Research article

Spatial Mapping of On-road Traffic Emission for Air Quality Management: A Case of Vinh Phuc Province

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Abstract

Keywords

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Vinh Phuc province is in the northern key economic region of Vietnam. The province has been facing challenges in air quality management as the number of vehicles has rapidly increased to meet the rising demand for transportation resources. This research was aimed to conduct an emission inventory and to build a spatial emission map for traffic activities in an attempt to improve air quality management in Vinh Phuc province. The vehicles were categorized into 5 groups: motorcycles, cars, light-duty vehicles (LDVs), heavy-duty vehicles (HDVs) and buses. Meanwhile, the streets were also categorized into 5 groups: highways, rural roads, urban streets, suburban streets and industrial streets. The results showed that motorcycles were the main means of transportation (93% of total vehicles) and they were also the major contributors to total emissions of NO_x, CO, VOCs (volatile organic compounds), CH_4, NMVOCs (non-methane volatile organic compounds) and especially in the cases of CO, CH_4, VOC and NMVOC emissions which contributed more than 90% of emissions. Cars were the main source of SO_2 emissions, contributing 51% of total SO_2 road traffic emissions. The emissions of TSP (total suspended particulate), PM_{10} and $PM_{2.5}$ were mostly generated from buses (about 32%), followed by motorcycles (about 18%). LDVs and HDVs contributed 18% and 15% to total particulate matter emissions, respectively. Spatial distribution analysis of CO, NO_x, SO_2, TSP, NMVOC and $PM_{2.5}$ which involved visual identification in polluted areas, showing that high emissions were in the southeast part of the province and the most polluted areas were Vinh Yen city, followed by Binh Xuyen district and Phuc Yen city. These results provide suggestions for local governments on how to design effective air quality control strategies.

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1. Introduction

Ambient air pollution was recognized as a cause of more than 4.2 million premature deaths per year all over the world mostly happened South-East Asia and Western Pacific Regions according to World Health Organization (WHO) estimation [1]. It was also found that more than 60,000 deaths from diseases such as heart disease, stroke and lung cancer in Viet Nam in 2016 were linked to air pollution [2]. Air pollutants can come from various sources including industry, traffic, and households, and each source makes its own contribution to total emission loadings. According to a Vietnam national report on urban air environment, road traffic was the largest air pollution source in the cities of Vietnam [3].

Vinh Phuc province is in the northern key economic region of Vietnam. The province is composed of two cities, Vinh Yen and Phuc Yen, and seven rural districts: Lap Thach, Tam Duong, Tam Dao, Binh Xuyen, Yen Lac, Vinh Tuong, and Song Lo districts [4] (Figure 1). According to statistics, Vinh Phuc province had 752,604 vehicles including motorcycles, cars, heavy-duty vehicles (HDVs), light-duty vehicles (LDVs) and buses [5]. Economic development and population growth caused a rapid increase in the number of vehicles on the roads, and the province, therefore, is increasingly facing problems with traffic-related air pollution. Although annual air quality monitoring in Vinh Phuc province found the CO concentration in ambient air to be less than the thresholds of 30,000 $\mu g/m^3$ and 10,000 $\mu g/m^3$ for 1-h and 8-h average concentrations, respectively, as stated in the National technical regulations for ambient air quality (QCVN 05/2013/BTNMT), the CO concentration has been increasing over the years [6]. The TSP and NO_2 concentrations at several monitoring places exceeded those listed in QCVN 05/2013/BTNMT (respective 24-h average concentrations for TSP and NO_2 are 200 and 100 $\mu g/m^3$). From the above, there is a need for better determination of air pollutant emissions and polluted areas to design an effective air quality management strategy in the province.

