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Street-scale dispersion modelling framework of road-traffic derived air pollution in Hanoi, Vietnam

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ABSTRACT

Traffic is an important source of air pollution in Vietnamese cities. The spatio-temporal variation of air pollution derived from traffic is poorly understood. Application of dispersion modelling can help but is hindered by the local scarcity of suitable input data. This study fills the data gap, by establishing a framework employing open-access global data to model emission from traffic activities in Hanoi. The outlined methodology explicitly defines road sources, calculates their emission, and employs background pollution profiles from Copernicus Atmospheric Monitoring Service (CAMS) to produce street-scale distribution maps for CO, PM_{10} and $PM_{2.5}$. Pollution hotspots are found near major traffic flows with the highest hourly average CO, PM_{10} and $PM_{2.5}$ concentrations at 1206, 87.5 and 61.5 μgm^{-3}, respectively. The relationship between concentrations and properties of the road network is assessed. Motorcycles are the main emitters of the traffic sector. Emission from Heavy Good Vehicles dominate during the night, with contribution percentages increase as it gets further away from the city core. Modelled concentrations are underestimated mainly due to low vehicular emission factor. Adjusting emission factors according to vehicle quality in Vietnam greatly improves agreement. The presence of non-traffic emission sources contributes to the model underestimation. Results for comparisons of daily averaged PM values are broadly in agreement between models and observations; however, diurnal patters are skewed. This results partly from the uncertainties linked with background pollution levels from CAMS, and partly from non-traffic sources which are not accounted for here. Further work is needed to assess the use of CAMS's concentrations in Vietnam. Meteorological input contributes to the temporal disagreement between the model and observations. The impact is most noticeable with CO concentrations during morning traffic rush hours. This study recommends approaches to improve input for future model iterations and encourage applications of dispersion modelling studies in similar economic settings.

1. Background and motivation

Poor urban air quality is a pressing concern for the Government of Vietnam as the country is routinely ranked among the most polluted globally. Vietnam was ranked 170th out of 180 countries by the 2018 Environmental Performance Index (Nhung et al., 2020). Hanoi, the capital, is the most polluted city in Vietnam (Hien et al., 2022a) and the 15th worldwide (IQAir., 2021). According to the Ministry of Natural Resources and Environment (2016), the main contributor to air pollution in Vietnam is rapid motorisation, with road-traffic activities taking up 70% of total emissions. Motorcycles (MC) dominate the vehicle fleet in Vietnam by number. These increased by approximately 400% between 1996 and 2006 (Huynh and Gomez-Ibañez, 2017). MC and personal cars' current annual growth rate is 16% and 20%, respectively (Trang et al., 2015). As a result, 60,000 deaths annually in Vietnam are linked to exposure to air pollution (Loan, 2018). Financially, respiratory illnesses cause Hanoi an annual loss of 20 million USD.

As a response to poor air quality, additional legislation and target standards have been put in place (Ministry of Natural Resources and Environment, 2021). Alongside this, monitoring has been implemented or where already available upgraded . In addition, specific actions to

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Abbreviations

ADMS	Atmospheric Dispersion Modelling System
CAMS	Copernicus Atmosphere Monitoring Service (CAMS)'s Global Atmospheric Composition Forecast Dataset
CERC	Cambridge Environmental Research Consultants
EF	Emission factor
EFT	Emission Factor Toolkit
GFS	NCEP's Global Forecast System
HCMC	Ho Chi Minh City
HD	Hang Dau station (part of HEPA network monitoring)
HEPA	Hanoi Environmental Protection Agency
HGV	Heavy Good Vehicle
LGV	Light Good Vehicle
MC	Motorcycle
NAEI	UK's National Atmospheric Emission Inventory
TY	Trung Yen station (part of HEPA monitoring network)

reduce emissions from the road-traffic sector were identified. These actions were to upgrade the vehicle fleet, regulate and improve fuel quality and upgrade national traffic infrastructure (Ministry of Natural Resources and Environment, 2016). However, due to limited in-country observational capability, e.g., up to 2016, there are only 17 air quality monitoring stations across the country (Duc et al., 2016), there is little or no evidence to use to assess the effectiveness of these or any other mitigation activities. This lack of an evidence base also limits the ability to undertake human exposure analyses (Nhung et al., 2020; Thuong et al., 2022).

2. Introduction

The use of air quality modelling to produce spatially and temporally resolved concentration fields for the study of emissions, pollution levels and pollutant transport is widely used for regulatory purposes and research (Holmes and Morawska, 2006; Tiwary and Colls, 2010). However, highly spatially and temporally resolved dispersion modelling is input intensive for heterogeneous environments. This is especially true for street-scale studies in an urban setting where rapid changes in pollutant levels are routinely encountered (Forehead and Huynh, 2018; Hood et al., 2018; Phuc and Oanh, 2018). This requirement for detailed a priori information is a challenge in developing economies where the infrastructure for collecting, collating and archival of this data is often limited and, even when available, is difficult to access. Critical information on fleet composition, road links, emissions by sector, detailed meteorological parameters and the atmospheric composition baseline values for required pollutants is needed but often absent (Fallah Shorshani et al., 2015; Ho, 2017; Shi et al., 2019).

Some dispersion models have been used to investigate air quality in urban areas of Vietnam (Nguyen et al., 2020; Vu et al., 2020; Bang et al., 2019; Amann et al., 2019). The results of these studies are difficult to apply to street-scale urban traffic management/planning or in assessing human health impact due to their relatively low spatial resolution (i.e., grid cells >1 km). Box models have been employed alongside regional modelling to improve output detail and calculate pollutants concentration within street canyons (Hung et al., 2010). However, the application of box models is limited to the simulation of individual roads. It cannot be employed at larger (e.g., district, city) scales due to the limited availability of high-resolution 3D products in Vietnam. Gaussian dispersion models, such as ADMS-Urban, AERMOD or OML, are often used for street-scale modelling of urban areas, partly due to their ability to simulate dispersion from large numbers of explicitly defined sources and fast calculation time (Leelőssy et al., 2014). The OML model has shown encouraging agreement between observed and modelled concentrations derived from road-traffic in Hanoi (Hung, 2010). Similarly, good results have been produced with AERMOD in HCMC, albeit the simulated emitting source was not road-traffic in these studies (Vu et al., 2019, 2022).

In response to the local data scarcity in Vietnam, this study aims to establish a framework consisting of necessary input data to improve the modelling of the distribution of road-traffic emissions in Hanoi. This is a first step toward producing a model system using detailed emissions derived from activity data (e.g., comprehensive traffic information, biomass burning). The resulting framework uses ADMS-Urban to calculate street-scale ambient CO and particulate matter (PM) concentrations. At this stage, chemical processes are not considered to reduce the strain on the modelling framework. Owing to its weak chemical reactivity and the dominant reliance on traffic emission (Panagi et al., 2020), CO was chosen as the pilot pollutant, even though it is not a significant concern to urban Hanoi (Ministry of Natural Resources and Environment, 2021). Modelled CO concentration is the primary tool to assess the suitability of input data outlined by this study. PM concentrations from traffic are also calculated but neglect the formation of secondary PM.

