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Inventory of gaseous emissions in the Barcelona geographical area during the Olympic Games

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ABSTRACT

This contribution aims to supply an up-to-date inventory of the gaseous emissions for one of the most populated urban zones in the Mediterranean basin, the area around Barcelona. As a first application, we have estimated the gaseous emissions that would result from the application of the special traffic measures during the Olympic Games, to compare them with the previous situation. The amount of the emissions as well as their geographical distribution have been compared.

The area under study is a square of 1521 km^2 (39*39 km^2), although around 500 km^2 are on the sea. For operating purposes, the work area has been divided in 1-km^2 cells. For each of the cells we have determined hourly emissions of CO, SO_2, NO, NO_2, as well as several volatile organic compounds (VOC): methane, other alkanes, alkenes, aromatics and aldehydes from CORINAIR emission factors.

Anthropogenic as well as biogenic emissions have been taken into account. The anthropogenic sources considered have been road traffic, industries, gas stations and air traffic; while the biogenic sources considered have been the hydrocarbon emissions from forests.

Because of the large volume of data involved, a computer program has been necessary to process data in order to get easily interpretable results. So, an emissions model (EMITEMA-EIM) was developed to compute and display the emissions interactively. The ARC/INFO GIS (Geographical Information System) environment has been adopted.

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INTRODUCTION

The air quality control is becoming nowadays more and more a challenge in the populated and industrial areas. To build an inventory of air pollutant emissions in a region is the first step necessary to estimate the air quality in that region and, then, to be able to control it.

An emission inventory should identify and include the different types of sources and their emissions located in the study area, in order to assess their importance, which is a key point to define future action plans. Furthermore, an emission inventory is necessary in air pollution modelling, because it provides the input emission data for applying chemical and/or photochemical models.

The project goal was to perform an inventory of the gaseous emissions within the Barcelona geographical area on August 5th, 1990 as a reference day. As a first application of the inventory, we have estimated the gaseous emissions that would result from the application of the special traffic measures adopted by the city council of Barcelona during the last Olympic Games (July 25th, 1992-August 9th, 1992), in order to compare them with the previous situation (August 5th,1990).

However, the comparison was not straightforward. During the last two-year span new roads were built. Also, traffic jams were expected because of the Olympic Games, and special traffic measures were adopted.

Currently, work is being done to validate the inventory that matches most closely the situation during the Games.

INVENTORY CHARACTERISTICS

The study area is a square of 1521 km^2 (39*39 km^2), although around 500 km^2 are on the sea. The area under study is the Barcelona geographical area which is one of the major urban conglomerations of the Mediterranean (4000000 inhabitants). There are currently around one million vehicles and important industrial activities. The territory can be described as being divided into three units placed more or less parallel to the coast: the coastal plain, the coastal mountain range and the pre-coastal depression. Figure 1 shows the study area with the digitized road network. The A-2 highway is located in the Llobregat valley, while the A-17 and A-18 are located in the Besós valley. Both valleys contribute to canalize the wind.

For operating purposes, the work area has been divided in 1-km^2 cells. For each of the cells we have determined the emissions of CO, SO_2, NO, NO_2, as well as several volatile organic compounds (VOC): methane, other alkanes, alkenes, aromatics and aldehydes from CORINAIR emission factors.

The inventory records the different heights where pollutants are emitted, to make it suitable as an input to a chemical model. 27 emissions levels have been defined, with 2500 m being the maximum emission height (to account for air traffic emissions). The grid-spacing in vertical direction is not constant.