Many parts of the world have conducted emission inventory (EI) since it is an important component of air quality management. The project "Clean Air for Smaller Cities in the Association of Southeast Asian Nations (ASEAN) Region" inventoried six air pollutants: NO_x, CO, SO_2, NMVOCs (non-methane volatile organic compounds), PM (particulate matter), and CO_2 from point sources, area sources, and mobile sources for ten cities in six Southeast Asian countries [7]. The Vietnamese cities of Can Tho and Bac Ninh were included in the project. The results of the EI provided useful information for policy making in air quality management. A comprehensive EI for Ho Chi Minh city in Vietnam was carried out using a combination of bottom-up and top-down approaches [8]. Based on the EI results, a spatial map of air emissions was developed and a forecast of emissions for Ho Chi Minh city by 2025 and 2030 was made. The EI results showed that motorcycles were the major contributors to emissions in Ho Chi Minh city as this vehicle group contributed 90% of CO, 68% of NMVOC, 63% of CH_4, 41% of SO_2, 29% of NO_x and 18% of $PM_{2.5}$. The spatial distributions showed the areas polluted with CO and NMVOC emissions were in the city center, and that the ports were polluted with NO_x, SO_2 and TSP. The emission forecast estimated that the pollutant emissions will increase about 30-50% by 2025 and 40-65% by 2030. Based on a detailed EI for road traffic in Ho Chi Minh city, various scenarios for reducing traffic emissions were proposed, and a plan for the local government to control emissions was designed [9]. Previous research on traffic EI in Hanoi city found that gasoline-fueled taxis and cars were the main contributors to CO and VOC emissions, and diesel-fueled buses were the major sources of PM and black carbon [10]. The air EI and modelling by meteorological model and air quality model in Can Tho city revealed that a pollution plume had developed in the northeastern part of the city [11]. The first air EI for point sources (industrial activities) and area sources was conducted in Hanoi city [12, 13]. The results showed that Son Tay town, Nam Tu Liem, Dong Anh and Thuong Tin districts contributed the highest emissions in industry, and high emissions from area sources were found in My Duc, Chuong My, and Soc Son districts.

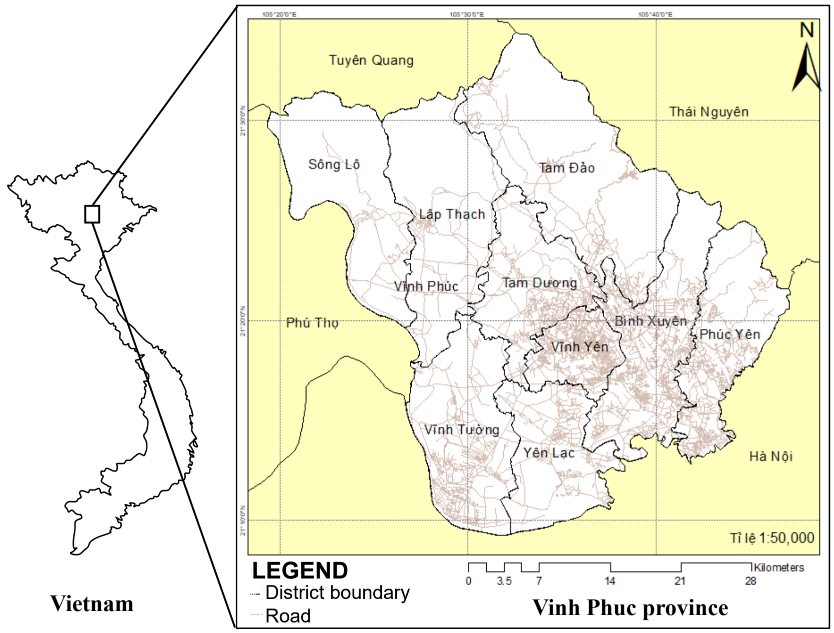

Figure 1. Location and road system map of Vinh Phuc province

There have been some studies conducting emission inventory (EI), however the data are not enough because the emissions are estimated basing on emission factors and the emission factors depend on local conditions. Generally, emissions are estimated based on emission factors (EFs) and the activities that produce the emissions. Road traffic emissions depend on the emission factors (EFs), which are generated from local transportation conditions (road type, speed, etc.) and vehicle characteristics (fuel use, production year, vehicle age, vehicle mileage, etc.). Several models were developed to calculate road traffic emissions in developed countries such as EMFAC, MOVES/MOBILE, DMRB, COPERT, where the data on vehicle emission factors are available. For developing countries, IVE, EMISENS were used to generate EFs based on various factors including vehicle characteristics, traffic flow distribution, road condition, etc. [7]. The IVE model was applied for the estimation of traffic emissions in Kathmandu [14], Bangkok, Ho Chi Minh, Hanoi [15], and the EMISENS model was applied for traffic emissions in Ho Chi Minh city, Can Tho, and Hanoi in Vietnam and other cities in foreign countries such as Algiers [16] and La Havana [17]. In this study, EI for road traffic in Vinh Phuc province was conducted using EMISENS model. This model, developed by Ho [18], was based on well-known Copert IV, a computer program to calculate emissions from road transport [19]. The EI results together with spatial information were then used to develop spatial map of road traffic emissions in Vinh Phuc province in order to support local air quality management.

