Assessing the air quality impact of nitrogen oxides and benzene from road traffic and domestic heating and the associated cancer risk in an urban area of Verona (Italy)

Marco Schiavon[a*], Martina Redivo[a], Gianluca Antonacci[b], Elena Cristina Rada[a,c], Marco Ragazzi[a], Dino Zardi[a,d], Lorenzo Giovannini[a,d]

[a] Department of Civil, Environmental and Mechanical Engineering, University of Trento, Via Mesiano 77, I-38123 Trento, Italy
[b] CISMA Srl, Via Siemens 19, I-39100 Bolzano, Italy
[c] Department of Biotechnologies and Life Sciences, University of Insubria, Via G.B. Vico 46, I-21100 Varese, Italy
[d] CINFAI – National Consortium of Universities for Atmospheric and Hydrospheric Physics, Piazza N. Mauruzi 17, I-62029 Tolentino, Macerata, Italy

Authors' email addresses:
Marco Schiavon: marco.schiavon@unitn.it
Martina Redivo: martina.redivo@hotmail.it
Gianluca Antonacci: gianluca.antonacci@cisma.bz.it
Elena Cristina Rada: elena.rada@unitn.it
Marco Ragazzi: marco.ragazzi@unitn.it
Dino Zardi: dino.zardi@unitn.it
Lorenzo Giovannini: lorenzo.giovannini@unitn.it

[*] Corresponding author: Address: Via Mesiano 77, I-38123 Trento, Italy; Email: marco.schiavon@unitn.it; tel.: +39 0461 282605; fax: +39 0461 282672

Abstract

Simulations of emission and dispersion of nitrogen oxides (NO_x) are performed in an urban area of Verona (Italy), characterized by street canyons and typical sources of urban pollutants. Two dominant source categories are considered: road traffic and, as an element of novelty, domestic heaters. Also, to assess the impact of urban air pollution on human health and, in particular, the cancer risk, simulations of emission and dispersion of benzene are carried out. Emissions from road traffic are estimated by the COPERT 4 algorithm, whilst NO_x emission factors from domestic heaters are retrieved by means of criteria provided in the technical literature. Then maps of the annual mean concentrations of NO_x and benzene are calculated using the AUSTAL2000 dispersion model, considering both scenarios representing the current situation, and scenarios simulating the introduction of environmental strategies for air pollution mitigation. The simulations highlight potentially critical situations of human exposure that may not be detected by the conventional network of air quality monitoring stations. The proposed methodology provides a support for air quality policies, such as planning targeted measurement campaigns, re-locating monitoring stations and adopting measures in favour of better air quality in urban planning. In particular, the estimation of the induced cancer risk is an important starting point to conduct zoning analyses and to detect the areas where population is more directly exposed to potential risks for health.

Keywords : AUSTAL2000; NO_x; COPERT 4; street canyon; human exposure; dispersion modelling.

Introduction

In urban areas, the exposure of the resident population to air pollutants is usually higher than in rural contexts. This depends on a combination of intense traffic and other sources of air pollution (e.g., industrial activities, energy production plants, domestic heating), contributing to the emission of a variety of substances, including both primary and secondary pollutants. Among primary pollutants, volatile organic compounds (VOCs) stand out for the toxicological effects that they may induce, as a consequence of long-term exposure via inhalation. In particular, benzene is classified as a carcinogen for humans by the International Agency for Research on Cancer (IARC), and is considered the most hazardous component of the traffic-related pollutants (Angelini et al., 2012). In fact, correlations between long-term exposure to benzene and the development of aplastic anaemia and leukaemia (especially acute myeloid leukaemia) were documented by several epidemiological studies (Baan et al., 2009; Lan et al., 2004). At European and North-American level, traffic-related benzene contributes for more than 80% to the total emissions (EEA, 2007; ATSDR, 2008). Benzene is emitted by evaporation from gasoline vehicles and as a component of the exhaust gas, since benzene is used as additive in gasoline. Secondary contributors to benzene in urban areas are industrial activities (especially petrochemical plants) and automobile refuelling stations.

Typical secondary pollutants are tropospheric ozone (O_3) and nitrogen dioxide (NO_2). The latter is naturally produced by oxidation of nitrogen monoxide (NO). NO_2 is also a precursor of O_3, which is linked to the former by a complex mechanism of chemical reactions. Mobile sources contribute for 40.5% to nitrogen oxides (NO_x) emissions in Europe, followed by energy production (22.5%), commercial, institutional and household activities (12.8%), energy use in industry (12.6%) and other sectors of minor relevance (11.6%) (EEA, 2014). Heating systems based on the combustion of natural gas (NG) are widespread in Europe for production of hot water, either for sanitary purposes or as heating source for dwellings, public buildings and commercial activities. Using NG instead of other fossil fuels entails lower emissions of carbon dioxide and substantial absence of other pollutants, with the exception of NO_x, the second most important compound emitted. Unlike NO (which is a harmless gas at ambient concentrations), NO_2 is known to have detrimental effects on humans, especially on children and people already suffering from lung diseases (Kulkarni and Gridd, 2008).

The compliance with air quality standards is a challenging issue in urban areas, especially where intense road traffic and other additional sources (*e.g.*, domestic heating, industrial or manufacturing activities) combine with unfavourable climatic conditions (e.g., atmospheric stability) and peculiar micrometeorological situations. In particular, wind intensity, air temperature and humidity are modified in an urban environment, compared to rural areas (Landsberg, 1981; Giovannini et al. 2011, 2013, 2014). At an urban scale, the environment induces effects also on rainfall intensity, air quality, formation of fog and hence on liveability of urban areas. In addition, the weak ventilation due to the presence of buildings tends to reduce the dispersion of pollutants, increasing their concentrations, especially during thermal inversion episodes.

The population exposure to air pollutants is then amplified in urban contexts by the lack of open spaces and by the complexity of the urban pattern, including relatively narrow channelled streets, lengthwise delimited by buildings. Stretches of roads displaying these features are called street canyons. If the ratio between the average height of the buildings (H) and the width of the canyon (W) is high enough to establish skimming flow conditions (at least higher than 0.65), the retention of pollutants within the urban canopy layer is amplified (Chan et al., 2001; Oke, 1988). Indeed, the main feature of a street canyon is to further favour the establishment of a strongly local air circulation, consisting in a helical vortex with an axis parallel to the canyon direction. Under these conditions, the transport of pollutants out of the canyon is limited (Britter and Hanna, 2003).

