A detailed urban road traffic emissions inventory model using aerial photography and GPS surveys

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ABSTRACT

The European Union (EU) legislation defines specific "zones" according to population density that require air quality to be assessed with greater detail. Such is the case of the "Greater Lisbon Zone" which is surveyed by a network of 24 monitoring stations and occasional extensive monitoring procedures using passive sampling or low-volume samplers. Given the relevance of road traffic air emissions in this urban area, results from the monitoring network had to be complemented with a detailed inventory of air emissions and air quality models. An alternative methodology was developed and tested to estimate traffic flows and air emissions at a very detailed level (road by road) while circumventing the high cost of implementing a more extensive monitoring system for road traffic. This new methodology is a bottom-up approach based in car counting from aerial photographs associated to GPS data to assess average speed of traffic flows, also for each road link. The inventory is adjusted to the total fuel consumption within the region (top-down approach).

Since 2004 the methodology is being tested in the air emission inventory of the Lisbon region and already six municipal areas are covered. In order to test the methodology the estimates of traffic flow have been compared with car counting. Air emissions were also compared, with good results, to measurements of air quality with passive samplers using multivariate statistical models.

This alternative methodology has the advantage of being sustained in real field data. The analysis demonstrates that it is particularly suitable for dense urban areas where road traffic is a prevalent factor in air quality, allowing better resource management and cost saving.

INTRODUCTION

Road traffic emissions are particularly important in the major urban areas of Portugal. Lisbon region is one of the most polluted Portuguese urban areas due to traffic[1].Changes in the urban structure in Lisbon occurring in the past decade lead to the closure or displacement of several industrial facilities, including an important crude oil refinery plant. Given that, nowadays there are only a few small industrial sources of air emissions and no large point sources, air emissions in Lisbon are dominated by road transportation and airport emissions. Road traffic emissions are the major source of NOx, corresponding to 44 per cent of the total emissions in the region, 34.6 per cent of NMVOC and 12.5 per cent of PM_{10}[2].

The concentration levels above the limit values occur mostly in traffic hot-spots in the Lisbon area. In the most recent years, violation of air quality limit values for human health protection - as determined in the European Union Directive 1999/30/CE of 22 April - have occurred in Lisbon frequently for PM10 (annual average limit value and daily limit value) and occasionally for NO2 (mean annual value). Consequently, the regional authority for air quality in Lisbon area - the Commission for Coordination and Regional Development of Lisbon and Tagus Valley (CCDR-LVT) - developed recently an Emission Reduction Plan[3], including the identification of measures and policies. In order to elaborate this plan it was decided, as a first step, to establish a detailed and suitable Air Emission Inventory that could serve as the basis for the implementation of an urban air quality model. This model would be used to identify major problems and to predict and assess the results of the measures and policies identified in the plan.

Traffic monitoring system within this urban area was found to be incomplete and limited to some main road lines and problematic intersections: On the other hand the available traffic data from this system was associated with sections instead of links, which was unsuitable for an inventory model. Other alternatives for assessing the traffic flow such as origin/destiny studies or implementation of mobile monitoring systems, would be too expensive, wouldn't have enough detail and would not be calibrated with real data. Therefore, an alternative approach to estimate traffic flow and road emissions had to be developed and tested.

This paper describes the development of an alternative methodology for making a very detailed spatial disaggregated inventory of traffic flow and air emissions from road transportation. This model is suitable to be used as input data in mathematical models and as a tool to support decision-making in air quality management. The method is based in easily available information and uses simultaneously a bottom-up and a top-down approach. The basis of the methodology was published before[4,5].

This paper presents the results of the application of the methodology to Lisbon city and surrounding urban areas. The use of a new methodology needs evaluation and, therefore two evaluation procedures were used to verify the results of this methodology and its applicability[6].

BODY

Special Needs of Urban Inventories of Air Emissions

An inventory model was necessary for Lisbon region in order to support the development of air quality policies and measures. To be effective this model had to consider regional circumstances:

- Car emissions are prevalent in this urban area over industrial sources;
- The inventory should answer the input needs of an air quality model of local range and therefore it has to be based on a bottom-up approach where traffic is allocated with a very detailed spatial disagregation, preferably for every road link. This is also necessary to accommodate and evaluate the policy measures that were developed;
- Due to budget constraints, it could not be possible to develop a system based on extensive and dedicated data collection. The system must rely as much as possible on available data, collected for other purposes.

On the other hand, the development of a suitable air emission inventory had to solve a set of constrains:

- Although Lisbon city has an automatic monitoring system of traffic flow (GERTRUDE), it is restricted to central and downtown areas, and clearly insufficient to create a developed inventory model;

- The composition of the vehicle fleet was insufficiently known, particularly in what concerns to the moving fleet, which is different from the existing car fleet;
- Driving conditions, particularly speed, was poorly known, in particular regarding time of travel within the urban network.

General Methodology Design: Bottom-up and top-down approaches

Emissions from road traffic are determined from the number of vehicles and how much do they move or, alternatively, from how much fuel is consumed in the area. While some pollutants are more dependent on how many kilometers are driven and on which driving conditions (NOx, CO, N2O, NMVOC), others are solely determined by how much fuel is burnt and its composition (that is the case of SOx and heavy metals). In the inventory model it was decided to find an agreement between these two different approaches and, for this purpose, the methodology comprehends a bottom-up approach in association with a top-down approach.

The bottom-up approach allocates traffic flow for each road link, while the top-down approach guarantees that estimated total kilometers driven in the study area, and corresponding fuel consumption, are in agreement with total consumption of fuel in the same period.

