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EMISSIONS AND AIR CONCENTRATIONS OF POLLUTANT FOR URBAN AREA SOURCES

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Abstract. *Urban air pollution estimation as well as greenhouse emissions rely on the preparation of good source inventories. Depending on the desired temporal and geographical scale of such inventories, two complementary calculations are generally proposed to estimate these emissions: the top-down and the bottom-up approach. This paper is divided in two sections, in the first part, a brief report of both methods are presented, applied to the mobile urban sources, which is then used to prepare a gridded emission pattern. In the second part, an urban area source dispersion algorithm is presented to compute the ambient concentration using the calculated gridded emission pattern for any particular meteorological conditions. The proposed method calculates the ambient concentration of the entire area, by convolving the response of one unit cell with the gridded emission pattern of the area under study. This method is computationally more efficient than applying the standard regulatory algorithms for any area shape. The results are then applied on a geographical information system.*

1 INTRODUCTION

Two complementary approaches are generally proposed to estimate the emissions from road vehicles: the top-down approach or the bottom-up approach. The selection of one of these methods will depend on the availability of input data and the desired spatial and temporal resolution. In the top-down approach, the total annual emission from mobile sources is calculated using the number of road vehicles actually running for a given region. At any time and street, the vehicle flux is estimated through indirect information such as population density, structure of the automotive park, fuel consumption, the number of cars per inhabitants, the average speed; the annual mean traveled distance; and the annual emission factors based on the fuel consumption. This information has acceptable spatial distribution, but a poor temporal resolution, usually on an annual base. To estimate the emissions from road vehicles in the bottom-up approach, traffic counting and speed recording in many streets are required. Also, it is convenient to determine the vehicle fleet distribution according to power, size, fuel, and typical vehicle use. The bottom-up method has high temporal resolution (normally an hourly base) with variable spatial resolution. It is clear, then, that this approach is more accurate but requires high data density. The emissions in each street is calculated using emission factors based on average traveled distances for each vehicle category. Usually this latter approach is selected in urban areas where this information is available. To compare both approaches one normally calculates the total annual emissions integrated on the same geographical scale. The advantage in using a geographical information system (GIS) is that most of the gathered or estimated information can be geographically distributed, simplifying the association of different temporal data.

In the first section of the paper, a gridded emission map for vehicular sources is calculated and crosschecked using the two mentioned approaches. In the second section, a simple algorithm to calculate the air quality at the urban scale is presented, using the gridded emission pattern prepared in the first section.

2 CALCULATION OF THE EMISSION PATTERNS

2.1 Top-down approach

The top down approach can be characterized as a sectoral analysis of the energetic consumption of the transportation sector. For these purpose we use information from public registers and surveys such us structure of the automotive park, the average traveled distances, fuel consumption, population density, car per inhabitants, source-destiny surveys, etc. Table 1 shows an example of the population density for the six Municipalities conforming the Great Mendoza, which was selected as case study area. Table 2 shows two destiny-source surveys prepared for years 1986 and 1998. This table specifies the modal distribution of the transport needs of the Great Mendoza Area, expressed as daily trips, also is included number of private cars and the public bus fleet circulating in the city. As it can be seen from both tables, there is a decrease in the use of public transportation, and consequently an important increase in the use of private cars, as well as an increase in the motorization rate. Table 3 shows the structure of the transport consumption, in terms of their own units (m^3, liters or MWh) for transportation mode, while Table 4 shows the energy consumption in terms of Tera Joules. Both tables are presented for year 1999. Finally Table 5 summarizes average indicators for the energy consumption of the transportation sector. Two main groups arise from these tables as mayor consumers: the private motorization (6500 TJ) and the freight sector (6300 TJ). The public transportation instead consumes only 1300 TJ. Comparing the energy per passenger per traveled km, the private motorization uses 0.9 J/km/pass, while the public transport uses only 0.2 J/km/pass, indicating, as expected, a better efficiency of the public transportation, despite the uses of old diesel buses.

Table 1: Population distribution of the Great Mendoza Area

Year	1970			1980			1991			2001		
Variable Municipality	Popul.*	Surface+ km^2	Den. Inhab. /km^2	Popul.	Surf. km^2	Den. Inhab. /km^2	Popul.	Surf. km^2	Dens. Inhab. /km^2	Popul.	Surf. km^2	Dens. Inhab. /km^2
Capital	118,568	28	4,235	119,088	30	3,970	121,620	32	3,801	110,993	32	3,469
Godoy Cruz	106,857	28	3,816	138,136	30	4,605	179,588	33	5,442	182,977	33	5,545
Guaymallén	103,859	88	1,180	157,867	93	1,697	206,371	97	2,128	251,339	100	2,513
Las Heras	63,367	65	975	102,791	67	1,534	145,587	70	2,080	173,814	72	2,414
Luján	21,183	45	471	36,650	50	733	54,367	55	988	83,576	59	1,417
Maipú	42,959	63	682	64,170	66	972	71,439	70	1,021	99,840	80	1,248
Great Mendoza	456,794	317	1,893	618,702	336	2,252	778,972	357	2,577	902,539	376	2,768

*Includes urban population, +Urban surface only. Source: INDEC[1], DEIE[2]

Table 2: Daily trips in Mendoza metropolitan Area for years 1986 and 1998.

