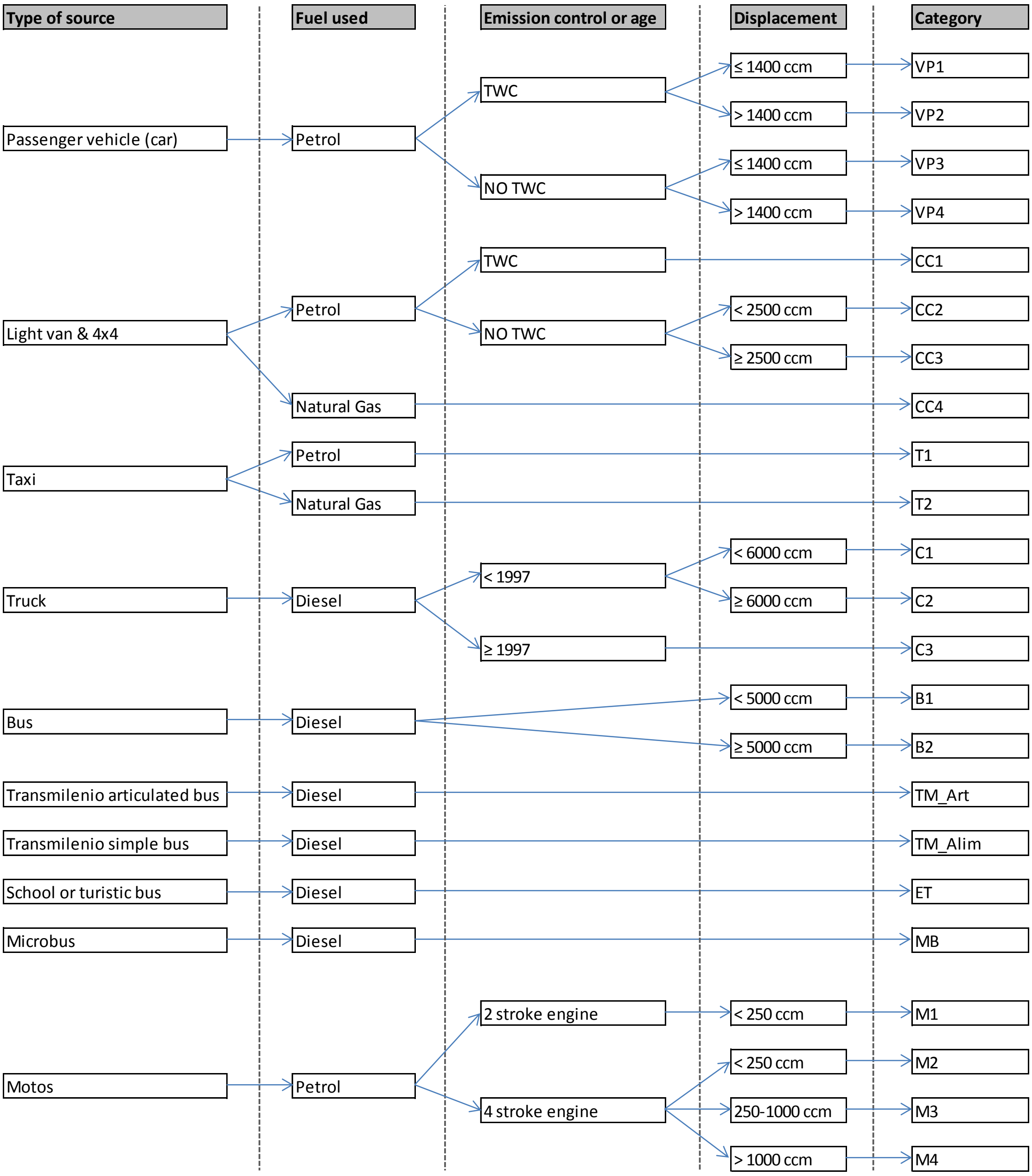
Particulate matter (PM)

Air pollutants called particulate matter include dust, dirt, soot, smoke, and liquid droplets. PM originates from a variety of sources, such as:

- Natural sources such as windblown dust and fires;
- Combustion sources such as motor vehicles, power generation, fuel combustion at industrial facilities, residential fireplaces, and wood stoves. Combustion sources emit particles of ash or incompletely burned materials;
- Activities such as materials handling, crushing and grinding operations, and travel on unpaved roads; and
- Interaction of gases (such as NH_3, SO_2, NO_x, and VOC) with other compounds in the air to form PM.

The chemical and physical composition of PM may vary depending on the location, time of year, and meteorology. "Fine" particles ($PM_{2.5}$) are generally emitted from combustion sources. Sulfate and nitrate secondary particles represent significant components of $PM_{2.5}$. "Coarse" particles (PM_{10}) can be emitted from sources including windblown dust, travel on unpaved roads, and materials handling.

Appendix II: Classification Diagram for the Vehicle Types in Bogotá based on engine technology and size, adapted from (CIIA, 2008b)



Appendix III: Base values for the emission factors (EF) used in this project, error values (Err.) and sources