Methodology Description

The quantity of pollutant that is emitted annually at each traffic road link (E_{pi}), in metric tones per year, is estimated by multiplication of emission factors (EF_{ptu} - g/km/vehicle), specific of each vehicle of class t (technology, age, engine size) that is using fuel f and moving at velocity u_i, according to the following equation:

Equation (1) $$E_{pi} = 365. \Sigma_f .\Sigma_t [EF_{ptfu}.vkm_i. 10^{-3}]$$

To estimate traffic flow, expressed in vehicles- kilometers (vkm), by a first approximation (bottom-up approach), mean annual traffic volumes are estimated at each road link from vehicle density and circulation velocity, using a single basic relationship for traffic flow:

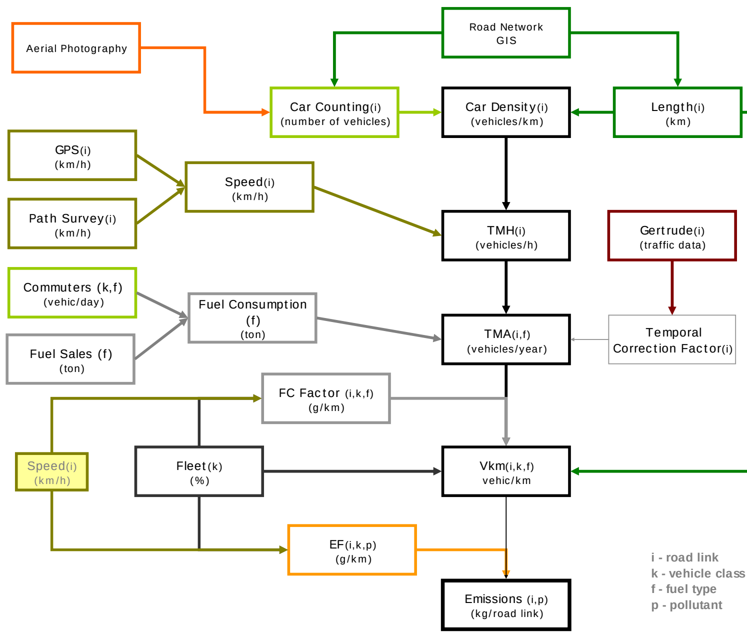
Equation (2) $$q^1{}_i = u_i.k_i$$

where, for each traffic road link i:

- $q^1{}_i$ =flow (vehicles/hr);
- u_i = average circulation speed in link (km/hr)
- k_i = density of cars in circulation (vehicles/km).

The density of cars in circulation, moving vehicles in a given moment, were obtained by counting vehicles in aerial photography (Ortho-photomaps) as explained below. Speed density was estimated, also for each road link, tracking speed in moving vehicles by two different methodological approaches.

Figure 1. Methodology overview



The secondary, top-down approach, calculates daily average vehicles kilometres (vkm^2) driven in each link after correction for total fuel consumption according to:

Equation (3) $$vkm^2_i = q^1 i. \Sigma_f \{TFC_f / [\Sigma_i (365. t_{FAC}. Fl_f. FC_{ufi}.q^1_i. ll_i)]\}. ll_i$$

where:

- vkm^2_i – estimated annual average daily traffic flow (vehicles.km/day);
- TFC_f – Total Fuel Consumption of fuel f (t/year);
- t_{FAC} – temporal factor used to convert traffic flow obtained at a specific time to average annual daily traffic flow;
- Fl_f.- percentage of vehicles using fuel f in the moving fleet;
- FC_{ufi} – average fuel consumption factor for each link i, dependent on velocity u_i, averaged over the total vehicle fleet – according to technology/age - using fuel f (gasoline, diesel oil and LPG) and ll_i is length of link i (km).

Analysis of Alternative Methodologies

The use of portable traffic counters, either placed in pavement or by video monitoring, could overcome the lack of extensive information about traffic flow. These techniques albeit rigorous are costly, involving heavy investment in capital and the need of large team to collect the data and treat it.

Others authors[7], used different approaches for the spatial allocation of air emissions in the Lisbon Metropolitan area, relying on Traffic Network Flow Models. These models estimate traffic demand on a geographical basis, from the transport network structure and knowing a matrix of Origin-Destination (O-D) based on survey to travelers. These allocation methods present advantages regarding a suitable spatial disaggregation for air quality modeling, and also the possibility of being a good supportive tool for urban or regional planning. Nevertheless, for these methodologies to be completely reliable they require previous calibration of the estimated traffic fluxes with empirical data, and they require substantial financial and time resources to be developed.

Finally an alternative approach often used when resources are scarce is using surrogate indicators to allocate emissions estimated at a higher level. Usually population numbers in each neighborhood are used as indicator. Although simple and ready to use these procedures are very crude and incapable of explaining traffic flow associated with commuting movements.

Brief Description of Case Study

The Lisbon city covers an area of 84 km^2 with a resident population of approximately 565 thousand inhabitants (accordingo to the latest census, in 2001). It is however surrounded by a larger area at the northern and southern margins of the estuary of Tagus river, called the Great Lisbon Metropolitan Area. This area comprehends approximately 2.1 million inhabitants, i.e. 26 per cent of total Portuguese population over an area of 2 750 km^2.

The above mentioned methodology was applied to the Great Lisbon Area at northern margin of the river Tagus, covering the municipalities of Lisbon, Oeiras, Cascais, Amadora, Odivelas, Loures and Vila Franca de Xira.

Daily commuting movements take a great importance in this area. On average about 621 thousand vehicle movements do cross Lisbon city borders every day from suburban areas around Lisbon, north and south of Tagus estuary. And this daily movement has been enhanced by the decrease of resident population in inner Lisbon city and its gradual transfer to adjacent suburban areas. In fact, from 1991 to 2001, about 16 per cent of residents in Lisbon have moved to neighbor areas.