Due to the complex morphology of the urban environment, to the limited dispersion occurring in street canyons and to the presence of fugitive emissions or several point sources, the measurements performed by conventional air quality monitoring stations (which are fixed in one single point) are generally not representative of large areas. For this reason strategic policies for air quality mitigation can be conveniently pre-evaluated by emission and dispersion models, which allow improving the spatial representativeness of the punctual measurements, thus extending the information on ambient air concentrations to a wider area. Several studies, combining air quality monitoring with a modelling approach, focused on the role of urban street canyons in determining critical situations of air pollution (Gallagher et al., 2013; Eeftens et al., 2013; Borge et al., 2014; Dons et al., 2014; Vardoulakis et al., 2007; Schiavon et al., 2014; Murena et al., 2009). However, to the authors' knowledge, the effect of emission sources other than traffic has not been modelled, in spite of the importance of other sectors, and in particular domestic heating, in determining the current air pollution levels.

Given the peculiarity of the urban environment in terms of emission and dispersion of air pollutants, this study aims at investigating the role of the dominant sources of air contaminants and the interaction of air pollutants with the urban morphology, characterized by the presence of street canyons. In particular, this study focuses on the evaluation of NO_x concentrations and on the comparison between the role of traffic and domestic heating, the two major sectors contributing to NO_x emissions. In addition, the cancer risk related to the exposure to benzene is estimated, considering the contribution of road traffic only, since emissions from vehicles are the dominant source in urban environments.

The target area for the present investigation is the city of Verona (Italy), a typical mid-sized urban area (nearly 400,000 inhabitants, including suburban surroundings) located in the Po Plain, which is known as one of the most air-polluted areas in Europe, for a combination of high emission levels and unfavourable meteorological conditions. The climate of the Po Plain and Verona is continental, characterized by cold winters, sultry summers and high relative humidity. Episodes of both ground-based and elevated thermal inversion frequently occur during winter (Andrighetti et al., 2009; Rampanelli and Zardi, 2004). Verona is the crossing of two main corridors, namely the North-South connection between Central Europe and Italy, along the Brenner corridor, and the connection between Eastern and Western areas of northern Italy. As a consequence, it experiences intense traffic flows on a daily basis. Also, traffic from daily commuting between the densely inhabited peri-urban area and the inner city contributes to air pollution.

The methodology adopted to reach the aforementioned goals is based on simulations by means of the emission and dispersion model AUSTAL 2000 (Umwelt Bundesamt, 2009). The present situation was simulated taking into account emissions from road traffic and domestic heating estimated from measured vehicular fluxes and NG consumption and considering the present vehicle fleet and domestic heater technologies. Moreover, additional scenarios were created to simulate the improvements achievable after adopting the latest models of domestic heaters and after introducing limitations to the movement of the vehicles registered before 1996, i.e., not complying with the EURO 2 (European Union, 1994) or newer European emission standards. Indeed, over the last twenty-five years, the European Community has set different emission standards, combining technological advances with the need for reducing the emissions of NO_x, VOC, carbon monoxide

(CO) and particulate matter. The last emission standard (EURO 6) entered into force in 2013 with the EC Regulation 715/2007 (European Union, 2007).

2. Material and methods

2.1 Area of study

The modelling activity focused on a neighbourhood of Verona, named Borgo Roma. To monitor the traffic within the urban area of Verona, a monitoring network was activated by the Municipality in 2009. The transits are detected by inductive loops embedded into the road surface.

Borgo Roma is characterized by high traffic, high population density (>20,000 inh km^{-2}) and presence of many different schools (from kindergartens to high schools). Unlike other areas of Verona, Borgo Roma is not served by the centralized district heating system of the town, which serves different neighbourhoods with a heat network managed by the Azienda Generale Servizi Municipali of Verona (AGSM Verona), a local municipal company. As a consequence, dwellings are heated up either by household hot-water heaters or by one central heater per building. Both heating systems are fuelled with NG. In the absence of a district heating system, NO_x emissions are locally produced, and add to the contribution from road traffic. Two main roads of Borgo Roma can be classified as urban street canyons, namely Via Scuderlando and Via Centro. The combination of canyon-like roads and high traffic fluxes, associated with potentially high release of benzene from road traffic, high population density, high number of scholars (thus, sensitive receptors) and additional local sources of NO_x beyond road traffic, makes Borgo Roma a potentially critical area in terms of impact on human health. An air quality monitoring station measuring NO_x is present within the area of study, along one of the major roads of the neighbourhood (Via San Giacomo). This allowed comparing the results of the simulations with data from measurements. Moreover background concentrations were retrieved by a rural air quality monitoring station, 8-km far from Borgo Roma. Finally benzene concentrations, measured by a station located along an urban road of

Verona (outside Borgo Roma) characterized by intense traffic, were compared with the results from simulations.

2.2 Calculation of the emissions

2.2.1 Estimation of the emissions from road traffic

Emissions emanating from road traffic were estimated from the vehicle fluxes along the road network. Hourly mean fluxes of vehicles typically occurring both in a summer and in a winter week were retrieved. Information on the typical vehicle fleet of Verona was retrieved from the 2012 Italian car census provided by the Automobile Club Italia (ACI).

NO_x and benzene emissions were estimated by using the COPERT 4 algorithm. This tool contains a large database of emission factors for a wide number of classes of vehicles and motorcycles. The calculation of the emission factors (expressed in $g\ km^{-1}\ veh^{-1}$) is mostly based on empirical relations, specific for each vehicle class. In particular, these relations depend on the mean vehicle speed and the annual mean air temperature. The emission factors for NO_x, CO and VOCs are increased by an amount which accounts for the “cold emissions”, since these compounds are removed by the three-way catalysts, which are ineffective at low temperatures (Ntziachristos and Samaras, 2000). VOC speciation is also available (EEA, 2013), so that emissions of benzene can be easily calculated.

Hourly average emissions of NO_x and benzene (expressed in $g\ s^{-1}$) along each stretch of road were calculated on the basis of the hourly vehicle fluxes, the length of the stretch, the composition of the vehicle fleet and the emission factors provided by COPERT 4. A mean driving speed of 40 $km\ h^{-1}$ and an annual mean temperature of 15°C were assumed for the calculation.