Fig. 1 illustrates this work's structure. Section 3 describes the definition of the framework. Section 4 breaks down the modelled results offering new insights into the spatial distribution of pollutants concentration, and its relationship with Hanoi's traffic network. This section also compares observed and modelled pollutants concentration to evaluate the model performance and address improvement points to the model inputs, namely traffic-related emission inventory, meteorology, and background pollution profile. Finally, Section 5 summarises this work's findings, contributions, and potential applications.

3. Materials and methodology

ADMS-Urban version 4.1, developed by Cambridge Environmental Research Consultants (CERC), is a quasi-Gaussian dispersion and chemistry model that offers detailed boundary layer parameterisations for physical transport processes and a simplified chemistry scheme for fast reactions. It has been applied for regulatory and research purposes and is extensively evaluated worldwide (Hood et al., 2018; Biggart et al., 2020). This study uses ADMS-Urban to calculate ambient CO and PM concentrations produced by road-traffic at street-scale in urban Hanoi for six months (October 01, 2018–March 31, 2019). This section describes the model domain, meteorological parameters, background pollution, the definition of road-traffic emission sources, and model layers. Lastly, air quality measurements and the model evaluating methodology are specified. This work does not consider chemical reactions and road canyon recirculation, which impact the concentration gradients in the vicinity of emitting sources (Biggart et al., 2020).

3.1. Model domain

The model domain is 24 × 27 km, spanning from (20.9, 105.7) to (21.1, 106.0), as illustrated by Fig. 2. It covers the most populated districts in Hanoi yet is small enough to retain the definition of explicit roads, without exceeding ADMS-Urban's limitation of emission source count.

3.2. Meteorological inputs

Being a variant of the Gaussian plume dispersion model, ADMS-Urban assumes the wind field to be homogeneous across the model domain (Holmes and Morawska, 2006). This work, therefore, only requires 1 set of meteorological conditions. Wind direction, wind speed, surface temperature, cloud cover, time of day and day of year were inputted. Temperature and cloud cover were obtained from observations at the Noi Bai International Airport, Hanoi. These data are made available by the HadISD project, published by the UK Met Office. HadISD

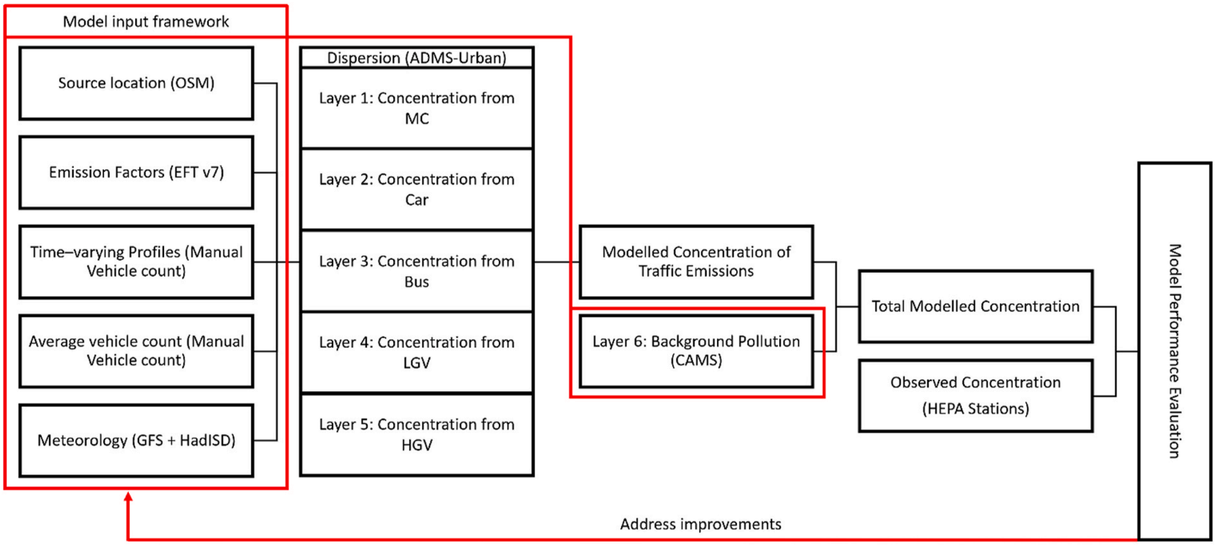

Fig. 1. Visual structure of this study's structure.

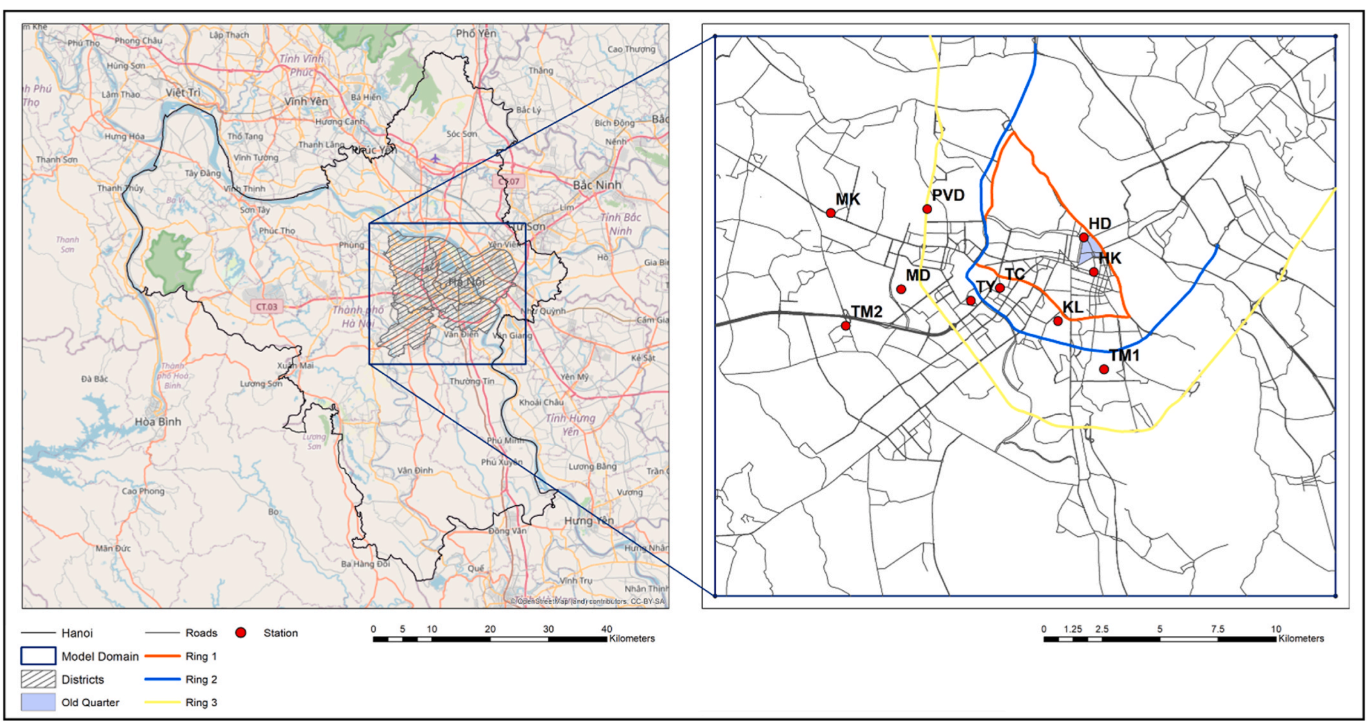

Fig. 2. Model domain and air quality monitoring stations in Hanoi. © OpenStreetMap contributors 2020. Distributed under a Creative Commons BY-SA License.

