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Improving the prediction of air pollution peak episodes generated by urban transport networks

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ABSTRACT

This paper illustrates the early results of ongoing research developing novel methods to analyse and simulate the relationship between trasport-related air pollutant concentrations and easily accessible explanatory variables. The final scope is to integrate the new models in traditional traffic management support systems for a sustainable mobility of road vehicles in urban areas.

This first stage concerns the relationship between the hourly mean concentration of nitrogen dioxide (NO_2) and explanatory factors reflecting the NO_2 mean level one hour back, along with traffic and weather conditions. Particular attention is given to the prediction of pollution peaks, defined as exceedances of normative concentration limits. Two model frameworks are explored: the Artificial Neural Network approach and the ARIMAX model. Furthermore, the benefit of a synergic use of both models for air quality forecasting is investigated.

The analysis of findings points out that the prediction of extreme concentrations is best performed by integrating the two models into an ensemble. The neural network is outperformed by the ARIMAX model in foreseeing peaks, but gives a more realistic representation of the concentration's dependency upon wind characteristics. So, the Neural Network can be exploited to highlight the involved functional forms and improve the ARIMAX model specification. In the end, the study shows that the ability to forecast exceedances of legal pollution limits can be enhanced by requiring traffic management actions when the predicted concentration exceeds a lower threshold than the normative one.

1. Research context and problem definition

Air pollution in urban areas is mainly due to the intense use of motorized transport for travelling, in particular private cars and heavy goods vehicles. This is a priority issue for transportation planners and public authorities, given the harmful effects of pollution to human health and the environment (Migliore et al., 2012; Bergantino et al., 2013).

Numerous studies (Heinrich et al., 2005; Zhang et al., 2012a) argue that acute exposure to air pollutants may cause serious health concerns such as eye irritation, breathing difficulty, cardio-vascular problems, while chronic exposure may lead to damage to the body's immune, neurological, reproductive and respiratory systems, cancer and even premature death. In November 2014, the British Committee on the Medical Effects of Air Pollutants reported that air pollution may be responsible for as many as 60,000 early deaths in Britain each year. This follows the study presented in 2010 by the World Health Organization (WHO) Regional Office for Europe and the Organization for Economic Co-operation and Development (OECD), covering the whole European region, including non-EU states such as Norway and Switzerland. For this macro-area, 600,000 premature deaths each year are estimated as a consequence of air pollution from small particles (produced by the exhausts of diesel vehicles) and nitrogen dioxide, NO_2 (WHO, 2010). Also the environment is affected in terms of global climate change and adverse effects for plants and eco-systems (Seinfeld and Pandis, 2006; Zhang et al., 2012a).

Various national contexts throughout the world have issued guidelines and regulations to protect human health and the environment. The United States Environmental Protection Agency (EPA) has set national air quality standards for six pollutants:

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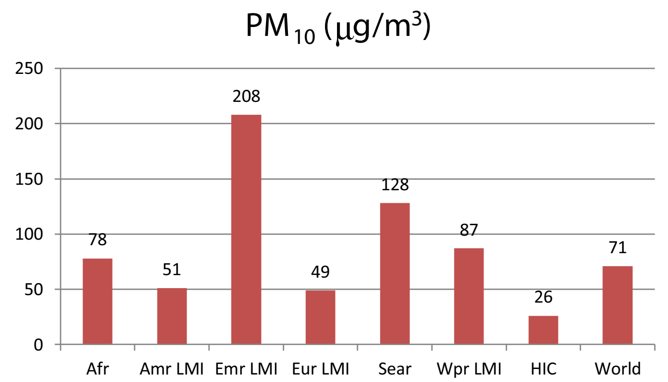

Fig. 1. PM_{10} levels by region, for the last available year in the period 2008-2012 (WHO, 2014). Afr: Africa, Amr: America, Emr: Eastern Mediterranean, LMI: Low and middle-income, Sear: South-East Asia, Wpr: Western Pacific, HIC: high-income countries.

sulphur dioxide (SO_2), NO_2, carbon monoxide (CO), ozone (O_3), lead (Pb) and particulate matter (Seinfeld and Pandis, 2006). In Europe, over the last decades, the European Union (EU) has adopted a range of environmental measures to improve the quality of life for the Community's citizens. The final step of this legislative process is the Directive 2008/50/EC (EU, 2008), which has integrated an extensive body of laws establishing health-based concentration standards for a number of pollutants in outdoor ambient air. The European Commission has the task of ensuring that the environmental law is applied by the Member States through infringement procedures.

Long-term measures like mode switch policies in favour of mass transit and public regulation on road use are pretty effective in abating atmospheric pollution in cities (Allen et al., 2011), but pollution peaks and the consequent exceedance of regulative concentration thresholds are often caused by substantial fluctuations of mobility patterns and weather conditions around their expected behaviours. Hence, air quality protection needs to be fine-tuned through the introduction, in the local policy portfolio, of further tools and actions for predicting extreme pollution events and managing traffic in real time, in order to prevent the predicted concentration peaks.

