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Development of land-use regression models for exposure assessment to ultrafine particles in Rome, Italy

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HIGHLIGHTS

- PNCs were measured directly outside 28 homes for three weeks in different seasons.
- LUR models were developed using standard and enhanced GIS-derived predictor variables.
- Traffic intensity, population density and urban green were the main predictors of UFP.
- Building and street configuration variables improved LUR model performance.
- PNC exposure at a fine spatial resolution was successfully assessed.

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ABSTRACT

The health effects of long-term exposure to ultrafine particles (UFPs) are poorly understood. Data on spatial contrasts in ambient ultrafine particles (UFPs) concentrations are needed with fine resolution. This study aimed to assess the spatial variability of total particle number concentrations (PNC, a proxy for UFPs) in the city of Rome, Italy, using land use regression (LUR) models, and the correspondent exposure of population here living. PNC were measured using condensation particle counters at the building facade of 28 homes throughout the city. Three 7-day monitoring periods were carried out during cold, warm and intermediate seasons. Geographic Information System predictor variables, with buffers of varying size, were evaluated to model spatial variations of PNC. A stepwise forward selection procedure was used to develop a "base" linear regression model according to the European Study of Cohorts for Air Pollution Effects project methodology. Other variables were then included in more enhanced models and their capability of improving model performance was evaluated. Four LUR models were developed. Local variation in UFPs in the study area can be largely explained by the ratio of traffic intensity and distance to the nearest major road. The best model (adjusted $R^2 = 0.71$; root mean square error $= \pm 1{,}572$ particles/

Abbreviation: LUR, Land Use Regression; UFP, UltraFine Particles; PNC, Particle Number Concentration (particles/cm^3); ESCAPE, European Study of Cohorts for Air Pollution Effects; NOx, nitrogen oxides; CORINE, COoRdination of INformation on the Environment land cover project; LAI, Leaf Area Index; AMS, Atmospheric Modelling System; CTM, Chemical Transport Model; NDVI, Normalised Difference Vegetation Index; VIF, Variation Inflation Index; LOOCV, Leave One Out Cross Validation.

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cm^3, leave one out cross validated $R^2 = 0.68$) was achieved by regressing building and street configuration variables against residual from the "base" model, which added 3% more to the total variance explained. Urban green and population density in a 5,000 m buffer around each home were also relevant predictors. The spatial contrast in ambient PNC across the large conurbation of Rome, was successfully assessed. The average exposure of subjects living in the study area was 16,006 particles/cm^3 (SD 2165 particles/cm^3, range: 11,075–28,632 particles/cm^3). A total of 203,886 subjects (16%) lives in Rome within 50 m from a high traffic road and they experience the highest exposure levels (18,229 particles/cm^3). The results will be used to estimate the long-term health effects of ultrafine particle exposure of participants in Rome.

1. Introduction

Epidemiological studies aimed to assess the relationships between particle exposure (mainly PM_{10} and $PM_{2.5}$) and health outcomes have been extensively carried out over the last two decades. PM exposure has been widely recognized to have an effect on cardiopulmonary diseases, lung cancer and premature mortality (Rückerl et al., 2011; Shah et al., 2013; Götschi et al., 2008; Guarnieri and Balmes, 2014; Pope and Dockery, 2006; IARC, 2013; Hamra et al., 2014).

Airborne particles ranging from 2 nm to 100 μm can be inhaled, and depending on their size and solubility, they can penetrate beyond the larynx to the airways and can reach deeper into the lungs. Although ultrafine particles (UFPs, 100 nm or less in diameter) contribute little to the mass of PM, given their small size, they are the dominant contributors to particle number. Concentrations of particles in different sizes (i.e. ultrafine, fine and coarse) can show little correlation due to their different sources and relevant formation mechanisms. Thus, particle mass reveals limited information about particle number and vice versa. The main sources of ambient UFPs in urban areas are combustion related emissions, mainly from vehicle exhaust, especially from diesel-powered engines (Morawska et al., 2008). Several processes affect particle number concentration: gas to particle conversion, coagulation, condensation, dilution and/or mixing, dry deposition, evaporation, nucleation and photochemical processes (Kumar et al., 2010; Kulmala et al., 2004; Holmes, 2007).