contains hourly synoptic climatological observations from over 8000 stations worldwide. Wind parameters were sourced from GFS, a weather forecast model produced by the NOAA's National Centers for Environmental Prediction (NCEP). Some dispersion models in Vietnam have employed meteorology from GFS (Dung et al., 2020; Bui et al., 2021; Le et al., 2022). GFS has a spatial resolution of 0.5° and a temporal resolution of 3 h. In this study, the GFS wind data were adapted to 1 h as input for ADMS-Urban.

ADMS-Urban offers the input of surface roughness term (Z_0), which represents the degree to which physical obstacles, such as buildings, other constructions, or vegetations, can have on wind conditions (Hood et al., 2018). Specifying Z_0 at the original location of wind data, i.e., the meteorological site, and at the desired modelling site allows the model to anticipate the differences in local surface morphology (The Met. Office and CERC, 2020). This work set Z_0 at both sites to be 1.5, a value most appropriate for large urban areas.

3.3. Background pollution

In this work, background pollution refers to any pollutants concentration that does not originate from anthropogenic sources in Hanoi. This includes emissions from natural sources and sources in neighbouring areas, especially upwind. Information on background pollution is obtained from the Copernicus Atmosphere Monitoring Service (CAMS)'s Global Atmospheric Composition Forecast Dataset (hereafter referred to as CAMS). CAMS is a modelled dataset that uses the Integrated Forecasting System (IFS) to simulate the concentrations from existing global emission datasets, namely Emissions Database for Global

Atmospheric Research (EDGAR) and Community Emissions Data System (CEDS) (Elguindi et al., 2020). The modelled result is assimilated with observations from satellites such as Moderate Resolution Imaging Spectroradiometer (MODIS) (Rémy et al., 2019), aiming to accurately forecast pollutants concentration and atmospheric conditions across the globe. CAMS's concentrations are highly valuable to developing countries with poorly understood regional pollution fields (Becker et al., 2021; Filonchyk and Peterson, 2022; Mohammadpour et al., 2022). As for studies in Vietnam, Bui et al. (2021) employ CAMS's emission data to address the relationship between emission, health and economic impacts. Additionally, IFS is used by the European Centre for Medium-Range Weather Forecasts (ECMWF) and offers essential parameters such as planetary boundary layer height, which has been employed as meteorological input by Hien et al., 2022b.

CAMS's concentration has a spatial resolution of 0.4° and 60 vertical pressure levels. Due to the nature of this work, only pollutants concentration at the surface, i.e., pressure = 1000 hPA, are used. Hourly PM concentration is available. CO, however, is only available at 3-h intervals. Fig. S1 shows the location of twelve CAMS's grid points closest to the model domain. Data from points too close to the model domain are ignored (points 5 and 8 in Fig. S1) to avoid double counting road-traffic emissions. Each of the remaining ten points is allocated with a section of 36°. At each hour, wind direction is used to find the corresponding point. Data at that point are then selected as the upwind pollutant's concentration and, thus, background pollution at that hour. For example, because Hanoi is most susceptive to south-eastern winds, CAMS point 12 contributes the most to the background pollution.

3.4. Road source, temporal variation of emission and model layers

Geographical data from OpenStreetMap (OSM) were used to define the location of explicit road sources in Hanoi. Being detailed and readily available, OSM fits the objective of overcoming data scarcity and has been widely used in similar research, e.g., by Biggart et al. (2020).

Road emission is a challenging input since both the in-use fleet population and vehicular emission factor (EF) are not well documented in Vietnam, similar to other developing countries (Roy et al., 2021; Azhari et al., 2021). This work reuses and collates traffic counts from previous studies to produce a quality, uniform, and detailed dataset of the fleet population in Hanoi. This method avoids conducting manual vehicle counting, which is expensive, time-consuming, and laborious (Bang, 2018). Traffic count data were sourced from four projects: Japan International Cooperation Agency (JICA) and Hanoi People's Committee (2007); Japan International Cooperation Agency (JICA) and Vietnam Ministry of Transport (2010); Phuc and Oanh (2018); Ho et al. (2020). Data were then sorted into a standardised classification system, which consists of four road types, including Motorway, Primary, Secondary, and Tertiary, and five vehicle types, including MC, Car (<12 seats), Bus (>12 seats), Light Good Vehicle (LGV) (<3.5 tonnes), and Heavy Good Vehicle (HGV) (>3.5 tonnes). Table S1 shows the resulting hourly average vehicle count. Due to insufficient traffic data, this study ignores the differences in vehicle count between weekdays and weekends. Regarding road-traffic EF, this work uses ADMS-Urban's integrated Emission Factors Toolkit (EFT) v7.0 issued by UK Defra. According to Hien et al. (2022a) and Oanh et al. (2012), the majority of the MC fleet in Vietnam (93–99%) have 4-stroke engines. This agrees well with the fleet composition defined in the EFT v7.0, in which 4-stroke engine accounts for 89% and 100% of MC in urban and rural areas, respectively. The unit for road-traffic EF is g km^{-1} s^{-1} $vehicle^{-1}$. As an example, Table S4 shows the calculated EI (unit = g km^{-1} s^{-1}) for a single road in Hanoi.

Hanoi bans HGV from operating in the urban core during rush hours. Similar urban traffic management plans are imposed in Beijing (Biggart et al., 2020) and Bangkok (Chalermpong et al., 2021). This creates an intriguing set of different vehicle count diurnal variations, in which MC, being the dominant fleet, has sharp gradients, while HGV exhibits an inverted pattern (Fig. S2). This work comprised five modules, one for each vehicle category, to evaluate the emission contribution of vehicle classes. All five modules simulate concentrations at the same specified points. The results would then be combined as layers to produce the modelled concentrations of traffic emissions, without background pollution. This method of layering model results is only possible because chemistry reactions are ignored; thus, background pollution information is not required to define the initial conditions. As such, background concentrations are added at the end, as the sixth layer, to produce the total modelled concentration field. This is the quantity most comparable with observations.