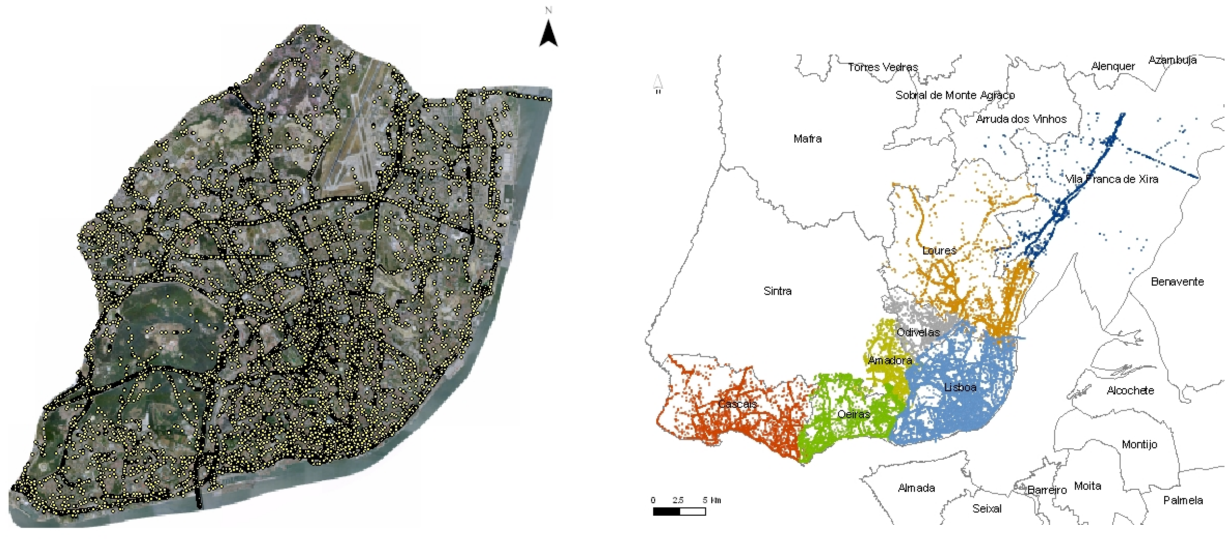
Lisbon area lays over a complex and irregular terrain that prevent air dispersion in same areas. The city layout is also dense and dominated by old and narrow roads where flow is slow and dispersion conditions impaired.

Data Information Sources

<u>Car Density</u>

Parameter k, density of cars in circulation, was estimated for each road link using aerial photography where moving vehicles at a given moment were spotted and placed in a GIS system. Several sets of ortho-photomaps were made available from the municipalities, and more than one set was used for each municipality, to reduce error. **Figure 2.a** displays the cars identified in the area of Lisbon city and **Figure 2.b** the whole Lisbon metropolitan area. **Figure 3** is an insight of the identification procedure in a busy area in central Lisbon.

Figure 2. (a) Identification of vehicles in the city of Lisbon (b) Great Lisbon Metropolitan area, with the municipalities of the northern margin of Tagus river highlighted



(a)

Figure 3. Identification of moving vehicles in central Lisbon area using aerial photos of 2001

Special care has to be taken during data collection:

- The vehicles identified should be exclusively those on movement. Parking vehicles should not be considered;
- The precise days when photos were collected has to be determined, in order to consider adequately the corrections for weekends and summer vacations;
- Vehicles were classified as light vehicles, heavy vehicles and motorcycles. Even with best quality photos more precise characterization of the vehicles is impractical.

After identifying the vehicles, a set of procedures were developed to allocate them effectively to each road link. On the first place, the size of the link must be long enough that congestions due to traffic lights do not cause artificial variations in traffic density along the road. That way, individual links in the SIG were joined until an appropriate length was obtained. In the case of sub-urban neighbourhoods (dormitories), where moving vehicles are scant, and to avoid the existence of roads without moving vehicles, this lead in extreme to the definition of neighbourhood road-nets were car density and vehicle flow were averaged.

Vehicle Speed

Adequate knowledge of vehicle speed is necessary in the inventory model to estimate traffic flow, but this variable is also as an important parameter affecting emission factors, considering that vehicle exhaust emissions and fuel consumption are strongly dependent on speed. Therefore, the estimation of the pollutant emissions from road transport requires a satisfying determination of vehicle speed. The aim must be to obtain average vehicle velocity in each road link.

Two different approaches were tested to estimate vehicle speed. In the first method pre-defined paths were defined in an area (**Figure 4**) and total distance and spent time was registered. Several trials were performed in different days and an average velocity was determined. First to the application of this method homogeneous neighborhood areas had to be defined (**Figure 5**), based on similarities of occupational dominance (residential areas, commercial areas, ware-houses or industrial areas). For the second method, driving speeds were monitored in vehicles moving with the main traffic flow and equipped with a GPS (**Figure 6**).