Source destiny Survey	Public / private transport city of Mendoza, daily trips			
Description	1986	Relative to total trips	1998	Relative to total trips
Public Bus (diesel)	398,190	50.8%	493,600	36.3%
Trolley bus (elect)	16,230	2.1%	14,950	1.1%
Corporative Bus	5,360	0.7%	6,000	0.4%
School Bus	1,450	0.2%	13,400	1.0%
Taxi (diesel-GNC)	7,030	0.9%	18,000	1.3%
Private Car	200,000	25.5%	354,750	26.1%
Share private car ride	43,000	5.5%	210,000	15.4%
Motorcycle	2,560	0.3%	35,150	2.6%
Bicycle	37,490	4.8%	102,665	7.6%
Walk > 1km	72,170	9.2%	111,150	8.2%
Total daily trips	783,480	100.0%	1,359,665	100.0%
Number of buses	600	/	1,000	/
Number of priv. vehicles	120,000	/	290,000	/
Number of trips Cars	250,030	31.9%	582,750	42.9%
Number of trips Bus	421,230	53.8%	527,950	38.8%
Population	691,900	/	903,100	/
Daily trips/ Inhab.	1.13	/	1.51	/
Motorization rate Inhab./ veh.	5.8	/	3.1	/
Bus use rate pass/trip	702.05	/	527.95	/

Source: DEIE[2]

Table 3: Fuel consumption for the metropolitan area for year 1999.

Transport consumptions	Gas	Gasolines		Gas-Oil	Electricity
Fuel	NCG	GR	GE	GO	EE
Unit	Thous. m3	Thous. lt	Thous. lt	Thous. lt	MWh
Private (Auto + taxi)	37,896	36,907	74,714	41,291	0
Public Bus & Trolley bus	369	0	0	28337	4221
Freight	17,605	21,975	3,505	124,554	0
Total	55,870	58,882	78,219	194,182	4,221

NCG: Natural Compressed Gas, GR: Car gasoline regular, GE: Car gasoline especial, GO: gas Oil, EE: Electricity

Table 4: Energy consumption of the transport sector for year 1999 (TJoules)

Year 1999	Net energy consumption TJoules					
	NCG	GR	GE	GO	EE	Total
Private (auto, taxi)	1,505	1,139	2,306	1,605	0	6,555
Public (bus, trolleybuses)	15	0	0	1,101	11	1126
Freight	699	679	108	4,840	0	6,325
Total	2,219	1,818	2,414	7,546	11	14,006

Table 5: Main indicators of the energy use in the transport sector

Energy use		1980	1990	2000
Private passenger transport energy use per capita	MJ/cap	9,649	7,581	7,208
Public transport energy use per capita	MJ/cap	1,888	1,483	1,410
Energy use per private passenger KM	J/(km.pass)		2.4	0.9
Energy use per public passenger KM	J/(km.pass)		0.1	0.2

2.2 Emission patterns

After calculating the energy consumption, it is possible to calculate the approximated average emission of the metropolitan area by multiplying the energy consumption by the proper emission factors for each gas, using, for example, the emission factor proposed by the International Panel for Climate Change[3,4]. Table 6 shows the proposed emission factor for each type of fuel, while Table 7 shows the total annual emission estimation for the transportation sector in thousand of metric tons or Gigagrams (Gg).

Table 6: Used emission factors from energy consumption

Emission factors	Tn/TJ	kg/TJ	kg/TJ	kg/TJ
Fuel / Pollutant	CO2	CO	NOx	CH4
Natural Gas	53.67	723.00	198.00	320.00
Gasoline	69.30	7,330.00	390.00	57.00
Kerosene	73.46	296.50	170.00	5.20
Gas Oil	73.30	510.00	716.00	60.00
Diesel Oil	73.30	510.00	790.00	0.80
Fuel Oil	73.30	503.20	790.00	0.80

Source IPCC [3,4]

Table 7: Annual average emissions from the transportation sector (in thousands of metric tons)

Gas / year	1980	1990	2000	Emission factors	
CO2	974	953	1,060	75.00	Tn/TJ
CO	65	64	71	5.00	Tn/TJ
NOx	5.2	5.1	5.7	400.00	kg/TJ
CH4	1.95	1.91	2.11	150.00	kg/TJ

2.3 Bottom up approach

To characterize the city emissions from a bottom-up approach it is necessary to gather traffic counting in main streets intersections and compute average driving speed. The vehicles at each street are grouped in different fuel, size and types categories. The emission factors are based on average emission per traveled distance (in g/km). The values for CO and HC, were taken from our own measurements[4,5], and from the literature[6] for NOx and PM_{10}. The emissions of air pollutants from vehicular sources, for a given street, and for an (yearly) average period, it is characterized by three main factors:

$$E = N \times e \times l \tag{1}$$

Where *E* (g/unit time) is the total emission in the time considered, *N* is the number of average circulating vehicles in the period, *e* is the pollutant specific average emission factor measured in g/km per vehicles, and *l* is the mean traveled distance in km. The emission factor *e* (g/km) is expressed as the mass of pollutant per unit length as a function of the traveled speed *v* and the vehicular type, fuel, etc. The total pollutant *E(m,i,k)* at all streets (or segments *i*) for each pollutant *k*, with traffic flow *N(m,i)* belonging to *m* different vehicular groups is calculated then as:

$$E(m,i,k) = \sum_k \left[\sum_i l_i \times \left(\sum_m \frac{p_m}{100} e(m,k,v_j) \times N(m,i) \right) \right] \tag{2}$$