3.5. Hourly air quality measurements and model performance statistics

This work has access to air quality data from ten roadside monitoring stations in Hanoi, managed by the Hanoi Environmental Protection Agency (HEPA) (Nam et al., 2018). Table 1 lists the name and location of HEPA stations, assisted by Fig. 2. The model performance evaluation is conducted using observations from these stations. The model explicitly defines receptor points using the coordinate of HEPA stations, allowing a direct comparison between modelled and the corresponding observed concentrations. Additionally, one of the HEPA stations, TY, offers meteorological measurements, including surface temperature, relative humidity, wind conditions and solar radiation. This study uses these data to evaluate the accuracy of the framework's meteorological configuration, described in Section 3.2.

Lastly, Table S2 lists the statistical measures used in this work to evaluate the model performance by comparing against concentrations at monitoring stations for the modelling period. *NMSE* (ideal value = 0), quantifies the overall model accuracy. *Fb* (ideal value = 0), indicates the tendency of overestimation or underestimation compared to the observed values. Correlation Coefficient, *R* (ideal value = 1), measures the degree to which modelled and observed values are linearly associated. *Fac2* (ideal value = 1), is the percentage of modelled concentrations within a factor of two of the corresponding observed values.

4. Results and discussion

4.1. Modelled street-scale concentration field

Fig. 3 shows long-term averaged concentrations of modelled CO, PM_{10} and $PM_{2.5}$. Hotspots form distinctly along key roads, such as the 2nd and 3rd Ring, and major cross-city routes. Junctions are especially prone to higher concentrations. Within the 1st Ring, pollution levels remain moderate, except for the tourism-heavy Old Quarter. These results align with Hanoi's urban planning scheme. Since 2008, the 1st Ring has marked a cultural conservation area that restricts new developments (e.g., road expansion) and aims to be equivalent to the EU's low-emission zones. Many minor roads converge near the Old Quarter, resulting in high modelled concentrations at HK and HD (Table S3). The highest modelled concentrations in Hanoi are 1206, 87.5 and 61.5 μgm^{-3} for CO, PM_{10} and $PM_{2.5}$, respectively. These values appear near

Table 1
Air quality measuring stations.

Name	Location	Latitude (°N)	Longitude (°E)
TY	Trung Yen	21.015	105.800
MK	Minh Khai	21.049	105.742
HD	Hang Dau	21.040	105.847
HK	Hoan Kiem	21.026	105.851
KL	Kim Lien	21.007	105.836
MD	My Dinh	21.020	105.771
PVC	Pham Van Dong	21.051	105.782
TC	Thanh Cong	21.020	105.812
TM1	Tan Mai	20.988	105.855
TM2	Tay Mo	21.006	105.758

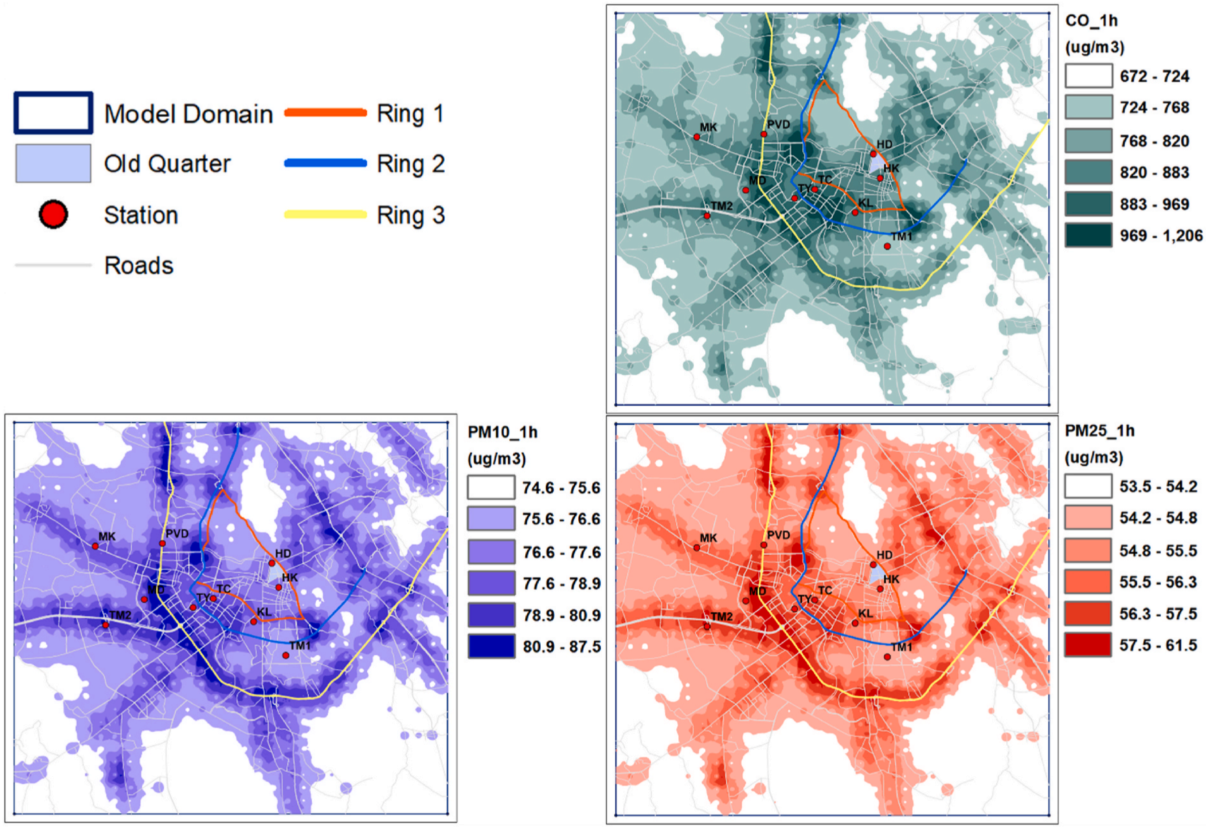

Fig. 3. Spatial maps of hourly mean modelled (a) CO, (b) PM_{10}, and (c) $PM_{2.5}$. © OpenStreetMap contributors 2020. Distributed under a Creative Commons BY-SA License.

the 3rd Ring and are similar to PM concentrations produced by the work of Luong et al. (2017), Quang et al. (2017), and Oanh et al. (2012). An ANOVA test was conducted on the modelled concentrations at stations to analyse the significance of spatial variation. Modelled CO yield a p-value of $2e^{-16}$, meaning the spatial distribution is statistically significant ($p < 0.05$). In contrast, modelled PM_{10} and $PM_{2.5}$ have p-values at 0.55 and 0.738, respectively, suggesting that the spatial variation for modelled PM is not significant. ($p > 0.05$). Fig. 3, produced based on the natural breaks (Jenks) classification, illustrates these results. As such, while the overall shapes are similar between modelled CO and PM concentration, the mapping of CO exhibits a clearer distinction between colour bands, with broader contours at low concentrations and more compact hotspots. Vice versa, the mapping of PM has lower degrees of variation between each level. Compared to the Vietnamese national ambient air quality standard (QCVN 05:2013/BTNMT), this work's modelled CO concentration stays under the regulatory threshold. PM_{10} exceeds the yearly average limit at 50 μgm^{-3}, and $PM_{2.5}$ exceeds the daily (50 μgm^{-3}) and the yearly level (25 μgm^{-3}). It is also worth noting that the Vietnamese standard is less strict than the equivalents recommended by the WHO, the EU and the US-EPA (Le et al., 2022).