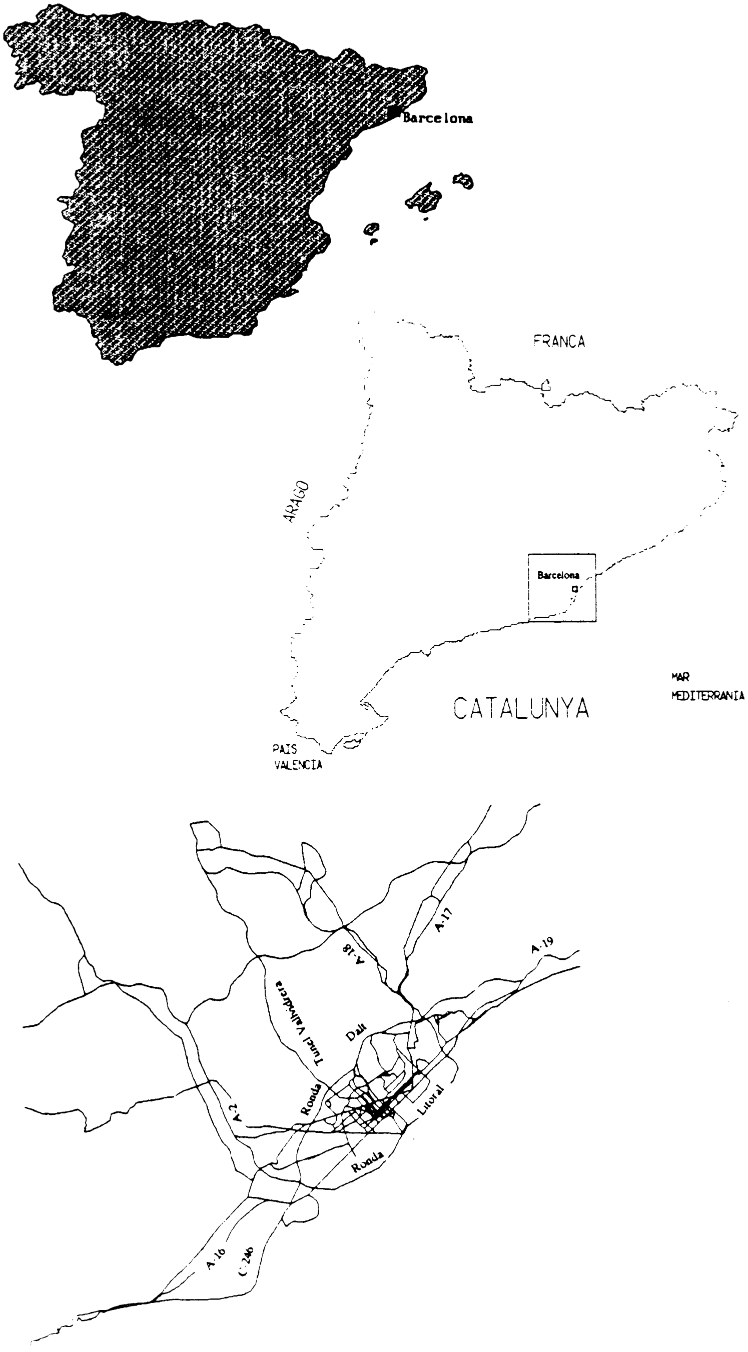

Figure 1 Study area with the main streets, roads and highways.

Concerning methodology, naming conventions and emission factors have been the ones described in project CORINAIR (Eggleston et al [4]), our aim being to make european inventories more and more homogeneous, transparent, and, in short, more comparable. As for the hydrocarbon distribution, we have followed Veldt's [11].

The inventory has been as accurate as possible. Anthropogenic as well as biogenic emissions have been taken into account. The anthropogenic sources considered have been road traffic, industries, gas stations and air traffic; while the biogenic sources considered have been the hydrocarbon emissions from forests. Notice that we haven't included domestic heating emissions.

Emissions are given in $kg/h/km^2$. The day chosen to model a typical summer day before the Olympics has been August 5th, 1990 while for the Olympic period, the chosen day has been July 26th, 1992. Both days were a Sunday during the summer holiday period, which results in most of the industries being closed.

Because of the large volume of data involved, a computer program has been necessary to process data in order to get easily interpretable results. So, an emissions model (EMITEMA-EIM) was developed to compute and display the emissions interactively. The ARC/INFO GIS (Geographical Information System) environment has been adopted. This system includes, apart from emission data, additional information like digitized maps of land uses, population density and other data like population census from 1970 to 1991, the road, highway and street network.

METHODOLOGY FOLLOWED FOR ROAD TRAFFIC EMISSIONS

We have selected the streets, roads, and highways whose Annual Average Daily Traffic (AADT) exceeds 30000 vehicles/day. AADT represents traffic over a seven day week. Figure 1 shows the study area with the digitized road network. The Upper Ring Road (Ronda de Dalt), Coastal Ring Road (Ronda Litoral) and the A-16 highway have been opened to traffic on May 1992, while the Vallvidrera tunnel has been opened on September 1991.