Figure 4. Definition of paths for speed determination according to method 1

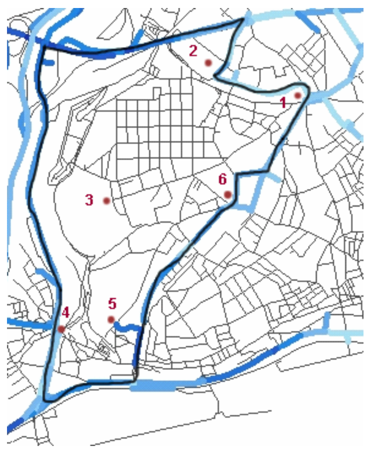


Figure 5. Definition of homogeneous neighborhoods

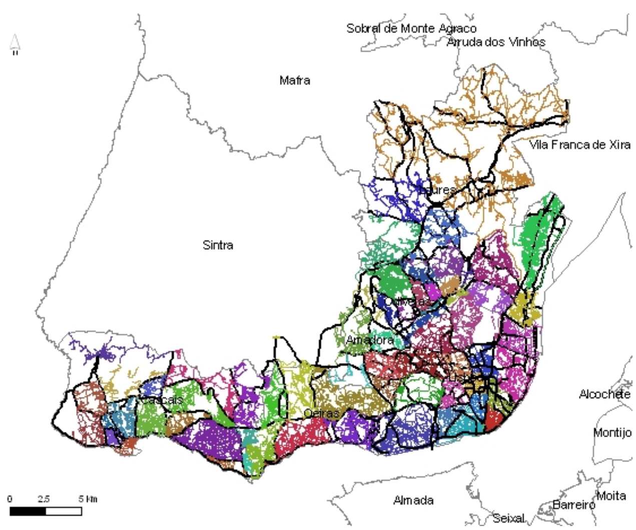


Figure 6. Collection of data with a GPS system

The first methodology is less expensive requiring no equipment except a car. Another advantage of this method is that it can work in certain conditions that prevent the use of the GPS technique such as when roads are two narrow causing the GPS signal to be too weak or when travelling in tunnels. Nevertheless it is less precise and it can not be used suitably to determine speed in each road link.

The GPS method, albeit more expensive both in equipment costs and treatment of data, gives more detailed information and allows the determination of speed with a very thin detail. It was also easy to calculate speeds and to convert the results into each link in the GIS system. The use of more sensible equipments provided with external antennae solved the loss of satellite signal in most cases, and in the end it was the preferred method.

Figure 7 shows the histogram of velocities for Lisbon, obtained with the GPS system. The average velocities in the area are presented in **Table** 1. These results are consistent with the values obtained from two European research projects (DRIVE-modem and BRITE-EURAM HYZEM) in which 80 representative European private cars were selected in France, Germany, UK and Greece and equipped with on-board data acquisition systems[8]: average speeds in those cities during weekdays range between 18 and 29 km/hr. These values are also consistent with the values determined for Lisbon estimated with VISUM model[7].

Figure 7. Histogram of velocities in Lisbon city

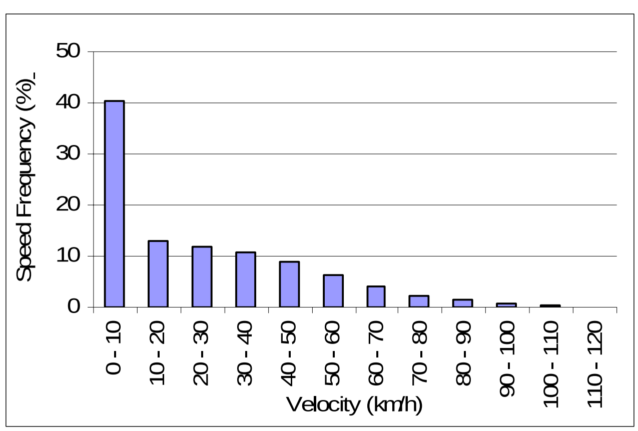


Table 1. Average vehicle speeds per municipality

Municipality	Main roads	Secondary roads
Cascais	39.4	28.2
Oeiras	49.2	28.3
Lisboa	25.1	28.1
Amadora	48.6	24.4
Odivelas	33.9	27.5
Loures	52.7	39.8

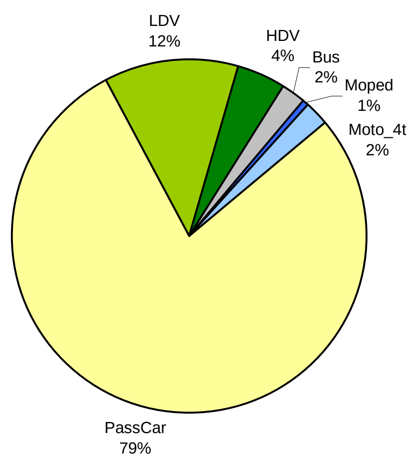
<u>Car Fleet</u>

For inventory model purposes what is necessary is the car fleet in motion, the moving fleet, and not the car fleet in existence i.e. the number of vehicles registered in this area.

There was an insufficient knowledge of the car fleet in the region under study. Although there is a reliable register of vehicles in each *Concelho*, made the Portuguese Assurance Institute (Instituto de Seguros de Portugal), and there are records of moving vehicles in major highways and freeways, there were no available studies concerning the composition of fleet as it moves in the inner urban areas.

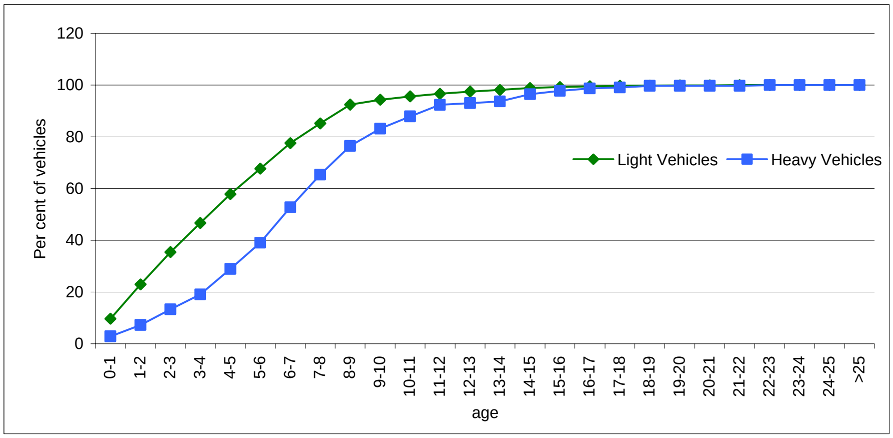
The composition of the vehicle fleet was established from an extensive survey recently made in the Great Lisbon area[9]. Collection of data and special inquiries to drivers were made in several days and places where cars in movement could be easily reached (Traffic lights and parking lots). About 17 800 results were obtained, which represents 5.4 per cent of the total vehicles registered in the area. Using this database it was possible to establish the per cent of vehicle categories per vehicle type (passenger car, light duty vehicle, heavy duty vehicle and buses), cylinder capacity, fuel use (gasoline, diesel and LPG) and age. Results (**Figure 8**) show that the great majority of vehicles were light vehicles, either passenger cars or LDV.