Type	CO [gr/km]		NOx [gr/km]		VOC [gr/km]		PM [gr/km]		SO2 [gr/km]	
	EF	Err.	EF	Err.	EF	Err.	EF	Err.	EF	Err.
VP1	7	3	0.7	0.2	0.9	0.4	0.0032	0.0022	0.34	0.12
VP2	9	5	0.9	0.5	0.9	0.5	0.0032	0.0022	0.34	0.12
VP3	60	20	1.63	0.77	7	3	0.0032	0.0022	1.63	0.56
VP4	70	25	2	1	9	3.5	0.0032	0.0022	1.87	0.64
CC1	10	8	1	0.5	0.7	0.3	0.0032	0.0022	0.25	0.09
CC2	75	20	3	1	10	3	0.052	0.0355	0.22	0.08
CC3	85	30	4	3	7.5	2	0.0022	0.0015	0.22	0.08
CC4	40	25	3	1	4	1.5	0	0	0	0
T1	8	3	2	1	1	0.5	0.002	0.0014	0.87	0.3
T2	13	4	4	1.5	5	1.5	0	0	0	0
B1	11	4.17	7.85	3.7	2.52	0.89	0.3	0.2	0.56	0.19
B2	11	4.17	11.32	5.33	2.1	0.74	1.2	1	0.75	0.26
MB	9	3.41	7.76	3.65	1.94	0.68	0.48	0.3278	0.57	0.2
C1	4	1.52	11.49	5.41	1.73	0.61	0.9	0.5	0.67	0.23
C2	4	1.52	13.11	6.17	1.86	0.66	0.8	0.5	0.75	0.26
C3	3	1.14	8.99	4.23	1.16	0.41	0.3	0.2	0.61	0.21
ET	11	4.17	7.85	3.7	2.52	0.89	0.6	0.4	0.56	0.19
TM_Art	4	1.52	14.65	6.9	0.69	0.24	0.3	0.2049	1.23	0.42
TM_Alim	3	1.14	11.49	5.41	0.59	0.21	0.23	0.1571	0.96	0.33
M1	13	4.93	0.05	0.02	6.62	2.33	0.2	0.1366	0.033	0.01
M2	17	6.45	0.25	0.12	1.76	0.62	0.03	0.0205	0.064	0.02
M3	22	8.34	0.35	0.16	2.05	0.72	0.04	0.0273	0.11	0.04
M4	18	6.83	0.7	0.33	3.38	1.19	0.07	0.0478	0.12	0.04

Source by color:	UNIANDES	Transmilenio SA	COPERT IV	Estimated

Appendix IV: Mobile sources emission factors for the different pollutants, each vehicle category and each road category of the first modeling attempt

*Emission factors NO_X [g/km*veh]*

NO_x	PRINC	SEC	RUR	TM_Art	TM_Alim
VP+CC	1.84	1.48	2.15	1.68	1.61
T	3.35	3.22	3.75	3.25	3.25
B+MB	8.83	8.80	9.23	8.78	8.76
C	10.65	10.55	11.05	10.54	10.55
ET	7.90	7.90	8.30	7.85	7.80
TM-Art	14.70	14.70	15.10	14.65	14.60
TM-Alim	11.60	11.50	12.00	11.49	11.50
M	0.25	0.19	0.35	0.22	0.21

Vel [km/h]	35	20	60	27	13

*Emission factors CO [g/km*veh]*

CO	PRINC	SEC	RUR	TM_Art	TM_Alim
VP+CC	36.15	50.13	30.62	40.60	44.38
T	8.32	19.18	4.81	11.14	13.48
B+MB	8.50	13.45	6.20	10.39	11.60
C	2.63	5.09	1.95	3.45	3.99
ET	7.60	11.50	6.20	11.00	10.00
TM-Art	2.90	5.80	2.00	4.00	4.70
TM-Alim	2.40	4.50	1.90	3.00	3.40
M	13.39	22.49	13.98	16.42	18.64

Vel [km/h]	35	20	60	27	13

*Emission factors SO_2 [g/km*veh]*

SO_2	PRINC	SEC	RUR	TM_Art	TM_Alim
VP+CC	0.80	0.80	0.80	0.80	0.80
T	0.32	0.32	0.32	0.32	0.32
B+MB	0.62	0.62	0.62	0.62	0.62
C	0.66	0.66	0.66	0.66	0.66
ET	0.56	0.56	0.56	0.56	0.56
TM-Art	1.23	1.23	1.23	1.23	1.23
TM-Alim	0.96	0.96	0.96	0.96	0.96
M	0.06	0.06	0.06	0.06	0.06

Vel [km/h]	35	20	60	27	13

*Emission factors VOCs [g/km*veh]*

VOCs	PRINC	SEC	RUR	TM_Art	TM_Alim
VP+CC	4.45	6.76	3.70	5.07	5.50
T	2.31	3.72	1.75	2.73	3.00
B+MB	1.37	2.75	0.82	1.72	2.01
C	2.10	3.65	1.32	2.62	2.98
ET	2.00	4.00	1.10	2.52	3.00
TM-Art	0.59	0.80	0.40	0.69	0.75
TM-Alim	0.10	0.15	0.06	0.12	0.14
M	5.22	4.41	5.21	4.94	4.78