CORINAIR's emissions factors (Eggleston et al [4]) have been used to estimate those emissions. To compute the emissions in a stretch of a roadway (r) of type k (street, road, highway), of length (l_r) for any hour, we sum the products of the number of cars of each type that drive through the stretch during an hour (t) by the length in km and by the corresponding emission factors.

$$\text{Emissions}_{(r,t)}\ (\text{g/hour}) = \Sigma_j\ l_r\ (\text{km}) \times \text{vehicles/hour}_{(r,t,j)} \times \text{emission factor}_{(j,t)}\ (\text{g/km})$$

$j = 1 \ldots 9$ vehicle categories

Emission factors

The emission factors are a function of the type of pollutant (NO_x, particles, VOC and CO), the driving mode (streets, roads, highways), and of nine different vehicle categories. However, we have neglected five out of these nine categories, since the modelled day was a holiday, and the percentage of heavy vehicles was extremely low. So, the division is as follows: motorcyles (2 and 4-stroke), gasoline cars < 3.5 t, diesel < 3.5 t and mopeds. The gasoline cars < 3.5t is the only category where instead of simple emission factors for one, two or three road types (driving modes), the emission factors are presented in a fully speed-dependent form and where the production year of the vehicles has been taken into account. The six periods of legal conformity have been pre-ECE state and periods of application of ECE 15/00, 15/01, 15/02, 15/03 and 15/04.

It's practically impossible to assess the composition of the fleet for each street, road or highway with regard to age and cylinder capacity. So, we have used the composition of the Barcelona provincial fleet according to 'Boletín Informativo. Anuario Estadístico General' [3] as shown in Figure 2.

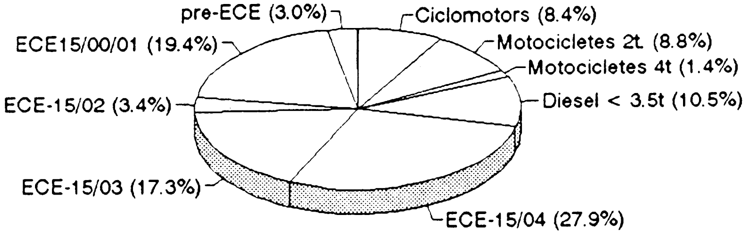

Figure 2 Composition of the light vehicles fleet in the province of Barcelona in 1990.

Notice that the VOC emission factors given by CORINAIR do not include *evaporative emissions*. These emissions are caused by the evaporation of gasoline even in parked vehicles and they come from four main sources: running losses, hot soak losses, diurnal losses and refueling losses. Some guidance is given, but there is not much data available. According to Muths [9], evaporative emissions represent 25% of the total VOC coming from road traffic. Our inventory includes this percentage.

Accounting for vehicle speed

Average speeds have been determined in each case by means of real data. For streets, the average speed is 32 km/h, 63 km/h for roads, and 108 km/h for highways. Table 1 shows the speeds for several european countries (Eggleston et al [4]), for comparison purposes.

Establishing the daily cycle

Since all data available on number of vehicles were daily totals, we had to establish a daily cycle of traffic intensities in order to know the amount of vehicles on the road for each hour of the day.

Highway companies and administrative institutions furnished hourly information about the number of vehicles passing through 15 control points (toll booths, spirers, etc). Each of these control points presented a particular cycle shape. We then assigned a cycle shape to each stretch depending on the proximity to each of the 15 control points and the kind of roadway involved, averaging several of these cycles if

Table 1 Vehicle speeds (in km/h) considered as representative for the characterization of the driving behaviour of gasoline vehicles < 3.5t on different road classes.

COUNTRY	URBAN	RURAL	HIGHWAY
F	22	65	95
FGR	36.1	45	115.5
UK	40	77	115
GR	20	60	90
Barcelona area	32.2	63.4	108.3

necessary.

Figure 3 provides an example of the hourly evolution in one of the 15 control points: the streets of Barcelona.