Three main variables needs to be estimated, the average flux in each segment, the average velocity, and the specific emission factor. In a GIS format, segments in the line type database represent a street; therefore the length of the segment is directly obtained. Besides to the street length, each record also stores other relevant information such as, width, number of vehicles, speed, etc. The streets are characterized according to three hierarchies: a) primary, including main city access and inter county freeway, b) secondary or intra county roads, and c) tertiary or residential roads. The hierarchies had been selected according to their traffic intensity, hourly variation, and dominant use. One important source of uncertainty is given by the actual distribution of the number of vehicles *N*. Although we use traffic counting and a source destiny survey to calibrate the data, it is necessary to use an underlying model to specifically assign a proper *N* and speed (*V*) to each segment, (in this study case, the Great Mendoza Area is divided in 25.000 segments approximately). To specify *N* and *V* we use the population density of the city, which produces a central area of attraction. The vehicular street counting and the corresponding average speed displayed certain proportionality as a function of the distance to the main central area and to the hierarchy of the street. These two variables, distance and hierarchy were used to compute the vehicular flux and speed in each segment, according to the following calculation:

$$\begin{aligned} V(i,j) &= V_0(j)\exp((1-d)/A) \\ N(i,j) &= N_0(j)\exp((1-d)/B) \end{aligned} \tag{3}$$

Where $V(i,j)$ (km/h) is the speed at segment i and hierarchy j; $N(i,j)$ is the number of vehicles per day at segment i and street hierarchy j, d is a normalized distance to the central district area (d=1 at the central area, d=0 at city outer limits); A and B are scale coefficients whose values are presented in Table 8. Similarly, to estimate the emission factor, we used the estimation of the on-road characterization presented by Gantuz et al[5] in Enief 2004, which for each segment took the following form:

$$\begin{aligned} E_{CO}(i) &= E_{0\,CO}(j)\times V(i,j)^{C(j)} \\ E_{HC}(i) &= E_{0\,HC}(j)\times V(i,j)^{D(j)} \end{aligned} \tag{4}$$

Where $E_{CO}(i)$ and $E_{HC}(i)$ are the emission factor at segment i for carbon monoxide and hydrocarbon respectively; $E_{0\,CO}$, $E_{0\,HC}$, C and D are coefficients presented in Table 8. Table 9 shows the average emissions factors according to the street hierarchy for CO and HC. Table 10 presents the emission for the entire city for the gasoline vehicles sector, using the two approaches: top down and bottom up, for the CO and HC. The bottom up computed total emissions are in good agreement with the top down fuel consumption approach within the variability of the available information. The emissions of CO and HC are emphasized, since the used emission factors were measured in several streets of the city. NOx emissions are linear dependent to the CO emissions since both are originated in the same source of pollution, therefore it is possible to calculate the total emissions of NOx, as a linear proportion of the CO emission factors, or alternatively using the emission factors established in the literature.

Table 8: Coefficients for the vehicular flux and speed at each segment

Variable	Hierarchy					
	Primary			Secondary		Tertiary
J	110	120	130	210	220	310
V0	60	40	40	30	25	20
A	1.2	1.2	1.2	1.1	1.1	1.1
N0	23000	17000	11000	5000	5000	3000
B	0.13	0.13	0.13	0.13	0.13	0.13
E0_CO	318.6	318.6	326.6	326.6	326.6	120
C	-0.421	-0.421	-0.321	-0.321	-0.321	-0.1
E0_HC	30	30	25	25	25	12
D	-0.6	-0.6	-0.1	-0.1	-0.1	-0.1

To test the sensibility of the emission calculation to the variability of the coefficients presented in Table 8, 200 cases of a Monte Carlo type simulation test was computed. The following uncertainties were included to the segment parameters: traffic flow: 70% deviation from the mean value; velocity: 40% deviation; emission factors: 50% deviation for CO and HC. These simulations try to reflect the daily variability within each street, either in traffic flux, average speed and the proper uncertainties of the vehicular emission factors. The calculation results shown in Table 11 and Table 12, demonstrate that the annual mean values are relative insensitive to random changes at the small scale.

After the above validation procedure, it is possible to produce an emission pattern of the mobile sources for different pollutant (see Figure 2). To better compare the emissions from the bottom-up with the top-down approach, the emission are calculated for each segment in pixels or grids of 350 × 350 m. The total emission of the city for each considered pollutant is computed by adding the emissions of all cells.

Table 9: Average Emission Factors (g/km) for gasoline vehicles, for CO and HC

EF (g/km)	Hierarchy					
	Primary			Secondary		Tertiary
J	110	120	130	210	220	310
E_CO GV	49.91	56.94	93.04	104.89	109.95	86.3
E_HC GV	2.14	2.58	16.9	17.55	17.81	8.63

Table 10: Total city emission calculated for gasoline vehicles Tn/year

Emission Tn/year	Top-down	Bottom-up	Relative Dif %
CO GV	30,908	33,319	7.8%
HC GV	5,099	4,293	-15.8%