Simulations considering a scenario without the movement of pre-EURO 2 vehicles were also performed, to investigate the effects of environmental policies including restrictions to the circulation of highly polluting vehicles. Indeed, several municipalities in Northern Italy have adopted such restrictions to improve air quality. Therefore, in this additional scenario, NO_x and benzene emissions were calculated only for vehicles satisfying at least EURO 2 requirements.

2.2.2 Estimation of the emissions from domestic heating

Detailed data on the consumption of NG and on the technologies of heaters of every building in the study area were provided by AGSM Verona. Beside NG consumption for cooking, which was assumed to be negligible with respect to the total consumption, NG is used both for domestic heating and to produce hot water for sanitary use. However, the use of NG for domestic heating in Verona is restricted to the period 15 October – 15 April, and for a maximum number of 14 hours per day. On the other hand, hot-water heaters operate during the whole year, even though with large differences in the consumption between winter and summer: the ratio between the mean NG consumption in summer and in winter is about 0.1. Furthermore, on the basis of the available data, the mean NG consumption can be sub-divided into three modulations, approximating the monthly, the daily and the hourly consumption normalized to the annual, the monthly and the daily averages, respectively. Finally, in the target area of the present study, buildings can be divided into three main categories: residential buildings, school buildings and commercial activities or offices. Given these considerations, three different sets of modulations can be assumed (Table 1).

In order to evaluate the rate of conversion of NG into air pollutants, the working conditions of the most diffused heating plants were taken into account in some detail. In fact, the NG-fuelled household heaters in use in Italy belong to three main categories: conventional, pre-mixed and condensing boilers. In conventional boilers, air and NG are mixed in the combustion chamber and hot water is supplied at constant temperature, with low efficiency if the thermal load is lower than the nominal one; in pre-mixed boilers, NO_x emissions are lower, thanks to the pre-mixing of air and NG that allows obtaining a homogeneous flame, lowering the generation of NO_x; condensing boilers allow for even lower NO_x emissions and for a higher efficiency, since they recover the latent heat of vaporization of the water produced in the combustion process by condensing the water vapour to liquid. In assigning NO_x emission factors, household heaters were evaluated separately from central heaters (*i.e.*, a single heater serving all the flats of a building). Central heaters can be further divided into three main categories as well, i.e., conventional, condensing and modulating boilers. The latter allow controlling the water temperature, avoiding energy waste and reducing emissions.

Table 1: Modulations of NG consumption, approximating the monthly, the daily and the hourly consumption normalized to the annual, the monthly and the daily one, respectively.

Type of building	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Residential	0.188	0.188	0.094	0.075	0.022	0.022	0.022	0.011	0.022	0.075	0.094	0.188
School	0.188	0.188	0.094	0.075	0.033	0.033	0.000	0.000	0.033	0.075	0.094	0.188
Commercial	0.166	0.139	0111	0.083	0.056	0.028	0.028	0.000	0.056	0.083	0.111	0.139

Type of building	Day						
	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Residential	0.033	0.033	0.033	0.033	0.033	0.033	0.033
School	0.042	0.042	0.042	0.042	0.042	0.042	0.000
Commercial	0.051	0.051	0.051	0.051	0.026	0.000	0.000

Type of building	Hour																							
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Residential	0.000	0.000	0.000	0.000	0.000	0.077	0.077	0.077	0.077	0.000	0.000	0.077	0.077	0.000	0.000	0.000	0.077	0.077	0.077	0.077	0.077	0.077	0.077	0.000
School	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.000	0.000	0.000	0.000	0.000	0.000
Commercial	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.125	0.125	0.125	0.125	0.000	0.000	0.125	0.125	0.125	0.125	0.000	0.000	0.000	0.000	0.000	0.000	0.000

The typical NO_x emission factors for household and central heaters available on the Italian market are listed in Table 2, on the basis of their type. The same emission factors were adopted in the calculation of emissions. The hourly NO_x emissions for each source were calculated by assuming of NG provided by AGSM Verona, equal to 35.6 MJ Nm^{-3}.

Table 2: NO_x emission factors adopted for household heaters and central heaters.

Size	Technology	NO_x emission factor [g GJ^{-1}]	Reference
Household heaters	Conventional boilers	50	EEA, 2013
	Condensing boilers	15	Bassi et al., 2005
	Pre-mixed boilers	17	Bassi et al., 2005
Central heaters	Conventional boilers	37	Bassi et al., 2005
	Condensing boilers	7	Bassi et al., 2005
	Modulating boilers	42	Bassi et al., 2005

Besides the scenario representing the current situation, an additional scenario was created to simulate the improvements achievable if all the hot-water heaters were condensing boilers.

2.3 Dispersion model

For the simulations of NO_x and benzene dispersion, the model AUSTAL2000 was adopted. AUSTAL2000 is a Lagrangian Particle Model which computes the transport of pollutants in the lower atmosphere at a local scale. AUSTAL2000 is able to take into account both horizontally and vertically variable meteorological and turbulence fields. The vector of turbulent velocity is randomly varied by simulating a Markov process (i.e., a stochastic process whose outcomes are finite and depend on the outcome of the previous stage) and the random parameters vary with the intensity of turbulence. The concentration is then computed by counting the particles in a given volume. AUSTAL2000 contains a diagnostic (mass-consistent) flow model called TalDIA; this module works on profiles of wind and classes of atmospheric stability to perform an economical calculation of the wind flow fields. TalDIA can take into account both orographic complexity and building effects, through the superposition of an unperturbed uniform flow field with one affected by obstacles (Umwelt Bundesamt, 2009). Taking advantage of this capability of the model, in this study the geometry of buildings was explicitly defined. Indeed, when zooming to the urban-canyon scale, the problem of considering explicitly the urban geometry is mandatory to adequately resolve local microclimatic conditions and, as a consequence, the heterogeneities in the spatial distribution of pollutants (Burian et al., 2006). In fact, in these complex cases, specific processes occur (Rotach and Zardi, 2007; Giovannini et al., 2011; Giovannini et al., 2013; Giovannini et al., 2014) that modify local circulations and turbulence mixing in the atmospheric boundary layer (de Franceschi et al., 2009), making the treatment of air pollution more complicated (Antonacci and Tubino, 2005; Gohm et al., 2009; de Franceschi and Zardi, 2009; Rada et al. 2011; Ragazzi et al. 2013).