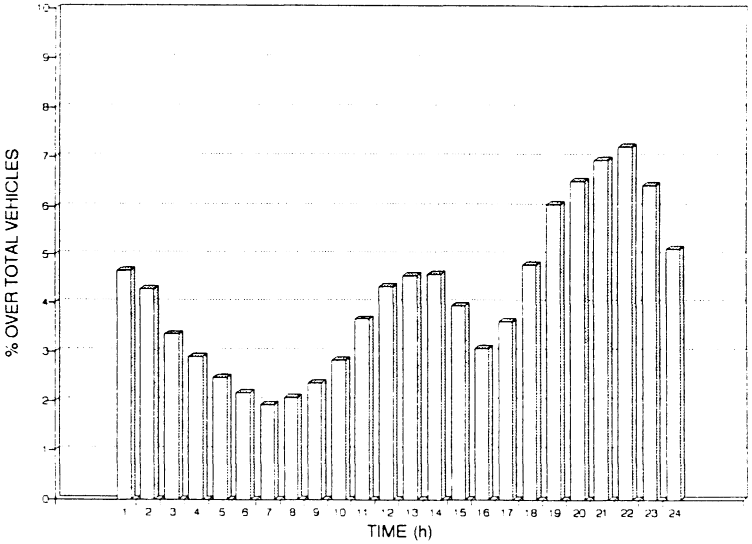

Figure 3 Daily cycle for the streets of Barcelona on August 5th, 1990.

The overall behaviour of the characteristic cycles is a gradual decrease of the traffic from 1 AM to 4 AM. After 5 AM there is an increase up to a maximum around noon, with another peak around 7 PM. On a working day, the first peak would move slightly to the right, 8-9 PM.

<u>Assessment of fluctuations around AADT</u>

Because AADT is a yearly average, it doesn't account for summer-to-winter or working day-to-holiday variations in traffic intensity.

From the real data collected for some of the roads, it was feasible to infer what the fluctuation was around AADT for each section, taking into account factors like geographic proximity and type of roadway. These correction factors were found to be between 51% and 160%.

Diffuse emissions from traffic

Since we haven't incorporated every town, road and street into the model, we had to consider diffuse emissions, i.e. emissions from sources not considered explicitly.

Let N be the number of vehicles-km in a cell. Then,

$$N\ (\text{vehicles-km}) = N_{\text{road traffic}}(\text{vehicles-km}) + N_{\text{diffuse}}\ (\text{vehicles-km})$$
$$N\ (\text{vehicles-km}) = N_{\text{road traffic}}(\text{vehicles-km}) + y * f$$

Where y is the amount of traffic according to Schmitz's [10] formula:

$$y = 10^{2.439}\ x^{0.985}\ (\text{million of vehicles-km})$$

and x is the population density.

f is a correction factor that depends on the amount of traffic. We assume that the higher the road traffic is within a cell, the lower the diffuse traffic must be as a percentage of the total. So,

cells with more than 100000 vehicles-km	f=0%
cells with 66666-100000 vehicles-km	f=33%
cells with 33333-66666 vehicles-km	f=66%
cells with 0-33333 vehicles-km	f=100%

METHODOLOGY FOLLOWED FOR GAS STATION EMISSIONS

After locating all the gas stations in the study area (150), a database was associated to the inventory, with data like: position (UTM), capacity, number of tanks, volume of sales, etc.

To compute hydrocarbon emissions from evaporation, one simply multiplies the daily cycle of the amount of gasoline sold by the emission factor (2.83 kg VOC/t gasoline). For the VOC distribution , we have followed Veldt [11].

METHODOLOGY FOLLOWED FOR INDUSTRIAL EMISSIONS

Emissions are estimated by applying CORINAIR's emissions factors. A database was associated to the inventory, with the following structure: N.A.C.E, municipality, production, consumption, type of fuel, height and diameter of the stack, UTM coordinates. Then, for each of the stacks, we computed the plume-rise using Verein Deustcher Ingenieure methodology [12].

We have assumed that the small and medium-size industries were closed (Morales et al [8]). It is a reasonable approximation, because August 5th, 1990 was a Sunday during the summer holiday period. Only large industries like power plants, cement industries, and incineration plants could be in operation. After some fields work, we verified that the more important industrial emissions came from one municipal waste incineration plant, one cement industry, and an important organic chemical industry.

METHODOLOGY FOLLOWED AIR TRAFFIC EMISSIONS

The Barcelona airport has two runways that can be used in both senses. After finding out the number of take-offs and landing for each runway and hour, we applied CORINAIR's emission factors for a Boeing-727 airplane.

A landing/take-off (LTO) cycle incorporates all the normal flight and ground operation modes, including: descent/approach from approximately 915 m. above ground level, touchdown, landing run, taxi in, idle and shutdown, startup and idle, checkout, taxi out, takeoff and climbout to 915 m.

Taking into account the angle of ascent and descent as well as the direction followed, the emission of each pollutant for each cell can be computed.

