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LISBON AIR QUALITY – EVALUATING TRAFFIC HOT-SPOTS

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ABSTRACT

This paper presents the results from air quality campaigns carried out in two Lisbon traffic hot-spots (*Entrecampos* roundabout and *Liberdade* avenue), aiming to define a more accurate and appropriate location for the referred traffic monitoring stations, which are intended to be representative of the near-kerbside environment.
The campaigns were performed in spring and summer of 2004 with an air quality mobile laboratory equipped with instruments for the continuous measurement of NO_X, CO and PM_{10}. The monitored concentrations were correlated with traffic counts and wind direction. The results indicated that the mean variation of particle and gaseous concentrations closely followed the traffic pattern. This relationship was not evident for wind direction, probably due to the multiplicity of road contributions. Comparing with the air quality legislation, the results show its fulfilment, except for PM_{10}, which often exceeded the limit-value.
In order to evaluate and simulate the flow and dispersion fields of air pollutants emitted by road traffic, a computational fluid dynamics (CFD) model was applied. The simulation of wind and PM_{10} dispersion fields for a 31 hours period was performed on a calculation domain centred at "Liberdade" Avenue. This domain is characterised by the presence of a group of buildings, streets and trees that result on a high geometrical complexity. Air quality data from the monitoring stations were used for the validation of the modelling results. Finally, this work stresses the importance of accounting for additional PM_{10} contributions, as the non-exhaust road traffic emissions and the urban background concentrations.

Key Words: road traffic emissions, air quality, urban area, measuring campaigns, CFD model

1. INTRODUCTION

Nowadays, the whole world largely depends on individual mobility, which has contributed to a general increase in comfort standards. However, the air pollution caused by vehicles exhaust emissions has shown negative environmental and health outcomes. The rapid demographic growth of the last decades has increased the concentration of human populations in cities. As a consequence, the total emissions from road traffic have risen significantly, assuming the main responsibility for the disregard of air quality standards (EEA, 2001), namely in the Lisbon city (Ferreira *et al.*, 2000).

The implementation of the European Framework Directive 1996/96/EC, which defines the pollutants to be measured and the systems to be used for those measurements, resulted in the development of *daughter* directives (including Directives 1999/30/EC and 2000/69/EC) that set the maximum levels for specific pollutants, which were transposed to the Portuguese Law through the Decree-Law nº 111/2002, from the 16^{th} of April.

During the last years, several directives were adopted and plans had to be established with the aim of controlling air quality. Also, there has been an improvement on fuels quality and treatment technologies, with visible results in the improvement of air quality. However, urban environments continue to congregate the inherent problems to the major concentration of people, inappropriate urban planning, growing of the private transportation – with implications in the environmental problems of the city.

An automatic network consisting of seven stations monitors the ambient air quality in Lisbon, providing hourly data on the main atmospheric pollutants. The stations are distributed throughout the city in order to assess the atmospheric pollution in representative areas. Two of them, located at "Liberdade" Avenue and "Entrecampos", could be regarded as typical urban traffic stations. During the last years, and especially in "Liberdade", the daily limit value for PM_{10} was exceeded more than 35 times per year. In this sense, one of the aims of this study is to analyse the location of the urban air quality stations in "Liberdade" and "Entrecampos" through the collection of data on air pollutants concentrations, meteorology and traffic fluxes. On the other hand, the current paper is focused on a modelling approach, complementary to the field campaign, for assessing the PM_{10} air quality levels in a domain centred at "Liberdade" Avenue for a 31 hours period.

During the last years, Computational Fluid Dynamics (CFD) models have proved to be a reliable tool for the simulation of wind and dispersion fields in complex geometries, which are typical in urban areas, assuming an important role on scientific research, policy support and regulatory purposes. The development of powerful numerical codes, supported by the constant increase on hardware performances, has largely contributed to the increase of modelling accuracy. The possibility of knowing the value of any variable related with the mean and turbulent flow or the associated dispersion of an air pollutant in any location of a given tridimensional (3D) study domain is, in fact, one of the main advantages of this technique. However, measurement and modelling are complementary methodologies, in particular due to the fact that a great effort on increasing the performance of models towards the simulation of PM_{10} is still needed, namely through the development of accurate methodologies for accounting for the contribution of the non-exhaust road traffic emissions and the urban background concentrations.