The computation domain used in this study is a rectangular area of 720 x 1035 m^2, including Via Centro and the most canyon-like part of Via Scuderlando, in addition to other important streets of the area (Fig. 1a). A cell size of 5 m x 5 m was chosen to represent the situation inside street canyons. The map containing the heights of the buildings was generated with the same resolution. Data on wind speed, wind direction and atmospheric stability classes were retrieved from a meteorological station managed by the local Environmental Agency (ARPAV) and located near the area of study. The meteorological data refer to the whole year 2012, to be consistent with the data on the vehicle fleet. The reference meteorological station, actually located outside of the two domains, was fictitiously re-located inside the smaller computation areas, north to the buildings, since the model requires the position of the anemometer inside the domain. Since the terrain around the buildings included in the calculation is flat, this shift from the real position to a fictitious location does not influence the calculation of the wind field inside the area covered by the building map. Street emissions were assimilated to line sources, whilst domestic hot-water heaters were represented by point sources. With regards to roads, the height of the emission source was set to 0.5 m above the ground and a vertical extension of the source (varying between 1.0 m for street canyons and 0.5 m for the remaining roads) was set to simulate the mechanical turbulence production by vehicle motions, which influences the pollutant dispersion at the source level. With regards to hot-water heaters, the source height was set equal to the height of the top of the chimneys, that is 0.5 m above the roof, in compliance with the Italian technical regulation No. 7129 of the Ente Italiano di Unificazione – Comitato Italiano Gas (UNI-CIG 7129) (Ente Italiano di Unificazione, 2008). In the absence of mechanically produced turbulence, the vertical extension of the source was set at 0.05 m, corresponding to the lateral opening of the chimneys. The emission points representing the chimneys of the buildings and the details of the hot-water heaters, classified by technology and size (household or central heaters) are reported in Fig. 1b.

Fig. 1: *a)* Area of study with representation of the computation domain and *b)* detail of the emission points representing the hot-water heaters.

Outside the area covered by buildings, the surface roughness was set to 0.9 m: as Borgo Roma is characterized by a very heterogeneous land use, this is an average roughness length between the value suggested in the CORINE maps for continuous coverage of buildings (1.0 m) and for areas with commercial and manufacturing activities (0.8 m) (Silva et al., 2007).

2.4 Cancer risk estimation

Since benzene is a carcinogenic pollutant, the estimation of the inhalation cancer risk related to the exposure to benzene was performed. The calculation is based on the concept of Inhalation Unit Risk (IUR), defined by the U.S. Environmental Protection Agency (U.S. EPA) as the upper-bound excess lifetime cancer risk derived from continuous exposure to 1 µg m^{-3} of a carcinogenic compound in air (U.S. EPA, 2014). This approach is adopted in order to obtain preliminary information on this potential criticality. The IUR proposed for benzene is 2.9E-05 (U.S. EPA, 2012). Thus, the annual mean concentrations of benzene were multiplied by the IUR.

3.Results and discussion

This section presents the results of the dispersion calculations, which consist in the maps of the annual mean concentrations of NO_x (emitted by road traffic and domestic heating) and benzene (emitted only by road traffic).

3.1 NO_x concentrations

3.1.1 Contribution from road traffic

The highest value of NO_x concentrations induced by road traffic is 61.9 µg m^{-3} and occurs near the junction between the two street canyons (Fig. 2a). This may be explained by considering that these joining canyons are one-way streets and, in the proximity of their junction, the circulation becomes two-way. It is significant to note that slightly lower NO_x levels also occur inside Via Centro with a maximum of 58.5 µg m^{-3}. Indeed, next to this point the canyon width is minimum (10 m), and the buildings display an average height of 10.5 m. It is important to notice that a kindergarten is located near this point. Thus, this concentration level is of great relevance from the toxicological point of view. Lower concentrations occur within Via Scuderlando, although a value of 48.2 µg m^{-3} is observed in the northern stretch of the canyon due to a *H* to *W* ratio higher than 1, and to the two-way traffic occurring there.

The current situation improves in the scenario forbidding the most polluting vehicles (pre-EURO 1 and EURO 1) to circulate (Fig. 2b). On average, the NO_x mean annual concentrations are about 13% lower than with the whole vehicle fleet. Like in the previous case, the highest value occurs at the junction between the two canyons (54.6 μg m^{-3}). A concentration of 51.6 μg m^{-3} is achieved in proximity of the bottleneck of Via Centro.