Vel [km/h]	35	20	60	27	13

*Emission factors PM [g/km*veh]*

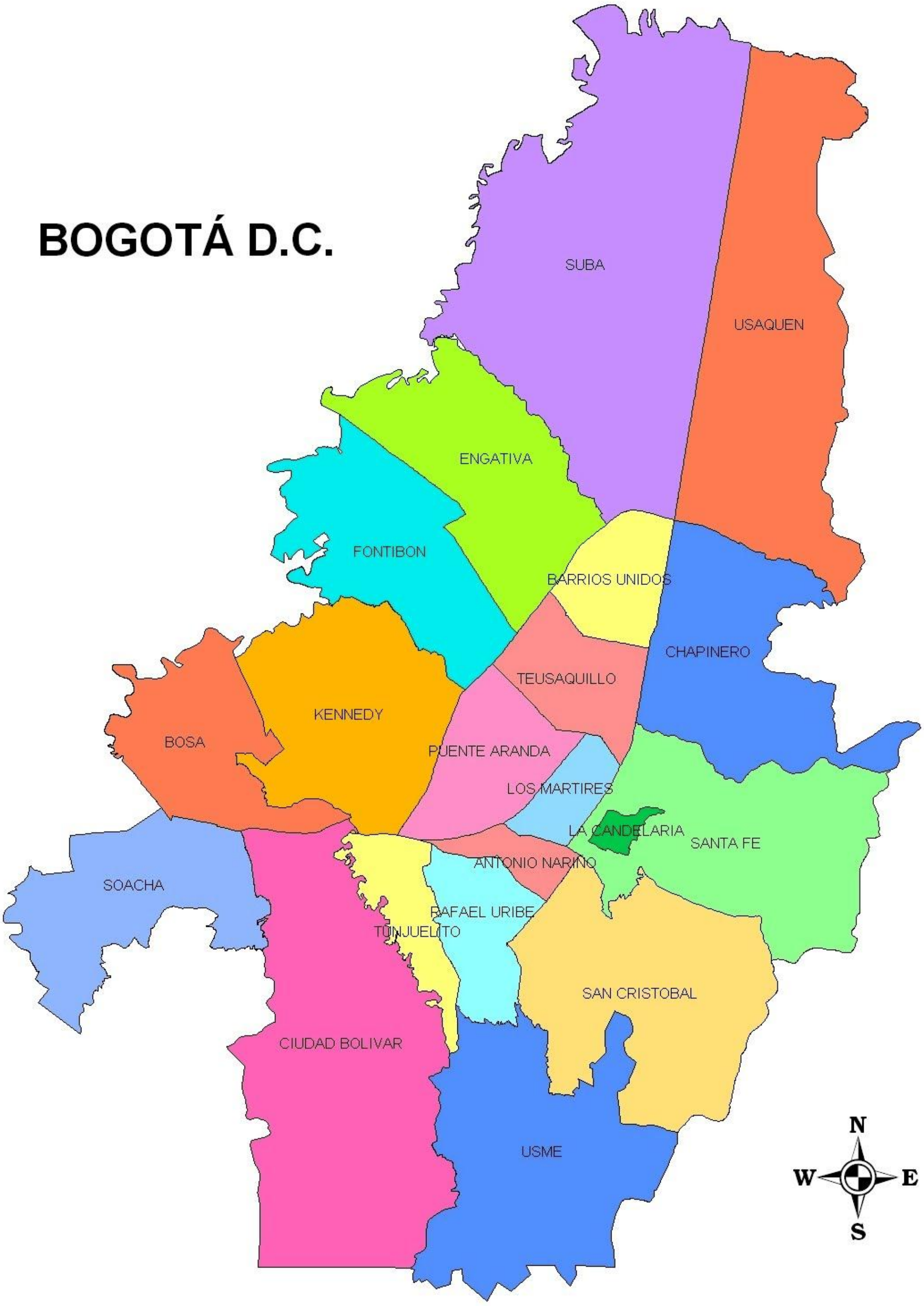
PM	PRINC	SEC	RUR	TM_Art	TM_Alim
VP+CC	0.01	0.01	0.00	0.01	0.01
T	0.00	0.00	0.00	0.00	0.00
B+MB	0.44	0.54	0.39	0.44	0.49
C	0.50	0.64	0.43	0.50	0.56
ET	0.55	0.41	0.20	0.55	0.63
TM-Art	0.25	0.38	0.17	0.25	0.33
TM-Alim	0.18	0.31	0.10	0.18	0.26
M	0.07	0.07	0.07	0.07	0.07

Vel [km/h]	35	20	60	27	13

Appendix V: Proportioned flux data as used for the distribution in time in the first application of the model

Hour	VP_CC	T	BMB	C	ET	M	TM
1	0.0116	0.0116	0.0024	0.0124	0.0047	0.0060	0.0130
2	0.0080	0.0080	0.0008	0.0137	0.0031	0.0033	0.0130
3	0.0065	0.0065	0.0006	0.0110	0.0022	0.0030	0.0325
4	0.0065	0.0065	0.0013	0.0162	0.0029	0.0029	0.0325
5	0.0101	0.0101	0.0092	0.0263	0.0171	0.0060	0.0455
6	0.0272	0.0272	0.0408	0.0420	0.0562	0.0269	0.0584
7	0.0477	0.0477	0.0633	0.0482	0.0804	0.0643	0.0584
8	0.0595	0.0595	0.0654	0.0428	0.0709	0.0811	0.0584
9	0.0544	0.0544	0.0644	0.0495	0.0654	0.0640	0.0584
10	0.0546	0.0546	0.0598	0.0631	0.0535	0.0588	0.0455
11	0.0548	0.0548	0.0552	0.0767	0.0416	0.0536	0.0455
12	0.0552	0.0552	0.0557	0.0699	0.0440	0.0530	0.0455
13	0.0559	0.0559	0.0567	0.0650	0.0492	0.0483	0.0455
14	0.0562	0.0562	0.0564	0.0619	0.0491	0.0502	0.0455
15	0.0603	0.0603	0.0553	0.0653	0.0475	0.0543	0.0455
16	0.0578	0.0578	0.0572	0.0663	0.0559	0.0595	0.0584
17	0.0553	0.0553	0.0592	0.0674	0.0642	0.0647	0.0584
18	0.0584	0.0584	0.0589	0.0567	0.0688	0.0769	0.0584
19	0.0573	0.0573	0.0576	0.0409	0.0633	0.0710	0.0455
20	0.0585	0.0585	0.0525	0.0321	0.0506	0.0476	0.0455
21	0.0499	0.0499	0.0478	0.0272	0.0380	0.0363	0.0325
22	0.0415	0.0415	0.0409	0.0181	0.0328	0.0319	0.0325
23	0.0296	0.0296	0.0279	0.0138	0.0255	0.0247	0.0130
24	0.0231	0.0231	0.0109	0.0136	0.0131	0.0120	0.0130

Appendix VI: Map of the 20 localities composing the district of Bogotá



(Source: http://sites.google.com/a/civilju.com/www/01_Bogota_Localidades.jpg)