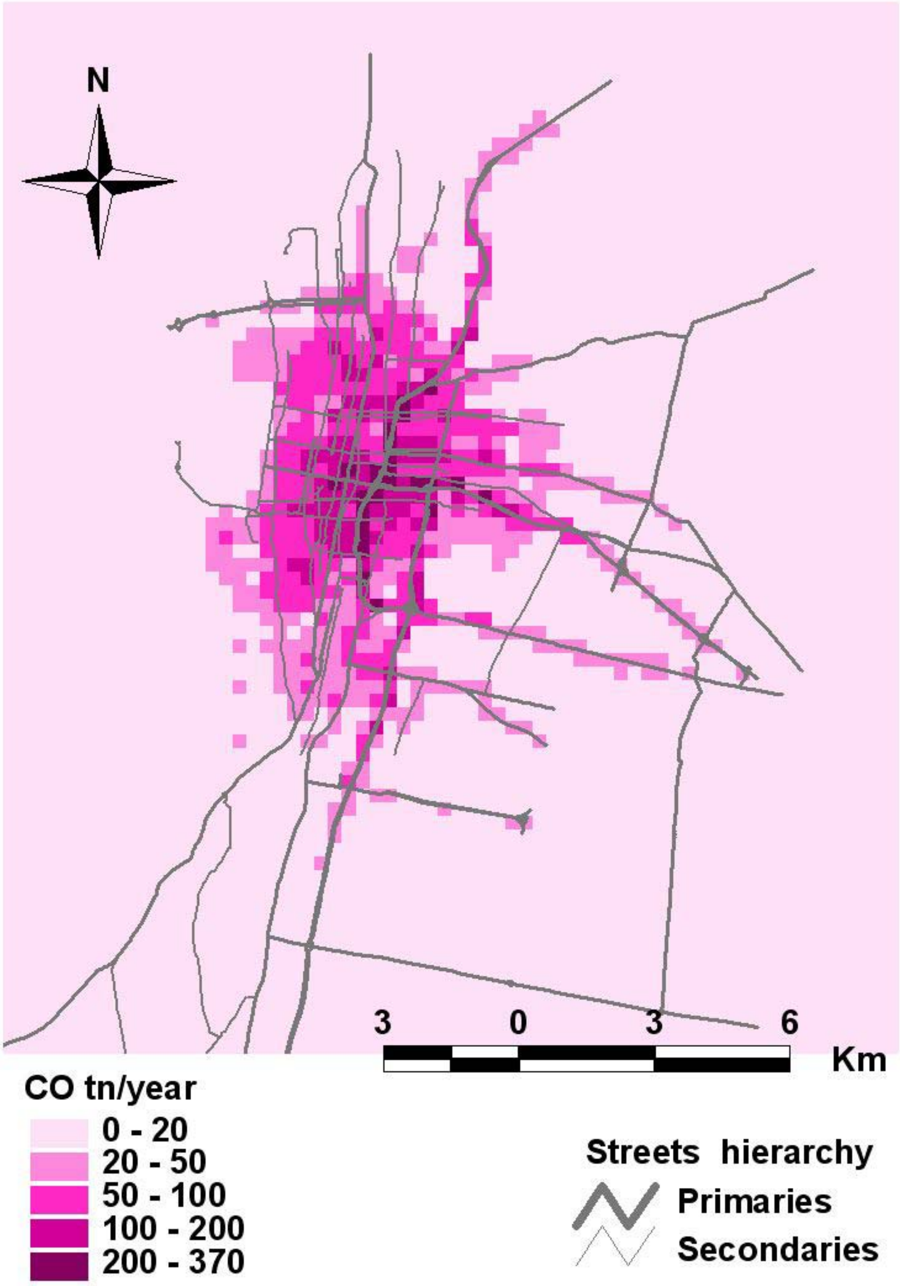
Table 11: Sensibility of the calculated emission factors

EF (g/km)	Street hierarchy					
J	110	120	130	210	220	310
E_CO GV						
Average	51.16	57.76	117.29	132.29	124.25	72.79
Deviation	1.68	2.84	2.03	1.44	0.92	0.16
% Variation	3.29%	4.92%	1.73%	1.09%	0.74%	0.23%
E_HC GV						
Average	2.4483	2.9143	14.08735	16.2424	16.6795	10.1885
Deviation	0.19	0.40	0.19	0.15	0.10	0.02
% Variation	7.67%	13.69%	1.32%	0.94%	0.59%	0.22%

Table 12: Sensibility of the total emissions

Emission Tn/year	CO_GV	HC_GV
Average	31,817	3,987
Deviation	447	48
% Variation	1.40%	1.20%

Figure 1: Gridded emission patterns for CO for the city of Mendoza



3 CALCULATION OF THE AMBIENT CONCENTRATION

3.1 Dispersion of area sources

In urban pollution problem, one is often confronted in calculating the cumulative effect of numerous small sources (residential areas, small business, vehicular emissions, etc), which are distributed over a large area. In such cases the emission rate is expressed as an average pollutant flux per unit area (g/m.s^2). One possible approach is to divide the urban sector in rectangular area sources. The ambient concentration may be calculated using the standard gaussian dispersion model applied to area sources. If an area has crosswind dimension *Dy* and along-wind dimension *Dx*, the concentration downwind can be calculated applying the gaussian dispersion model for an infinitesimal area $dy \times dx$

$$\begin{aligned} C(x,y,z) &= \frac{q}{\pi \times u} \int_0^{Dx} \frac{1}{\sigma_y \sigma_z} \exp\left(\frac{-z^2}{2\sigma_z^2}\right) \left[\int_{-Dy/2}^{Dy/2} \exp\left(\frac{-y^2}{2\sigma_y^2}\right) dy \right] dx, \\ &= \sqrt{\frac{2}{\pi}} \frac{q}{u} \int_0^{Dx} \frac{1}{\sigma_z} \exp\left(\frac{-z^2}{2\sigma_z^2}\right) \times erf\left(\frac{D_y}{2\sigma_y \sqrt{2}}\right) dx \end{aligned} \tag{5}$$

Where q is the area source emission rate in g/(m.s^2), σ_y, σ_z are the dispersion coefficients in the cross-wind and vertical directions y and z; u is the wind speed (m/s) along the axis x. The error function *erf(x)* is a measure of the area under the gaussian distribution function. For large areas the error function is approximate one, so the above equation (for ground level concentrations) can be simplified as

$$C(x,0,0) = \frac{q}{u} \sqrt{\frac{2}{\pi}} \int_0^{Dx} \frac{1}{\sigma_z} dx \tag{6}$$