Figure 8. Moving vehicles per vehicle type



From the database it was also possible to establish the dependence of vehicle age to its occurrence in the fleet. The results, presented in **Figure 9**, show, as was expected, that heavy vehicles are older than light vehicles.

Figure 9. Age distribution of light vehicles and heavy vehicles in Lisbon area

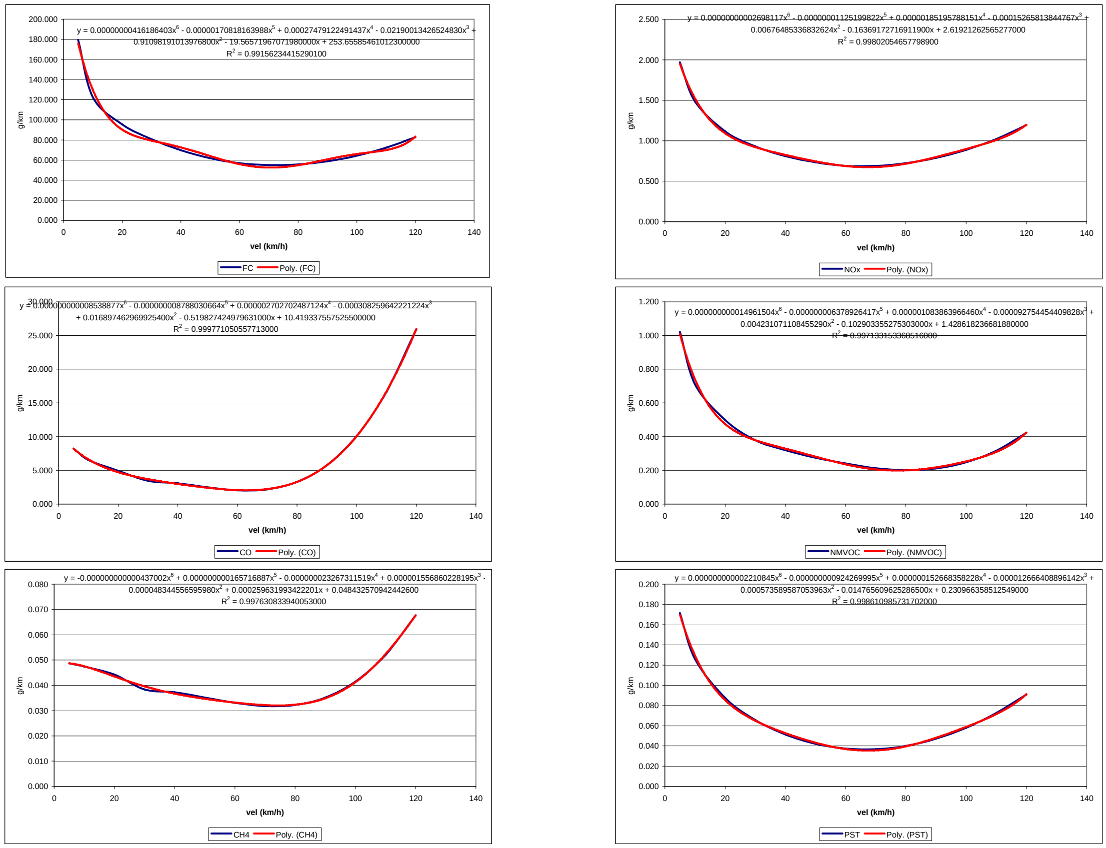


Emission Factors

Studies made in several European countries were synthesised in a set of algorithms published in EMEP/CORINAIR Emission Factor Handbook[10] and which use is recommended by the European Environmental Agency. Each emission factor is represented as a non-linear regression curve, usually with vehicle average speed as independent variable, for each specific vehicle type (passenger cars, light duty vehicles, heavy duty vehicles, buses, coaches mopeds and motorcycles) and considering parameters such as the size of engine - for light vehicles, in c.c. - or vehicle size - weight for heavy vehicles and the technology of emissions abatement (Euro I, II, etc).

The emission factors for each individual vehicle type were used to calculate the weighted average emission factor for each vehicle travelling in the region, considering the car fleet discussed before. A set of average polynomial functions were obtained (**Figure 10**).

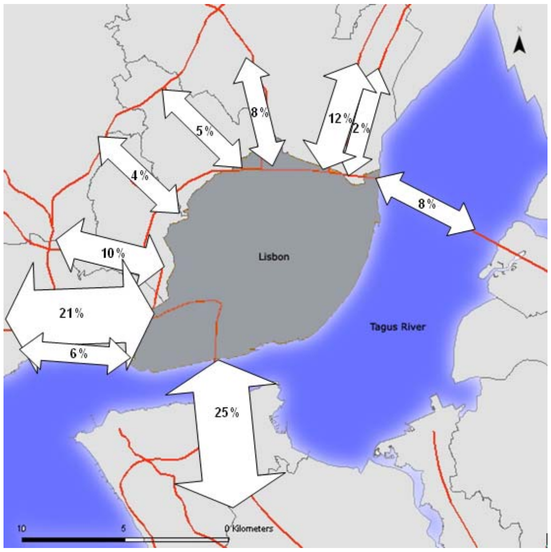
Figure 10. Emission Factors as function of vehicle speed for the average car fleet in Lisbon area (2003)



Commuting Traffic

According to the available statistical information from the Institute of Roads (IEP), during the year 2000, approximately 621 thousand vehicle movements on average crossed Lisbon city borders every day, typically entering in Lisbon in the morning and leaving it in the evening. Commuting movements are concentrated in ten major entrance points (**Figure 11**), two of them though bridges over the Tagus estuary.