The overall goal of this work is to contribute to a better understanding of the air quality problem in urban traffic hot-spots by performing measurements and modelling studies of atmospheric pollutants concentrations in Lisbon.

2. MEASUREMENT CAMPAIGNS

2.1 “Entrecampos”

The choice of the sampling points took into account the North and South extremities of “Entrecampos” looking forward to be the most representatives of population exposure to pollutants levels originating from the nearest traffic ways: the roundabout itself; “Forças Armadas” Avenue (West); “Estados Unidos da América” Avenue (East); “República” Avenue (North and South). The sampling point related to the measurements carried through 15 and 21st October 2004 is close to the Air Quality Station (AQS) of “Entrecampos”, continuously measuring the same pollutants of the mobile unit of air quality (SNIF air lab).

Figure 1 presents the diagrams with the location of the campaign sampling points.

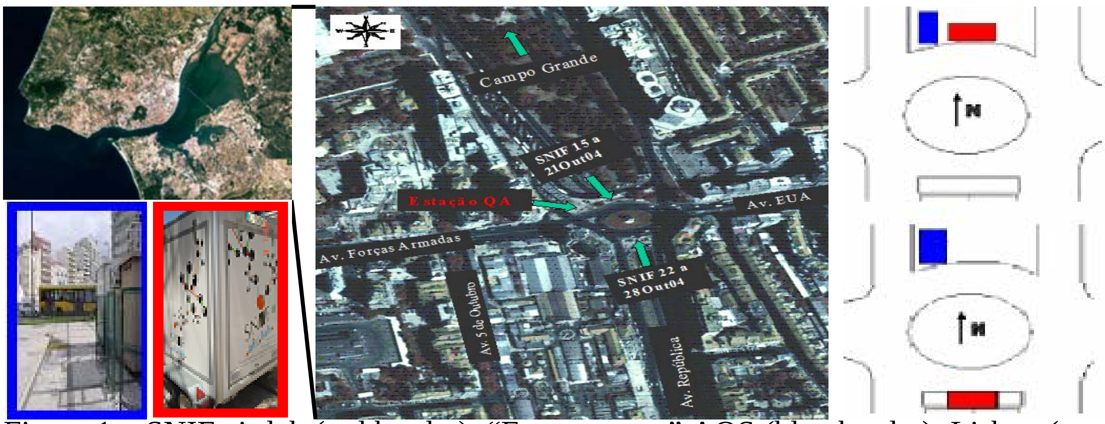

Figure 1 – SNIF air lab (red border); “Entrecampos” AQS (blue border); Lisbon (top and left) and “Entrecampos” (centre) ortophotomaps; SNIF location (red) and “Entrecampos” AQS (blue) in 15th to 21st October (top and right) and 22nd to 28th October (down and right).

All the NO_2 and CO results fulfil relevant norms, established in the National Decree-Law nº111/2002, 16 April. The mean values registered for PM_{10}, measured especially at the SNIF, exceeded the limit-value plus the margin of tolerance for the year 2004 (55 µg.m^{-3}). The meteorological data (10 m high) were recorded at the Portuguese Meteorological Institute, located near the Lisbon airport, a few kilometres away from the measurement spot. Figure 2 presents the mean values obtained in the 2 weeks campaign (15-21 and 22-28, October).

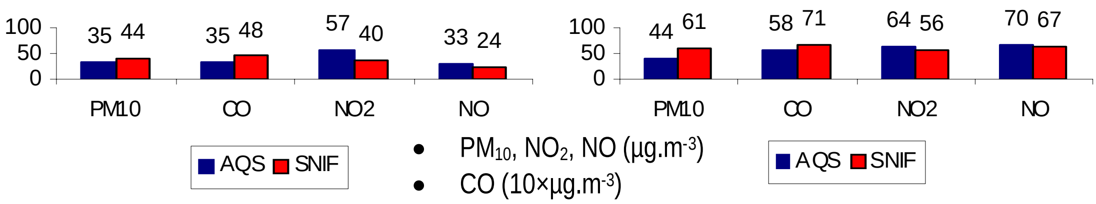

Figure 2 – Mean values of PM_{10}, NO_2, NO (µg/m^3) and CO (10×µg/m^3) obtained at the AQS and SNIF (left: October, 15 – 21; right: October, 22 - 28).