For a simple case, where $\sigma_z = ax^b$, it is possible to obtain the result presented by Gifford and Hanna[7] for urban area sources:

$$C(x,0,0) = \frac{q}{u} \sqrt{\frac{2}{\pi}} \frac{x^{(1-b)}}{a(1-b)} \tag{7}$$

The average ambient concentration at an arbitrary receptor due to a set of area sources is then:

$$C(x,0,0) = \sqrt{\frac{2}{\pi}} \frac{1}{u \times c(1-d)} \left\{ \left(\frac{x_i}{2}\right)^{1-d} Q_0 + \sum_{i=1}^{n} Q_i \left(\frac{x_i}{2}\right)^{1-d} \left[(2i+1)^{1-d} - (2i-1)^{1-d}\right] \right\} \qquad (8)$$

Where *a, b, c, d* are the Brookhaven National Laboratory parameter values[8] and exponents of the dispersion parameters $\sigma y = a\, x^b$; $\sigma z = c\, x^d$; Q_i (i=0, 1, 2, …, N) are the emission strengths in each of the grid cells upwind Similar approach for urban areas, has been also presented by Mazzeo and Venegas[9]:

$$C(x,0,0) = \frac{a\left[Q_0 x^b + \sum_{i=1}^{N} (Q_i - Q_{(i-1)})(x - x_i)^b\right]}{\left(\left|A\right| k\, z_0^b u_*\right)} \qquad (9)$$

Where x is in the mean wind direction; a, b and A are parameters that depend on atmospheric stability; Q_i (i=0, 1, 2, …, N) are the emission strengths in each cells upwind, k is von Karman´s constant, z_0 is the surface roughness length and u_* is the friction velocity.

3.2 Convolution with a basic cell

The contribution of a particular cell to the entire grid of *nx* × *my* cells can be calculated applying the above equations for a basic rectangular grid (in this particular case of 350 × 350m) with a normalized emission rate of 1 μg/(m.s^2). Using a set of meteorological data, different patterns for a given temporal and meteorological averages may be calculated, such as hourly, daily, monthly or annual averages or maximum values. Figures 2 through 4 show how an emitting grid influences the ambient concentration at all other cells. As it can be seen, the ambient concentration in one grid is mostly defined by the emission of the own cell, plus additional pollution transported from the neighbors cells. The advantage of a gridded emission patterns is that, for a given meteorological condition, each cell will contribute in the same way to all of their neighbors' cells, scaled by the emission of that particular grid. Consequently, the ambient concentration of the entire city, of dimension (*Lx*, *Ly*), will be the convolution of the emission pattern of the basic cell *P*(*x,y*) multiplied by the proper emission in each cell *E*(*x,y*):

$$C(x,y,0) = \int_0^{Lx} \int_0^{Ly} E(\lambda,\tau) \times P(x-\lambda, y-\tau)\, d\lambda\, d\tau \qquad (8)$$

The EPA ISCST3 regulatory model[10], also has proper algorithms to treat area sources, similar to Eq. (5) for rectangular sources. Moreover this computer program has the flexibility to define area sources with different rectangular shapes, but it is limited to a fixed number of areas and the computation could take a long time for big area sources. Instead it is here proposed, to apply the same regulatory model, but for only one unit basic emitting cell, (for a particular set of meteorological conditions), obtaining a concentration pattern over a spatial grid of $P(x,y)$ of arbitrary dimension (as already said, in this case we used a grid of 30 x 30 cells), which acts as the natural response of the emitting cell. Then the ambient concentration of the entire area is the superposition of the basic response with the entire emission grid $E(x,y)$. The pollutant dispersion due to big industrial sources can be calculated using the standard point source procedures of the regulatory models[10]. The computed area sources should be then added as background concentrations to the fixed source calculations. In former publications we have calculated the ambient concentration due to industrial sources[11,12] for the Metropolitan Area of Mendoza.

Figures 5 and 6 show several example of the computed air quality, due to vehicular sources for different meteorological conditions. As it can be seen, the pollution generated at the central district area is dispersed to the neighbor's district, according to the actual meteorological conditions. Finally Figure 7 shows an annual average situation.

4 CONCLUSIONS

Urban air pollution estimation as well as greenhouse emissions rely on the preparation of good source inventories. Depending on the desired temporal and geographical resolution of such inventories, two complementary calculations are generally proposed to estimate these emissions: the top-down and the bottom-up approach. This paper was divided in two sections, in the first part, a summary of both methods were presented, particularly applied to the mobile urban sources. The crosschecked calculation using both approaches leaded to a well-calibrated gridded emission pattern. In the second part, we present a simplification of the standard urban area source dispersion algorithm to compute the ambient concentration of gridded emission pattern. The advantage of a gridded emission patterns is that, for a given meteorological condition, each cell will contribute in the same way to all their neighbors' cells, but scaled by the emission of each emitting grid. The proposed method calculates the ambient concentration of the entire area, by convolving the response of one unit cell with the gridded emission pattern of the area under study. This methods is computationally more efficient than applying the standard regulatory algorithms for any area shapes. The results are then applied on a geographical information system.