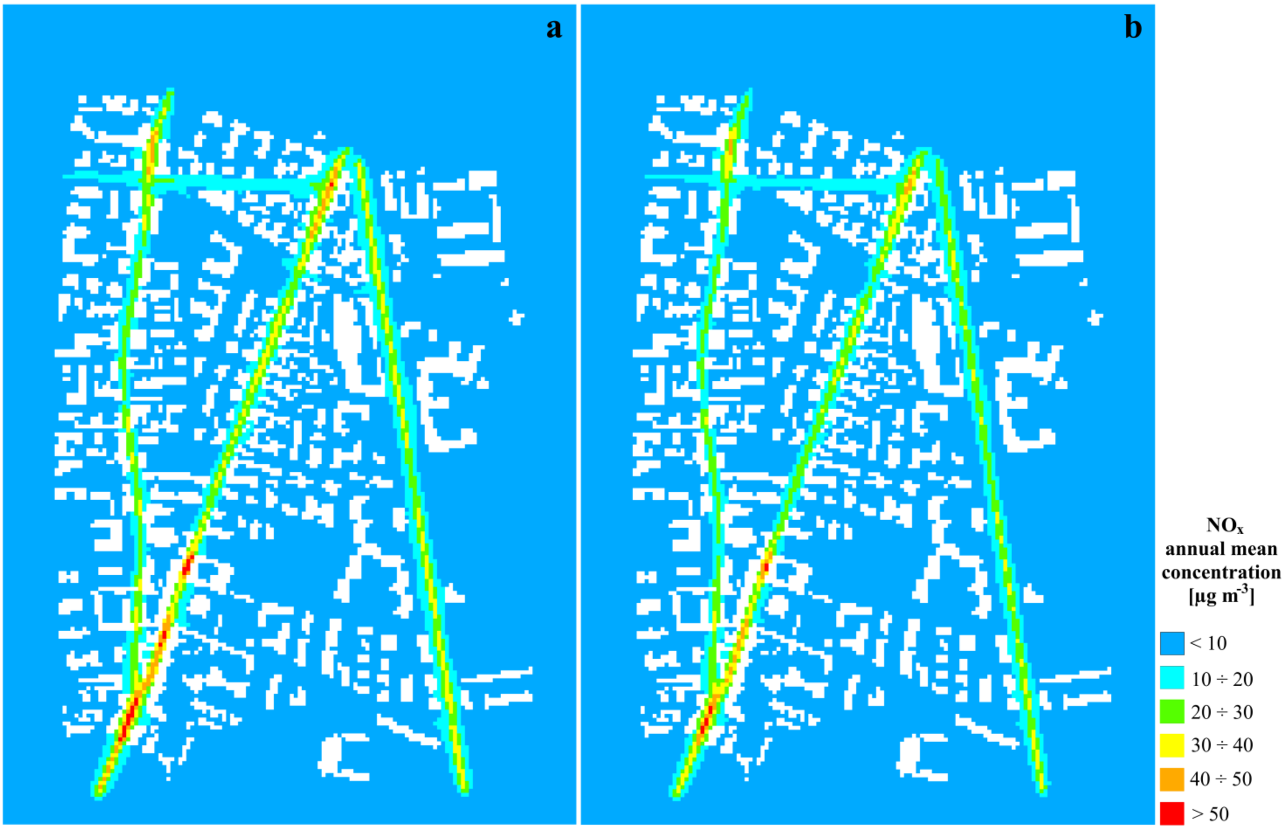

Fig. 2: Maps of the NO_x annual mean concentrations induced *a)* by the whole vehicle fleet and *b)* only by the EURO 2 and latest vehicles; hereinafter, for the colour version of figures, the reader is advised to refer to the on-line version of this article.

3.1.2 Contribution from domestic heating

Inside street canyons, NO_x annual mean concentrations induced by hot-water heaters represent about 25% of the NO_x annual mean concentrations induced by road traffic (Fig. 3a). The contribution of domestic heating is generally higher away from roads, where the impact of the emissions from road traffic is less important. However, the highest NO_x annual mean concentration (14.4 µg m^{-3}) occurs in the proximity of a building close to Via Scuderlando. Concentrations up to 13.7 µg m^{-3} occur in a courtyard of a building near Via San Giacomo. As the chimneys are located close to the limit of the urban canopy layer, and not inside the street canyons, their contribution also affects background areas. Since the concentration maps are calculated on an annual basis, the contribution from domestic heating is expected to be much more influential during winter, when much higher NO_x concentrations are consequently foreseen.

Appreciable improvements could be obtained by adopting more efficient (and less polluting) hot-water heaters, such as condensing boilers (Fig. 3b). In this case, the highest NO_x annual mean concentration reduces to 4.9 µg m^{-3}, which is achieved in a courtyard surrounded by buildings, in the proximity of Via Scuderlando.

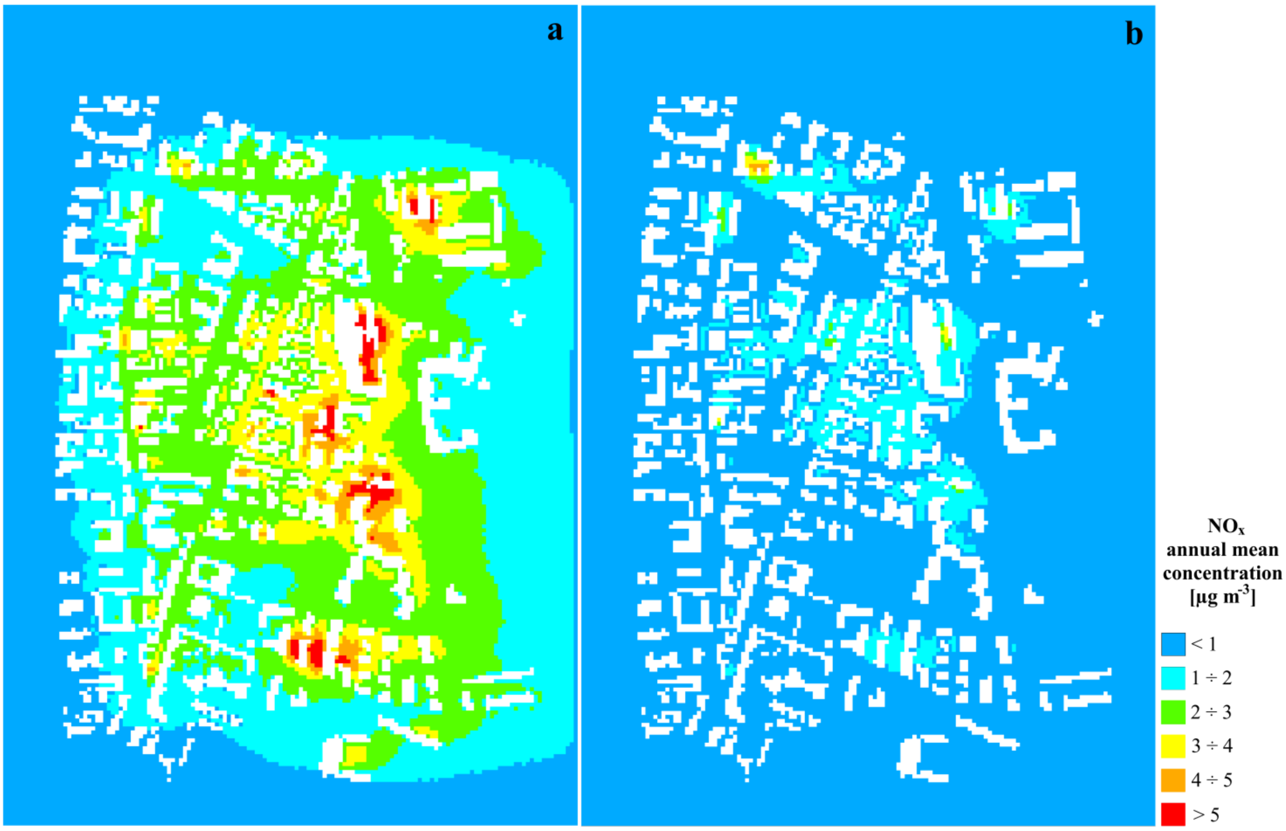

Fig. 3: Maps of the NO_x annual mean concentrations *a)* induced by the current hot-water heaters and *b)* in the hypothesis of replacing the current hot-water heaters with condensing boilers.