As shown, there was a consistent increase on the pollutants concentrations, at the AQS and SNIF, from the first to the second week. Concerning the meteorological parameters, there were no significant differences between both periods. The mean concentration values at the urban background stations ("Olivais" and "Loures"), increases comparing the first week to the second: 10-20% on PM_{10}, 34-104% on NO_2 and 7-82% on CO. There were also increases at AQS and SNIF: 26-39% to PM_{10}, 13-40% to NO_2, and 47-66% to CO. So, according to the meteorological data and from the results for the several pollutants measured at those stations, we can conclude that this phenomenon can be related with an increase of pollution, on a regional level, with consequent local effects.

During the campaign the five mentioned wind directions represent about 90% of the measured hours, while the three left wind directions (North, West and Northwest) had a rare occurrence. Consequently, the corresponding concentration values were unimportant and the respective averages subjected to enormous errors that could make difficult the analysis of the other results.

Figure 3 presents the hourly average results obtained at the AQS and SNIF; the percentage of occurrence of each wind direction and intensity ($m.s^{-1}$); and the traffic flux.

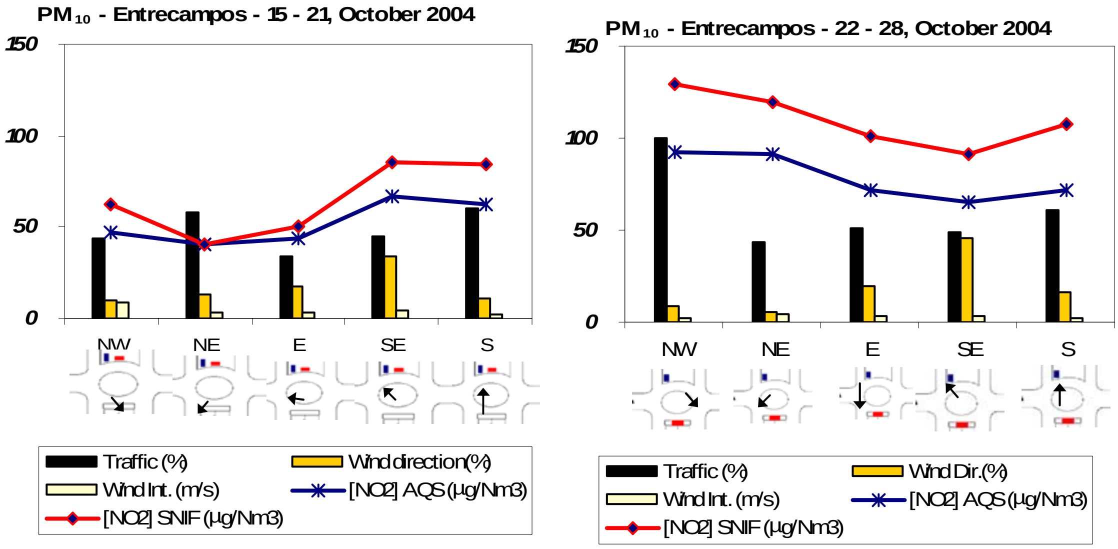

Figure 3 – Mean values of PM_{10} obtained (Left: October, 15 – 21; Right: October, 22 – 28) at the AQS and SNIF, according to the wind direction; % of prevalence according to wind direction; mean relation of the traffic flow observed for each wind direction; and wind intensity ($m.s^{-1}$).

From the data collected some conclusions can be taken:

- As expected, the highest PM_{10} concentrations were recorded at SNIF, when compared with the AQS. Similar values were uniquely observed when wind direction was from NE (1^{st} week). From this direction, the air comes from the

North entry of the "Entrecampos"´s tunnel and from the woody area that extends from "Entrecampos" to "Campo Grande";

- during the two weeks, the highest concentration levels correspond to wind directions favourable to draining of air masses in the traffic zone, concerning the sampling points: 1st week – SNIF registered higher values of Southeast wind; 2nd week – in a opposite point in the round, higher values of NW and NE wind were registered.

