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

APPLICATION OF THE SIRANE STREET-NETWORK DISPERSION MODEL TO TURIN, ITALY: FROM INPUT DATA RECONSTRUCTION TO MODEL EVALUATION

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Abstract: The growing need to monitor and reduce urban air pollution requires the adoption of reliable models for assessing pollutant concentrations at street level. This study presents a preliminary application of the SIRANE dispersion model to the city of Turin (Italy), focusing on nitrogen oxides (NO_X, NO_2, NO) and ozone (O_3) during February 2022. Emissions from both road traffic and residential heating were reconstructed, while meteorological inputs and background concentrations were provided by ARPA Piemonte. Model results were compared with hourly observations from the monitoring network within the municipality. SIRANE was able to reproduce the main spatial and temporal patterns, especially for NO_2. These preliminary results highlight the model's potential for operational applications in Turin and indicate key directions for future improvements.

Key words: *Urban air quality, dispersion modelling,* NO_X.

INTRODUCTION

Urban air pollution remains one of the main environmental health risks in Europe. Nitrogen dioxide (NO_2) and particulate matter (PM_{10}, $PM_{2.5}$) are among the pollutants most frequently exceeding EU limit values, with well-documented adverse health effects.
Turin, with approximately 850,000 inhabitants and an area of 130 km², lies in the Po Valley, a region particularly susceptible to air pollution, partly due to its geographical conformation. According to ARPA Piemonte (Regional Agency for Environmental Protection), NO_2 annual means at several traffic stations remain close to or above the EU limit of 40 $\mu g\ m^{-3}$.

Urban-scale air quality models are essential tools for quantifying pollutant exposure, testing mitigation scenarios, and supporting decision-making. Whereas regional models provide an overview at a coarser scale, street-scale dispersion models can capture the heterogeneity of concentrations between different urban streets or districts and identify critical areas more accurately. SIRANE is one such model, designed to represent dispersion in complex urban geometries with high spatial resolution.

The objective of this study is to systematically apply SIRANE to the city of Turin, focusing on a pilot simulation for February 2022. The work involves:

1. Reconstructing emission inventories for traffic and heating;
2. Running SIRANE to simulate hourly concentrations of NO_2, NO_x, NO and O_3;

3. Comparing results to ARPA monitoring data to evaluate model performance and identify priorities for improvement.

THE STREET-NETWORK MODEL SIRANE

In this study, the dispersion of atmospheric pollutants was simulated using the SIRANE model (Soulhac et al., 2011, 2012), developed by the Atmosphere, Impact & Risk group at the Laboratoire de Mécanique des Fluides et d'Acoustique (École Centrale de Lyon). One of the model's strengths is its ability to consistently represent dispersion on an urban scale while maintaining high spatial resolution on individual streets. Based on the concept of the urban road network, SIRANE represents the main transport phenomena within the urban canopy: advection along the road axis, turbulent diffusion at the interface with the external atmosphere, and exchanges at intersections. Above the urban canopy, the atmospheric flow is modelled as a boundary layer flow over a rough, horizontally uniform surface; external dispersion is described using a Gaussian model with parameters derived from the Monin-Obukhov theory.
The model calculates average hourly concentrations under steady-state conditions and includes the chemical reactions of the NO_x cycle. The main required inputs are: road network, meteorological data, emissions and background concentrations. SIRANE has been extensively validated through wind tunnel experiments and observational data, particularly for the city of Lyon (Soulhac et al., 2017), and then applied in several European cities, including some studies in Italy.

CASE STUDY

Turin is a metropolitan city in north-western Italy and the fourth most populous in the country. Located at the foot of the Alps, within the Po Valley, its geographical conformation combined with intense human activity favours the stagnation of atmospheric pollutants and contributes to the high emission levels observed. According to the European City Air Quality Viewer of the European Environment Agency (which assesses air quality in European cities based on WHO guidelines), Turin shows annual concentrations of NO_2 and $PM_{2.5}$ above the recommended values, placing it among the European urban centers with a significant health risk associated with prolonged exposure to air pollutants.
The modelling domain adopted in this study corresponds to the municipal boundary and includes both the historic centre, characterized by Roman grid plan and typical urban canyons, and the more open suburban neighbourhoods. It includes major high-traffic arteries, minor residential streets and a section of the ring road. The geometry of the road network required for SIRANE (Fig. 1a) was reconstructed from detailed GIS data on buildings, from which the width of road sections and the height of buildings were derived.
Previous applications of SIRANE to Turin include a study comparing dispersion patterns in Turin and Lyon over a larger domain (Bo et al., 2020); here, the goal is to develop a configuration that could serve as a baseline for operational use by local authorities.