The model's high detail level provides new insights into the relationship between the road network's properties and pollutants concentration. As the distance from Ring Roads increases, the modelled pollutants concentration decrease. The 3rd Ring exhibits the sharpest decay of modelled concentrations with distance, while modelled concentrations near the 1st and 2nd Rings demonstrate more gradual slopes (Fig. S3). The reason is that while the road network becomes sparse outside the 3rd Ring, the 1st Ring is surrounded by many short, crowded road segments, which allow modelled concentrations within its vicinity to stay constant. At 50 m away, modelled concentrations near the 3rd Ring decrease by 46.0, 1.4, and 0.9 μgm^{-3} for CO, PM_{10} and $PM_{2.5}$, respectively. These values are 22.5, 0.6, and 0.4 μgm^{-3} for the 2nd Ring and 16.1, 0.3, and 0.2 μgm^{-3} for the 1st Ring. The vicinity of the 3rd Ring exhibits the highest average modelled concentrations of PM, followed by those near the 2nd. For CO, the highest modelled values appear near the 2nd Ring (Fig. S3). This is because the 2nd and 3rd Ring mark the boundary of the developing zone, which contains many Trunks and Motorways. These road types have higher counts of heavy vehicles, thus producing more PM. In contrast, the inside of the 2nd Ring marks the residential area, mainly comprising Primary, Secondary and Tertiary roads. These roads have a large MC fleet and, thus, higher CO emissions. Likewise, Secondary and Tertiary roads especially have minimal PM discharges. Because the area near the 2nd Ring contains the broadest range of road categories, which correspond to the source's emission intensity, average modelled concentrations in this area have the greatest degree of variation, as shown by the wide spread of blue scatter points in Fig. S3.

Other than source strength, physical and chemical mechanisms, combined with pollutant lifetimes, determine the decay of concentrations. As a result, future models incorporating chemistry processes and physical obstacles should exhibit sharper concentration gradients as the distance from major roads increases.

The above findings are produced for the first time in Vietnam thanks to the explicit definition of road sources within the established input framework. Such detailed insights on the relationship between Hanoi's road network and concentrations at close proximity bring potent benefits to the study of human exposure and suggestions for monitoring sensor deployment. The outlined framework can also adapt to higher levels of detail by adjusting the emission of each road according to new data, such as traffic speed or real-time vehicle count, which are being developed in urban Vietnam using automated traffic cameras (Mien and Duy, 2022). Similar models can be achieved for non-traffic emission sources such as waterways defined as line sources. Despite the current weak database in Vietnam, the outlined input framework has successfully aided the modelling of traffic emission in Hanoi, made allowance for future growths and demonstrated a wide range of contributions and potential applications.

4.2. Contribution of vehicle categories

This work separately models the emission from each vehicle class (Section 3.4) and so can estimate the contribution to pollutant concentrations from specific classes, spatially and temporally. This allows evaluation of the relationship between the traffic network, its components and air quality impact. With CO at monitoring stations, the dominance of MC is apparent at 87% of modelled concentrations of traffic emissions. Likewise, the contribution of other vehicle classes shows insignificant changes spatially (Fig. S4a). Temporally, only between 22:00 and 5:00 does the CO contribution of MC drop below 80%, allowing the percentage of CO from Car, LGV and HGV to improve (Fig. S5a). However, because these vehicle categories have minimal CO emission, the modelled CO concentrations of traffic emissions during this period are low, less than 110 μgm^{-3}.

With PM, while MC is still responsible, on average, for 66% of the modelled concentrations of traffic emissions, the contribution from HGV increases as it gets further from the city centre, ranging from 5% at HK up to 17% at MK (Figs. S4b and c). Even though HGV only takes 0.7% of the vehicle fleet population, its contribution to PM dominates during the night from 0:00 to 4:00, peaking at over 60% averaged across all stations (Fig. S5b &c). At 2:00, HGV takes up to 68% of $PM_{2.5}$ concentration at stations outside the 3rd Ring. Although NO_x was not simulated in this work, because HGV can emit up to 39.2 times more NO_x than MC (estimated using EFT v7.0), these results hint at the high NO_x contribution of HGV. The significant contribution of PM from HGV, especially those that are old and outdated, has been suggested by many studies in the South-East Asia region, e.g., Myanmar (Huy et al., 2020), Thailand (Cheewaphongphan et al., 2017), and Indonesia (Lestari et al., 2022), all of which have considerable numbers of MC). The above finding, therefore, suggests that further investigations should be made toward HGV in Vietnam instead of focusing solely on MC.

Car also has notable contributions at 9 and 13% of CO and PM, respectively. However, its involvement stays relatively constant throughout the day. Overall, current findings are very comparable with those in Ho et al. (2019), such as that MC contributes 91% of yearly total traffic CO emission, whereas HGV contributes 7.5% of PM. In addition, this study's definition of road-traffic emission and the layered model structure have greatly enhanced the spatial and temporal understanding of the emission contribution of vehicle classes. Future research can implement this work's outlined model input framework to study the impact on air quality according to the changes in the vehicle fleet, namely the proposed ban of MC after the year 2030 in Hanoi.

4.3. Model evaluation

Table S3 summarises the calculated statistics of model performance. Modelled concentrations produced in this study are a tool to evaluate and improve the input for modelling road-traffic emission in Hanoi. As such, this section discusses the uncertainties that remained with the prediction, causes, and approaches to refine the input framework.

4.3.1. Impacts of vehicle quality in Vietnam to modelled concentrations

Fig. 4 illustrates the diurnal variation of background, modelled, and observed CO. Overall, the modelled CO can capture the morning and evening traffic rush hours at 7:00 and 18:00, respectively, as well as the reduced concentration during the night (22:00–4:00) and lunchtime (10:00–14:00). However, the prediction shows substantial underestimation with the averaged modelled CO concentration at 837 μgm^{-3}, 42% lower than the observed. This leads to a high *NMSE* at 2.24 and a negative *Fb* at −0.53 (Table S3). Such underestimation is caused mainly by the undervalued vehicular EF inputted to calculate the traffic emission inventory. The vehicle fleet in Vietnam has much lower quality than those in developed countries (Tung et al., 2011; Ho et al., 2020). Because this study employs EF taken from the EFT v7.0, designed for the UK's vehicles, the magnitude of modelled road source emission is lower than in reality in Vietnam. The work of Thanh et al. (2021) addresses this issue by modifying the UK's National Atmospheric Emission Inventory (NAEI) with Vietnamese vehicle quality, such as that only 63% of MC satisfies the EURO 2 standard and 75% of cars meet the EURO 4 (Ho et al., 2020). Table S4 compares emission inventory calculated using EFT v7.0 and modified NAEI. By applying appropriate inputs for vehicle quality, a single Primary road in Hanoi with a constant traffic flow speed of 35 kmh^{-1} should receive a 375% increase in CO and 170% in exhaust PM emission rate compared to the current configuration.

