Modelling Human Exposure to Air Pollutants in an Urban Area

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A modelling approach was applied to an urban area, in order to study the effects of urban canopy in favoring critical situations of exposure to traffic induced air pollutants. The atmospheric dispersion of NOx, emitted by road traffic, was simulated inside the urban canopy layer by means of the COPERT algorithm and the AUSTAL2000 dispersion model. As expected, high concentrations occurred inside street canyons with consequences on the human exposure. The positive effect of traffic management options, such as incentivizing the public transportation and excluding the most pollutant vehicles from the circulation, was also investigated.

Keywords: urban street canyon, traffic, exposure, NO_2

Road traffic is one of the main sources of atmospheric pollution in urban areas, where the contribution of traffic flows, congestions and high population density typically increases the exposure of the settled population to pollutants [1-3].

One of the most important family of traffic-related pollutants is represented by nitrogen oxides (NO_x), whose main contributors to their emissions in Europe are the mobile sources (38.4%), followed by the energy production sector (21.1%), the commercial, institutional and household sectors (14.8%), energy use in industry (13.4%) and other minor sectors (12.3%) [4].

Unlike nitrogen monoxide (NO), nitrogen dioxide (NO_2) produces adverse effects on human health, such as the development of bronchitis, pneumonia, asthma and the pulmonary growth reduction in chronically exposed adults and children [5, 6]. To preserve the human health, the World Health Organization (WHO) established a limit value of 40μg m^{-3} for the annual mean concentration of NO_2. An hourly threshold of 200 μg m^{-3} was also set in order to prevent the effects of acute exposure, such as medium airways inflammations and amplification of allergic reactions [5].

Since emitted NO tends to be rapidly converted to NO_2, also within the O_3 chemical reactions forced by solar radiation [5], NO_2 is commonly found near the emission sources. Thus, NO_2 can be considered a typical indicator of air pollution from road traffic in urban areas. Critical situations for European urban areas (such as intense road traffic and particular meteorological conditions due to the complex urban structures) make the compliance of the imposed limits a difficult task. The compactness of urban fabrics, the presence of streets with highly developed buildings in the vertical dimension and the lack of open spaces favour the stagnation of pollutants and increase the population exposure. The structuring elements of the urban fabric are the so-called street canyons, intended as narrow roads laterally delimited by two continuous rows of buildings. At this spatial scale, the street canyon represents the basic geometric unit of the urban fabric and defines the vertical dimension of the urban canopy layer, which is the atmospheric layer included between the soil and the roofs [7], after which the urban boundary layer starts to develop. The canyon length (L), its width (W) and the height (H) of the buildings are relevant parameters for the dispersion of pollutants [8].

The understanding of air quality processes in an urban area is facilitated by high resolution simulations. Numerical models are very important for the dual purpose of simulating air quality scenarios and obtaining fields of concentration in areas not covered by the air quality monitoring stations.

This study aims at presenting a methodology to study the role of urban street canyons in the stagnation of pollutants and to detect critical situations of exposure to air pollutants in a densely built area. This work was carried out by applying the COPERT emission algorithm and the AUSTAL2000 dispersion model to an urban area of the town of Verona (Italy). The choice of road traffic as the only emission source is due to the fact that other sources (*e.g.*, domestic heating and industrial activities) generally emit above the urban canopy and their contribution is not dominant inside canyons with high traffic. The analysis considers NO_2 as the reference pollutant to evaluate the contribution of road traffic to human exposure in street canyons.

Experimental part

Materials and methods

The town of Verona is located in the Po Plain and is characterized by a continental climate with frequent episodes of thermal inversion [9], especially during the wintertime, like most of the other cities in the Po Plain. Verona is also the junction of important roadways (4 state roads, 1 ring road and 2 highways). From the beginning of 2009, the Municipality has activated a monitoring network of the vehicle fluxes by means of inductive loops, to obtain information about the traffic intensity in selected areas of the town.

As a first step, a preliminary GIS analysis was performed in order to select a particularly critical area of Verona in terms of population density, presence of sensitive receptors (*e.g.*, school buildings) and lack of green areas.

