MULTI-SECTOR ATMOSPHERIC EMISSION INVENTORY FOR HANOI, VIETNAM

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), Vietnam

Abstract

Hanoi continues to face severe air quality challenges, frequently exceeding WHO guidelines for fine particulate matter less than 2.5 micrometres 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 high-resolution, multi-sectoral atmospheric emissions inventory. A hybrid "top-down" and "bottom-up" approach was employed. Activity data were gathered from municipal statistics, traffic counts, and industrial surveys, while local emission factors were applied to represent the unique vehicle fleet (dominated by motorcycles) and the prevalence of agricultural residue burning.

This emission inventory has allowed local regulators to prioritise air quality management activities as it contextualises the sector contributions to total $PM_{2.5}$ emissions. It has been revealed that there are multiple contributions to the current particulate matter burden within the city, including the most visible contributors (2-wheeled motorised transport), as well as industry and power generation. It also highlights the contributions from other airsheds, including regional haze and transboundary pollution. This paper presents the state of the current emission inventory, the insights that it reveals, and suggests next steps for air quality management in this airshed.

This is Part A of a two-part paper series. Part B provides commentary on best practice for city-wide atmospheric dispersion modelling, noting the strengths and weaknesses of the current emission inventory.

Keywords: Hanoi, Emission Inventory, Source Apportionment, Clean Air Action Plan.

1. Introduction

1.1. Air quality context in rapidly developing Southeast Asia

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 in developing Southeast Asian economies. Ambient concentrations of $PM_{2.5}$ routinely fail to satisfy international and national standards within major metropolitan centres, resulting in respiratory illnesses, cardiovascular complications, and premature mortality across large populations. Industrial activity and seasonal transboundary biomass open burning provide a regional background, while poorly regulated urban vehicle fleets contribute to urban airshed degradation. Tackling, and ultimately managing, this situation requires going beyond ambient air monitoring toward the use of robust and effective environmental governance tools.

1.2. Air quality in Hanoi

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 cannot keep pace, Hanoi faces chronic, severe fine particle pollution. The magnitude and extent of the $PM_{2.5}$ challenge in Hanoi relative to other regions of Vietnam is illustrated in Figure 1.

Annual average ambient $PM_{2.5}$ concentrations within the municipal territory have historically hovered between 46 µg/m^3 in urban locations and up to 49 µg/m^3 adjacent to primary transport corridors. It is estimated that 40% of the total population (3.2 million) in Hanoi were exposed to concentrations exceeding 45 µg/m^3 (World Bank 2021).

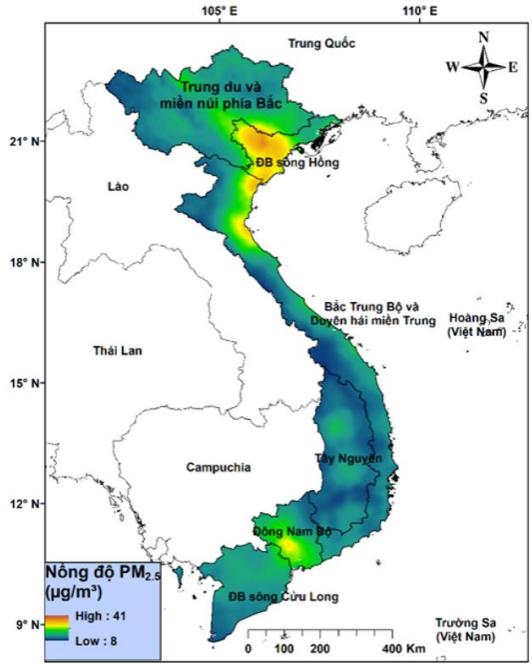


Figure 1. Annual average $PM_{2.5}$ concentrations across Vietnam, 2021 (VNU-UET, Live & Learn & USAID 2021).

These values are consistently above Vietnam's national ambient technical regulations (25 µg/m^3 under QCVN 05:2023/BTNMT) and exceed the updated World Health Organization (WHO) annual guideline limit of 5 µg/m^3 by an order of magnitude.

1.3. Source data availability

Previous atmospheric assessment frameworks in Vietnam have frequently relied on coarse regional or global gridded emission inventories (such as REAS or EDGAR-HTAP) scaled at broad macro-resolutions (>1 km). These generalised top-down profiles allocate source loads using global spatial proxies, such as population count maps, which fail to capture unique, hyper-local urban realities. Most notably, global proxies cannot accurately model the unique structure of Vietnam's urban transportation sector, without local adjustment, where two-wheeled motorised vehicles comprise over 90% of the active operating fleet. Many of these motorcycles use outdated engine standard tiers (pre-Euro, Euro 1, and Euro 2 setups), exhibiting high real-world emission rates that are systematically undervalued by unadjusted global default emission factors.