3.1.3 Joint contribution of road traffic, domestic heating and background

The NO_x annual mean concentrations induced by road traffic and domestic heating were finally added up to the NO_x annual mean concentration measured by the rural air quality station (54.4 μg m^{-3}). The highest NO_x annual mean concentration (117.8 μg m^{-3}) still occurs at the junction between the two street canyons (Fig. 4a). Concentrations up to 115.3 μg m^{-3} occur at the bottleneck of Via Centro, about 50 m from the kindergarten.

Important improvements could be achieved by introducing restrictions to the circulation of the most polluting vehicles (pre-EURO 1 and EURO 1) and, at the same time, adopting more efficient (and less polluting) hot-water heaters, such as condensing boilers (Fig. 4b). In this case, the highest total NO_x mean concentration, on an annual basis, is 109.4 μg m^{-3}, still located at the junction between the two street canyons. Concentrations lower than 107.0 μg m^{-3} are achieved everywhere else. Inside street canyons, a 10% reduction of NO_x annual mean concentrations is estimated.

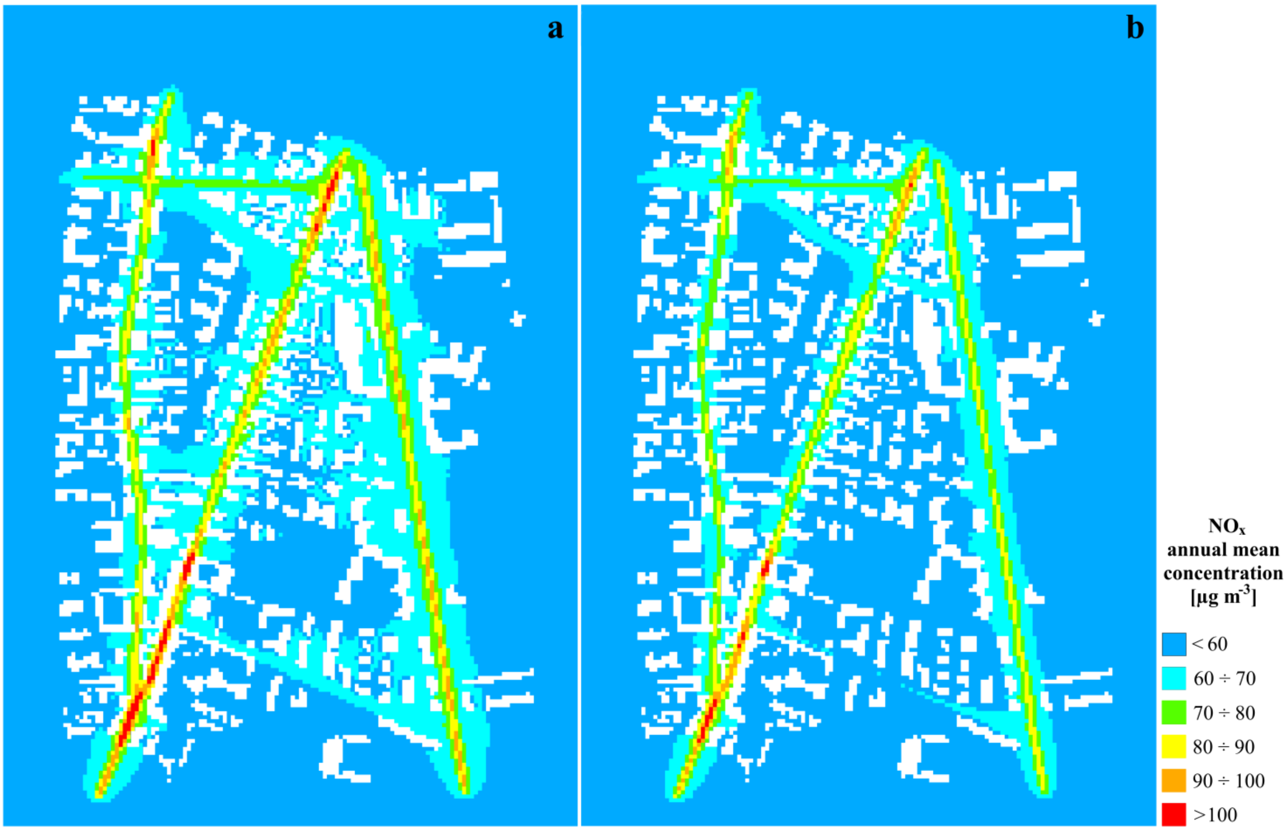

Fig. 4: Maps of the NO_x annual mean concentrations *a)* induced by the whole vehicle fleet together with the current hot-water heaters in use and *b)* in the hypothesis of allowing the circulation only to EURO 2 and newer vehicles and replacing the current hot-water heaters with condensing boilers.

3.1.4 Validation of the results

Model results were validated by comparing the NO_x hourly measurements taken at the urban air quality station in via San Giacomo with the NO_x hourly concentrations obtained as the sum of model results (in the present situation at the receptor point corresponding to the urban air quality station) and the hourly concentrations measured by the rural air quality station. The annual mean concentration calculated by the model is 69.8 μg m^{-3}; the 25th, 50th, 75th and 95th percentiles of the hourly concentrations are 30.8, 51.7, 83.9 and 193.1 μg m^{-3}, respectively. The annual mean concentration measured at the same location by the urban air quality station during 2012 is 111.0 μg m^{-3} and the 25th, 50th, 75th and 95th percentiles are 32.0, 62.0, 148.0 and 363.0 μg m^{-3}, respectively. As a result, on an annual basis, the mean concentration calculated by the model is about 35% lower than the mean concentration measured by the reference station. The lowest percentiles (25th and 50th), calculated by the model, are in good agreement with those measured, but the highest percentiles (75th and 95th) are considerably lower with respect to the corresponding statistics calculated from the measurements. This may be due to emission peaks (*e.g.*, traffic congestions or simply higher traffic fluxes) occurring during periods of the year not covered by the traffic data used in this study. Such situations could be adequately considered by coupling the meteorological data with hourly traffic data covering the whole solar year. However, it is worth reminding that other sources (*e.g.*, energy production and distribution, industrial activities, agriculture, non-road transport) may contribute to NO_x concentrations, but their role was not included in this study due to the difficulties in localizing all the sources, retrieving their emission factors and modelling the respective emissions. NO_x concentrations were also measured by 40 passive samplers distributed in the urban area of Verona during the ESCAPE Project (Cyrys et al., 2012), although the locations of the samplers are not published. On average, the 25th, the 50th and the 75th percentiles of the concentration values collected are 61.0, 83.0 and 110.6 μg m^{-3}, respectively (Cyrys et al., 2012).