Given the above, this research focuses on the investigation of traffic-related air pollution with the final aim of developing enhanced mathematical models to support short-term decisions for sustainable mobility of road vehicles in urban areas. In more detail, the study addresses the challenge of forecasting accurately the concentration of NO_2, which is subject to an hourly standard of concentration, to enable local authorities to mitigate or even prevent exceedances of concentration limits through real-time traffic management.

By achieving the identified objective, this research will be of strategic importance in many national contexts. The worldwide scale of atmospheric pollution problems has been acknowledged in the 2014 version of the WHO Ambient Air Pollution database consisting mainly of urban air quality data (WHO, 2014). In the report, annual concentration means of PM_{10} and $PM_{2.5}$,[2] for about 1600 cities of 91 countries in the 2008–2013 period, have been calculated. As can be seen in Fig. 1, the world's annual mean levels of PM_{10} by region range from 26 to 208 $\mu g/m^3$; in addition, the world's average is 71 $\mu g/m^3$ against the recommended value of 20 $\mu g/m^3$. Particular concern is associated to the East side of the planet, where countries like China, India, Nepal, Bangadlesh, Mongolia and, in the Mediterranean Area, Egypt, Iran, Jordan, Afghanistan, Pakistan far exceed the world's yearly mean concentration of PM_{10}.

The 2014 Air Quality in Europe Report (European Environment Agency, 2014) states that, in EU cities, exposure to atmospheric pollution levels exceeding the WHO concentration limits (in general stricter than the EU standards) is significantly widespread for various chemical agents. In 2012, above limit exposure to PM_{10} and $PM_{2.5}$ respectively involved 64% and 92% of the total EU-28 urban population. Moreover, in the case of O_3, in the same year, the exposure incidence rose to 98% of people living in towns. Despite the clear decreasing trend of NO_2 yearly mean concentration over the recent years,[3] in 2011, 21 European countries still recorded exceedances of the limit values at one or more monitoring stations. Specifically, in the United Kingdom, the NO_2 levels have exceeded the WHO and EU target values persistently. This is confirmed by the fact that, in the early part of 2014, the European Commission launched legal proceedings against the UK for its failure to cut excessive levels of NO_2 (EU Press Release Database, 2014). Lastly, while exposure of Europeans to CO concentrations above the EU and WHO thresholds is negligible, in the case of benzene (C_6H_6), around 10% of the EU-28 urban population is subject to pollution above the WHO levels and, in the case of SO_2, the value is 37%.

This paper presents the early stage of ongoing research on air quality modelling, which refers to NO_2, a toxic gas emitted by road vehicles, industry and households, which, even in the case of short-term exposures (from 30 min to 24 h), may irritate the eyes, nose, throat and lungs, while, in the long-term, may affect lung function permanently. Furthermore, it is the main precursor for ground-level ozone, that is very harmful to human health.

For NO_2, the EU environmental legislation (EU, 2008) sets two types of standard: the hourly mean concentration which cannot go beyond the level of 200 $\mu g/m^3$ more than 18 times each calendar year; whilst, the annual average of hourly concentrations is not allowed to exceed 40 $\mu g/m^3$. Moreover, the 2008 Air Quality Directive also defines an 'alert' threshold value of 400 $\mu g/m^3$. When this threshold is exceeded over three consecutive hours in areas of at least 100 km^2 or an entire air quality management zone (whichever is the smaller), authorities have to implement short-term action plans.

In the research presented here, the relationship has been modelled to explore NO_2 hourly concentration in terms of explanatory variables which relate to urban transport and influence emissions, along with weather conditions, that are responsible for dispersion and transformation of pollutants.

2. Review of literature and research gaps

Few studies on real-time air quality forecasting near urban roads have appeared in the relevant scientific literature. Amongst some that are particularly interesting for this work, since they investigate the relationship between nitrogen oxides' levels and meteorological as well as transport-related variables, include Kukkonen et al. (2003); Cai et al. (2009); Galatioto and Bell (2013); Nagendra and Khare (2006); Perez and Trier (2001); Viotti et al. (2002). The leitmotiv of these studies is to consider the Artificial Neural Network (ANN), from the domain of Artificial Intelligence science, found to be the most effective tool to predict air quality in urban areas. In some cases, this methodology is compared with other approaches, but these are usually linear regression models or deterministic methods simulating the physical processes involved.

[2] Particles with diameter smaller than 10 and 2.5 microns, respectively.

[3] Between 2003 and 2012, in EU-28, the NO_2 annual mean concentration on average fell by 18%.