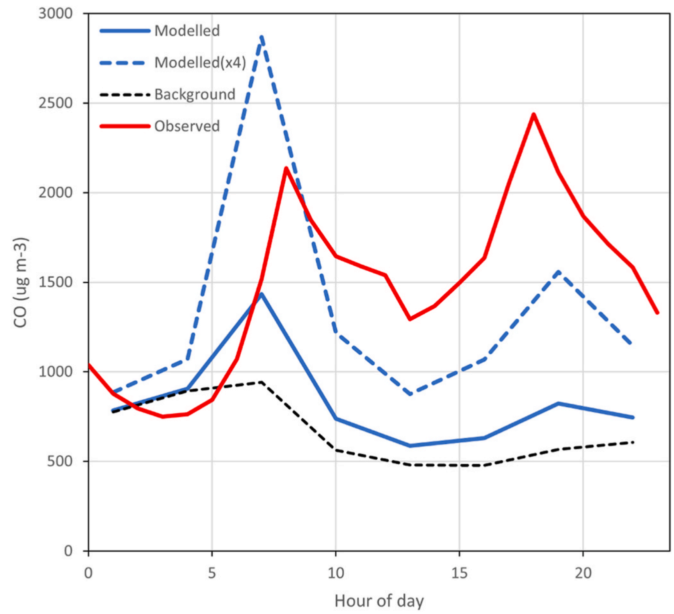

Fig. 4. Mean diurnal variation of modelled and observed CO concentrations. Modelled = modelled concentration of traffic emission + background. Modelled (x4) = 4x modelled concentration of traffic emission + background.

From the above difference in EF, modelled (x4) CO is hypothesised to equal the sum of background and four times CO concentrations from traffic. This calculation, while experimental, can illustrate the correct concentrations from traffic in Hanoi, calculated using vehicle quality appropriate EF. From Fig. 4, modelled (x4) and observed CO have similar diurnal trends, suggesting that adjusting the emission rate can improve the agreement. Still, there remain some discrepancies with diurnal variation after EF correction. The causes are the contribution of non-traffic emission sources and the impacts of meteorology. These are discussed in the following sections. As for monthly variations, although the trend of modelled CO agrees well with the observed concentrations, it is underestimated due to the low traffic emission (Fig. S6). Modelled (x4) CO benefits from the adjusted vehicular EF and has improved agreement. This encouraging result indicates that the input framework has employed a good traffic count variation baseline.

Similarly, the undervalued vehicular EF also cause underestimations with modelled PM concentrations from traffic. Modelled PM from traffic (without background) are low, peaking at 7:00 with concentrations at 7.3 and 4.7 μgm^{-3} for PM_{10} and $PM_{2.5}$, respectively. These values correspond to only 3.4 and 4.0% compared to the observed PM_{10} and $PM_{2.5}$ concentrations. With adjusted EF, the predicted PM concentration from traffic (without background) can nearly double (Table S4). This result aligns with findings from Hien et al. (2021), which estimates vehicular exhaust to contribute 8.0% of the total measured $PM_{2.5}$ concentrations in Hanoi.

While the model input framework remains in the early stages, it outlines the core pathways to improve the traffic EI in urban Vietnam. It is acknowledged that traffic EI has been studied in great detail by previous research (Tung et al., 2011). However, this work does so in conjunction with dispersion modelling applications. As such, instead of focusing on perfecting the EI, the framework allows the adoption of new information to improve the model gradually. Such novel application is essential to Vietnam, considering the current weak database and rapid rate of development.

4.3.2. Contribution of other emission sources and uncertainties with background pollution information

Even though road-traffic is an important emission source and the recognised dominant emitter of CO concentration in urban Hanoi, to achieve comprehensive, accurate distribution mapping of pollutants, developments similar to this study must be found for other, non-traffic sources. According to Nguyen et al. (2022), non-traffic sources, including agricultural, residential, commercial, and industrial, account for approximately 25% and 67% of the total CO and PM2.5 emission, respectively. Each of these sources has its spatio-temporal emission profile. For instance, while commercial and industrial sources are active throughout the day, biomass burning occurs from morning to late afternoon. In addition, the type and quantity of fuel consumption for the residential sector drastically differ between Hanoi's urban and rural areas (Nguyen et al., 2022). Likewise, farmers in Hanoi perform biomass (rice straw) burning primarily in June and November. The emission of rice straw burning causes concentrations in sub-urban areas to reach 19.3 μgm^{-3} for PM_{10} and 17.6 μgm^{-3} for $PM_{2.5}$, but has an insignificant impact on concentrations in the urban core due to the minimal rice-cultivating land area presented (Le et al., 2022).

From Fig. 4, modelled (x4) CO prediction from 0:00 to 4:00 agrees well with the observed concentration. However, from 9:00 to 0:00, modelled (x4) CO is underestimated by a steady value of roughly 500 μgm^{-3}. This result indicates the contribution from non-traffic sources. For example, cooking using coal briquettes in homes and restaurants is a known source of emission in Hanoi (Hien et al., 2021; Huyen et al., 2021; Nghiem et al., 2020), with active emissions time from 8:00 to midnight (Nguyen et al., 2022). The impact of non-traffic sources on CO concentrations is most apparent at station HD. HD is located at the very centre of the city within the tourism-heavy Old Quarter, so it is susceptive to a much higher pollution input from residential and service-related activities. As such, HD has a distinctively higher observed CO concentration at a factor of three compared to the averaged observed value. The performance of modelled CO at HD is poor, with *NMSE*, *Fb*, *R* and *Fac2* at 5.22, −1.31, −0.08 and 0.21, respectively (Table S3). The negative *R*-value at HD supports the presence of other emission sources. To improve agreement with observations at HD, the model's emission inventory would require in-depth ground truth information to reflect the zonal distribution of emission sources in Hanoi.

Apart from HD, comparisons between modelled and observed CO at the remaining nine stations produce encouraging results (Fig. S7). Due to the low magnitude of inputted traffic emissions, there are underestimations with modelled CO, indicated by *Fb* ranging between 0.14 and −0.77 (Table S3). Still, 60% of the predictions stay within the factor of two of the observations. *R*-value at stations (excluding HD) range between 0.16 and 0.28, indicating a positive correlation between modelled and observed CO concentrations, albeit weak. These results reconfirm the model's ability to predict the temporal variation of CO concentrations in urban Hanoi, thanks to the input data framework proposed by this study.

As for PM, the averaged modelled concentrations at stations are 77.1 μgm^{-3} for PM_{10} and 55.3 μgm^{-3} for $PM_{2.5}$ (Table S3). Modelled PM_{10} is comparable with the observed value, with minimal bias (*Fb* at −0.05), while modelled $PM_{2.5}$ is overestimated by 11.5 μgm^{-3}, with a positive bias (*Fb* at 0.23). The overall degree of error is low, with *NMSE* at 0.59 and 0.77 for modelled PM_{10} and $PM_{2.5}$, respectively. Likewise, most predictions stay within a factor of two of the corresponding observations (*Fac2* at 0.64 for both PM_{10} and $PM_{2.5}$). Overall, this study's estimations of PM are encouraging.