3.2 Benzene concentrations and cancer risk estimation

The annual mean benzene concentrations emanating from the whole vehicle fleet exceed the limit value (5 μg m^{-3}) at the junction between the two street canyons (maximal value of 6.7 μg m^{-3}), in the southern end of Via Centro (maximal value of 5.7 μg m^{-3}), at the bottleneck of Via Centro (6.4 μg m^{-3}), at the northern end of the same street (5.8 μg m^{-3}) and in the canyon-like part of Via Scuderlando (5.3 μg m^{-3}) (Fig. 5a). When restricting the movement of pre-EURO 1 and EURO 1 vehicles, the annual mean benzene concentrations were within the stipulated European air quality standards (Fig. 5b). Benzene concentrations induced by EURO 2 and newer vehicles in the street canyons are about 43% lower than the concentrations induced by the whole vehicle fleet. The effect of the more and more restrictive limits on hydrocarbons, imposed by these emission standards, is clearly visible.

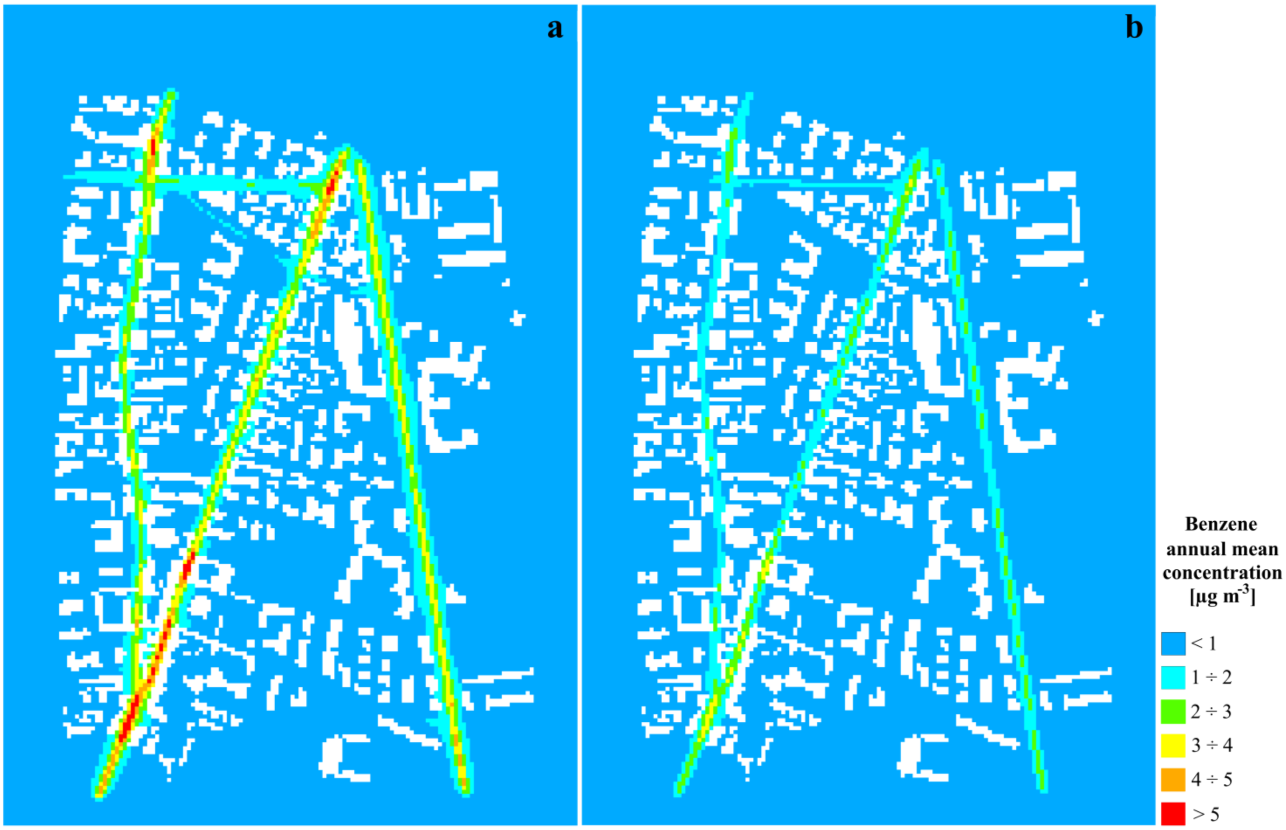

Fig. 5: Maps of the benzene annual mean concentrations induced *a)* by the whole vehicle fleet and *b)* only by the EURO 2 and latest vehicles.

The annual mean concentration measured during 2012 by the urban air quality station taken as reference for benzene was 1.81 µg m^{-3}. This value is similar to the annual mean concentration calculated in proximity of the kindergarten and considering the whole vehicle fleet. The 25th, 50th, 75th and 95th percentiles of the series measured are 0.8, 1.5, 2.7 and 4.4 µg m^{-3}, respectively, and the maximum value is 5.9 µg m^{-3}. These values are also comparable with the concentrations calculated by AUSTAL2000 (25th percentile: 1.1 µg m^{-3}; 50th percentile: 1.6 µg m^{-3}; 75th percentile: 2.1 µg m^{-}

^{3}; 95th percentile: 2.7 µg m^{-3}; maximum: 3.4 µg m^{-3}). Slightly lower concentrations were calculated in proximity of the air quality station of Via San Giacomo. Due to the absence of rural stations measuring benzene, no background concentrations were considered. This lack of information impedes considering potential contributions coming from sources located outside the domain. The difference between the 95th percentiles of the hourly concentrations measured at the reference urban air quality station and of the hourly concentrations calculated by AUSTAL2000 in the vicinity of the kindergarten of Via Centro might be explained also with the presence of fugitive emissions, in addition to the background concentrations that were not possible to estimate in this study.

