23rd International Conference on
Harmonisation within Atmospheric Dispersion Modelling
for Regulatory Purposes
15-19 September 2025, Hamburg, Germany

EXTENDED ABSTRACT

Abstract title: Experimental and numerical study of pollutant dispersion from traffic sources in a real urban neighbourhood

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Summary

The present study aims to assess the impact of urban morphology and vegetative elements on the dispersion of pollutants emitted at ground level from traffic source. A neighbourhood in the historical city centre of Bologna (Italy) is selected as a case study: it is characterised by the presence of heavily trafficked roads, high trees and green areas. Airflow dynamics and pollutant concentration are reproduced and analysed by, both, laboratory experiments and high-resolved numerical simulations. Reynolds-Averaged Navier–Stokes (RANS) simulations are first validated against the experiments, then utilised to investigate the dispersion of pollutants in the city neighbourhood. Subsequently, full scale meteorological variables are used to inform the numerical simulation, through a downscaling procedure, to better reproduce and study the pollutant dispersion under a realistic atmospheric condition. The study enables a comparative analysis based on both experimental and numerical investigations, applied to a real urban geometry.

Introduction

Urban air pollution from traffic sources poses significant public health risks, particularly if it accumulates at pedestrian level, where citizens are most exposed (Ren et al., 2023; Di Sabatino et al., 2015). The complexity of the urban fabric plays a role in influencing airflow dynamics, which can lead to unexpected outcomes in pollutant dispersion characteristics. A real neighbourhood of the historical city centre of Bologna (Italy) has been identified as a case study for laboratory and numerical investigation (Fig. 1). The university areas surrounding via Irnerio in the north-east sector of the city has been selected for the study as it experiences heavy traffic and a frequent presence of university students and staff. The Irnerio street and the surrounding areas are studied in detail to investigate ventilation for a complex urban fabric, with the aim of realistically reproducing the interaction between the urban morphological elements and the atmospheric wind. Airflow dynamics and pollutant dispersion are studied through both laboratory-scale experiments and high-resolved numerical simulations. The experimental results are used for the validation of the numerical model. Detailed insights into city canopy layer dynamics and the overall effects on pollutant dispersion are provided, advancing our understanding of urban morphology's role in ventilation. The simulations are also carried out with meteorological inputs, obtained from the city's measurement stations to study in detail the interaction between urban morphology and realistic weather conditions.

The presented study is part of a broader project: GREENPOLIS, PRIN 2022. Simulations and analyses are still in progress; hence, preliminary results will be shown in this contribution.

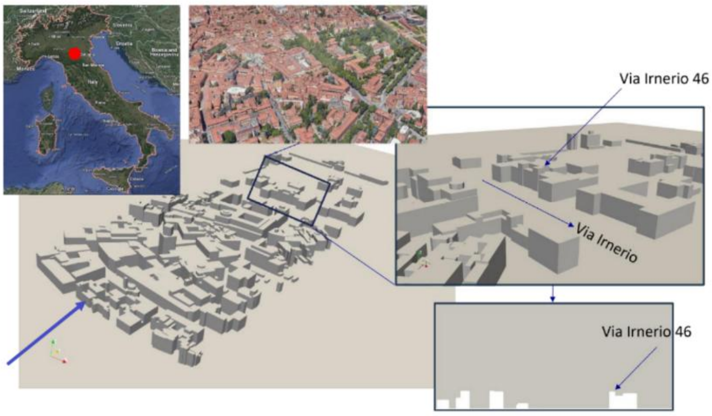
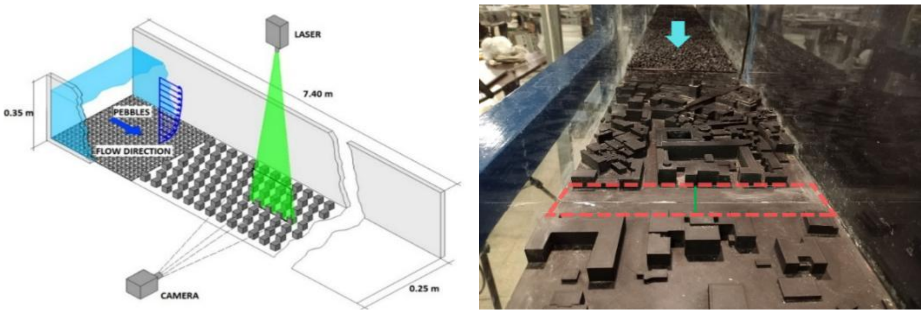


Figure 1 . Geometry and location of the case study (in panel-left and top) of the computational domain with Via Irnerio 46 building (in panels-right)

Problem description and methodology

Airflow and pollutant dispersion in the chosen city neighbourhood are reproduced in the laboratory taking advantage of the water-channel facility of the Department of Civil, Building and Environmental Engineering of Sapienza University of Rome. The experimental system is composed of a closed-loop water channel with dimensions 7.40 m in length, 0.25 m in width, 0.35 m in height. The water depth and water velocity are controlled by a floodgate at the end of the channel, while a constant-head reservoir supplies the flume. The water depth is 0.16 m. A scale model (1:1000) has been used to reproduce the area of interest (Fig. 2b). In the centre of the street, the pollutant (Rhodamine-WT) is emitted from a 0.5-mm-wide slit, which simulates the emission from road traffic.