2. Materials and Methods

2.1 On-road vehicle emission inventory

The road vehicle emission inventory was conducted by EMISENS model [18]. The model generates EFs for road traffic sources by combining the top-down and bottom-up approaches. In this model, the road traffic emissions for each pollutant is the sum of hot emissions (E_{hot}), cold emissions (E_{cold}), and evaporation emissions (E_{evap}) as shown in equation (1), where *i* represents pollutants: CO, NO_x, SO_2, VOC, CH_4, NMVOC, TSP, PM_{10} and $PM_{2.5}$; and *j* represents vehicle categories: motorcycles, cars, buses, high-duty vehicles (HDVs), and light-duty vehicles (LDVs).

$$E_{i,j}(g) = E_{hot,i,j}(g) + E_{cold,i,j}(g) + E_{evap,i,j}(g) \tag{1}$$

E_{hot} refers to the products of fuel combustion when an engine reaches heat stability. It can be computed by hot emission factors - EFs (e_{hot}) and total kilometers traveled (L), as shown in equation (2). e_{hot} (g/km) is dependent on vehicle characteristics (e.g., vehicle age, vehicle type), fuel type and vehicle speed.

$$E_{hot,i,j}(g) = e_{hot,i,j}(g/km) \times L_j(km) \tag{2}$$

E_{cold} refers to fuel combustion products that occur when an engine is at the warming up stage and the engine temperature is lower than the ambient temperature and can be calculated from cold EFs (e_{cold}) and total kilometers traveled (L) as shown in equation (3). Cold EFs (e_{cold} – g/km/vehicle) can be computed by equation (4), in which *V* is vehicle speed (km/h), t_a is ambient temperature (°C), and *A*, *B*, and *C* are coefficients relating to vehicle categories. The coefficients *A*, *B*, *C* are referenced from Table 6.1 of COPERT III [20].

$$E_{cold,i,j}(g) = e_{cold,i,j}(g/km) \times L_j(km) \tag{3}$$

$$\frac{e_{cold,j}}{e_{hot,j}} = A \times V_j(km/h) + B \times t_a(^{o}C) + C \tag{4}$$

E_{evap} are emissions generated by gasoline vehicles including emissions from running losses (E_{rulo}), hot soak (E_{hoso}) and diurnal losses (E_{dilo}), as shown in equation (5). E_{rulo} (g/day) occurs while vehicles are running on roads. E_{rulo} (g/day) depends on vehicle characteristics, kilometers traveled, and total vehicle number. E_{hoso} (g/day) occurs when a vehicle engine stops, and fuel evaporates due to hot temperature. E_{hoso} depends on vehicle characteristics and ambient temperature. E_{dilo} occurs due to differences between day and night temperatures.

$$E_{evap}(g) = E_{rulo}(g) + E_{hoso}(g) + E_{dilo}(g) \tag{5}$$

Therefore, the necessary input data to the EMISENS model includes vehicle characteristics such as vehicle technology, vehicle type, age, daily kilometers traveled, average speed, and emission factors, and road characteristics such as street length, street type, traffic flow, traffic conditions, and traffic diurnal curves. The methods used to collect the necessary data are described in the following section.

2.2 Traffic count

The traffic counting was manually performed in 88 streets in March 2021. The streets were categorized into 5 groups, as guided by the EMISENS model, which were highways (3 roads), urban streets (25 streets), suburban streets (25 streets), rural roads (5 roads), and industrial streets (30 streets located in an industrial zone). At the same time, the vehicles were categorized into 5 groups, which were motorcycles, cars (< 15 seats), buses, heavy-duty vehicles (HDVs) (vehicles with total gross weight > 3.5 tons), and light-duty vehicles (LDVs) (vehicles with total gross weight < 3.5

tons). By standing at the street side or watching a video of the road, the number of vehicles were counted. The counting at the street sites was performed for 15 and 30 min every hour from 6 a.m. to 7 p.m.; and the traffic flows for 1 h were then extrapolated. We also installed a camera on the streets for 24 h and counted the traffic flow based on camera data.