The reconstruction of the vehicle fluxes moved from the data acquired by the traffic monitoring network, consisting in hourly mean fluxes related to a summer and a winter week.

The emissions were calculated by means of the COPERT algorithm, proposed by the European Environmental Agency (EEA) as a tool for evaluating emissions from road traffic within the CORINAIR Programme. The model allows estimating the emissions of the main pollutants related to road traffic: NO_x, CO, PM, VOC, CH_4, CO_2, SO_2, Pb and other metals. Information about the vehicle fleet was provided by the Automobile Club

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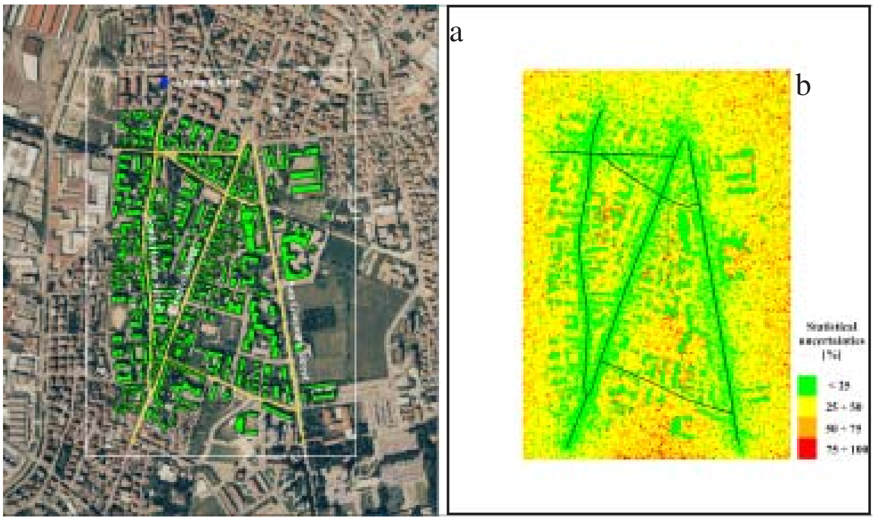

Fig. 1. a) Computational domain with location of the anemometer, digitization of the streets and the buildings and b) map of the statistical uncertainties for the simulations performed

d'Italia (ACI) [10]. The calculation of NO_x emissions was performed for a whole solar year, in order to compare the concentration maps of the dispersion model with the limit values on annual basis. The hourly vehicle fluxes (together with information on the length of each road) were used to calculate the total NO_x emissions (expressed in g s^{-1}) along each street during the whole year, on the basis of each hourly flux, the composition of the vehicle fleet, each street length and the emission factors for each vehicle class. The latter were calculated by assuming an annual mean temperature of 15°C and a mean speed of 45 km h^{-1}, since the streets considered allow a flowing stream of vehicles.

After calculating the NO_x emissions, the input files for the dispersion model were prepared. The model adopted was AUSTAL2000, a quasi non-stationary three-dimensional lagrangian model, which works on an average of stationary states, opportunely scaled along the flow field. AUSTAL2000 is able to compute the transport of pollutants at a local scale. The meteorological pre-processor (TalDIA) incorporates its own algorithm to assess the effects of buildings on the wind flow, which is quite useful in urban areas, and provides 3D flow fields for the dispersion model. When explicitly defining the obstacles, as in the present case, the parameterized roughness (z_0) adopted used in dispersion algorithms is not used. TalDIA is a diagnostic flow model providing an economic calculation capability based upon profiles of wind and atmospheric stability (according to the Klug-Manier parameterization, conceptually similar to the Pasquill stability). The required data about atmospheric stability classes, wind speed and wind direction for the reference year, were evaluated from a meteorological station managed by the Regional Environmental Protection Agency of Veneto near the study area. In addition, a map of the building heights was elaborated with Quantum GIS and Grass GIS and entered into the model.