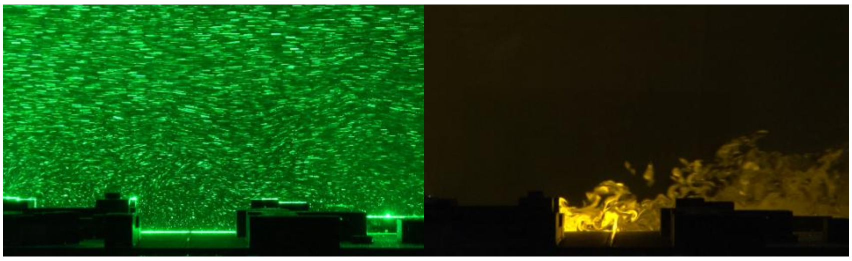
The acquisition system consists of a green laser and a high-speed camera. The test section is illuminated by an all-solid-state green laser (Fig. 2a) with a wavelength of 532 nm and a power output of 8 W, producing a thin light sheet with a depth of 0.5 mm. A CMOS high-speed camera (Mikrotron EoSens 1362; 1280x1024 pixel resolution, acquisition frequency 250 Hz) is used for image grabbing.



(a) *(b)*

Figure 2 (a) Layout of the experimental setup and (b) downstream view of the city model in the water channel. The red dashed line in (b) refers to Via Irnerio, the green line is the signature of the interrogation area i.e., the vertical plane parallel to the streamwise direction passing through the centre of the channel (see Figure 3). The cyan arrow indicates the flow direction in the water channel

The working fluid is seeded with non-buoyant particles (diameter ~$2{\cdot}10^{-5}$ m) which enable efficient flow visualization and quantitative estimation of the velocity field through Feature Tracking technique. Planar Laser-Induced Fluorescence (PLIF) technique is employed to measure the Rhodamine concentration field. In this way, it is possible to determine two-dimensional velocity and concentration fields along vertical or horizontal planes. In this contribution, the results obtained along one vertical plane parallel to the channel axis will be discussed (Figs. 3a and 3b). More details regarding the experimental setup and data analysis can be found in Di Bernardino et al. (2018).



(a) *(b)*

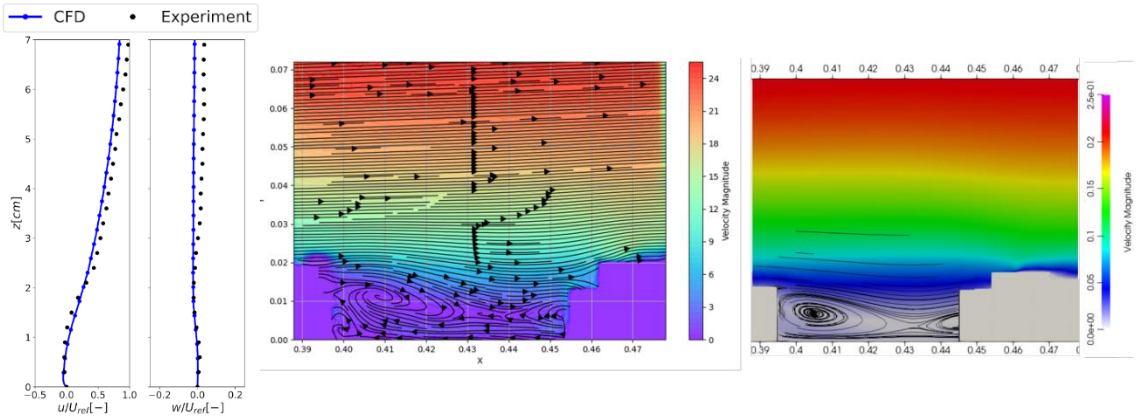
Figure 3 (a) Example of particle displacement along a vertical plane parallel to the streamwise direction. (b) Snapshot of the passive tracer emitted at ground level from the linear source

The use of a Reynolds-Averaged Navier–Stokes (RANS) model complements the experiments, providing a three-dimensional, full picture of the airflow dynamics and the pollutant dispersion mechanisms in the selected areas. The computational grid is composed by an unstructured mesh of about 16 million cells, refined near the solid boundaries to ensure a direct resolution of the wall-boundary layer (Cintolesi et al., 2021). To dissect the observed complexity of the flow field, a systematic multi-plane analysis can be conducted, extracting different planes from the simulations. In this contribution, one horizontal plane is described (Fig. 5b).
The validated numerical model, integrated with full-scale meteorological simulations, enables the implementation of a downscaling process. This procedure allows for the development of methodologies where small-scale numerical and experimental data are

applied at high resolution, an ongoing challenge, and to link the small-scale to meteorological simulations through the downscaling process.

