HARMO22
22nd International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
10-14 June 2024, Pärnu, Estonia

ENHANCING URBAN AIR POLLUTION MODELLING THROUGH NETWORK SCIENCE APPROACHES

Sofia Fellini [1], Tianyang Li [2] and Maarten van Reeuwijk [3]

[1]Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino.
[2] Department of Civil and Environmental Engineering, Imperial College London, SW7 2AZ, London, UK

Abstract: We model the relations between emissions of a passive scalar inside streets and the resulting concentrations in the other streets of the neighborhood as the weighted links of a complex network. We test that the adjacecny matrix (*A)* of this network can be used in a linear model to predict air pollutant concentration, including NO-NO_2-O_3 chemistry, under varying emissions in the streets. The physics of the underlying problem is used to infer *A* for different wind speeds. An indicator for population exposure in the streets is developed, and it is shown that the out-degree of the exposure matrix *E* represents the effect of a change in emissions on the exposure reduction in all streets in the network.

Key words: *Urban air pollution, network science, photochemical smog, exposure reduction.*

INTRODUCTION

The vast majority of the global population exceeds WHO pollution limits, with middle- and low-income countries disproportionately affected. Urbanization drives city administrations to develop air quality plans, primarily targeting traffic emissions, the main contributors to urban pollution. Effective traffic policies require quantifying local emissions' impact, often through source apportionment techniques based on simulations using air quality models. Modeling urban air pollution is complex due to factors like turbulent dispersion driven by complex urban geometry, spatial-temporal emission patterns, and physico-chemical transformations of pollutants like NO_2-NO-O_3 chemistry.

One potential approach to address this complexity is to utilize simplified modeling techniques. Among these, SIRANE (Soulhac et al., 2011) stands out as an operational street network model for urban dispersion, validated through wind tunnel experiments and field campaigns. In pursuit of further simplification, Fellini et al. (2019, 2020, 2021) developed a complex network-based propagation model, drawing on concepts from network science. This approach not only offers computational advantages but also aims to uncover the physical mechanisms driving dispersion processes, highlighting the role of city's geometric and topological properties.

Building on this foundation, in this research, we utilize a complex network approach to pinpoint optimal locations for emission reduction in urban neighborhoods. Instead of creating a new dispersion model, we leverage the network approach to enhance the capabilities of existing operational tools, such as the SIRANE model. This approach facilitates generating numerous scenarios from a single dispersion simulation of a passive scalar, greatly improving computational efficiency. Additionally, it simplifies modeling the relationship between pollutant emissions and their impact on citizens, as well as conducting source apportionment analyses.

METHODOLOGY

In classical street network models, streets are typically represented as links connecting intersections (Figure 1.a), while in our approach, streets are represented as nodes and emission-impact relationships as directed links, allowing distant streets to be connected (Figure 1.c). The network structure is described mathematically by the weight matrix A, where non-zero elements indicate connections between pairs of nodes, with their values representing the importance of the connection (Figure 1.d). The link weights encapsulate all information regarding pollutant transport between streets.

The primary assumption in this study is that pollutant transport within and between streets can be approximated as:

$$\boldsymbol{C} = A\boldsymbol{Q} \quad (1)$$

where $\boldsymbol{Q}$ and $\boldsymbol{C}$ are the transport emissions $[g/s]$ and concentration in each street $[\mu g/m^3]$ respectively, and A_{ij} is an entry of the weight matrix that represents how emissions in street j result in concentrations in street i. Equation (1) assumes a linear relationship between emissions and concentration.
To construct the weight matrix A, simulations are conducted using SIRANE, assuming zero background concentration and only street emissions of a gas acting as a passive scalar, simulated through ozone (O_3) emissions. Under these assumptions, each j-th column of the weight matrix (**Errore. L'origine riferimento non è stata trovata.**.c-d) is filled by simulating a unit ozone emission in the j-th street of the network. These simulations occur under neutral meteorological conditions, at a single wind speed U_0 and one wind direction ϕ at a time, repeated for 8 wind directions, i.e., i.e. $A_0(\phi) = A(U_0, \phi)$.

To determine the optimal location for emission reduction in the urban area, a metric quantifying citizen exposure is needed. Pollutant exposure depends on pollutant concentration, population exposure, and inhalation rate. Thus, exposure in each street can be estimated as:

$$\boldsymbol{e} = q\boldsymbol{p} \circ \boldsymbol{C} = q\boldsymbol{p} \circ A\boldsymbol{Q} = E\boldsymbol{Q}, \quad (2)$$

where $\boldsymbol{p}$ and $\boldsymbol{C}$ are vectors providing pollutant concentration and the number of inhabitants in each street, q is the inhalation rate (assumed constant), and E is the resulting exposure matrix.

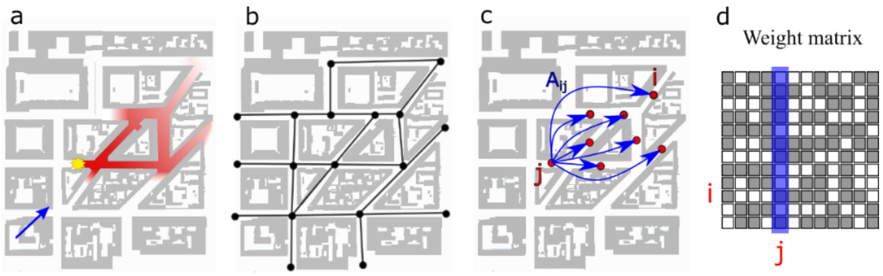

Figure 1: A diagram illustrating pollutant dispersion in a dense city (a), a classical street-network layout (b), the emission-concentration network employed in this study (c), and the associated weight matrix (d).