METHODOLOGY FOR BIOGENIC EMISSIONS

The VOC emission from forests stand for a relatively important percentage of the total emission (25%). These emissions correspond according to Lloyd et al [7] to isoprene and alpha-pinene.

The map of land uses built into EMITEMA-EIM shows that there are 271 km^2 of evergreen forests, which is 17.8% of the study area. Due to the lack of CORINAIR emission factors, we have applied those in Lübkert et al [6]. The emissions are given by the formula:

$$E\ (\mathrm{mg/m^2 hour}) = 10^{(a*T\ -b)}$$

where a and b are factors that depend on the time of the day and the type of forest (caducious or evergreen) and T is the air surface temperature in °C.

SITUATION DURING THE OLYMPIC GAMES

The situation during the Olympic Games was quite different from that of August 5th, 1990. First of all, several road were built during the last two years: A-16, Ronda de Dalt, Ronda Litoral, Vallvidrera tunnel. Second, the city council of Barcelona adopted special traffic measures (several streets were closed). Third, traffic jams were expected between 11 AM and 13 AM, and between 19 PM and 21 PM in several highways going into the city of Barcelona (A-2, A-17, A-19 and C-246).

RESULTS AND CONCLUSIONS

The inventory corresponds to the situation on August 5th, 1990. This day was Sunday (non-working day) and August, this is to say summer holidays period in Spain. So, most of the industries in the study area were closed and therefore the weight of the industrial emissions is (purposely) very reduced compared to a working day in a

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working month. This day was chosen to reduce the emissions from industries and focused on road traffic emissions.

The main source of emissions is the road traffic (see Figure 4). Globally, in the whole study area, it represents about 320 t/day, i.e., about 52% of the total amount of pollutants emitted; 77% of the total emissions correspond to CO and NO_x, and 58% of these emissions come from road traffic. If we also consider the diffuse traffic the total amount is 521 t/day, i.e., 78% of the total amount of pollutants emitted.

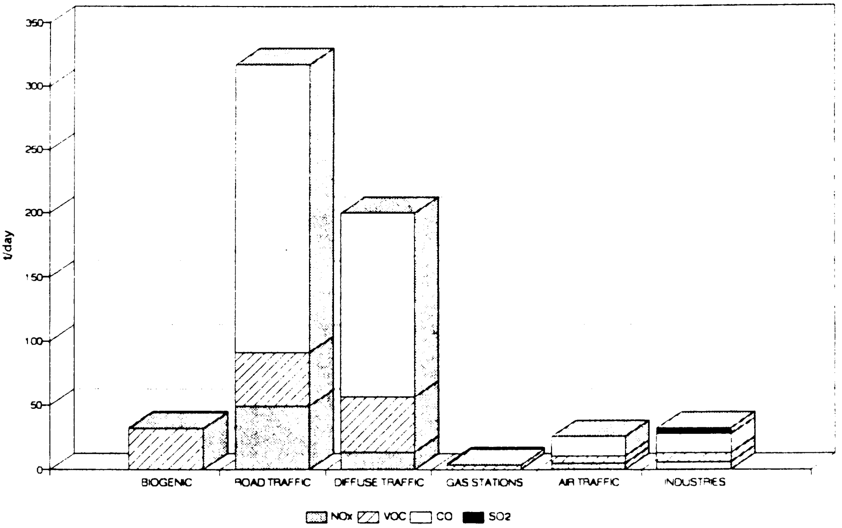

Figure 4 Total amount of pollutants emitted by each source in the whole study area (August 5th, 1990)

Although the inventory of industries for this day is very small, the industrial emissions represent around 85% of the total emissions of SO_2.

The biogenic emissions are not negligible at all, since we have estimated that they represent about 25% of the total emissions of VOC. In contrast with the other pollutant emissions, which are concentrated in Barcelona city, suburbs and highways, VOC emissions are distributed much more homogeneously around the whole study area.

Concerning the time evolution of the emissions, it is strongly influenced by the behaviour of the road traffic (Figure 5). So, two emission peaks of CO and NO_x can be observed at the rush traffic hours (12 AM and 19 PM). The peaks at these hours are typical in a summer holiday in Barcelona. In the case of VOC, the time evolution is much softer due to the biogenic emissions, which are the biggest producers of VOC, depend on the daily cycle of air temperature.