The related maps of the cancer risk induced by continuous and long-term exposure to benzene are presented in Fig. 6a, when considering the whole vehicle fleet. It is important to remind that such maps report only the benzene-related cancer risk induced by road traffic. In the area of study, contributions from other sectors are secondary, since other potential sources of benzene like industrial activities are not located inside the domain. Since the inhalation cancer risk is proportional to the concentration, the highest value (1.95E-04) occurs at the junction between the two street canyons, while a slightly lower risk value (1.85E-04) was calculated in proximity of the kindergarten of Via Centro. These results should raise the attention of municipal authorities with regards to traffic management and urban planning, since situations of exposure that are normally underestimated may result in potentially dangerous consequences on human health. Given that the acceptable cancer risk proposed by the U.S. EPA is between 1E-06 and 1E-04 (U.S. EPA, 1989), the southern and northern ends of Via Centro, the northern part of Via Scuderlando and the junction of the two canyons would imply a cancer risk exceeding this acceptability range. When restricting the movement of pre-EURO 1 and EURO 1 vehicles, the cancer risk is reduced by about 43% in street canyons, reaching 1.12E-04 at the junction between the two street canyons and 1.05E-04 in proximity of the kindergarten of Via Centro (Fig. 6b). With the exception of these two cases, the cancer risk is everywhere lower than the upper acceptability limit.

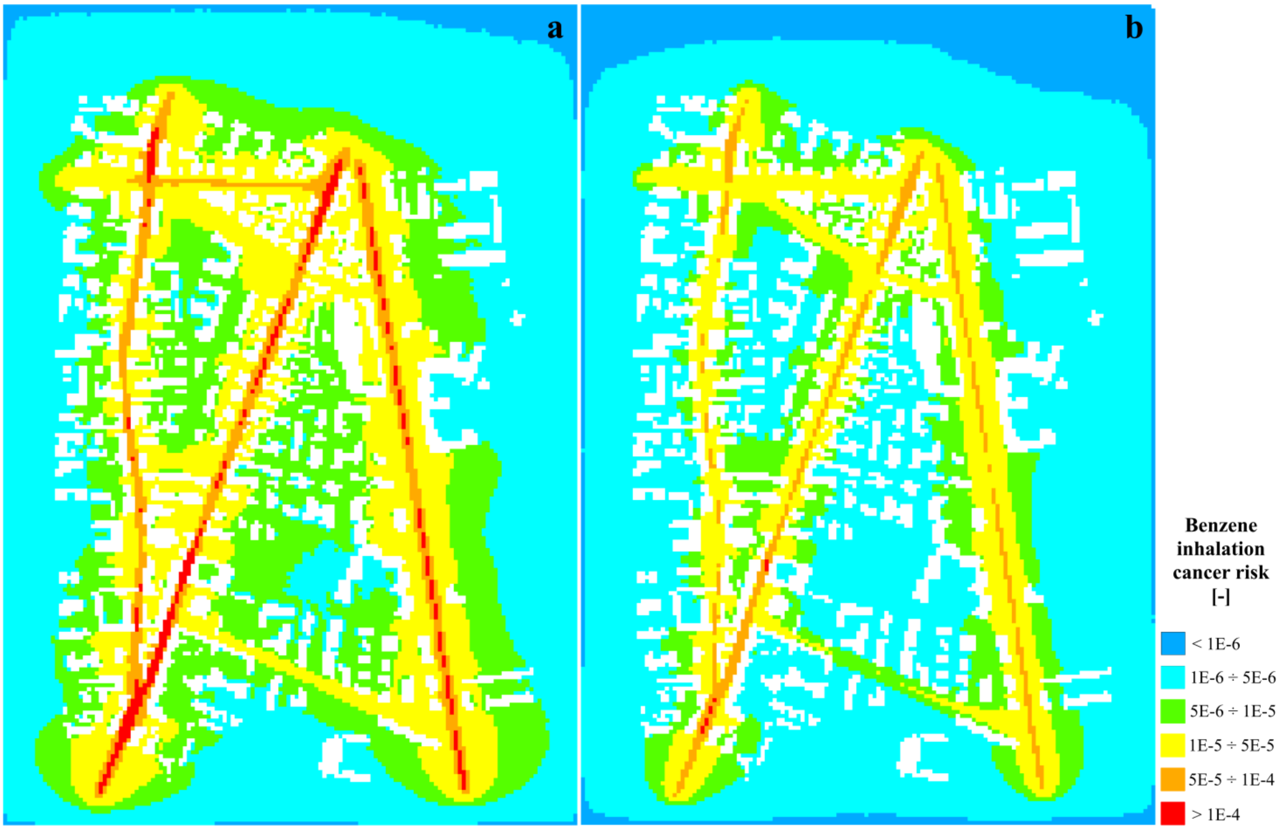

Fig. 6: Maps of the cancer risk related to lifelong exposure to benzene concentrations induced *a)* by the whole vehicle fleet and *b)* only by the EURO 2 and latest vehicles.

Conclusions

The air quality simulations carried out over an urban area of Verona, characterized by street canyons and typical urban emission sources (road traffic and domestic heating), highlighted potentially critical situations of human exposure that may not be detected by the conventional network of air quality monitoring stations. As a matter of novelty, in addition to road traffic, the contribution of domestic heating in terms of NO_x was also considered, since this sector plays an important role in the emissive framework of urban areas. However, in spite of the effort of considering an additional sector, the annual mean concentration calculated by the model is about 35% lower than that measured by the reference air quality station. This may be due to missing contributions from industrial activities in the peripheral areas and/or to stronger dispersion computed in the proximity of the measuring point.

The air quality scenarios considering restrictions to the most polluting vehicles and the adoption of enhanced hot-water heaters showed the improvements expectable from good examples of environmental policies, although the weak dispersion occurring within street canyons limits the decrease in pollutants concentration that would be expected in open areas.

In spite of being based on unavoidable approximations, the estimation of the benzene-related cancer risk gives an overview of the criticalities expected in urban street canyons and, in general, in the urban environment, where road traffic represents the dominant source of benzene. The methodology here applied provides a basis for air quality management policies, such as planning air quality monitoring campaigns, re-locating air quality stations and supporting decisions on urban planning. The latter would be especially important for the location of particularly sensitive communities, such as hospitals or schools: locating sensitive buildings far from emission sources and street canyons or in open spaces would allow reducing the risk for health. To this regard the concept of exposure is of great interest, especially due to the fact that the current European legislation does not consider the proximity between emission sources and settled population. The estimation of the induced cancer risk is an important starting point to conduct zoning analyses and to detect the areas where population is directly exposed to potential health risks.

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