1.4. Hanoi's air quality legislation

In response to these baseline data constraints and worsening public health indicators, the People's Committee of Hanoi City officially issued Decision No. 1142/QĐ-UBND, codifying the city's comprehensive Air Quality Management Plan to 2030. This administrative mandate establishes an aggressive, legally binding governance target: implementing coordinated inter-sectoral mitigation initiatives to achieve a 20% reduction in annual average ambient $PM_{2.5}$ concentrations by the year 2030.

1.5. Hanoi's multi-sectoral inventory

To guide this policy, the city has commissioned an integrated, hybrid top-down and bottom-up data framework. This includes systematically combining municipal statistics databases with automated traffic surveillance camera counts, specialised household energy surveys, local agrarian crop metrics, and in-stack continuous emissions monitoring to construct Hanoi's first high-resolution, multi-sectoral gridded emissions. 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.

2. Emission inventory architecture

2.1. Top-down emission estimation

Top-down inventory estimation derives total emission loads for an entire administrative or geographic sector by multiplying high-level aggregate activity datasets by generalised default emission factors (EFs). Activity indicators typical of this framework include macro fuel parameters, such as total municipal sales records for petroleum products or national industrial coal consumption. Once macro-scale pollutant loads are established, spatial allocation algorithms are applied to distribute these emissions into sub-regional or grid cells. This downscaling process relies on spatial proxies or surrogates, such as gridded population density maps, land-use classifications, or basic total road link networks.

Top-down emission inventories typically use minimal administrative resources and provide a fast, cost-effective method to estimate broad pollutant distributions. However, they have significant

limitations when applied to fine street-scale dispersion modelling.

2.2. Bottom-up emission estimation

A bottom-up approach constructs atmospheric emissions profiles by tracking individual, highly spatially resolved source activities. This methodology calculates total municipal pollution fields by aggregating data from single emitting units or detailed grid components.

In the bottom-up approach, emissions are calculated for individual sources or activity units and then aggregated: $E = \Sigma(A_i \times EF_i \times C_i)$, where C_i represents control efficiency, fuel characteristics or technology-specific correction factors.

Bottom-up parameters trace specific micro-level factors:

- Point Sources: Continuous emission monitoring systems (CEMS) streams from stack monitors, physical source sampling, and technology-specific fuel configurations.
- Mobile Sources: Dynamic vehicle counts per hour, link-specific travelling velocities, vehicle kilometres travelled (VKT), and vehicle compositions.
- Area Sources: Field surveys, questionnaire interviews, and operational tracking parameters specific to distinct communities.

The bottom-up estimation method offers high reliability, precise spatial attribution, and high temporal resolution. However, executing a complete bottom-up inventory is highly resource-intensive, demanding extensive manual data collection and field work.

2.3. The hybrid inventory

Given the practical data constraints in developing city contexts, a balanced approach is required. This combines the broad coverage of top-down parameters with the precise detail of bottom-up inventories.

In a hybrid (or “sandwich”) framework, major emission sectors (such as large-scale fossil-fuelled power utilities or primary arterial transit rings) apply bottom-up tracking driven by telemetry or road camera datasets. Concurrently, smaller, scattered sub-sectors (such as residential domestic cooking) utilise top-down macro indicators, allocating fuel or product sales statistics across grids. This hybrid inventory approach ensures complete sectoral coverage, allowing municipal authorities to construct high-resolution gridded emission geodatabases under constrained budgets.

For the Hanoi inventory, a hybrid approach was adopted by applying bottom-up methods to major and data-rich sources, such as traffic links and large point sources, while top-down allocation was used for dispersed or data-limited sources, including residential combustion and open burning.

3. Source types

3.1. Mobile sources (transportation)

A bottom-up data processing framework was developed for the road-traffic sector using open-access geographical information. Explicit line sources within the study area were established by extracting the municipal road network infrastructure from OpenStreetMap (OSM) spatial vectors. This structural network was filtered to include only major regional roadways (specifically motorways, trunk links, primary roads, secondary arterials, and tertiary collector streets) while non-motorised infrastructure and residential pathways were excluded. Road geometries, car-lane counts, and canyon widths were defined by cross-referencing OSM metadata fields with national building height constraints and construction standards. Tunnels and bridge overpasses were integrated into the spatial domain based on layer attributes and traffic direction tags.

To determine hourly source intensity, traffic counts and fleet profiles were synthesised across all main road types from four municipal projects and technical studies. Hourly emissions were estimated by combining road-link activity, fleet composition, vehicle-specific VKT, speed-dependent emission factors and temporal profiles differentiated by weekday, weekend and restricted freight vehicle access periods.

The vehicle population was classified into five target categories: two-wheeled motorcycles (MC), personal cars, buses/coaches, light duty vehicles (LDV), and heavy-duty vehicles (HDV). Diurnal traffic variation profiles were mapped for each vehicle category using continuous historical tracking databases. While motorcycles represent the dominant urban transit class, often exceeding 90% of total vehicle volume, regulatory vehicle traffic management schemes in Hanoi ban heavy freight vehicles from entering the inner-city core during peak hours. This creates an inverted, night-dominant traffic flow profile for the HDV category. Average vehicle populations and travel habits were parameterised across the network, assuming constant daily vehicle kilometres travelled (VKT) for individual types.