2.2. "Liberdade" Avenue

This campaign took place at the "Liberdade" Avenue, in 16th to 21st May 2004. The obtained results in SNIF and AQS (see figure 4) for NO_2 and CO fulfil the boundary-values stipulated in the national law nº111/2002. The mean values of PM_{10} measured, especially at the SNIF, exceeded the limit-value plus the margin of tolerance for the year 2004 (55 µg.m^{-3}).

Figure 4 presents the mean values obtained at the 2 sampling sites (16th to 19th and 19th to 21st May 2004), related to the hourly average values of each pollutant:

- NO and NO_2 were not measured in the first campaign period, due to problems with the analyser;
- the pollutants concentrations obtained during the first period at the SNIF were higher than those measured at the AQS. The SNIF was situated between the main traffic way of "Liberdade" Avenue and the AQS, registering a higher influence of traffic. These data showed that human exposure can be worse than expected;
- during the second measuring period, the opposite occurred: the values obtained at the AQS were always higher than SNIF's. There was an almost null difference concerning CO. During the second measuring period the SNIF was more distant than the AQS from the main way of "Liberdade" Avenue, and so, under less traffic exposure and particle resuspension. These facts could influence positively the obtained results.

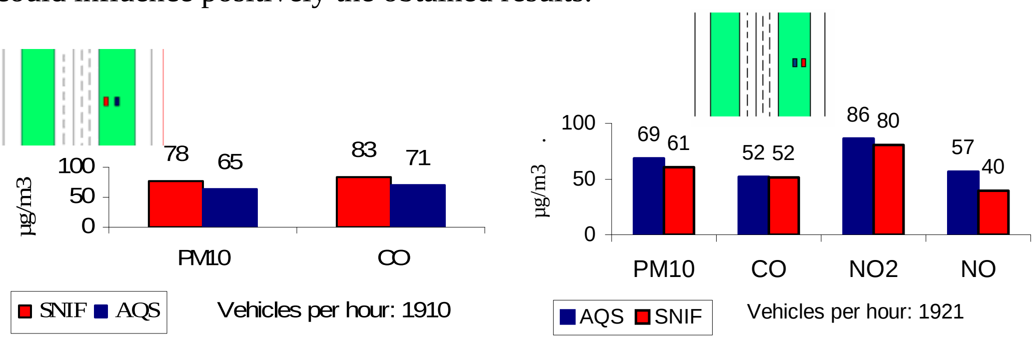

Figure 4 – Mean values of PM_{10} (µg.m^{-3}), CO (10×µg.m^{-3}), NO_2 (µg.m^{-3}) and NO (µg.m^{-3}) obtained at the AQS (blue) and SNIF (red), between 16th to 19th May (left) 19th to 21st May (right); and hourly mean traffic flux.

3. MODELLING APPLICATION

The hourly simulations of PM_{10} dispersion were performed for the period between 17h on the 19th of May and 24h on the 20th of May 2004. The methodology beyond the developed work was based on the application of the commercial CFD model FLUENT (Fluent Inc., 2003), version 6.1.18 for Unix platforms, previously applied by the authors (Amorim *et al*., 2005) with successful results for the simulation of CO dispersion in a typical urban area. In the core of the solver, the model applies the Reynolds-averaged Navier-Stokes (RANS) equations for solving the mean flow, while all the scales of turbulence are modelled through the application of the k-ε model. Both flow and dispersion fields were obtained applying an Eulerian approach. The selected domain (see Figure 5), comprising an area with 700 × 700 (L × W) m^2, was centred at “Liberdade” Avenue. In order to deal with the high geometrical complexity of buildings an unstructured mesh was created.