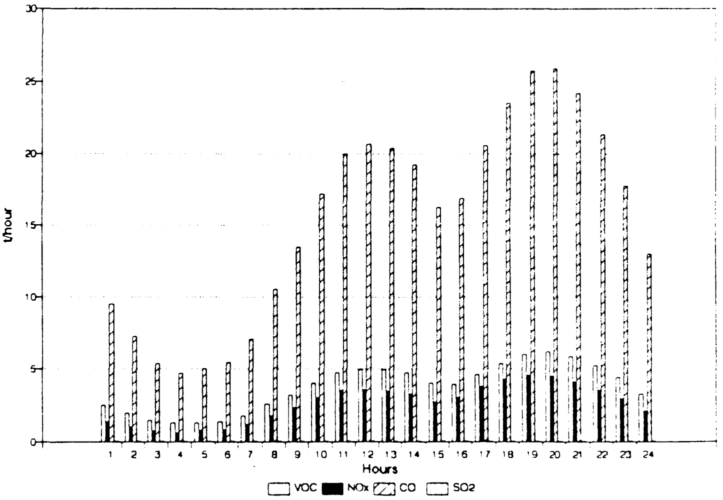

Figure 5 Hourly evolution of the total emissions in the first layer (up to 20 m) of the study area (August 5th,1990).

Figure 6a shows the geographical distribution of VOC on August 5th, 1990, while Figure 6b shows the situation foreseen during the Olympic Games (1992). We can expect that during the O.G., emissions should have decreased inside the city due to the special traffic measures taken by the city council, while at the entrances and exits of Barcelona we can expect an increase of hydrocarbons, because of traffic jams. In these traffic jams, the hydrocarbon levels increased by 350 kg/h, due to the speed reduction.

The differences between both situations (before and during the O.G.) do not rely only on the special traffic measures in the ocassion of the O.G., but also on the new roads around Barcelona (2 ring roads, a highway and a tunnel) which were built after 1990 and they have allowed to decrease the traffic inside the city around 10%. In order to know the influence of the special traffic measures as well as traffic jams during the O.G., we have included in Figure 6a the new roads.

A comparison with other inventories has been done (Almbauer et al [1], Lara [5]). The NO_x emissions are quite similar.

Currently we are validating the inventory that matches most closely the situation during the Games with the real data collected.

We should notice the uncertainty of some emission factors, such as those of 2-stroke motorcycles > 50 cc, and the absence of emission factors for the biogenic emissions coming from mediterranean forests. The emission factors for air traffic are also very limited, since they only refer to one aircraft type (Boeing 727). Although CORINAIR emission factors have been revised and improved, it would be worthwile to try to extend them in order to do emission inventories more and more reliable.