Figure 2: Ambient concentration pattern for 1 hour

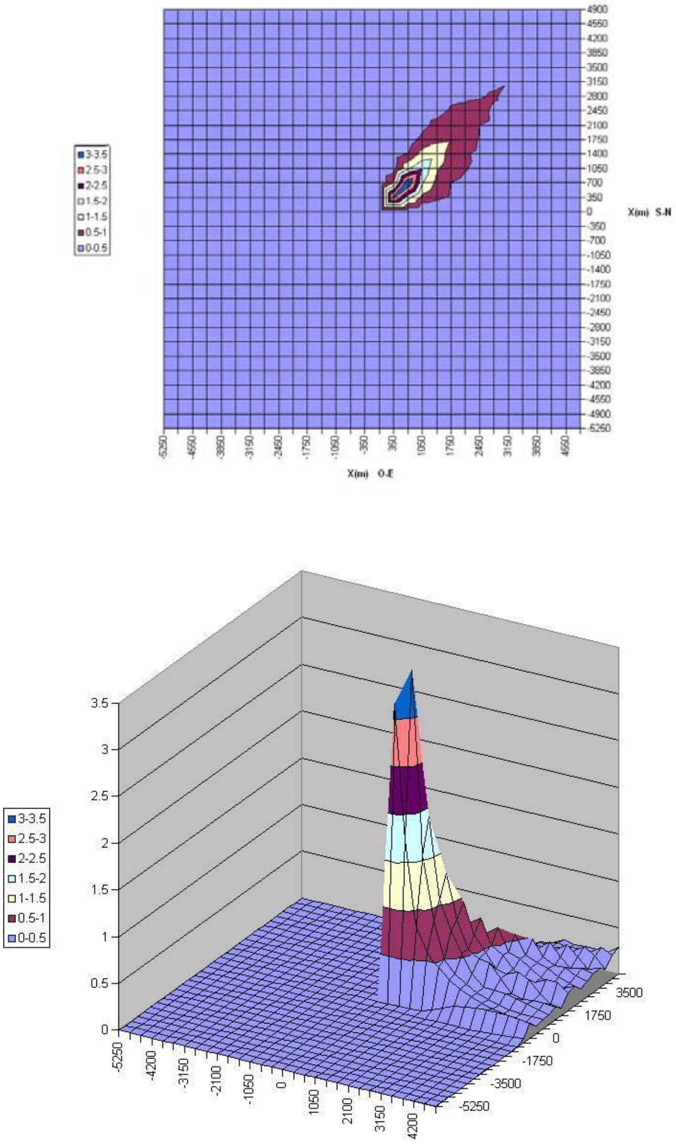


Figure 3: Ambient concentration pattern for 24 hour average.

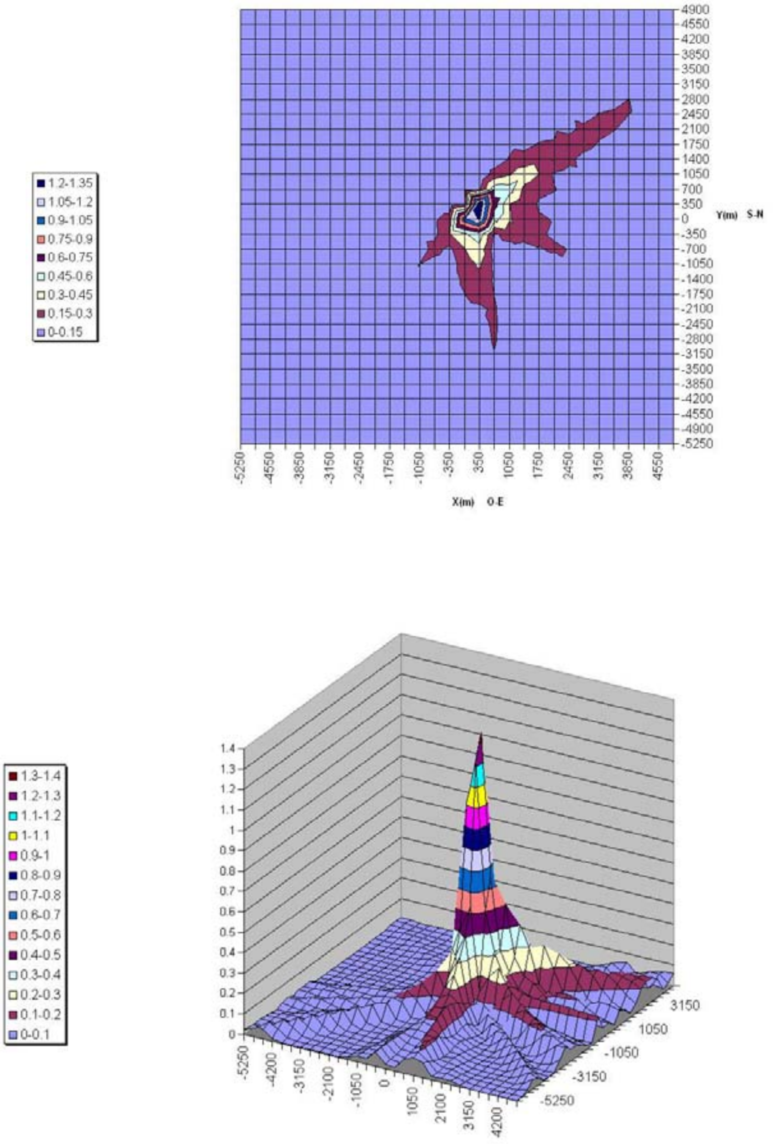


Figure 4: Ambient concentration pattern for 1 year average.

