LEVERAGING THE HANOI EMISSION INVENTORY TO INFORM AIR QUALITY MANAGEMENT

Damon Roddis[1], Dr Iain Cowan[1], Russ Francis[1], Jane Barnett[1], Ethan Edwards[1], Cong Vu[1], Ly Bich Thuy[2], Assoc.Prof. Dr. Pham Thi Thanh Nga[3], Dr.Tran Thanh Thuy[3], Assoc.Prof. Dr. Doan Ha Phong[3]

[1] Zephyr Environmental, Australia

[2] School of Chemistry and Life Sciences, Hanoi University of Science and Technology (HUST), Vietnam

[3] Institute of Meteorology, Hydrology, Environment and Marine Sciences (IMHEMS)

Abstract

Hanoi continues to face severe air quality challenges, frequently exceeding WHO guidelines for fine particulate matter less than 2.5 micrometers in aerodynamic diameter ($PM_{2.5}$). As part of the response to what has become a major public health concern, the city has developed its first igh-resolution, multi-sectoral atmospheric emission inventory. The details of this inventory are described within Part A of this two-part paper series.

This paper comprises Part B of the paper series, where we provide commentary on best practice for city-wide atmospheric dispersion modelling, noting the strengths and weaknesses of the current Hanoi emission inventory. Ultimately, the work provides a scientific baseline for Hanoi's 2030 Clean Air Action Plan, with the inventory suggesting that a 20% reduction in $PM_{2.5}$ is achievable only through a hybrid of initiatives. The prioritisation of air quality internventions will ultimately be informed by employing fit-for-purpose urban scale atmospheric dispersion mddelling.

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Keywords: Hanoi, Emission Inventory, Source Apportionment, CMAQ, CHIMERE, Dispersion Modelling, Clean Air Action Plan.

1. INTRODUCTION

1.1. Air Quality Context

Over the past several decades, nations across Southeast Asia have experienced remarkable economic transformation, characterised by rapid globalisation, urbanisation, and a subsequent surge in motorised private mobility. While this progress has yielded substantial economic benefits, it has placed unsustainable pressure on the regional atmospheric environment. Consequently, air quality throughout the region has deteriorated significantly, elevating urban air pollution to a critical public health and environmental crisis (Ngo K.Q. 2020).

Among various atmospheric contaminants, fine particulate matter ($PM_{2.5}$) has emerged as the most widespread threat to public health.

Vietnam's capital city, Hanoi, encapsulates the air

quality challenges faced by emerging Asian megacities. Characterised by dense, rapidly growing urban populations and a transport infrastructure that has failed to keep pace, Hanoi faces chronic, severe fine particle pollution.

of 1.4. Hanoi's Multi-Sectoral Inventory

As part of its air quality management policy, the city has commissioned an integrated, hybrid top-down and bottom-up atmospheric emission inventory. This inventory explicitly quantifies and maps the distinct criteria pollutant emissions (PM_{10}, $PM_{2.5}$, SO_2, NO_x, and CO) generated by point, area, and mobile categories at municipal scale. A detailed overview of the Hanoi emission inventory is provided inPart A of this paper series.

The Hanoi emission inventory is the first step in developing a science-based air quality management strategy for the city. The emission inventory provides the empirical, scientific baseline required to fuel numerical simulation models, execute source apportionment configurations, and reliably evaluate emission reduction policies to meet Hanoi's statutory 2030 Clean Air Action Plan targets.

Running advanced urban-scale chemical transport models or street-scale dispersion simulations requires detailed, highly disaggregated activity datasets. Modellers require precise parameters mapping explicit road line links, real-world vehicle kilometres travelled (VKT), dynamic vehicle category compositions, local fuel parameters, and high-resolution point source stack telemetry. Part A of this paper series discusses how these challenges have been addressed.

2. THE WIDER AIR QUALITY MANAGEMENT STRATEGY

2.1.1Beyond the emission inventory

An effective urban air quality management strategy requires an evidence-based approach to evaluate the cost-benefit relationships of policy interventions. Vietnam's national guidelines (Document No. 3051/BTNMT-TCMT), present a structured framework, with air quality monitoring and the development of atmospheric emissions inventories comprising the foundation. Without the baseline multi-sectoral inventory, the evaluation of future policies, such as localised industrial zoning or vehicle emission limits, remains speculative, without the empirical evidence required to make science-based policy decisions.