However, modelled PM exhibit skewed diurnal variation, with concentrations underpredicted in the daytime and overpredicted at night and early morning (Fig. 5). At all ten stations, there are positive correlations between observed and modelled PM. However, they remain weak, with *R*-values ranging from 0.22 to 0.35. Such poor diurnal temporal agreement is caused mainly by the shape and magnitude of background PM. As such, there are significant discrepancies between background and observed PM concentrations (Fig. 5), suggesting that CAMS's concentrations are not optimal as background information for modelling traffic emissions in the urban core. Regarding monthly temporal variations, this study's PM predictions agree well with the observed trend, except around November when both PM_{10} and $PM_{2.5}$ are overestimated (Fig. S8). This result indicates that emissions from rural-specific sources, e.g., rice straw open burning, are included in the background pollution information, as modelled by CAMS, but not in observations. It is important to reiterate that this is the first time CAMS's concentrations are employed as Hanoi's background pollution. Uncertainties therefore remain. Further work is needed to assess the applicability of CAMS's forecast concentrations in Vietnam, similar to those done in other regions, e.g., Ryu and Min (2021), Ali et al. (2022), and Jin et al. (2022). Overall, although the framework established by this study produces a useable background concentration dataset, future models should employ additional information on background pollution, preferably from upwind PM monitoring sensors at various distances from Hanoi's urban core. Likewise, decision-makers are suggested to allocate resources to widen the area of air pollution monitoring.

4.3.3. Effect of meteorology on modelled concentrations

This section discusses the discrepancies in wind conditions and solar radiation to evaluate the impact of meteorological input on model performance and address improvements to the outlined model input framework. Because this study uses upscaled modelled winds from GFS, which originally had a temporal resolution of 3 h, the inputted wind speed exhibits sharp steps (Fig. 6a). All three datasets have the prevailing wind directions from southeast and northeast (Fig. S9). TY has the lowest average wind speed at 1.56 ms^{-1}, followed by CAMS's meteorology at 1.98 ms^{-1}. This work's winds are significantly stronger than the rest, at 2.54 ms^{-1}, causing the simulated atmosphere in the traffic model to become unstable. Such an overly diffusive condition contributes to the underestimation presented by the modelled CO concentrations after 9:00 (Fig. 4). TY is located within the urban core, and is surrounded by more complex terrain and higher surface roughness. This results in a lower wind speed. In contrast, winds from this work's input and CAMS are stronger because these are modelled and averaged across several grid points, most of which are in suburban areas with flatter terrain. For this reason, the input framework should adjust the near-surface physical dynamic in future models.

Regarding solar radiation, from Winter to early Spring in Hanoi, emissions can accumulate because of reduced sunshine duration, less radiation, and thus less buoyancy in the atmosphere (Tran et al., 2020). The model has correctly calculated the sunrise duration. However, the estimated solar radiation ($K+$) is overestimated. While $K+$ for CAMS and TY gradually increase in the morning (from 7:00 to 8:00), this work's $K+$ abruptly rises to at least a factor of two higher than the rest (Fig. 6b). High solar radiation increases the surface sensible heat flux and causes the simulated atmosphere to heat up faster and to a higher magnitude. Subsequently, it creates an unstable and diffusive atmospheric condition that swiftly disperses emissions produced in the morning rush hour. High $K+$ in the morning explains the early arrival of modelled CO morning peak at 7:00, an hour sooner than the observed trend (Fig. 4). This work uses ADMS-Urban to compute solar radiation via cloud cover. The said process may introduce errors that result in overestimations. The next iteration of the model input framework should therefore explicitly define solar radiation. CAMS exhibits $K+$

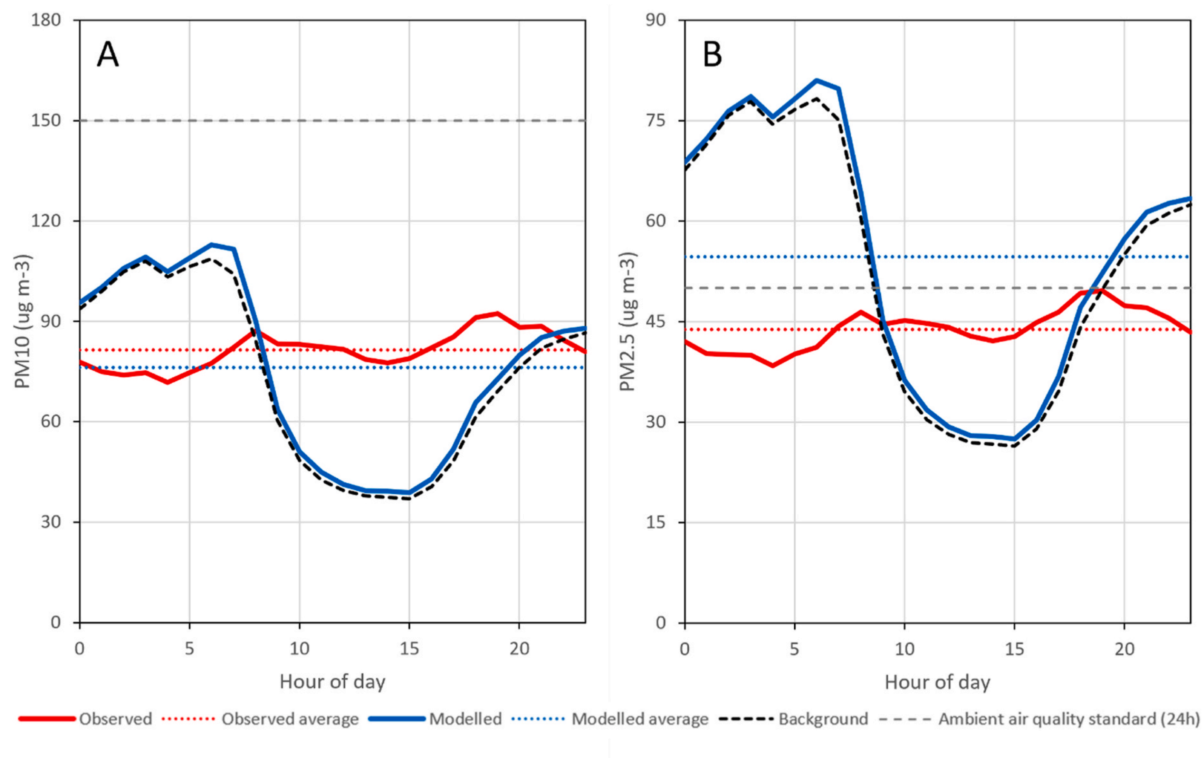

Fig. 5. Mean diurnal variation of modelled and observed (a) PM_{10}, and (b) $PM_{2.5}$ concentrations.