Appendix VII: Maximum values for each category in the road survey

Survey Point	All	Light	Bus	Truck
KR 10 X CL 19	6876	3906	2117	95
AUTOPISTA NORTE X CL 127	17559	14758	413	747
AV. BOYACÁ X CL 72	11962	8315	1186	732
AV. AMÉRICAS X KR 42B - CL19	8620	6481	819	410
AUTOPISTA SUR X AV 68	8715	5385	765	617
AUTONORTE X CL 170	12262	9899	506	783
KR 7 X CL 85	5528	4506	400	118
AC 6 X KR 24-27	8577	6200	714	353
AV. BOYACÁ X CAI YOMASA	2053	1073	446	301
AV 1 DE MAYO X TV 42	7340	5238	789	395
AK 68 X AC 26	19028	14784	1568	687
CL 26 X KR 92	8633	6556	816	602
AV. BOYACÁ X CL 13	14839	9059	1067	1222
AV. BOYACÁ X AV V.CIO	6093	3196	635	662
KR 13 X CL 53	3391	2488	510	49
KR 91-94 X CL 131	2537	1120	892	86
KR 7 X CL 127	5589	4629	618	190
KR 10 X AV 1 DE MAYO	4587	2270	1350	109
KR 7 X CL 45	5962	4642	781	74
AV. SUBA X CL 100	11032	8914	586	291
AV. A MEJÍA X AV 1 DE MAYO	4520	1919	775	398
KR 15 X CL 100	6912	5538	768	137
AV. V.CIO X AV G. CORTES	4330	1983	991	289
AV. CENTENARIO X AV. CALI	11839	7363	1020	2013

Source: Road survey data provided from the Secretaria Distrital de Movilidad (SDM)

Appendix VIII: Results of the road survey data analysis

Survey Point	All	Light	Bus	Truck	Combined
KR 10 X CL 19	MEDIUM	LOW	VERY HIGH	LOW	**MEDIUM**
AUTOPISTA NORTE X CL 127	VERY HIGH	VERY HIGH	LOW	HIGH	**HIGH**
AV. BOYACÁ X CL 72	HIGH	HIGH	HIGH	HIGH	**HIGH**
AV. AMÉRICAS X KR 42B - CL19	HIGH	MEDIUM	MEDIUM	MEDIUM	**HIGH**
AUTOPISTA SUR X AV 68	HIGH	MEDIUM	MEDIUM	HIGH	**HIGH**
AUTONORTE X CL 170	VERY HIGH	HIGH	MEDIUM	HIGH	**HIGH**
KR 7 X CL 85	MEDIUM	MEDIUM	LOW	LOW	**MEDIUM**
AC 6 X KR 24-27	HIGH	MEDIUM	MEDIUM	LOW	**MEDIUM**
AV. BOYACÁ X CAI YOMASA	LOW	LOW	LOW	LOW	**LOW**
AV 1 DE MAYO X TV 42	MEDIUM	MEDIUM	MEDIUM	LOW	**MEDIUM**
AK 68 X AC 26	VERY HIGH	VERY HIGH	VERY HIGH	HIGH	**VERY HIGH**
CL 26 X KR 92	HIGH	MEDIUM	MEDIUM	HIGH	**HIGH**
AV. BOYACÁ X CL 13	VERY HIGH	HIGH	HIGH	VERY HIGH	**VERY HIGH**
AV. BOYACÁ X AV V.CIO	MEDIUM	LOW	MEDIUM	HIGH	**MEDIUM**
KR 13 X CL 53	LOW	LOW	MEDIUM	LOW	**MEDIUM**
KR 91-94 X CL 131	LOW	LOW	MEDIUM	LOW	**MEDIUM**
KR 7 X CL 127	MEDIUM	MEDIUM	MEDIUM	LOW	**MEDIUM**
KR 10 X AV 1 DE MAYO	MEDIUM	LOW	HIGH	LOW	**MEDIUM**
KR 7 X CL 45	MEDIUM	MEDIUM	MEDIUM	LOW	**MEDIUM**
AV. SUBA X CL 100	HIGH	HIGH	MEDIUM	LOW	**HIGH**
AV. A MEJÍA X AV 1 DE MAYO	MEDIUM	LOW	MEDIUM	LOW	**MEDIUM**
KR 15 X CL 100	MEDIUM	MEDIUM	MEDIUM	LOW	**MEDIUM**
AV. V.CIO X AV G. CORTES	MEDIUM	LOW	MEDIUM	LOW	**MEDIUM**
AV. CENTENARIO X AV. CALI	HIGH	MEDIUM	HIGH	VERY HIGH	**HIGH**

Source: Road survey data provided from the Secretaria Distrital de Movilidad (SDM)

Appendix IX: Illustration of the Thiessen algorithm

The Thiessen algorithm defines areas of influence around each of a set of points using the perpendicular bisectors of the lines between all the points (ET Geo Wizards, 2010).

All the points of a given set of points are connected by straight lines. These lines are then divided in halves using the perpendicular bisectors. The zones delimited by the bisectors are the influence zones for each point. Any location in a given zone is closer to the point at the center of this zone than to any other point of the set. The concept is illustrated in Figure 21.

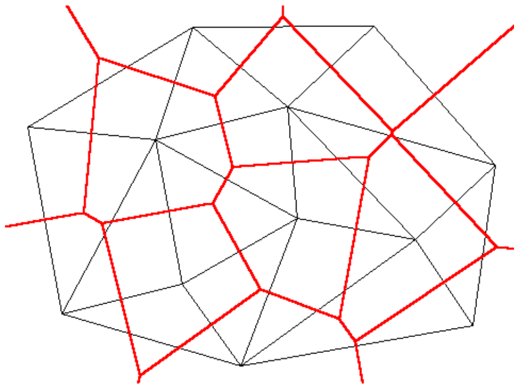


Figure 21: grey lines connect all the points of an input dataset, red lines define the boundaries of the polygons using a Thiessen method (source: www.ems-i.com)

Appendix X: Mobile sources emission factors for the different pollutants, each vehicle category and each road category of the second modeling attempt

*Emission factors CO [g/km*veh]*

CO	PRINC_B	PRINC_M	PRINC_A	PRINC_MA	SEC_B	SEC_M	SEC_A	RUR	TM_Art	TM_Alim
VP_CC	40.60	40.60	40.60	40.60	50.13	50.13	50.13	33.38	0.00	0.00
T	11.14	11.14	11.14	11.14	19.18	19.18	19.18	6.57	0.00	0.00
B_MB	13.45	13.45	13.45	13.45	11.60	11.60	11.60	8.50	0.00	0.00
C	5.09	5.09	5.09	5.09	3.99	3.99	3.99	2.63	0.00	0.00
ET	11.00	11.00	11.00	11.00	11.50	11.50	11.50	6.90	0.00	0.00
TM-Art	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.35	0.00
TM-Alim	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.40
M	16.42	16.42	16.42	16.42	22.49	22.49	22.49	13.68	0.00	0.00