RESULTS

We construct the weight matrix A for the South Kensington case study, located west of central London, UK, comprising 46 streets. Eight matrices are developed for eight wind directions, assuming a constant wind speed of $U_0 = 5$ m/s. Subsequently, a random $\boldsymbol{Q}$ vector is generated, and results from the linear model (Eq. 1) are compared with those from SIRANE simulations. This comparison is repeated 20 times, and the outcomes are depicted in Figure 2(a), where each point represents the concentration in a single street for a specific wind direction and initial random emission distribution. The results reveal a strong alignment between the two models, indicating the system's predominantly linear nature and the correct implementation of the matrix approach.
The analysis of mass balances in SIRANE models indicates that the matrix A should be inversely proportional to the mean wind intensity above roof level. Consequently, we can generalize the weight matrix A for any wind speed as:

$$A(U, \phi) = \frac{U_0}{U} A_0(\phi) \quad (3)$$

where U_0 is the reference velocity (5 m/s in this study) and A_0 is the corresponding weight matrix. This scaling allows the simulation of scenarios with ten different wind intensities using Eqs. (1) and (3).

Concentration predictions are compared in Figure 2(b) with the outcomes of simulations performed with SIRANE, demonstrating strong agreement.

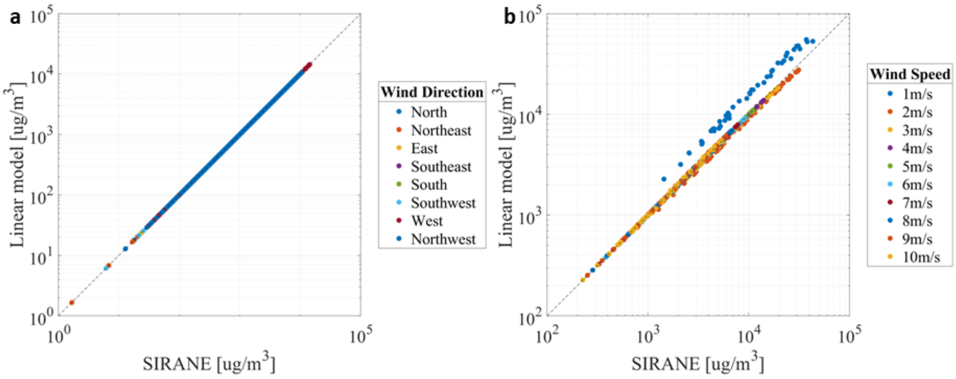

Figure 2. a) Comparison of street concentrations predicted by SIRANE and the linear model under various wind directions and a constant wind speed (5 m/s). b) Simulating diverse wind speed scenarios and comparing the results with SIRANE predictions.

By leveraging the linear and simplified model between emissions and concentrations, we then aim to address a scenario where a borough aims to reduce traffic emissions to maximize health benefits for citizens. To achieve this goal, it is crucial to assess the contribution of emissions in each street to urban air pollution and exposure, a process known as source apportionment. Following this strategy, we modify the emission-exposure model introduced in Eq. 2 to analyze exposure variations due to changes in pollutant emissions:

$$\delta \boldsymbol{e} = E\delta \boldsymbol{Q}. \quad (4)$$

The total exposure reduction R_j due to an emission reduction $\delta Q_j = -\delta Q$ in street *j* can be then expressed as:

$$R_j = -\sum_i \delta e_i = -\sum_k \delta Q_k \sum_i E_{ik} = \delta Q \sum_i E_{ij}, \quad (2)$$

where the last step uses that δQ_k is different from 0 only in street *j*. Note that $\sum_i E_{ij}$ is formally defined in graph theory as the *outdegree* of node j (d_j^+), i.e. the sum of weights assigned to the links directed away from the node (Newman, 2010). So, the optimal place to reduce emissions corresponds to the node with the highest outdegree in the defined weighted network.

Finally, the model is extended to the analysis of photochemical smog (see Li et al. 2023). To this aim, we employ a two-step algorithm to reconstruct the concentrations of reactive pollutants in the streets. This process involves applying matrix A and a non-linear function for chemical transformations in the streets. By linearizing the exposure model, we obtain an expression of the exposure reduction metric for reacting chemical species, showing that it can be approximated with a rescaling of the metric for the passive case. This scaling is valid only if the background concentration of pollutants and the emission ratio NO_2-NO are kept constant for each street.

DISCUSSION

Our research emphasizes that the most effective strategy for enhancing public health involves reducing emissions in streets with high aspect ratios. When we exclude the immediate impact of emissions within the same street where pollutants are released, our findings demonstrate that streets with extensive interconnections offer the most significant reductions in exposure.

The proposed model's simplicity and adaptability make it suitable for future improvements and applications in various scenarios, accommodating emission reductions in multiple streets, diverse atmospheric conditions, and more precise dispersion simulations. In summary, our network approach offers a new perspective on a long-standing problem, introducing valuable metrics that inform traffic and emission management decision-making.

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