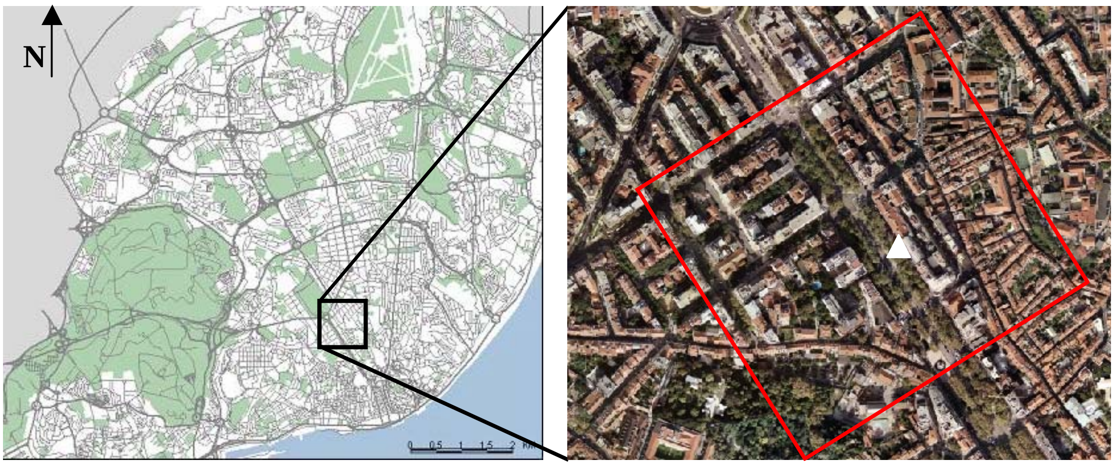

Figure 5 – Map with the location of the simulation domain of “Liberdade” Av. [adapted from http://lisboainteractiva.cm-lisboa.pt/]. The location of the AQS is represented by the white triangle.

The densely foliaged tall trees that flank both sides of the Avenue along its entire length were digitally originated as 3D elements with a porosity defined according to a sink-term (S_i) added to the momentum transport equation. This term represents a simple parameterisation of the loss of wind speed due to pressure and viscous drag forces exerted by leaves and branches, and is expressed in Einstein notation as follows:

$$S_i = -C_0\,|v|^{C_1} = -C_0\,|v|^{(C_1-1)}v_i \qquad (1)$$

where v is the wind velocity at that specific computational cell and C_0 and C_1 are empirical coefficients tuned to 10 and 1, respectively. Although empirical, this approach allows to obtain accurate results when compared to a more realistic vegetative canopy model already tested (Amorim *et al*., 2005).

The hourly mean values of road traffic emissions of PM_{10} were estimated through the application of the Transport Emission Model for Line Sources (TREM) (Borrego *et* *al*., 2003 and 2004), using as main input the vehicles counting data with distribution by classes.

In figure 6, examples of PM_{10} concentration fields for four different wind directions (in meteorological coordinates) are shown: 350º (18h on the 19th), 24º (1h on the 20th), 159º (14h on the 20th) and 216º (16h on the 20th). As can be seen, there is a clear accumulation of PM_{10} along the Avenue, with the formation of some hot-spots. The location of those higher concentrations shows that the dispersion pattern is highly influenced by the wind direction.