*Emission factors NO_x [g/km*veh]*

NOx	PRINC_B	PRINC_M	PRINC_A	PRINC_MA	SEC_B	SEC_M	SEC_A	RUR	TM_Art	TM_Alim
VP_CC	1.68	1.68	1.68	1.68	1.48	1.48	1.48	2.00	0.00	0.00
T	3.25	3.25	3.25	3.25	3.22	3.22	3.22	3.55	0.00	0.00
B_MB	8.80	8.80	8.80	8.80	8.76	8.76	8.76	8.83	0.00	0.00
C	10.55	10.55	10.55	10.55	10.55	10.55	10.55	10.65	0.00	0.00
ET	7.85	7.85	7.85	7.85	7.90	7.90	7.90	8.10	0.00	0.00
TM-Art	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.70	0.00
TM-Alim	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.50
M	0.22	0.22	0.22	0.22	0.19	0.19	0.19	0.30	0.00	0.00

*Emission factors PM [g/km*veh]*

PM	PRINC_B	PRINC_M	PRINC_A	PRINC_MA	SEC_B	SEC_M	SEC_A	RUR	TM_Art	TM_Alim
VP_CC	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00
T	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B_MB	0.54	0.54	0.54	0.54	0.49	0.49	0.49	0.44	0.00	0.00
C	0.64	0.64	0.64	0.64	0.56	0.56	0.56	0.50	0.00	0.00
ET	0.55	0.55	0.55	0.55	0.41	0.41	0.41	0.38	0.00	0.00
TM-Art	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.00
TM-Alim	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26
M	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.00	0.00

*Emission factors SO_2 [g/km*veh]*

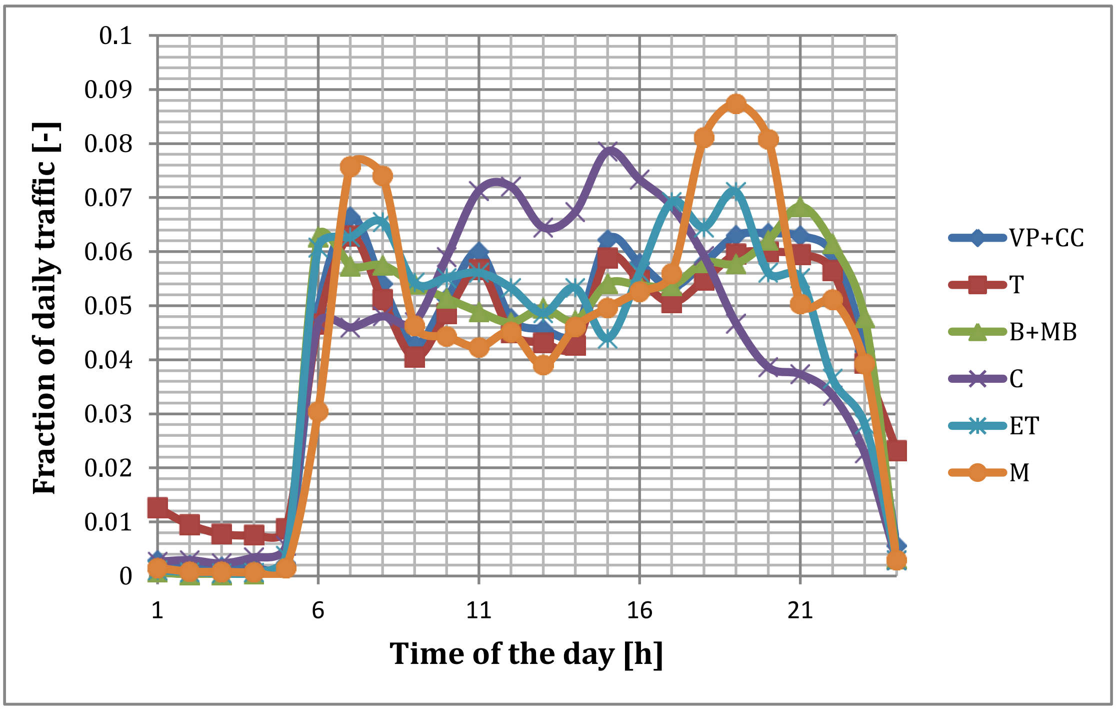
SO2	PRINC_B	PRINC_M	PRINC_A	PRINC_MA	SEC_B	SEC_M	SEC_A	RUR	TM_Art	TM_Alim
VP_CC	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.00	0.00
T	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.00	0.00
B_MB	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.00	0.00
C	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.00	0.00
ET	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.00	0.00
TM-Art	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.23	0.00
TM-Alim	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.96
M	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.00	0.00