Under the next stage of the municipal framework, the inventory data must then be integrated into a dispersion and chemical transport modelling system. This allows regulators to move beyond static observations and execute policy scenario simulations. For Hanoi, this should serve as the tool to prioritise targeted municipal interventions.

Such interventions provide the scientific pathway to achieve the mandated 2030 Clean Air Action Plan target (20% reduction in ($PM_{2.5}$ concentrations).

2.2. Integration of Atmospheric Chemistry

The inclusion of atmospheric chemistry in any future dispersion modelling exercise is critical to its ability to inform future $PM_{2.5}$ reduction scenarios.

Secondary aerosol components may account for a substantial fraction of $PM_{2.5}$ mass in Hanoi, particularly during pollution episodes during the winter monsoon. For example, as illustrated in Figure 1, over 50 percent of particulate matter mass, based on chemical composition collected in Hanoi is anticipated to comprise secondary particulate matter (i.e. formed because of the interaction of primary pollutants).

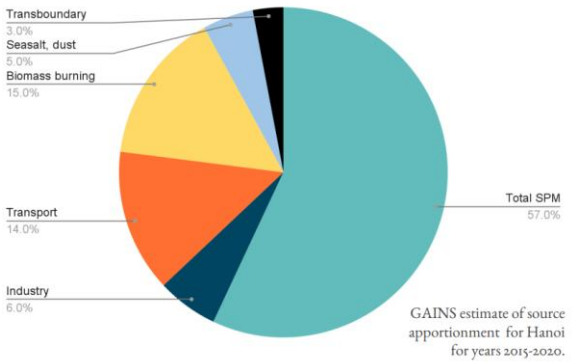


Figure 1. Estimates of Particulate Matter Source Apportionment, 2015-2020 (World Bank, 2021).

When evaluating the completed Hanoi inventory for advanced chemical transport simulations, structural parameters must be assessed to determine whether atmospheric chemistry is technically feasible or meaningful. The current inventory isolates criteria compounds (PM_{10}, $PM_{2.5}$, SO_2, NO_x, CO) but excludes volatile organic compounds and non-methane hydrocarbons (VOCs/HCs) for certain area and point categories. This data gap introduces challenges for atmospheric chemistry simulations:

A. The Photochemical Ozone (O_3) Limitation

Photochemical atmospheric chemistry models rely heavily on the non-linear relationship between nitrogen oxides (NO_x) and reactive organic gases (VOCs/HCs) to simulate the hydroxyl radical (OH) oxidation reaction chain. This pathway drives the formation of ground-level ozone (O_3) and secondary organic aerosols (SOA). Because hydrocarbons are omitted from this municipal data, the VOC/NO_x ratio inside the model calculation will be incomplete.

Full photochemical ozone simulation would be highly uncertain without complete VOC and hydrocarbon speciation. Therefore, ozone-related results should be interpreted cautiously unless additional VOC emission inputs are developed. The chemical transport software cannot accurately solve the photolytic chemical balance, leading to severe underpredictions or false sensitivities in secondary O_3 generation.

B. Secondary Inorganic Aerosol (SIA) Chemistry

In contrast to volatile organic reactions, simulating secondary inorganic aerosol pathways—specifically the chemical oxidation of gas-phase precursors into particulate sulfate (SO_4-), nitrate (NO_3-), and ammonium (NH_4+) complexes, remains technically viable. The Hanoi inventory provides complete, disaggregated source streams for SO_2, NO_x, NH_3 and solid fuel area indicators. Therefore, chemical transport platforms can compute inorganic equilibrium modules (e.g., ISORROPIA II). This allows for the reliable modelling of secondary particulate loading, which is critical for policy formulation.

C. Geographic Boundary Context

The spatial domain of the municipal inventory is bound within the administrative limits of Hanoi City. Key ambient components, such as background regional haze and transboundary particulate fare driven by regional chemical processing outside the city boundaries. Executing standalone local grid chemistry is, therefore, less meaningful unless the inventory is embedded within a broader regional nested modelling framework (e.g., WRF-CMAQ at 9 km resolution). This larger structure uses global reanalysis datasets (such as CAMS or GEOS-Chem) to supply incoming chemical boundary parameters, allowing local chemical simulations to remain robust and contextually accurate.