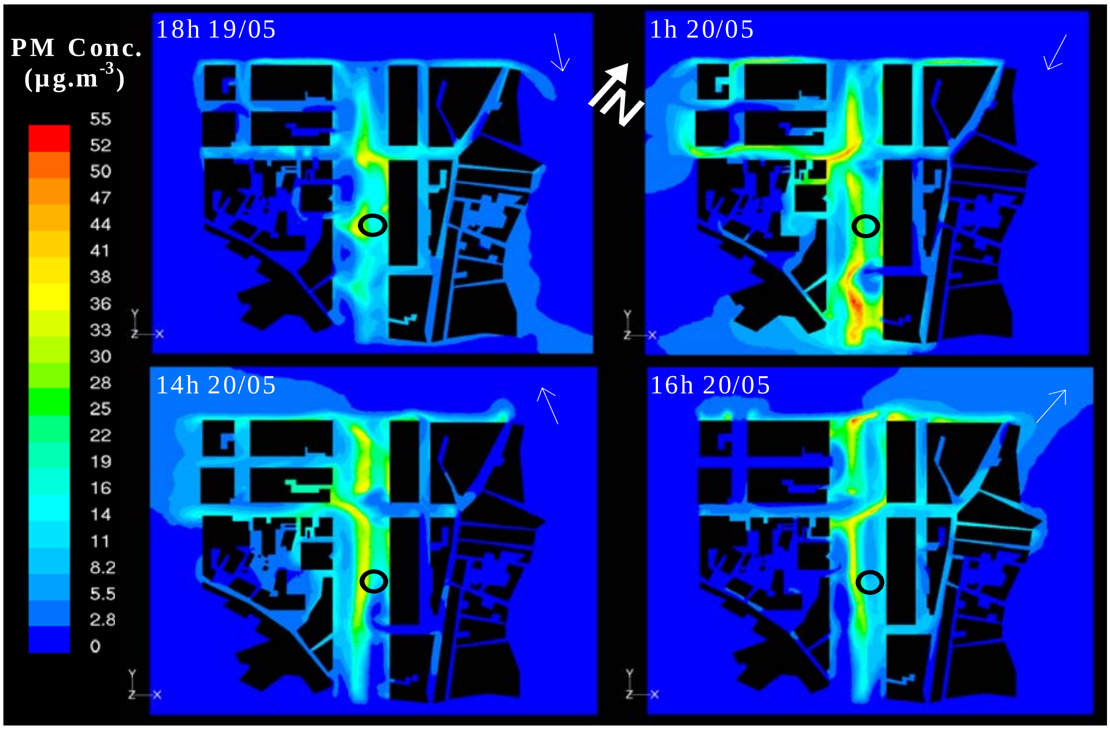

Figure 6 – 3 m high horizontal PM_{10} concentration fields corresponding to four distinct wind directions. The location of the AQS is represented by the black circle. Vectors indicate wind direction angle.

In figure 7, the temporal variation of the hourly mean values of wind velocity, PM_{10} emissions and PM_{10} concentrations in ambient air are presented.

One of the conclusions that can be taken from the analysis of figure 7 is that PM_{10} concentrations simulated by FLUENT (black solid line), with the consideration of the direct exhaust pipe emissions only, are significantly inferior to the measured ones (grey solid line). Therefore, a methodology was applied in order to consider the influence of the non-exhaust traffic related PM_{10} emissions, which include brake-wear, tire wear and resuspension of loose material on the road surface.