RECONSTRUCTION OF INPUT DATA

The study area covers an area of approximately 16 km × 15 km. The pilot simulation was conducted for the month of February 2022, with a one-hour time step, as required by the SIRANE model. February was chosen because it represents the winter season in the study area, when emissions from residential heating are typically at their peak, contributing significantly to air pollution levels.

The reconstruction of **traffic emissions** is a crucial element in the study, given that in Turin in 2019, approximately 75% of NO_x emissions came from road transport (IREA, EMEP-CORINAIR methodology).
Linear emissions for each pollutant *i* and for each road segment *j* are calculated using the formula

$$E_{ij} = L_j \, Q_j Ef_i \quad (1)$$

according to the COPERT (Tier 2) methodology.

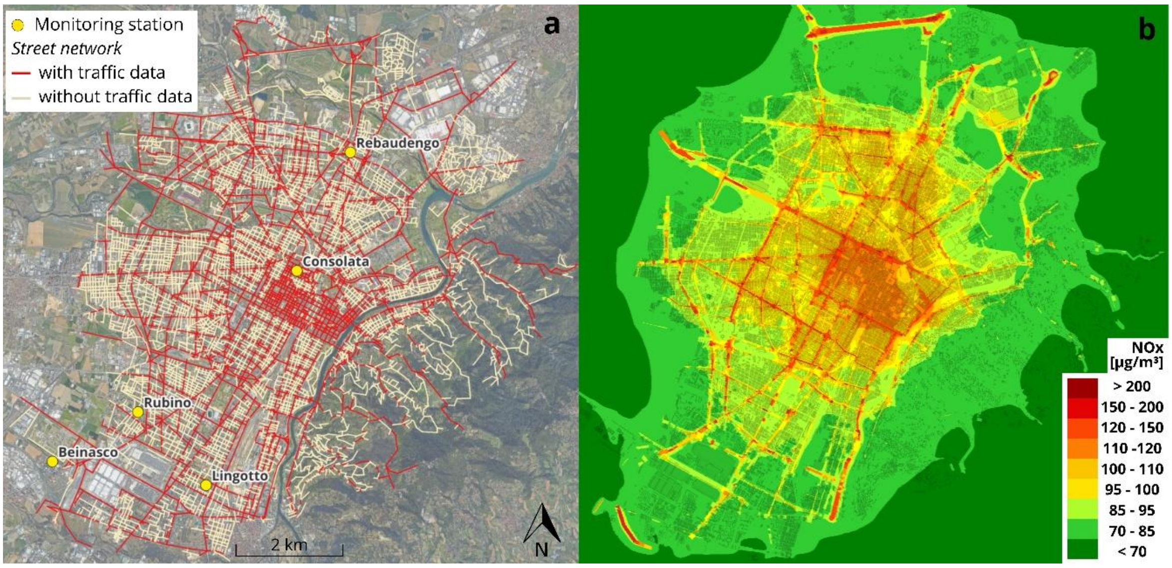

Figure 1: (a) Road network geometry used as SIRANE input, with links having traffic flow data shown in red and links without traffic data in white; yellow dots indicate air quality monitoring stations. (b) Mean NOx concentration map simulated by SIRANE for February 2022.

In this formula, L_j represents the length of the road segment, Q_j the average daily flow of vehicles on that segment. Ef_i is the average emission factor for the pollutant in question, calculated as the weighted average of the typical emission factors provided by ISPRA National Emission Inventory and applied to the composition of the vehicle fleet of the municipality of Turin (published by the Automobile Club d'Italia, ACI 2022), taking into account category, fuel type and Euro class. The average daily vehicle flows, provided by the company 5T, cover the city's main arteries and some secondary roads. They were then projected onto the street network (Fig. 1a). The daily emissions thus obtained are modulated through hourly time profiles derived from the Lyon case study (Soulhac et al., 2012).