*Emission factors VOCs [g/km*veh]*

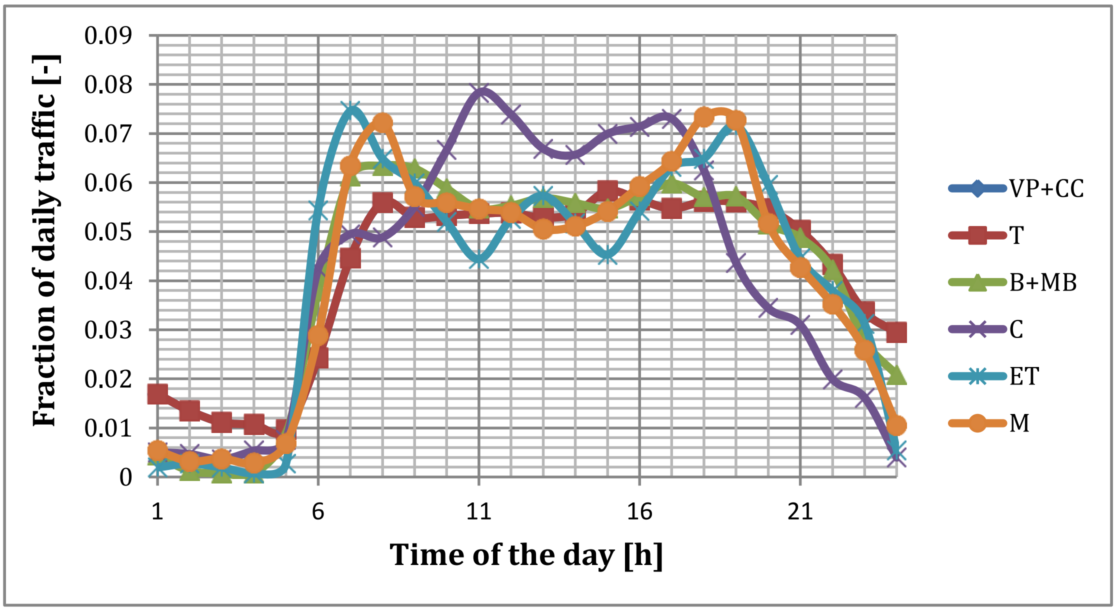
VOCs	PRINC_B	PRINC_M	PRINC_A	PRINC_MA	SEC_B	SEC_M	SEC_A	RUR	TM_Art	TM_Alim
VP_CC	5.07	5.07	5.07	5.07	6.76	6.76	6.76	4.07	0.00	0.00
T	2.73	2.73	2.73	2.73	3.72	3.72	3.72	2.03	0.00	0.00
B_MB	2.75	2.75	2.75	2.75	2.01	2.01	2.01	1.37	0.00	0.00
C	3.65	3.65	3.65	3.65	2.98	2.98	2.98	2.10	0.00	0.00
ET	2.52	2.52	2.52	2.52	4.00	4.00	4.00	1.55	0.00	0.00
TM-Art	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.70	0.00
TM-Alim	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14
M	4.94	4.94	4.94	4.94	4.41	4.41	4.41	5.22	0.00	0.00

Appendix XI: Graphical analysis of the traffic distribution in time on the different main road subcategories

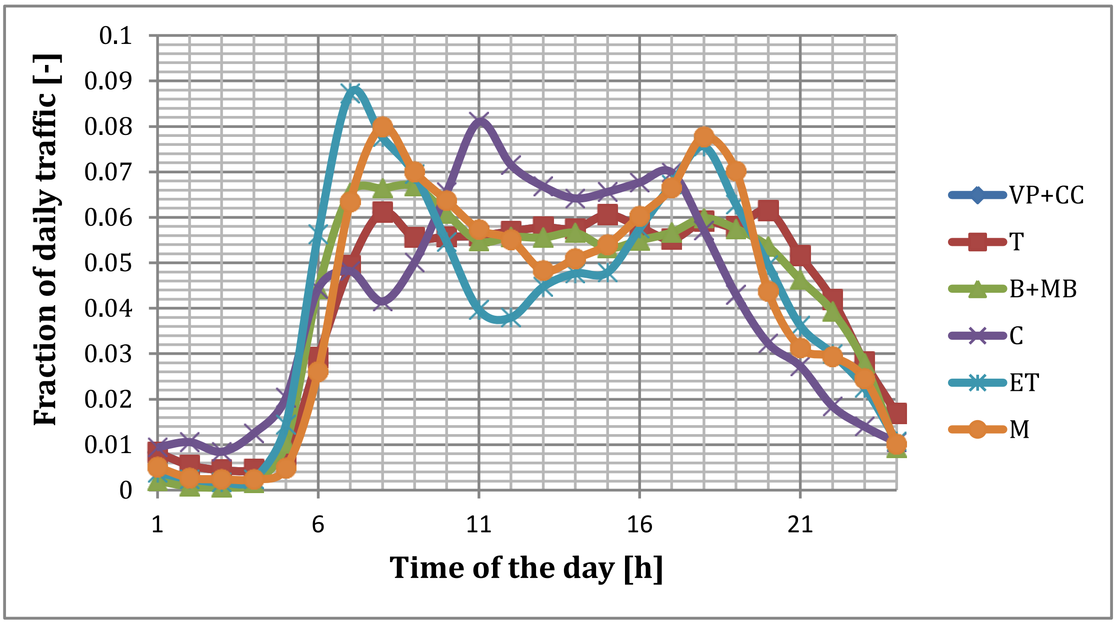
Traffic charge evolution in time, as fraction of daily traffic: Low traffic



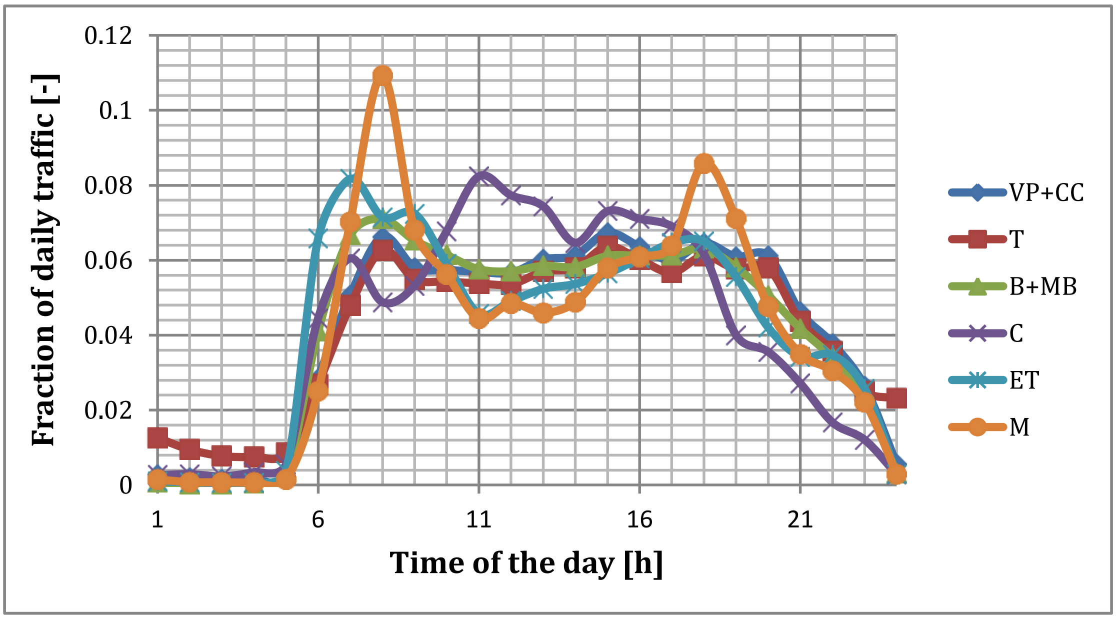
Traffic charge evolution in time, as fraction of daily traffic: Medium traffic