2.3 Questionnaire survey for the characterization of the vehicles

A questionnaire survey was conducted in March 2021 to collect the data for five vehicle groups. The collected information included vehicle category, fuel type, engine size, loading capacity, production year, vehicle age, vehicle mileage (odometer readings), and number of trips per day. Vehicle kilometers travelled was then estimated using the relation between odometer reading and vehicle age.

Table 1 presents the number of vehicles in Vinh Phuc province. The proportion of motorcycles, cars, buses, HDVs and LDVs were 93%, 4%, 0.5%, 0.6%, and 1.8% of the total number of vehicles [4]. The number of questionnaires for motorcycles was determined from the total number of motorcycles (700,307) using Yamane's formula (equation 6) [21], with an error of 0.05. The sample size for motorcycles was thus calculated to be 400. Since motorcycles were the dominant means of transportation, the questionnaire survey was implemented for 800 motorcycles. The remaining types of vehicles were then gathered in one group with sample size of 334 which was divided proportionally. The number of questionnaires for cars, buses, HDVs, and LDVs were then 200, 25, 58, and 51, respectively.

$$n = \frac{N}{1 + N(e)^2} \tag{6}$$

in which n is sample size, N is population size, and e is acceptable sampling error.

Table 1. Number of vehicles and questionnaires

Vehicle Categories	Number	Number of Questionnaires
Motorcycles	700,307	800
Cars	30,509	200
Buses	4,693	25
HDVs	3,599	58
LDVs	13,496	51

Note: HDVs: heavy-duty vehicles, LDVs: light-duty vehicles

2.4 Emission factors (EFs)

Many developed countries have established official EFs but the data of Vietnam is limited. The EFs applied in this study were collected from previous studies in Ho Chi Minh city [22, 23], China [24], and other countries, with the evaporation emission EFs collected from Copert IV [19]. The target pollutants in this study were CO, NO_x, SO_2, VOC, NMVOC, CH_4, TSP, PM_{10} and $PM_{2.5}$.

2.5 Development of spatial map of CO, NO_x, SO_2, TSP, NMVOC and $PM_{2.5}$ from on-road vehicles in Vinh Phuc province

The emission maps for road vehicles were developed for each pollutant based on the emission loadings obtained from the emission inventory and from spatial information such as spatial coordinates, administrative and road system maps of Vinh Phuc province. To distribute the parameters spatially, ArcGIS software was used. Important features such as points, lines, and polygons can be styled in ArcGIS. The administrative map presented the boundaries of the cities and districts of the province. On-road emissions are displayed based on the road system. The domain of this research was Vinh Phuc province which was 35 km × 35 km. The domain was then divided into cells with the resolution of each cell being 1.5 km × 1.5 km. The area of each cell was therefore 2.25 km^2. The emissions of a pollutant in each cell depended on road density and emission loading. The levels of emissions varied by color display. Types of fuel by vehicle categories are presented in Table 2. Gasoline was the main fuel of motorcycles and cars, while diesel was the main fuel of trucks and buses.

Table 2. Fuel use by on-road vehicle categories in Vinh Phuc province

Vehicle Categories	Fuel Use		
	Diesel	**Gasoline**	**CNG***
Motorcycles	0%	100%	0%
Cars	8.5%	91.5%	0%
HDVs	100%	0%	0%
LDVs	82.35%	17.65%	0%
Buses	100%	0%	0%

*CNG: Compressed natural gas

3. Results and Discussion

3.1 Characterizations of on-road vehicles

The characteristics of on-road vehicles obtained from the questionnaire survey are presented in Table 3. The Table shows that 60% of motorcycles met the Euro II standard with an average age of 4-14 years, 24% met the Euro III standard with an average age of < 4 years, and 16% met the Euro I standard and previous standard, which means that the vehicles were manufactured before 2007. Regarding cars, 77% met the Euro VI standard with an average age of < 6 years, and about 15% met the Euro V standard with an average age of 6-10 years. The rest of cars (about 8%) were of older type. The questionnaire results also indicated 76% of the HDVs met Euro VI standard with an average age of < 8 years, followed by Euro V HDVs at 19% with an average age of 8-13 years. The remaining HDVs, which constituted about 5% of the total, met the previous standard. Concerning LDVs, 57% met the Euro VI standard, 4% met the Euro V standard, and a large proportion of 39% were using old technology. For buses, the results showed that 92% met Euro VI with an average age of < 8 years.