Since the emissions calculated by COPERT referred to NO_x, as sum of the volumetric fractions of NO and NO_2, it was decided to convert them to NO_2 emissions. For the present case, based on the results from other studies concerning street canyons [11, 12], a constant value of 0.3 was assumed for the NO_2 to NO_x concentration ratio. Actually, an empirical relation to calculate the mean annual NO_2 concentration from the corresponding NO_x concentration, calibrated on field measurements, was proposed in a previous study [13]. This relation describes well the conversion of NO_x in the free field, but underestimates the NO_2 concentration within street canyons, since this approach is not able to consider the effect of stagnation of NO_2 in confined spaces [12].

The emission sources were made to coincide with the streets and parameterized by linear sources. The source heights were set at 0.5 m above the ground, while the vertical extension was assumed to be dependent on the typology of the streets: for street canyons, a vertical extension of 1 m was assumed, whilst, for the remaining streets, the vertical extension was set to 0.5 m. This choice reflects the fact that the stronger mechanical by-produced turbulence within a street canyon from vehicle motions affects the dispersion of pollutants at the source level and contributes to a better mixing of these compounds. A value of 0.9 m was adopted for the surface roughness outside the area covered by the buildings, according to the indications of the CORINE maps, as a result of averaging out the suggested values for terrains with continuous coverage of buildings and terrains with commercial and manufacturing activities [14], as in the case of the area object of this study. The result of the dispersion calculation is the concentration field of the pollutants (in this case NO_2) at 1.5 m above the ground, averaged over subsequent time intervals.

The final aim of this study is the creation of a qualitative exposure map, which can give indications on the most interesting points (with exclusive respect to the domain considered) where to set a monitoring campaign. Exposure depends both on the concentration of the pollutant of interest and on the population density within the study area [15]. The population exposure can be assessed, in a GIS environment, by creating a raster map, based on the product between the concentrations of pollutant and the population density. Thus, the map containing the annual mean concentrations was multiplied by the map of the population density.

Results and discussions

The calculation domain is an area of 720 x 1035 m^2 including two street canyons: Centro Street and Scuderlando Street (fig. 1a). The AUSTAL2000 output files are maps of the annual mean and maximal hourly concentrations. In addition, the model creates a map with the statistical uncertainties of the calculated concentrations: precisely, AUSTAL2000 calculates an estimation of the uncertainty, which is directly proportional to the statistical significance of the lagrangian scheme. This map contains, for each cell, the ratio between the standard deviation and the calculated concentration. In this case, satisfying statistical uncertainties were achieved (fig. 1b).

The annual mean concentrations are everywhere lower than the limit value of 40 μg m^{-3}, with a maximum of 27 μg m^{-3} near the junction between the two canyons (fig. 2a). However, only traffic-related NO_2 was taken into account, since the first objective of this work was the estimation of the effect of street canyons in limiting the dispersion of the pollutants. The second highest value (26 μg m^{-3}) occurs inside Centro Street. Indeed, next to this point, the width of the street canyon is minimal (10 m).

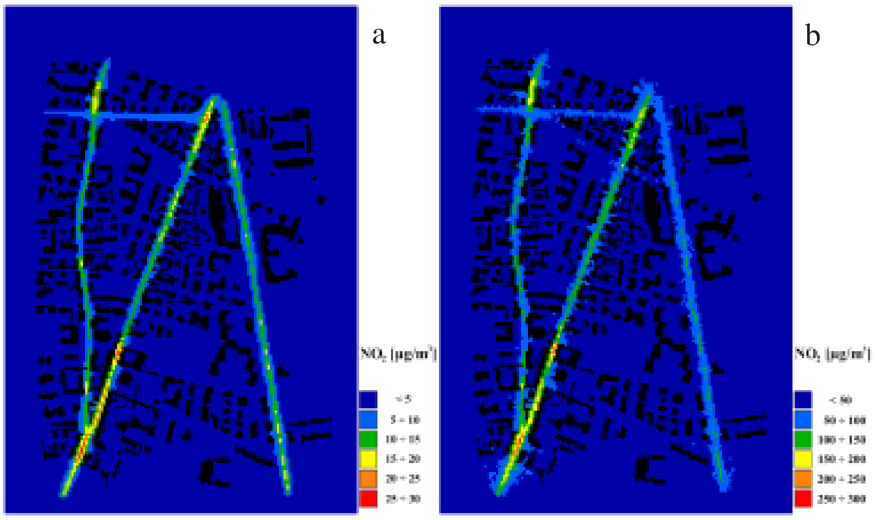

Fig. 2. a) Annual mean and b) maximal hourly concentrations of NO_2 considering the whole vehicle fleet