Vehicular emission factors (EF) for criteria pollutants were assigned by fuel type, vehicle category and emission standard, using locally available measurements where possible and internationally recognised emission factor databases adjusted to

Vietnamese fleet characteristics where local data were unavailable.

3.2. Stationary sources (industrial point & power generation)

The stationary source inventory was developed by establishing a master point registry of industrial manufacturing installations and utility operations across the inventory domain.

Detailed field audits and engineering surveys were conducted across 50 major industrial installations. These installations were prioritised based on emission potential, fuel use, technology type, spatial distribution, and sectoral representativeness.

Sourced parameters tracked technological configurations, clinker kiln designs, stack location coordinates, and combustion fuel consumption rates. Continuous Emissions Monitoring Systems (CEMS) were cross-referenced to extract real-world concentrations, hourly volumetric exhaust gas flow rates, and true operating temperatures directly from the stacks. CEMS data were screened using QA/QC procedures, including checks for missing values, outliers, abnormal operating conditions and consistency between concentration, flow rate and operating hours.

For remaining minor facilities, emission estimates were calculated by combining activity indicators from secondary environmental reports referencing the Japan International Cooperation Agency (JICA) and regional manuals.

3.3. Area sources (domestic, agricultural, craft villages and fugitive emissions)

Area sources comprise smaller, geographically dispersed activities that collectively introduce criteria pollutant loads into Hanoi's airshed. To address these highly unmapped contributions, localised data were established for individual sub-sectors:

- Domestic Cooking and Residential Combustion: Fuel selections (liquefied petroleum gas (LPG), kerosene, charcoal briquettes, or raw biomass) were disaggregated by urban and rural zones.
- A household survey of these 400 samples was designed using Yamane’s formula, with stratification between urban and rural districts to capture differences in fuel use, cooking behaviour and residential combustion patterns.
- Agricultural Open Biomass Burning: Field burning of crop residue post-harvest (specifically rice-straw combustion) represents a major area source during harvest seasons. Total residue fuel mass was computed by linking seasonal crop acreage and crop yield indices with land-use maps and quality checks derived from agricultural survey datasets.
- Mixed Infrastructure and Fugitive Dust: Civil engineering projects, building construction, and commercial operations were parameterised by tracking ongoing building floor area metrics and project schedules. Fugitive dust from local mining and quarries were compiled via targeted field audits across five primary operating facilities, tracking open processing zones and heavy vehicle operations. Finally, open municipal solid waste burning was parameterised via population density data and unmanaged waste generation metrics.
- Surveys were completed of 20 targeted sites among Hanoi's 1,350 registered historic craft communities that are characterised by low fuel efficiency and weak control technologies. Craft villages were selected to represent major production types, fuel-use intensity, control technology status and potential emission significance within Hanoi’s registered craft village system.

4. Findings and conclusions

The transportation sector is expected to be a major contributor to urban emissions. Its relative importance should be quantified through model-based source apportionment. The data highlights that particulate matter management cannot focus on mobile fleets alone. Industrial processing / combustion account for a significant portion of criteria pollutant emissions, while area sources generate significant particle pollution. Furthermore, the role of transboundary pollution transport and regional haze are anticipated to heavily influence ambient urban PM concentrations during the stable atmospheric conditions of the winter monsoon.

The implementation of Hanoi’s first comprehensive multi-sectoral atmospheric emission inventory establishes a foundational regulatory baseline for the city's environmental governance. The inventory approach demonstrates a reproducible and flexible framework to overcome the persistent challenges of data scarcity in resource-constrained environments. Combining a hybrid top-down and bottom-up data integration approach enables the successful quantification and spatial grid mapping of primary criteria pollutants at a localised resolution across the municipal territory.

Key areas of uncertainty found when building the inventory include:

- Activity data (reliance upon limited survey data for residential and craft village emissions)
- Emission data (CEMS data may not be reliable, vehicle emissions data may require additional tuning to local conditions)

- Spatial resolution (Area source spatial disaggregation is at 3 km x 3 km).

This study has several limitations. First, incomplete VOC and NH_3 emission data constrain the reliability of ozone and secondary aerosol simulations. Second, several dispersed sources rely on top-down allocation and survey-based assumptions. Third, uncertainty quantification and model validation should be strengthened in future work. Future work should focus on improving VOC and NH_3 inventories, developing chemical speciation profiles, conducting uncertainty analysis, validating modelled concentrations against monitoring data and implementing source apportionment and emission reduction scenario simulations.

The inventory is the first step in a wider tool box to build the Hanoi air quality management plan (Part B of this paper). The other tools needed to inform the Hanoi air quality management plan include:

- Atmospheric chemistry
- Atmospheric dispersion modelling
- People exposure estimates

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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