Figure 11. Relative importance of commuting vehicles crossing daily Lisbon borders (IEP data for 2000).



A special survey made to road traffic commuters at the major entrance of Lisbon city (data acquisition from FCT in 2004) allowed the determination of the per cent of vehicles entering into Lisbon area and that usually fill their tanks outside Lisbon area.

Fuel Sales and Consumption

Statistical information of fuel sales for road transportation in each *Concelho* (municipality) in the Lisbon area was available from 1990 to 2003 from the General Directorate of Geology and Energy[11].

Due to the significant importance of daily traffic commuting movements into Lisbon city (*Concelho*) during the day, the fuel that is consumed inside Lisbon city is higher than fuel sales inside the same area. That way fuel consumption in Lisbon city was incremented with the part of the fuel that was imported in car cranks during the morning entrance and that is consumed in movements inside Lisbon, and was also subtracted from the fuel that is exported in the vehicles moving out in the evening and that was not burnt in Lisbon city:

Equation (4) Consumption = Sales + Import in commuters (car tanks)

For the remaining *concelhos* surrounding Lisbon an equivalent approach had to be made, considering, this time, that the fuel that is added is that part of fuel that is entering the *Concelho* in the car's tanks and that is burnt during the crossing of the area. In a similar way outgoing vehicles export fuel in tanks to adjacent *concelhos* and eventually into Lisbon center. These mass balances were made independently for gasoline and diesel oil.

Equation (5) Consumption = Sales + (Vehicle Inflow - Vehicle Outflow) * FC * Length

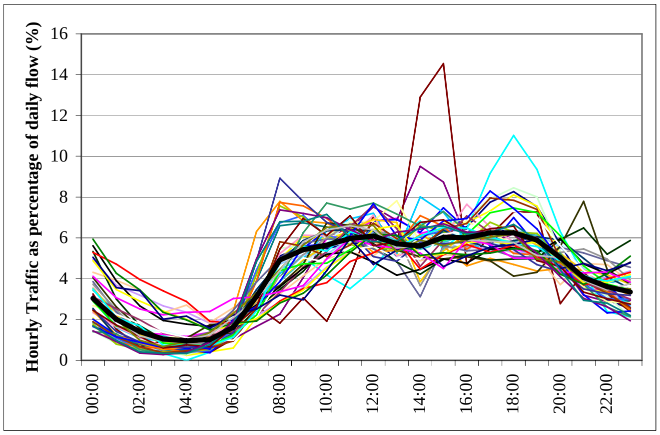
where

- FC = Fuel consumption factor.
- Length = Traveling distance inside *concelho* area.

Time Factor

Parameter time factor (t_{FAC}) that converts the vehicle density determined at the time when aerial photography, was established from the analysis of the 10 most representative monitoring points from the GERTRUDE system and the average evolution of hourly traffic volume (**Figure 12**).

Figure 12. Daily Evolution of Hourly Traffic monitored in Lisbon by GERTRUDE system in ten selected monitoring points, for weekdays and weekend days. Average trend is shown in black bold. (Source: Lisbon Municipality).

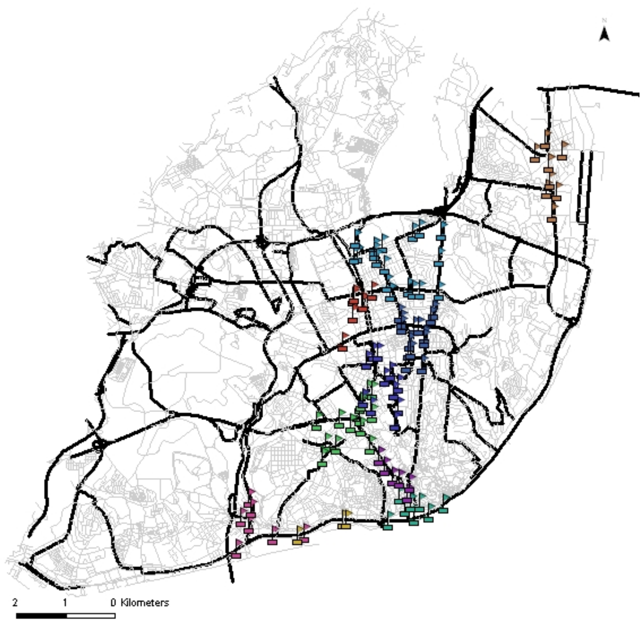


Traffic Monitoring Data

Traffic monitoring data is not extensive to all traffic links in Lisbon. The system, in operation since the 70s, is based on GERTRUDE - *Gestion Electronique de Règulation en Temps Réel pour l´Urbanisme, les Déplacements et l´Environnement*. It is composed of a set of static traffic counters placed in the main arteries of Lisbon, in particular in troublesome crossings (**Figure 13**). These were installed to improve traffic management and amelioration of the public transportation system. Despite these limitations results from this system were used to:

- Estimate the parameter t_{FAC}, as explained before;
- Evaluate the results of the methodology, verifying if estimates can reproduce actual monitoring data.