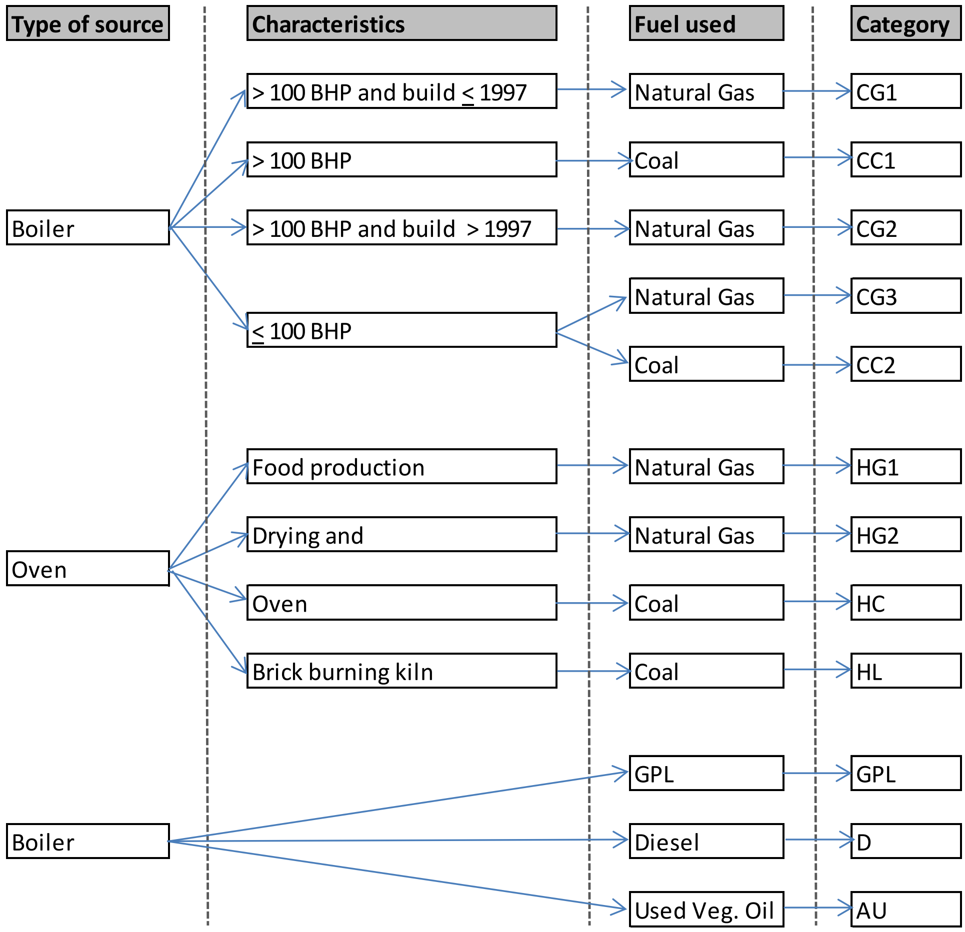
Traffic charge evolution in time, as fraction of daily traffic: High traffic



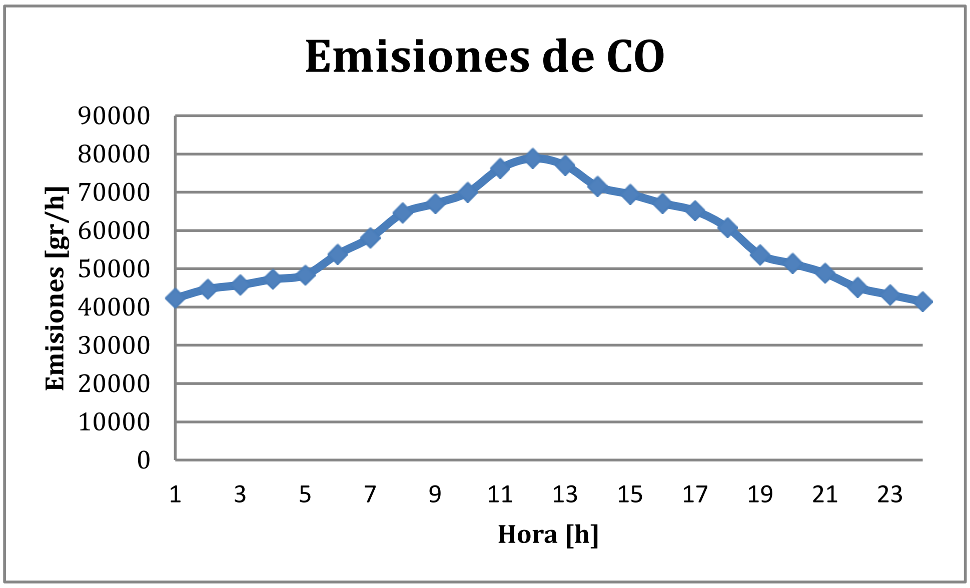
Traffic charge evolution in time, as fraction of daily traffic: Very high traffic