3. OPTIMAL ATMOSPHERIC DISPERSION MODELING PLATFORM SELECTION

3.1. Evaluating System Capabilities Relative to Sourced Data Metrics

Selecting an appropriate numerical modelling platform requires aligning the software's mathematical capabilities with the spatial resolution and chemical limitations of the completed emission inventory.

Model selection should be based on clearly defined criteria, including chemical mechanism capability, spatial resolution, source apportionment functionality, treatment of near-road gradients, boundary condition compatibility, computational feasibility, and flexibility for policy scenario analysis.

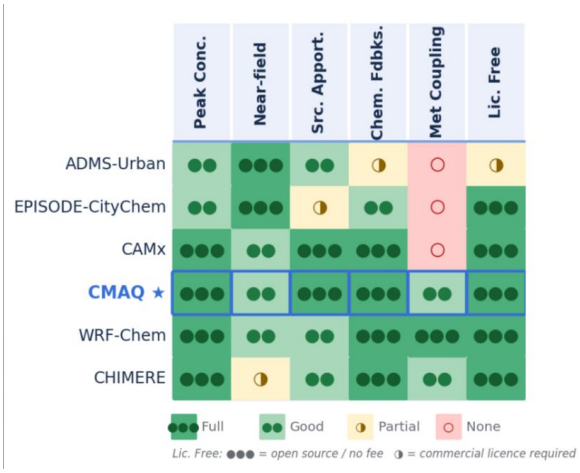
Hanoi's urban airshed features distinct traffic patterns and strong seasonal background pollution. To support urban policy planning, the platform must balance local street-scale gradients while tracking macro-level transboundary transport fields.

Furthermore, the data boundaries of the inventory, specifically the exclusion of detailed volatile organic compound and non-methane hydrocarbon datasets (VOCs/HCs) for certain area and point sectors, impose constraints on the choice of modelling architecture. Traditional multi-pollutant grid systems that rely on full photochemical reactions to simulate local ozone (O_3) dynamics become technically limited under these parameters, as the missing hydrocarbon components skew the photochemical balance. However, since the multi-sectoral inventory provides disaggregated municipal output grids for primary criteria particulates (PM_{10}, $PM_{2.5}$) and inorganic gas-phase precursors (SO_2, NO_x, CO, NH_3), selecting a platform that balances primary dispersion calculation alongside secondary inorganic aerosol (SIA) transformations is paramount.

3.2. Comparative Analysis of Available Simulation Suites

To identify the most viable platform for Hanoi's context, six prominent simulation suites were evaluated across key operational objectives. The comparative evaluation metrics are structured in Table 1:

Table 1. Capability Matrix and Technical Comparison of Urban Dispersion Platforms



While specialised local suites like ADMS-Urban provide excellent near-field line calculations, they require distinct, independent meteorological inputs and cannot dynamically incorporate the broader regional backgrounds that heavily influence Hanoi's airshed. Conversely, while WRF-Chem has excellent inline meteorological coupling, it does not support sub-grid roadside transformations or runtime source sector tagging, requiring completely separate model runs to isolate individual source categories.

As mapped out in Table 1, the CMAQ (v5.4) platform delivers the most versatile combination of software capabilities to satisfy Hanoi's air quality management strategy objectives.

Finally, it is understood that some limited airshed

modelling work has recently been completed using the French model, CHIMERE. CHIMERE is considered to be inferior to CMAQ in two key areas; near-field impacts and source apportionment:

- Near-field: CMAQ incorporates RLINE as an operational sub-grid module that computes near-road concentration gradients within each grid cell, accounting for vehicle-induced turbulence and roadway geometry, alongside Plume-in-Grid (PinG) which tracks industrial stack plumes as individual Lagrangian puffs until they dilute to grid scale. CHIMERE has neither. It is a purely Eulerian grid model that instantaneously dilutes all emissions — from roads and stacks alike — into the full volume of whichever grid cell they fall in. At 3 km resolution (such as the current resolution of the Hanoi emission inventory) this means near-road concentrations are underestimated and near-stack chemistry is misrepresented, particularly for the NO_x-rich near-source regime where ozone titration is most intense.
- Source apportionment: CMAQ's Integrated Source Apportionment Method (ISAM) performs inline sector tagging within a single model run, simultaneously attributing $PM_{2.5}$, NO_2, and O_3 concentrations to multiple source sectors — transport, industry, residential combustion, open burning, trans-boundary — with full chemical mechanism consistency throughout the simulation. Unlike CMAQ-ISAM, CHIMERE applications commonly rely on scenario-based sensitivity simulations for source contribution analysis, which may be computationally more demanding and less applicable for nonlinear secondary pollutants. Source apportionment in CHIMERE relies on running the model repeatedly with emissions from each sector switched off and differencing the results against the baseline. This is computationally expensive (requiring one additional full model run per source sector), and for secondary pollutants such as ozone and secondary inorganic aerosols, the non-linearity of atmospheric chemistry means that zeroing out one sector's emissions changes the chemical environment for all others, making the attributed contributions sensitive to the order and combination of sectors removed. ISAM avoids this problem by propagating sector tags through the chemical mechanism analytically in a single pass, producing more robust and internally consistent apportionment — particularly important for Hanoi where multiple large source categories interact chemically in a congested urban airshed.

3.3. Multi-Scale Nested Grid Architecture with CMAQ

Implementing CMAQ for Hanoi utilises a robust, multi-scale nested grid design driven by weather data from the Weather Research and Forecasting (WRF) model. A typical configuration may be:

- Domain 1 (9 km Resolution Regional Grid): Extends across Southeast Asia and Northern Vietnam to track long-range regional chemistry and

transboundary pollution transport.

- Domain 2 (3 km Resolution Intermediate Grid): Covers the Red River Delta, functioning as a smooth meteorological nesting stepping stone.
- Domain 3 (1 km Resolution Municipal Grid): Mapped over Hanoi's urban core to handle full atmospheric chemistry and execute specialised sub-grid modules:
  1. RLINE Sub-Grid Model: Explicitly simulates vehicle-induced turbulence and road geometric configurations for near-road pedestrian exposure mapping.
  2. Plume-in-Grid (PinG) Module: Tracks large industrial point sources as individual Lagrangian puffs, preserving near-stack nitric oxide (NO) titration of ozone (O_3) until the plume dilutes into grid scales.

5.4. Informing Policy Interventions using CMAQ Modules

The operational advantage of the open-source US EPA CMAQ suite stems from its extension modules, which directly address Hanoi's clean air policy demands:

- Integrated Source Apportionment Method (ISAM): Tags emissions by sector at runtime. This approach isolates and quantifies the exact contribution of motor vehicles, industrial operations, power generation, residential combustion, and transboundary pollution to ambient $PM_{2.5}$ fields at every location.
- Detailed Emissions Scaling (DESID): Allows users to selectively scale or adjust emission inputs by sector, species, and region at runtime, based on specific policy scenarios. Regulators can simulate specific mitigation controls, such as implementing alternative transport or replacing outdated engines, without reprocessing the entire master inventory.
- Decoupled Direct Method (DDM): Automatically computes analytical sensitivity coefficients, calculating the precise change in ambient $PM_{2.5}$ per unit change in primary source emissions to identify the most effective air quality management interventions.

6. CONCLUSION

The implementation of Hanoi’s first comprehensive multi-sectoral atmospheric emission inventory establishes a foundational regulatory baseline for the city's environmental governance.

Based on the parameters and geographic limits of the finalised data, an open-source, multi-scale nested WRF-CMAQ system represents the optimal modelling architecture for Hanoi. Although gas-phase ozone modeling is structurally constrained by the current lack of complete hydrocarbon speciation, the WRF-CMAQ framework excels at tracking primary particulates and calculating secondary inorganic aerosol (SIA) oxidation pathways—compounds that comprise a major portion of Hanoi's winter PM mass. Utilising runtime extension modules like ISAM and DESID allows policy makers to execute analytical sensitivity checks and scale targeted emission interventions directly without reprocessing the entire master inventory.[

Ultimately, this integrated project will act as a vital tool for environmental policy validation, providing the necessary scientific infrastructure to support Hanoi's Clean Air Action Plan.

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