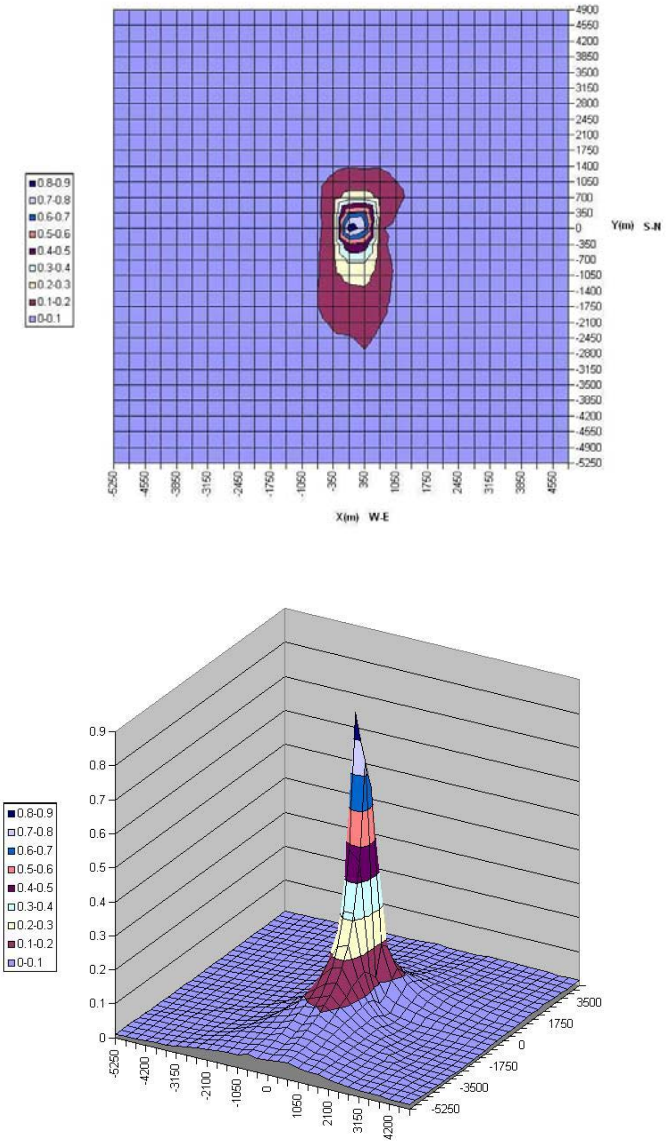


Figure 5: Ambient concentration of CO calculated at 05:00hs of day 06 June 1996

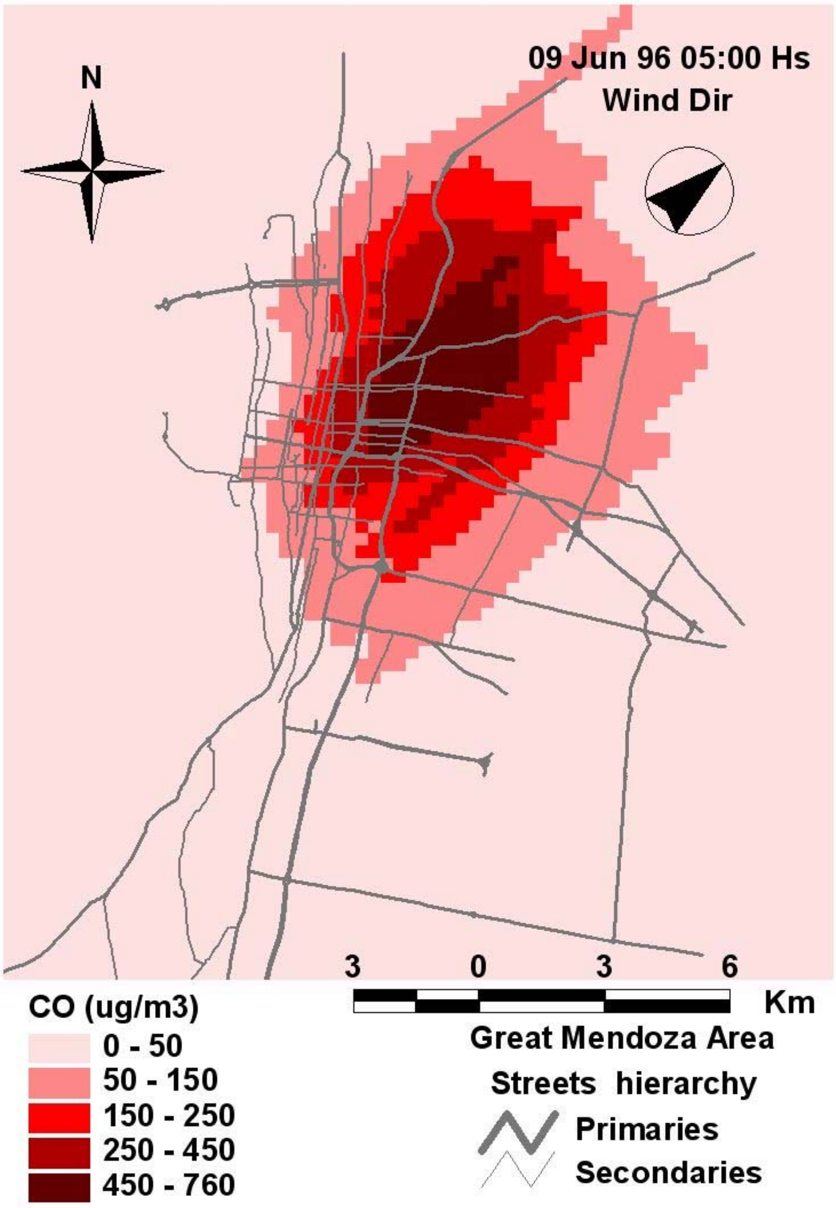


Figure 6: Ambient concentration of CO calculated at 15:00hs of day 09 June 1996