Because of the scientific interest on the toxicological properties of ultrafine particles (Seaton et al., 1995), several studies have been carried out to assess their spatial and temporal variability across urban, suburban, rural and remote locations at one or a few measuring sites (Aalto et al., 2005; Kumar et al., 2010, 2014). The short term health effects of exposure to UFPs have been studied using the total Particles Number Concentration metric (PNC) as a proxy for UFPs concentration (Belleudi et al., 2010; Von Klot et al., 2002; Andersen et al., 2008; Song et al., 2011).

Few epidemiological studies about long-term exposures to ambient UFPs have been carried out, mainly due to the lack of data on spatial contrasts in UFP concentrations (Ostro et al., 2015). Since ultrafine monitoring networks are lacking, ad hoc measurements are needed to fill the knowledge gap. The limited information available shows great spatial variability across urban settings, resulting in possible different exposure patterns among residents in the same urban context (Kumar et al., 2014; Klompmaker et al., 2015). Only recently have reliable emission inventories of particle numbers been compiled for several European cities, allowing to estimate the dispersion of PNCs via a deterministic approach (Kukkonen et al., 2016).

A few studies have attempted to assess PNCs spatial variability through empirical models such as land use regression (LUR) modelling. These studies, carried out in Amsterdam (Hoek et al., 2011), Girona (Spain) (Rivera et al., 2012), Vancouer (Abernethy et al., 2013), New Delhi (Saraswat et al., 2013), Toronto (Sabaliauskas et al., 2015; Weichenthal et al., 2016a), Montreal (Weichenthal et al., 2016b), Switzerland (Eeftens et al., 2016) and Augsburg (Wolf et al., 2017) have shown that LUR models can be effective tools for assessing high resolution within-city variability of UFPs. LUR models have not yet been developed in any large Mediterranean city, where the pattern of concentrations variability, due to the climate, is completely different from those of previously published studies.

The main objective of this study was to estimate UFPs spatial patterns in the city of Rome (Italy), using the ESCAPE (European Study of Cohorts for Air Pollution Effects) LUR modelling approach (Eeftens et al., 2012; Beelen et al., 2013), and to assess population exposure. Moreover, we aimed to evaluate the usefulness of variables other than those used in ESCAPE, in order to improve the model's performance.

2. Material and methods

2.1. Study area

Rome is the largest Italian city, with 2.9 million inhabitants in a 1,285 km^2 area. It is one of the largest European cities, with severe problem of traffic and pollution (Renzi et al., 2017).

The main sources of particles are road vehicles exhaust and small-scale combustion units (thermal capacity < 50 MWth) used in the civil sector for heating, while emission from industries is relatively low (ISPRA, 2009).

The warm months of June to September are characterized by large-scale high-pressure systems. During daytime hours convective mixing of the lower atmosphere occurs and dissipates the inversion layer; the mixing period starts very early in the morning and lasts until the late evening. Prevailing winds comes from the SW (sea breeze). During a typical night, the atmosphere restabilizes, and low winds from the north prevail. The cold months (November–March) are characterized by moderately low temperatures, with prevailing north winds. Periodically, high pressure systems produce temperature inversions, weak winds, and poor dispersion conditions leading to stagnation, which is associated with pollutant accumulation in the lower layers of the atmosphere.

From 2001 to 2010, PNC has been continuously measured in a single traffic oriented site, within the framework of the HEAPPS study (Aalto et al., 2005; Marconi et al., 2007). The decreasing trend of PNC and primary gaseous pollutants observed over the last decade was due to more stringent vehicle emission standards (Euro III and Euro IV, Directive 98/69/EC, 2002/80/EC, 2002/51/EC, 2002/80/EC, 2006/120/EC), a reduction of sulphur content in both diesel and petrol fuels, the banning of coal, combustible oil and other solid fossil fuels for non industrial combustion plants (Cattani et al., 2010).