Emissions from domestic heating, provided to SIRANE as surface data on a grid of 167 cells, were reconstructed in collaboration with the EST Lab of the Politecnico di Torino.
Starting from the Energy Performance Certificates (APE) and the surface area (m^2) associated with each building, the annual energy consumption was estimated. Once aggregated on the analysis grid, the data were converted into emissions. For each cell, an aggregate annual emission is obtained for heating systems not served by district heating and powered by natural gas. For this simulation, emissions were distributed evenly over the winter period (15 October - 15 April).

Hourly **meteorological data** and **background pollutant concentrations** were obtained from public monitoring networks managed by ARPA Piemonte. The Turin Caselle site was used for meteorology (wind direction, precipitation, solar radiation, temperature, and wind speed), while background concentrations of NO, NO_2, NO_x and O_3 were calculated as the average of hourly values recorded by background stations located outside the municipal domain.

RESULTS AND DISCUSSION

The simulated data were compared with measurements from five monitoring stations located within the municipal boundary (Fig. 1a), ensuring full spatial and temporal correspondence. The hourly concentrations of NO_x, NO, NO_2 and O_3 calculated with SIRANE were compared with measurements from the stations.

An initial analysis focused on the statistical distribution of the simulated and measured data, ignoring the temporal sequence. As an example, the Q-Q plots for NO_x, NO and NO_2 for the reference sites are shown in Fig. 2a-c. Overall, the agreement is good, with the model tending to underestimate the highest concentrations and slightly overestimate the lowest values, particularly for NO_2. The underestimation of high concentrations may be due to missing traffic emission data on secondary roads. The best fit is observed for NO_2 at all stations, in line with what has been reported in the literature for applications of the SIRANE model.

For a more detailed evaluation of the model, the time series of concentrations were analyzed. The time trend for the Turin Consolata station is shown in Fig. 2d. The strength of the model lies in its ability to bridge the gap between background concentration and the values observed at monitoring stations, providing a realistic representation of the increase due to local emissions. Although the general trend is well captured, peak concentrations tend to be underestimated.