Figure 13. GERTRUDE traffic monitoring stations in Lisbon City (source: Lisbon Municipality)



Main Results

Air emissions from road traffic in six *concelho* in the northern part of Lisbon area were estimated for NO_x, SO_x, PM_{10} and NMVOC in metric tones per year. Only exhaust emissions were considered, and other contributing sources related to traffic flow, such as gasoline evaporation, tire and break wear and re-suspension of loose material from road surface were postponed for subsequent phases of this project.

Figure 14. Distribution of emissions from road traffic in the Great Lisbon area north of Tagus river

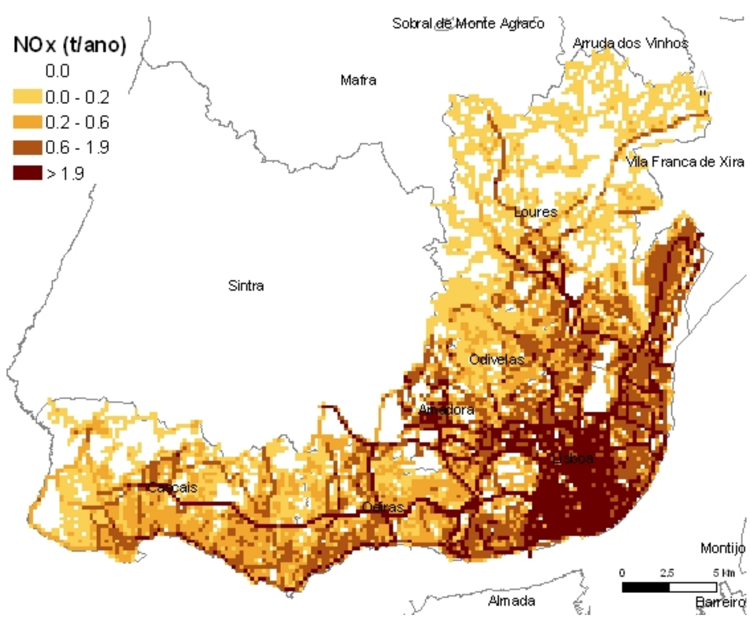


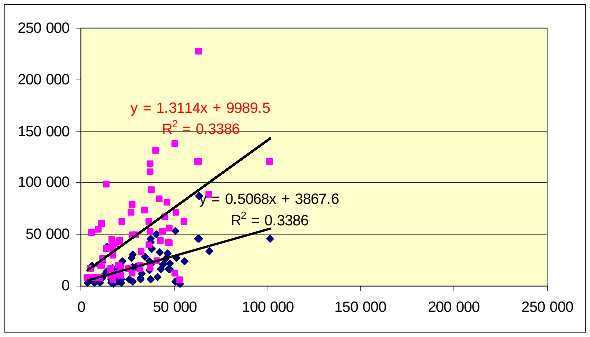
Figure 15. Detail of the emissions from road traffic in one selected areas in Lisbon

Validation of the Methodology

Vehicle Flow

For a set of 65 links average annual traffic volumes were available from the GERTRUDE system (110 monitoring stations for year 2000). These values were compared to the traffic volumes that were estimated for the same links using the methodology that was described in this paper. The estimated traffic volumes are, for all monitoring points, reasonably similar to the values obtained by the GERTRUDE traffic monitoring system.

Figure 16. Simple linear regression between traffic monitored at GERTRUDE system and traffic estimates. Black: bottom-up approach; Red: top-down approach

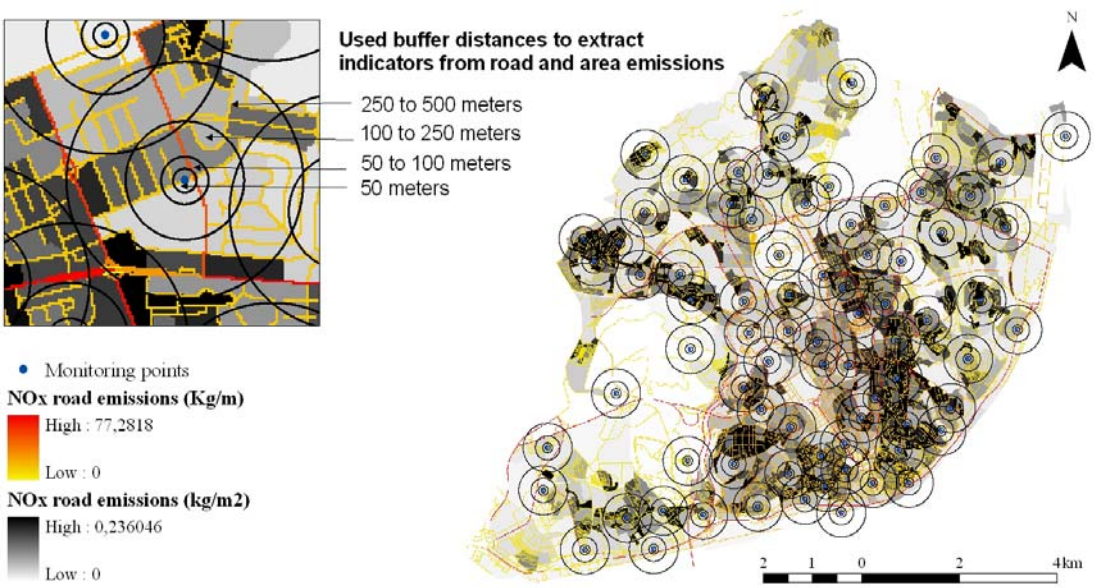


Pattern of Air Emissions

Another way to evaluate the spatial desegregation of the emissions relays on the use of multi-regression models and GIS tools, finding relations between emissions and air quality results from extensive passive diffusive sampling monitoring[12]. With this methodology it is also possible to obtain high resolution air quality annual maps for urban areas. One study[6] evaluated the NO2 inventory model in Lisbon city building several multi-regression models between emissions statistics, both road emissions and area emissions (emissions from static combustion and diffuse sources from domestic and service sectors), and results from monitoring campaigns.