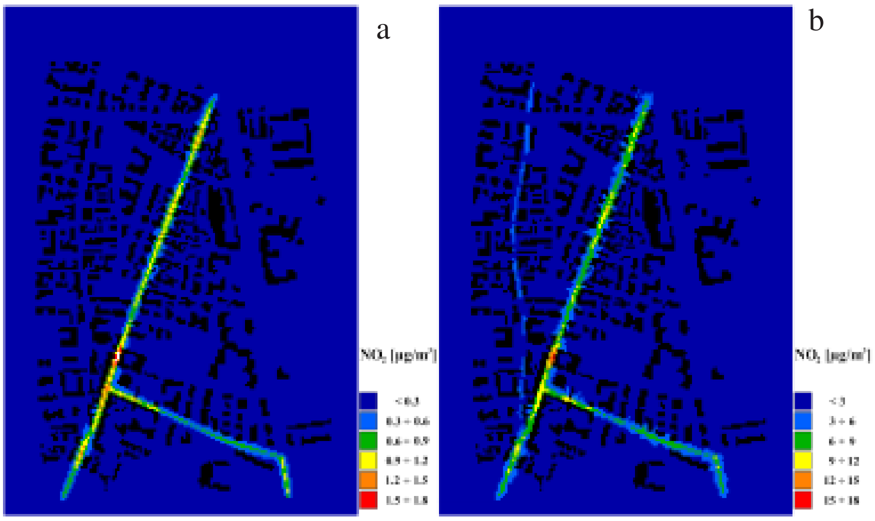

Fig. 3. a) Annual mean and b) maximal hourly concentrations of NO_2 considering the only contribution of urban buses

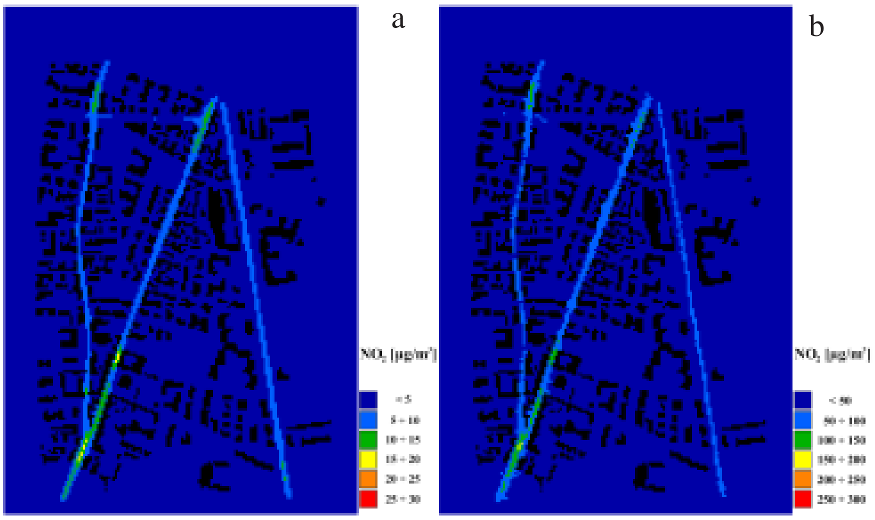

Fig. 4. a) Annual mean and b) maximal hourly concentrations of NO_2 considering only EURO 2 and later vehicles

Similar considerations can be expressed about the map of the maximal hourly concentration: these reaches the highest levels at the same points of the annual mean concentration map (fig. 2b). The maximal concentration (270 µg m^{-3}) occurs next to the junction between Centro Street and Scuderlando Street, while a concentration of 227 µg m^{-3} occurs in the narrowest stretch of Centro Street. Lower concentrations occur within Scuderlando Street, although a value of 200 µg m^{-3} is observed in the northern stretch of the canyon, due to a *H* to *W* ratio higher than 1 and to intense traffic fluxes. It is interesting to highlight the fact that the concentrations along San Giacomo Street, a road without characteristics of street canyon but with the highest traffic fluxes, result everywhere lower than the concentrations obtained within the two streets canyons.