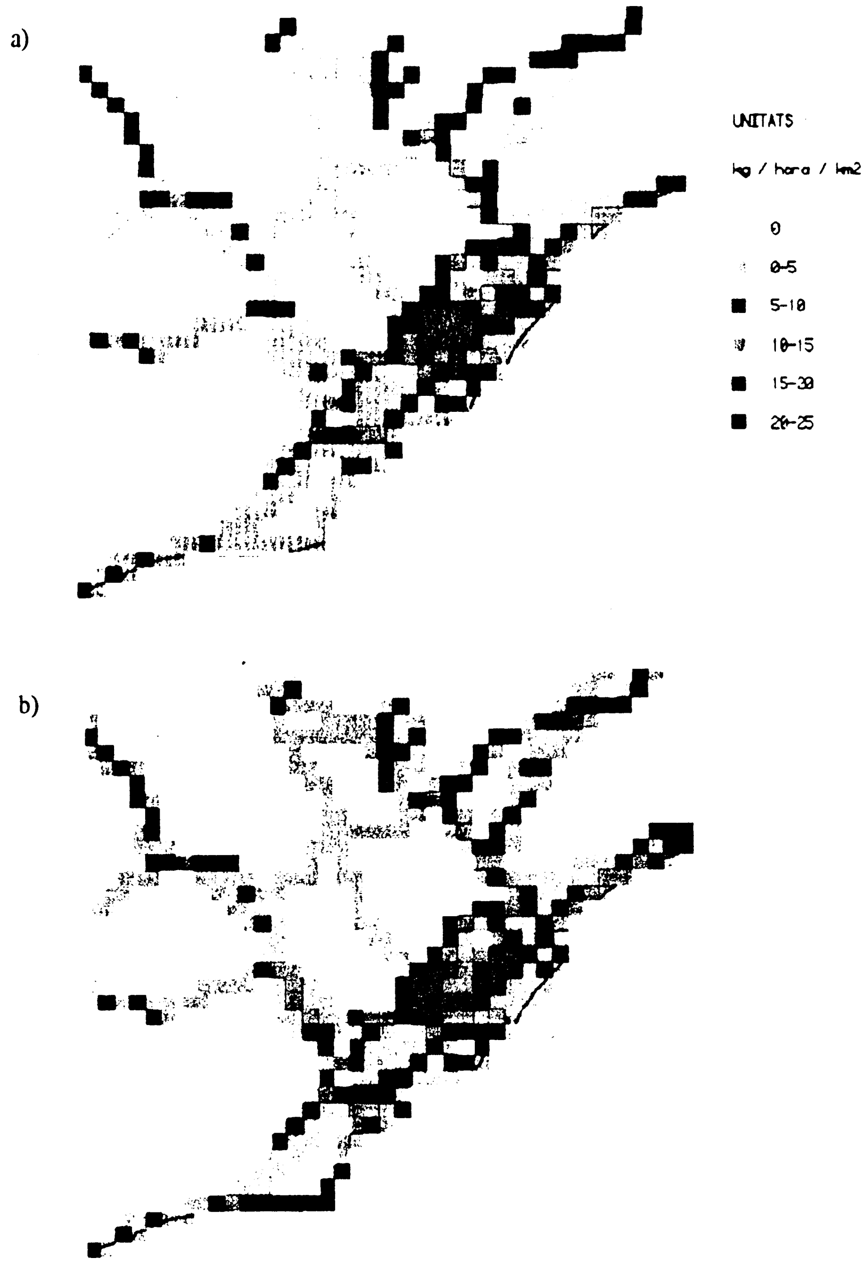

Figure 6 Geographical distribution of VOC emissions due to road traffic at 12 AM for: a) the situation before the Olympic Games (August 5th, 1990 + new roads) and b) the situation foreseen during the O.G (July 27th-August 9th, 1992)

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REFERENCES

1. Almbauer R., Pucher K., Sturm P.J. 'A computer program for determinig traffic emissions'. Zannetti P. (Ed). *Computer Techniques in Environmental Studies III.* Proceeding of ENVIROSOFT 90, Montreal, Computational Mechanics Publications and Springer-Verlag, 1990.
2. Bouscaren R., Veldt C., Zierock K.-H. CORINE Emission Inventory Project. Final Report. 6614(85)02, 1986.
3. *'Boletín Informativo. Anuario Estadístico General'.* Dirección Gerneral de Tráfico. Ministerio del Interior. Madrid. 1990.
4. Eggleston H.S., Gorissen N., Joumard R., Rijkeboer R.C., Samaras Z., Zierock K.-H. Report of the CORINAIR Working Group on Emission Factors for Calculating 1985 Emissions from the Road Traffic, Volume 1: Methodology and Emission Factors, EUR Report 12260 EN, Luxembourg 1989.
5. Lara J. 'Contaminación atmosférica en Bilbao: ayer, hoy y mañana', *Revista Técnica de Medio Ambiente*, Vol. 24, pp 29-34, 1991.
6. Lübkert, Schöpp. IIASA, Luxemburg/Wien, 1989.
7. Lloyd A., Atkinson R., Lurmann F., Nitta B. 'Modeling potential ozone impacts from natural hydrocarbons-I. Development and testing of a chemical mechanism for the NO_x- Air photooxidations of isoprene and α-pinene under ambient conditions', *Atmospheric Environment*, Vol.17, pp. 1931 - 1950, 1983.
8. Morales C., Cremades L., Baldasano J.M^a. 'Measurements of air pollution on a high-traffic level highway with influence of land -see breeze'. Highway pollution. Fourth International Symposium. Madrid, 18-22 May.
9. Muths R. 'Pertes d'hydrocarbures par evaporation'. *Pollution Atmosphérique*, Vol.121, pp. Gener-Febrer de 1989.
10. Schmitz S. ' Schadstoffemissionen des Strassenverkehrs', *Informationen zur Raumentwicklung*, pp. 725-741, Heft 12. 1990.
11. Veldt C., Bakkum A. TNO Report for the Commission of the European Communities. DG XI CORINAIR Emission Factors. 8722-17303, November 1988.
12. Verein Deutscher Ingenieure. Dispersion of Air Pollutants in the Atmosphere.Determination of Plume Rise. VDI 3782, pp. 2-15. June, 1985.