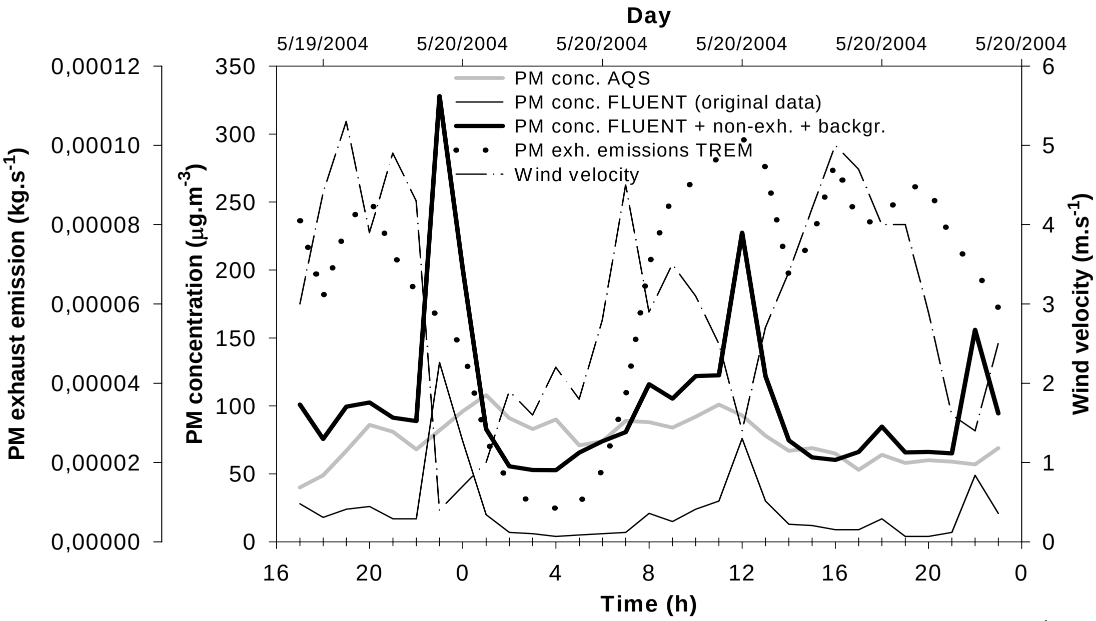

Figure 7 - Evolution with time of the mean hourly values of wind velocity (m.s^{-1}) at the inlets boundaries, PM_{10} road traffic emissions (kg.s^{-1}) estimated by TREM for the "Liberdade" Av., PM_{10} concentration (µg.m^{-3}) measured in the AQS and simulated by FLUENT (original data and with the consideration of non-exhaust emissions and background concentrations) for the same location.

The PM_{10} emission factor of this non-exhaust contribution ($EF_{non\text{-}exhaust\ PM10}$, in g.km^{-1}) was calculated through the following equation:

$$EF_{\text{non-exhaust PM10}} = 55.92 \cdot v^{-0.82} \cdot \left(sL/2\right)^{0.65} \cdot \left(W/3\right)^{1.5} \qquad (2)$$

where, sL is the road surface silt loading, defined as 0.2 g.m^{-2} (value proposed by Düring *et al*. (2002) for a "good" surface urban street), v is the average vehicle speed, equal to 50 km.h^{-1}, and W is the average vehicle weight of the fleet mix (1.1 t for cars, 1.9 t for light duty vehicles and 9 t for trucks, according to Düring *et al*. (2002)). This equation is based on the EPA (2003) model for the estimation of the dust emissions from dry paved roads, to which a speed component was added according to the methodology developed by Tchepel (2003).

The minimum and maximum quotient between total emission and exhaust pipe emission were, respectively, 1.9 at 1h and 4.4 at 6h, which are in agreement with the values found by Düring *et al*. (2004) for some motorways and major arterial roads in Germany, indicating that the non-exhaust contribution can be even greater than the direct exhaust one.

The PM_{10} background concentration was obtained as a mean value for two urban background air quality stations, "Loures" and "Olivais", which are located at, respectively, N and NE of the domain. For this reason, this methodology is expected to give more accurate results for wind directions in the quadrant N/NE. Minimum and maximum values of this background concentration are, respectively, 27.5 µg.m^{-3} at 17h on the first day and 62.5 µg.m^{-3} at 9h of the second one.

With the inclusion of these additional terms a much better agreement is found between simulated and measured values (solid bold line versus solid grey line, respectively). As can be seen, three distinct peaks are found which largely surpass the measured concentrations. These discrepancies correspond to the hourly simulations of 23h on the 19th and 0h, 12h and 22h on the 20th of May. These four hourly periods for which the difference between measured and simulated values is greater are, in fact, a result of the extremely low wind velocities (less than 1 m.s^{-1} at 10 m in height) registered. Moreover, the vegetative canopy contributes to an even higher reduction of the wind speed at the location of the AQS. The sensitive analysis applied to the 23h on the 19th showed that increasing the wind speed from the original 0.4 to 2 m.s^{-1} and 5 m.s^{-1} a decrease of, respectively, 78 and 91 % in the PM simulated value is obtained.

The Normalized Mean Squared Error (NMSE) for the air quality values simulated by FLUENT with the consideration of the non-exhaust and the background contributions is 0.487. However, neglecting the values corresponding to the observed peaks, this statistical parameter decreases to 0.086, indicating a very good modelling performance (significantly better than 2.061, for no non-exhaust and background additional inputs). According to the Directive 1999/30/EC there are not yet data-quality objectives for assessing the uncertainty associated to PM_{10} modelling in terms of hourly or daily averages. New legislation is therefore necessary to fulfil this gap.