The contribution of the public transportation (urban buses) was also studied. As shown in figure 3a and 3b, its contribution to the NO_2 concentration is minimal. The maximal hourly contribution to NO_2 concentrations occurs in Centro Street (18 µg m^{-3}). At the same point, the maximal hourly concentration calculated for the whole car fleet was 210 µg m^{-3}. The highest annual mean concentration contribution is 2 µg m^{-3}, which also occurs at the same point. The same cell showed a concentration of 26 µg m^{-3} for the simulation with the whole fleet. Therefore, the contribution of urban buses to the total NO_2 concentrations is about 8%.

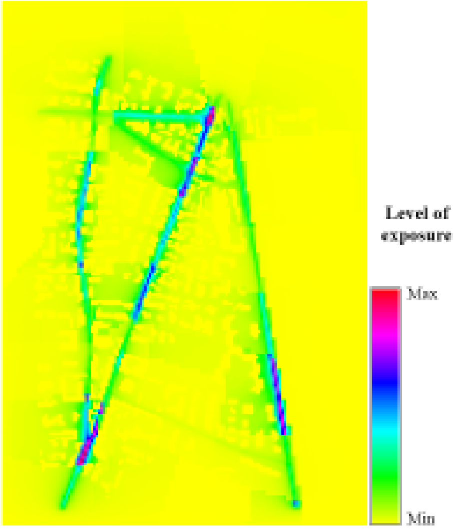

Fig. 5. Qualitative map of the population exposure to NO_2 emitted by road traffic inside the urban area under investigation

To assess the effectiveness of possible measures to restrict the circulation to the most recent (and, thus, less polluting) vehicles, a new simulation was performed with the exclusion of EURO 0 and EURO 1 vehicles. Both the concentration maps show a sensible reduction of NO_2 concentrations with respect to the simulation with the entire vehicle fleet (fig. 4a and 4b). Similarly to the previous simulations, the highest annual mean concentration (17 $\mu g\ m^{-3}$) occurs near the junction between Scuderlando Street and Centro Street; at the same point, the maximum hourly concentration also occurs (168 $\mu g\ m^{-3}$). Since the highest concentrations of the previous simulation were 27 and 270 $\mu g\ m^{-3}$ (respectively for the annual mean and the maximal hourly concentration), in both of the cases a restriction to the circulation of EURO 0 and EURO 1 vehicles (and a following reduction of the fluxes) leads to a concentration reduction by about 40%. This result is in line with the findings of a study that examined the effects of traffic restrictions on the NO_2 concentrations within an urban area [16].

As a final step, the level of exposure of the population inside the street canyons was estimated (fig. 5), in accordance with the methodology presented in the previous section. It is important to say that this map provides that zones with the highest exposure levels are located near the intersection between the two canyons and at the northern stretch of Centro Street.

Conclusions

The results of the simulations highlight the problem of the dispersion of pollutants within a complex urban area; in particular, the simulations pointed out to what extent the morphology and density of the buildings are important to favour the stagnation of pollutants within the urban fabric. This explains why the highest NO_2 concentrations occur within the two identified street canyons, although the traffic fluxes were lower than those observed for other roads without buildings. The simulations allowed to identify the most critical zones, thus providing a useful insight for the planning of monitoring campaign of air quality (*e.g.*, with the use of passive samplers, as well as mobile or even fixed stations). Simulations on shorter periods would allow detecting the most critical periods of the year and, then, would give indications about the most interesting period for the samplings.

As a future step, the combination of all the most relevant NOx emission sources (i.e., traffic, domestic heating and industrial processes) would provide a tool to support decisions for the urban planning. This would be especially important for the location of sensitive activities such as hospitals or schools.

The concept of exposure is of great interest, especially due to the fact that the current legislation does not consider the location of the emission sources and the settled population. Therefore, exposure maps provide an interesting starting point to conduct zoning analyses and to detect the areas where the population is more exposed to potential health risks.

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