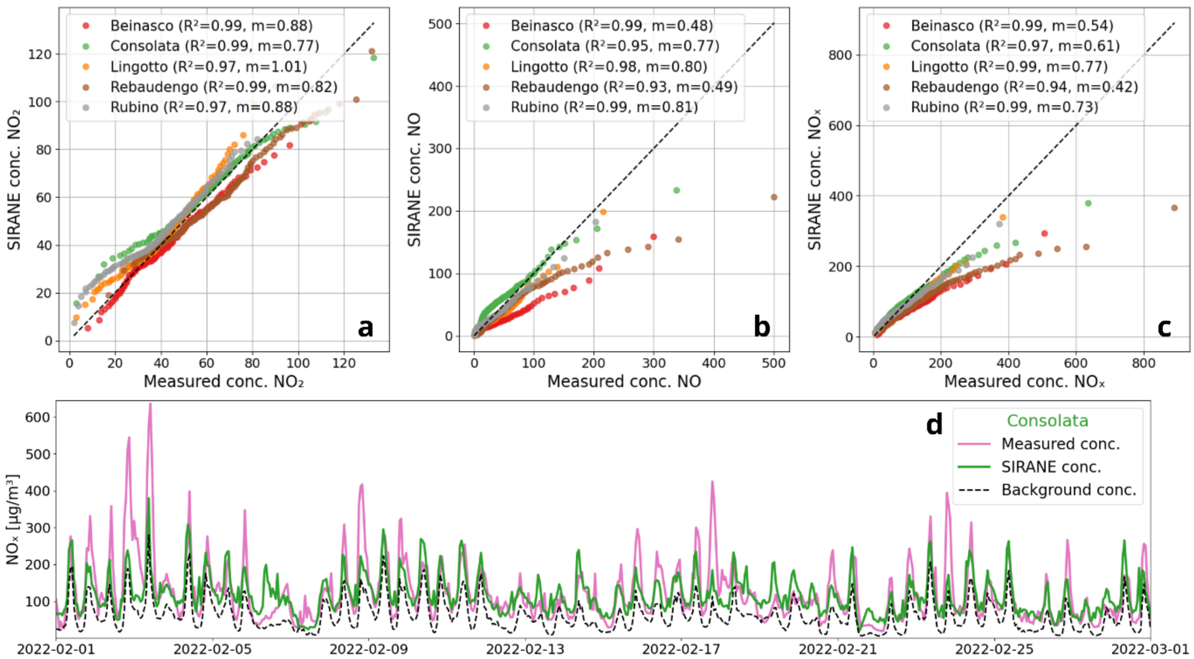

Figure 2: Q-Q plots of simulated and measured hourly concentrations of NO_x (a), NO (b) and NO_2 (c) at the five monitoring stations. (d) Time series of simulated, measured and background hourly concentrations of NO_2 for the Turin Consolata station.

Finally, Table 1 shows various statistical metrics typically used to evaluate the performance of air quality models (Chang & Hanna, 2004): Bias Fractions (FB), Root Normalized Mean Square Error (rNMSE), Geometric Mean (MG), Geometric Variance (VG) and fraction of data where predictions are within a factor of two of observations (FAC2). According to the criteria of Chang and Hanna (2004), a model's performance is considered good if: $|FB| \leq 0.3$, $rNMSE \leq 2$, $0.7 \leq MG \leq 1.3$, $VG \leq 1.6$ and $FAC2 \geq 0.5$.
In the simulation considered, most of the monitoring stations and pollutants analyzed meet these criteria, confirming the model's good predictive capacity, particularly for NO_2, which shows a better correspondence. However, for NO and NO_x, greater deviations are observed, especially in the rNMSE and FAC2 values, indicating greater difficulty in reproducing the temporal and spatial variability of these pollutants.

Table 1: Statistical indices comparing measured and modelled concentrations at monitoring stations. Values in bold meet the acceptability criteria of Chang and Hanna (2004).

Station	Pollutant	FB	rNMSE	MG	VG	FAC2
Beinasco	NO_2	**-0.07**	**0.37**	**0.93**	**1.16**	**0.93**
	NO	**-0.09**	**1.44**	**0.89**	2.60	0.49
	NO_X	**-0.23**	**0.80**	**0.79**	**1.29**	**0.79**
Consolata	NO_2	**0.08**	**0.34**	**1.10**	**1.20**	**0.91**
	NO	0.32	**0.77**	1.44	1.73	**0.62**
	NO_X	**0.03**	**0.51**	**1.03**	**1.19**	**0.89**
Lingotto	NO_2	**0.11**	**0.33**	**1.13**	**1.15**	**0.92**
	NO	**0.13**	**0.99**	**1.20**	2.55	**0.54**
	NOx	**-0.01**	**0.59**	**0.99**	**1.29**	**0.82**
	O_3	**0.26**	**0.62**	1.33	**1.47**	**0.70**
Rebaudengo	NO_2	**-0.06**	**0.34**	**0.94**	**1.12**	**0.94**
	NO	**-0.20**	**0.87**	**0.79**	**1.57**	**0.69**
	NO_X	-0.32	**0.76**	**0.71**	**1.20**	**0.80**
Rubino	NO_2	**0.20**	**0.40**	**1.26**	**1.31**	**0.85**
	NO	0.37	**0.96**	1.59	2.66	**0.50**
	NO_X	**0.16**	**0.56**	**1.19**	**1.37**	**0.78**
	O_3	**0.03**	**0.62**	**1.03**	**1.49**	**0.75**

FUTURE DIRECTIONS

This pilot study identified the main actions needed to refine the model. These include: (i) sensitivity analysis to quantify the impact of different emission sources and input parameters; (ii) introduction of hourly, daily and seasonal modulations for heating emissions, potentially correlated with ambient temperatures; (iii) adoption of specific traffic profiles for Turin, derived from local monitoring data collected every 10 minutes on some of the city's main roads; (iv) extension of simulations to longer periods to analyze different meteorological and seasonal conditions.

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