4. CONCLUSIONS

The air quality characterization in “Entrecampos” and “Liberdade” Avenue, that involved the results of the mobile laboratory (SNIF) and the AQS, allowed to conclude that:

- NO_2 and CO results fulfil the respective air quality norms, stipulated in the Decree-Law n. º 111/2002, of 16th of April. Some of the PM_{10} daily average values, specially in the SNIF, exceeded the respective limit value plus the margin of tolerance;
- it is still possible to verify that the SNIF had normally higher values than the AQS, probably because of the greater proximity to the road;
- it is clear the influence of wind direction in the pollutants levels, namely for PM_{10}, and specially in “Entrecampos”;
- the proximity to the traffic way of the “Liberdade” Avenue, generally represents greater concentration values, to the exception of the CO, whose trend is not so evident;
- the results indicated that the mean variation of particle and gaseous concentrations followed the traffic flow rate, but not so evidently in relation to wind direction, probably due to the multiplicity of road contributions.

The performed simulations showed that current methodologies for PM_{10} dispersion modelling allow to obtain acceptable results on air quality assessment within complex urban areas. Nevertheless, the importance of the contributions of non-exhaust road traffic emissions and urban background concentrations on total PM_{10} concentrations fully justifies the need of improving the accuracy in the quantification of these additional sources of particulates.

Further developments on this specific area of research should allow to contribute to the establishment of adequate data-quality objectives for assessing the uncertainty associated to PM_{10} modelling established by the European Law.

The campaigns results and the performed simulations allow us to obtain important information for the development of adequate methodologies towards air quality evaluation. It may also be used to promote the necessary knowledge of the potential risk for human health in traffic hot-spots areas and to guarantee the existing fulfilment of the norms and legislative aspects.

5. ACKNOWLEDGMENTS

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REFERENCES

Amorim, J.H., Miranda, A.I., Borrego C., 2005. The effect of vegetative canopy on urban air pollutants dispersion: an application to Lisbon city centre. Proceedings from the 14th International Symposium on Transport and Air Pollution (TAP), 1-3 June 2005, Graz, Austria. pp. 89 – 98.

Borrego, C., Tchepel, O., Costa, A.M., Amorim, J.H., Miranda, A.I., 2003. Emission and dispersion modelling of Lisbon air quality at local scale. Atmospheric Environment 37, 5197-5205.

Borrego, C., Tchepel, O., Salmim, L., Amorim, J.H., Costa, A.M., Janko, J., 2004. Integrated modelling of road traffic emissions: application to Lisbon air quality management. Cybernetics and Systems: An International Journal 35 (5-6), 535-548.

Düring, I., Jacob, J., Lohmeyer, A., Lutz, M., Reichenbächer, W., 2002. Estimation of the "non exhaust pipe" pm10 emissions of streets for practical traffic air pollution modelling. Proceedings from the 11th International Symposium Transport and Air Pollution (TAP), 19-21 June 2002, Graz, Austria. Vol. I, pp. 309-316.

Düring, I., Bächlin, W., Bösinger, R., Müller, W.J., Lohmeyer, A., 2004. Experiences when modelling roadside PM10 concentrations. Proceedings from the 9th International Conference on Harmonisation within Dispersion Modelling for Regulatory Purposes. 1-4 June 2004, Garmisch Partenkirchen, Germany. Vol. 1, pp. 208-212.

EEA - European Environment Agency, 2001. TERM 2001; Indicators tracking transport and environment integration in the European Union, Copenhagen; ISBN 92-9167-307-2.
EPA, 2003. AP-42 Emission Factors, Fifth Edition, Volume I. Chapter 13, Miscellaneous sources. Section 13.2.1. Paved Roads, 12 p.
Ferreira, F., Tente, H., Torres, P., Cardoso, S., Oliveira, J., 2000. Air Quality and Management in Lisbon; Environmental Monitoring and Assessment, vol. 65; pp 443-450.
Fluent Inc., 2003. FLUENT 6.1 User's manual, Fluent Inc., Lebanon.
Tchepel, O., 2003. Emission modelling as a decision support tool for Air Quality Management. PhD Thesis, University of Aveiro, Portugal, 213 p.