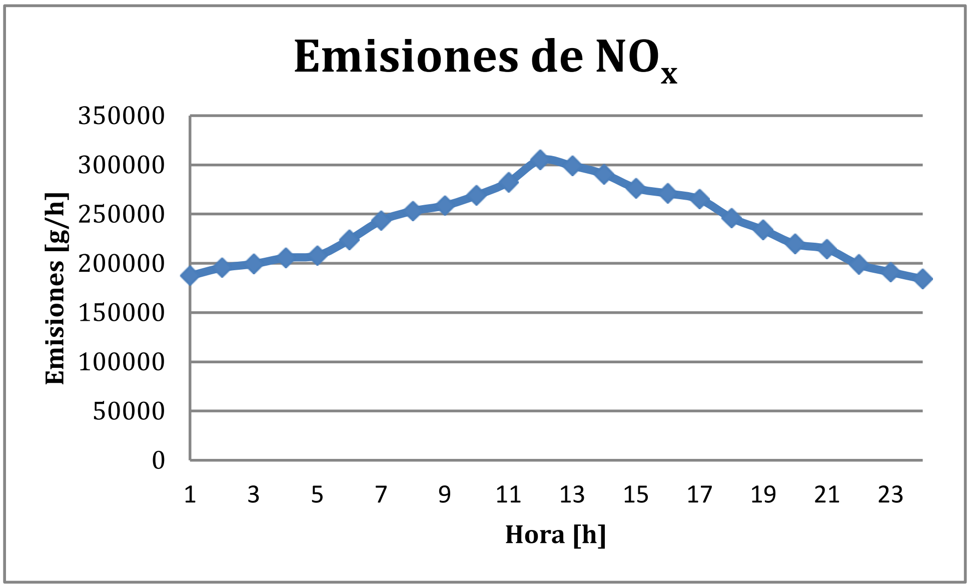


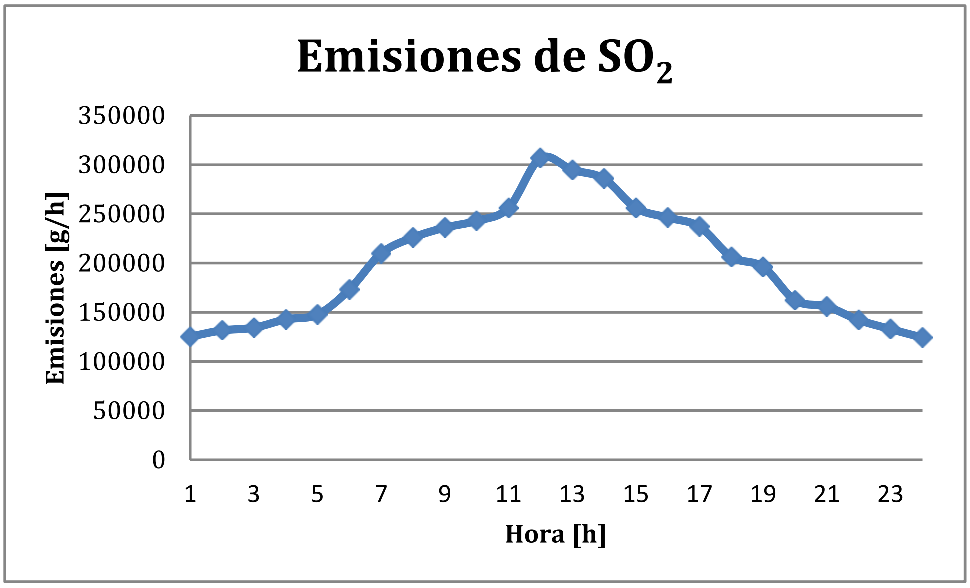
Appendix XII: Classification Diagram for the Industrial Categories in Bogotá based on their technology and size, adapted from (CIIA, 2008a)



Appendix XIII: Graphical representation of the hourly industrial sources emissions for the pollutants considered in this project



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250000
200000
150000
100000
50000
0
Emisiones [g/h]
1
3
5
7
9
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13
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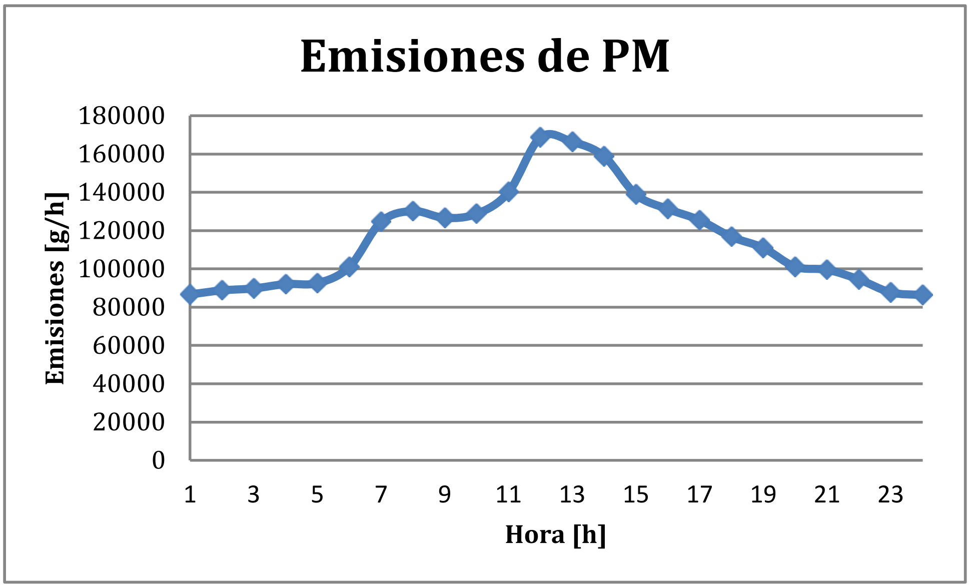
21
23
Hora [h]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160000
140000
120000
100000
80000
60000
40000
20000
0
Emisiones [g/h]
1
3
5
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21
23
Hora [h]

Appendix XIV: SO2 emissions from mobile sources at 08h00, based on the second application of the model