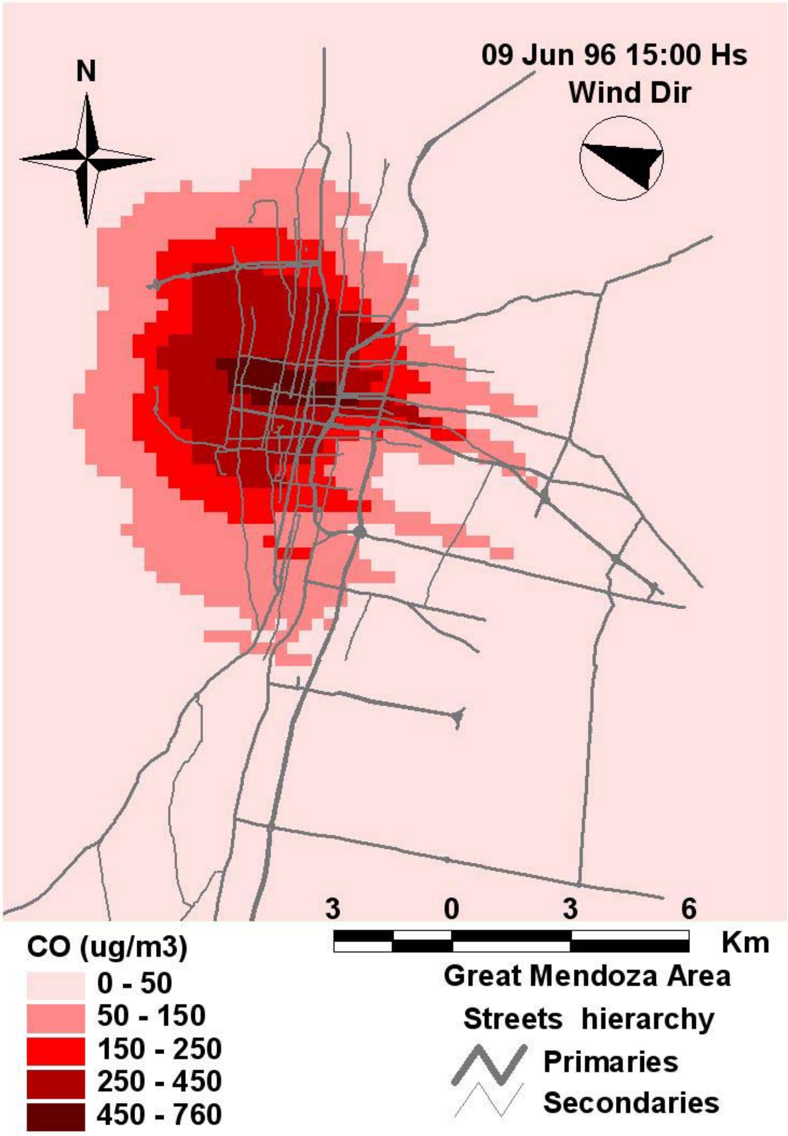
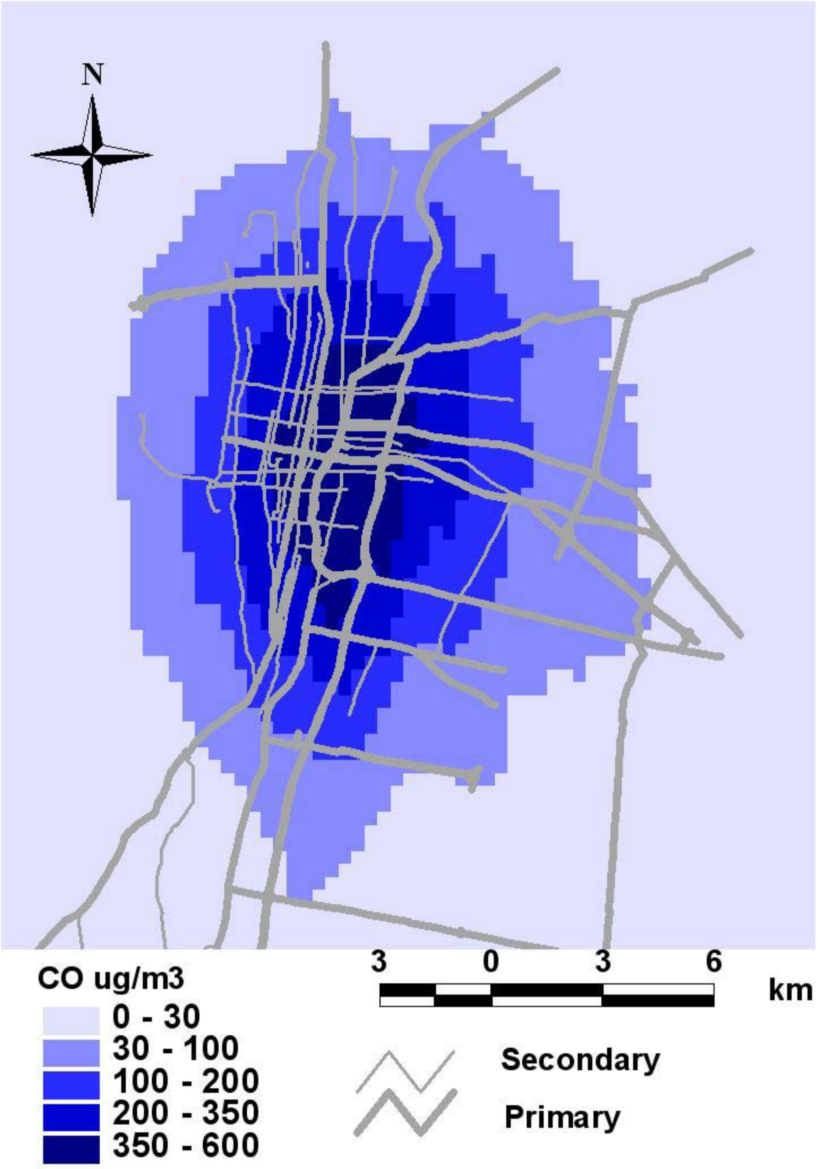


Figure 7: Annual mean values for CO (ug/m3)



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