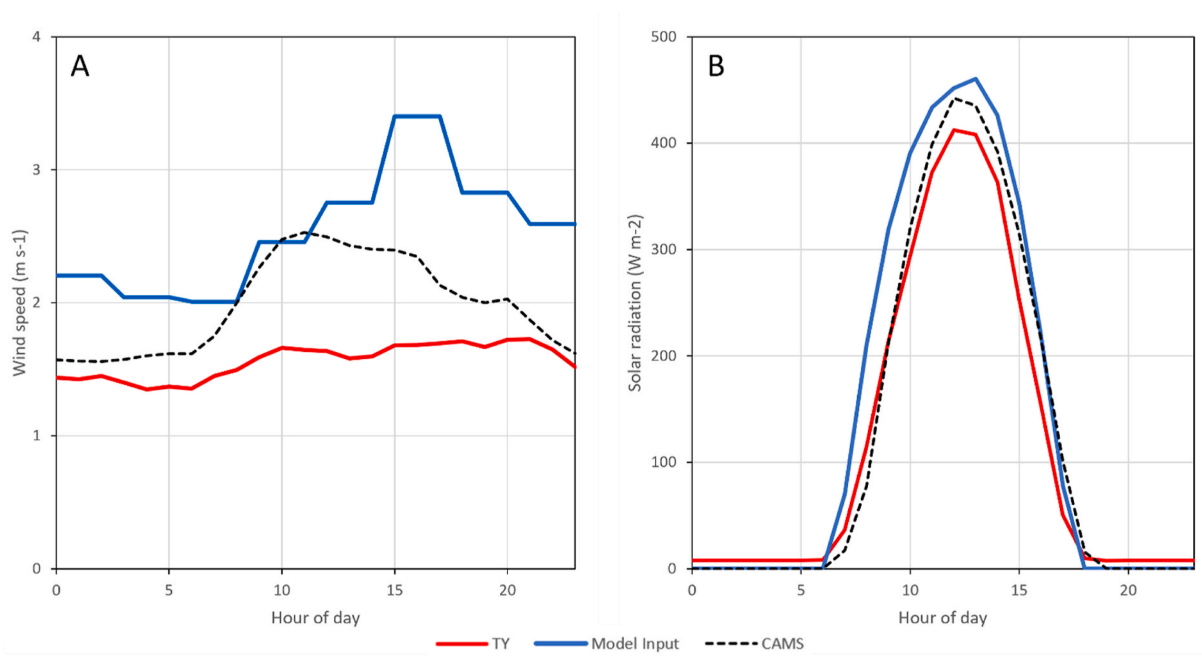

Fig. 6. Mean diurnal variation of (a) wind speed, and (b) solar radiation.

values similar to TY and its wind data have a high temporal resolution (Fig. 6), so future models can employ CAMS's meteorology to replace the current configuration.

Lastly, considering the infrastructure level of a developing country, it is important to acknowledge the uncertainty associated with air quality observations. This work implements a wide range of global datasets, largely independent of in-country information. As such, the outlined model input framework tackles the local data scarcity and proposes a basis for modelled results to be a mutual benchmark for observations. In other words, this work's contribution extends beyond model inputs, with the potential to improve the limitation of monitoring data themselves.

5. Conclusion

Dispersion modelling offers important information on the spatio-temporal variation of air pollution. However, cities in Vietnam and similar developing economies encounter data scarcity when implementing dispersion modelling. This study addresses the data challenge by establishing a framework employing existing, publicly assessable information as model input. ADMS-Urban uses the outlined input framework to resolve street-scale distribution maps for road-traffic-related CO, PM_{10} and $PM_{2.5}$ in Hanoi for six months from October 2018 to March 2019.

Modelled results provide valuable, highly detailed information on the relationship between Hanoi's road traffic properties and pollutant concentration. For instance, the average modelled concentration for CO, PM_{10} and $PM_{2.5}$ are 837, 77.1 and 55.3 μgm^{-3}, respectively. Modelled CO satisfies the local regulatory threshold, while PM exceed the limits. Hotspots form near major traffic flows and intersections, with the highest concentrations at 1206, 87.5 and 61.5 μgm^{-3} for CO, PM_{10} and $PM_{2.5}$, respectively. Most of the Hanoi's residential area has uniform modelled concentrations due to the dense network of small roads. Although HGV only accounts for 0.7% of the vehicle fleet population, it dominates the PM emissions during the night. Furthermore, contribution percentages from HGV increase further from the city centre. These findings demonstrate how dispersion modelling, equipped with appropriate input data, can inform policymakers and future research.

The model–observation discrepancy is discussed to address improvement points to the model input. Simulated pollutants concentration from traffic show encouraging agreements but are underestimated. Therefore, future emission inventories should allow for the low vehicle quality in Vietnam. Poor understanding of background pollution contributes substantially to the disagreement between modelled and observed PM. This work recommends that resources are allocated to widen the field of PM concentration monitoring, for example, upwind monitoring stations in sub-urban areas of Hanoi. The current meteorology input produces an overly unstable simulated atmosphere, allowing pollutants to disperse more quickly than they should. The model input framework should therefore improve its wind field data and provide additional meteorological parameters, namely solar radiation.

The model input framework established in this study focuses on road-traffic emissions in Hanoi. Similar developments should be done to the emissions from other sources, namely industrial and residential, to produce comprehensive concentration fields. The framework contains systematic, duplicatable processes to construct input data, which encourage the application of dispersion modelling in urban Vietnam and similar economic settings.

Code availability.

ADMS-Urban is a commercial product, copyright belongs to Cambridge Environmental Research Consultants (CERC). The underlying software code is therefore not publicly available. Technical specifications can be obtained from https://www.cerc.co.uk/environmental-software/technical-specifications.html (last access October 01, 2022). Contact CERC to request further information on the model development and license availability.

Credit author statement

Ngo Quang Khoi: Conceptualization, Methodology, Data curation, Visualization, ADMS modelling, Formal analysis, Writing (*Original draft, Edit, Revise, Submit and Response*). Le Anh Hoang: Methodology (*Air quality measurement*), Data curation, Writing *(Edit)*. Bang Quoc Ho: Methodology (*Traffic-count data*), Data curation, Writing (*Edit*). **Neil R. P. Harris, Gillian H. Drew** & **Mohammed Iqbal Mead**: Supervision, Writing (*Edit*).

Author contribution

Khoi Quang Ngo processed the input data, and set up, ran the model. Khoi Quang Ngo processed model output and performed analysis. Le Anh Hoang provided air quality measurement data and assisted with the related data curation. Bang Quoc Ho provided traffic vehicle count data and assisted with the related data curation. This paper is written by Khoi Quang Ngo with guidance from Neil R.P. Harris, Gillian H. Drew, and Mohammed Iqbal Mead. All the authors read and improved the manuscript.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Modelled output data underlying this study can be accessed through the Cranfield University repository (CORD) at doi:10.17862/cranfield.rd.22085978 (last access: 13 February 2023) (Ngo, 2023). Data are available under the terms of the Creative Commons Attribution 4.0 International (CC BY 4.0). Further resources in support of this work's findings may be accessed by contacting the authors. Air quality measurement data and traffic count data are available upon request from our VNU and VNU-HCM partners, respectively.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.116497.

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