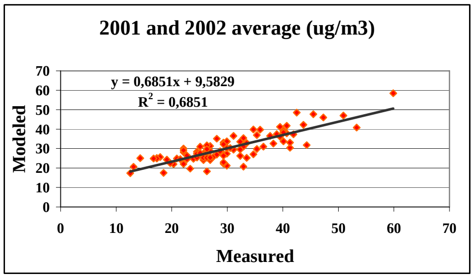
Two extensive campaigns[13] were available from two different meteorological conditions, in the summer of 2001 and in the winter of 2002. In each campaign, passive diffusive samplers measuring pollutants, such as nitrogen dioxide, were exposed during a one-week period in order to complement the automated continuous stations. Around 100 sampling points (**Figure 17**) were located in the city of Lisbon and classified according to a traffic level criterion as background, intermediate, and hot spot. . A global average concentration for each of the 100 monitoring locations for the 2001-2002 period was calculated using a linear regression which relates the average results of the fixed stations during the periods of the campaigns and the 2001-2002 average at the same stations. The variation explained by the model was 89 per cent. This value shows that, although the time extent of campaigns was very short, the results have a very good correlation with the annual averages. The multi-regression models were developed considering rings with different diameters (**Figure 17**).

Figure 17. Diffusive samplers and Rings of influence used to extract the statistics for area and road emissions inventory (10 meters grid) at several distances from the monitoring locations



To build the multi-regression models, basic statistics (average, minimum, maximum, standard deviation, sum and count) characterizing the road and area emissions (converted to a 10 meter grid) in the vicinity (50 meters, 50-100m, 100-250m and 250-500m) of each monitoring point were calculated in ArcGIS 9.0 using Buffering tools and Zonal Statistics from Hawth's Analysis tools extension. These statistics were introduced into SPSS 12.0 to model the 2001-2002 NO2 average concentrations using multi-linear regression forward and backward stepwise options with a 0.05 significance level criteria for the selection of the independent variables. To obtain the spatial pattern, a grid of 100m was built. For each point the same statistics as for the campaign points were calculated and the model was applied. To validate the models, the fixed station's results were then removed from the input data.

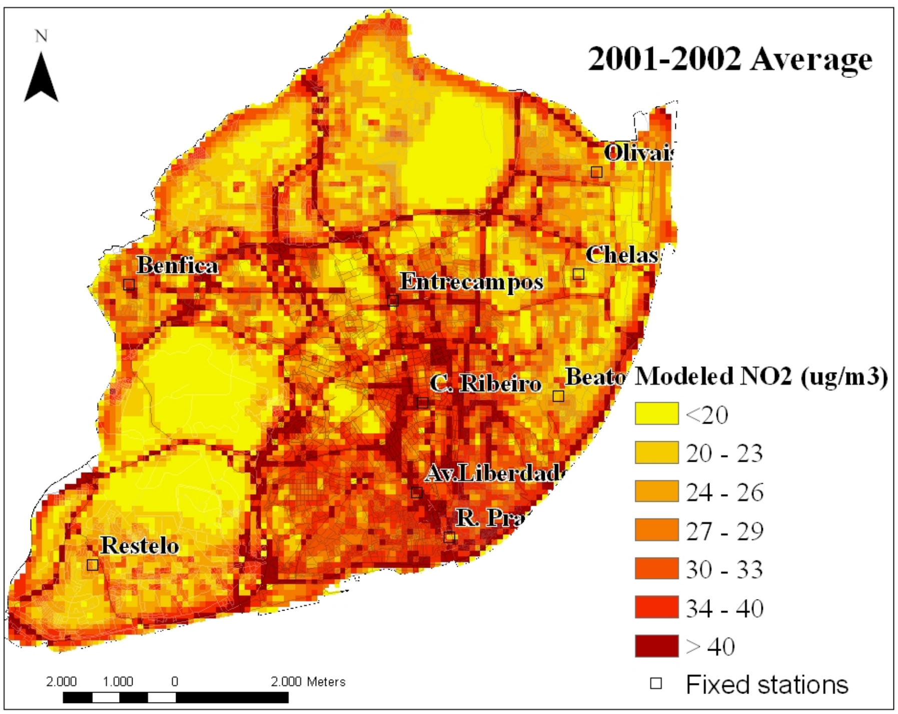
Figure 18. Best fitted NO_2 model including road and area emissions influence at several distances.



R	0,83
R Square	0,69
Adjusted R Square	0,63
Std. Error of the Estimate	5,45

The use of interval rings of all sizes (between 0-500m), and both emission sources created the best explanatory model. The model which achieved the best fit and the most relevant statistics is presented in **Figure 18**. In the end the inventory model explains more than 60 per cent (R Square) of the spatial variability of the nitrogen dioxide concentrations within the Lisbon area. The regression model was applied to a grid 100x100 m grid in Lisbon city (**Figure 19**), resulting in a very detailed mapping of emissions.

Figure 19. Detailed average concentrations of NO_2 in Lisbon area estimated using the best fit regression model and the air emissions inventory model



CONCLUSIONS

The studies reported in this article show that this new spatial allocation methodology is reliable and very valuable for the establishment of emission inventories with a substantial level of spatial detail. This approach is also relatively inexpensive, if aerial photography is available and has the advantage of being based in field data. It was found that the methodology may be applied to both dense urban central areas and low density sub-urban areas. In spite of small methodological differences the methodology shows viability in all cases. The results of this methodology go beyond air emission models, and could be used to derive detailed traffic monitoring surveys or noise mapping.

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