Preliminary results and remarks

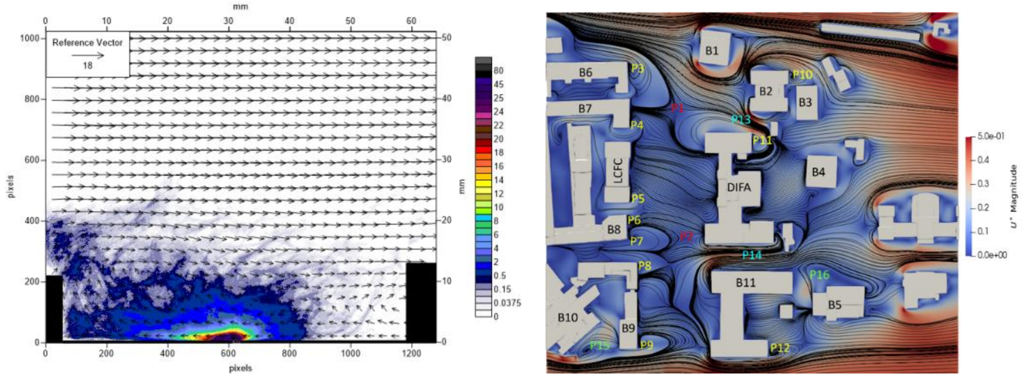
Figure 4 shows the comparison between the measured and simulated streamwise and vertical velocity components averaged in time. Overall, the agreement between the two is satisfactory, both qualitatively and quantitatively. As expected, the mean flow shows, within the canyon, a primary vortex near the upstream wall and a secondary vortex near the downstream wall. These vortices may determine potential pollutant accumulation zones. Figure 5a reports the instantaneous velocity (vectors, cm/s) and concentration (colour, arbitrary units) fields obtained experimentally. It corresponds to the same vertical plane shown in Figs. 3 and 4. The average concentration is essentially governed by the streamwise flow, parallel to the bottom, which advects the pollutant upstream. The area with the highest concentration values is in the left (upstream) half of the canyon.



(a) *(b)*

Figure 4 (a) Comparison between experimental (symbols) and numerical (blue line) averaged streamwise (u) and vertical (w) velocity components taken along a vertical profile passing through the centre of the canyon. U_{ref} is the reference (undisturbed) mean streamwise velocity. (b) The two panels show the streamlines for the experiment (left) and the numerical simulation (right)

The horizontal planes obtained by the numerical simulations allow for the identification of other key flow features. Figure 5b shows the horizontal plane located at z/H=0.05, where H is the height of the DIFA (Department of Physics and Astronomy “Augusto Righi”) building. Key flow features are distinguished using color-coded markers. Points P1 and P2 are local stagnation points characterized by null velocity. Corner vortices are prevalent throughout the domain, arising primarily from flow separation at sharp building edges. The channelling effect, marked by P13 and P14, manifests as localized acceleration of the flow between narrow urban corridors. Such effect is particularly important for understanding ventilation potential and pollutant transport in densely built environments. In conclusion, the combined use of experimental and numerical methodologies proves to be particularly effective for characterizing ventilation dynamics within urban canyons.



(a) *(b)*

Figure 5 (a) Mean velocity (vectors) and concentration (colours) fields, obtained by laboratory measures. Vector unit is cm/s, concentration in arbitrary units.(b) Flow field, obtained by numerical simulations, at a horizontal plane at z/H=0.05, (H is the height of the DIFA building). Labels: building in black, corner vortices in yellow, saddle points in red, channeling zones in cyan, recirculation regions in green, shear layers in pink

As future perspective, the validated models will serve as a foundation for conducting detailed parametric studies and in-depth analysis to explore the role of urban vegetation in regulating airflow and pollutant dynamics in urban canyons. With this objective, the previously described analysis will be repeated, incorporating the vegetative elements of the area of interest in the models, thereby enabling a comparison of the results. This study will provide valuable insights to guide urban planners in optimizing vegetation design to improve air quality, reduce health risks, and create sustainable urban environments.

This work received financial support under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1, Call for tender No. 104 published on 2.2.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU. Project Title "Multi-scale investiGation of natuRe-basEd solutions for thE mitigatioN of urban heat and POLlution ISland (GREEN-POLIS)" authorised by MUR – CUP J53D23002560001 - GA No. 20224HHCK7_001.

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