3.2 Traffic flow distribution

Figure 2 shows the daily vehicle composition in urban streets in Vinh Phuc province. The results show that motorcycles were dominated (64.3%), followed by cars (32.3%), LDVs (1.8%), HDVs (1.1%), and buses (0.5%). The other street types in the survey also displayed a similar trend, with motorcycles being the main form of transportation in Vinh Phuc province (93%). Comparing with the vehicle composition in other research for Ho Chi Minh city [8], Hanoi city [25] and Can Tho city [11], motorcycles were the dominant vehicle type in those cities as well.

Table 3. Characteristics of on-road vehicles in Vinh Phuc province

Vehicle Categories		Vehicle Emission Standards					
		Euro I	**Euro II**	**Euro III**	**Euro IV**	**Euro V**	**Euro VI**
Motorcycles	Proportion	16%	60%	24%			
	Average age	> 14 years	4-14 years	< 4 years			
Cars	Proportion	8%				15%	77%
	Average age	11 - 22 years				6 - 10 years	< 6 years
HDVs	Proportion	5%				19%	76%
	Average age	14 - 22 years				8 - 13 years	< 8 years
LDVs	Proportion	39%				4%	57%
	Average age	14 - 22 years				8 - 13 years	< 8 years
Buses	Proportion					8%	92%
	Average age					8 - 10 years	<8 years

Notes: HDVs: Heavy-duty vehicles; LDVs: Light-duty vehicles

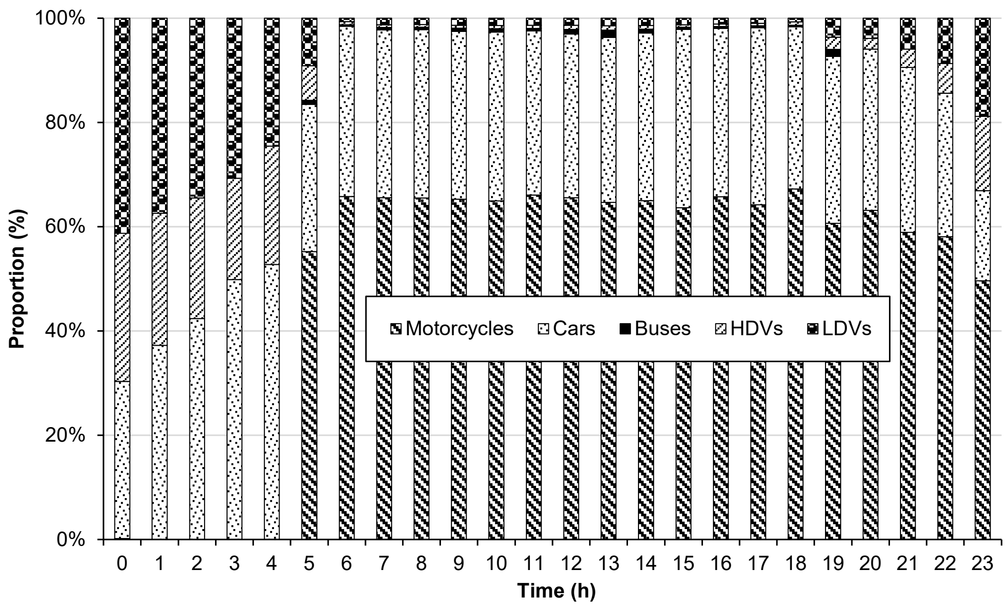

Figure 2. Daily variation of vehicle composition on urban streets (HDVs: Heavy-duty vehicles; LDVs: Light-duty vehicles)

The daily vehicle numbers in Figure 3 show two distinct peaks, the first from 7 a.m. to 9 a.m. and the second from 5 p.m. to 7 p.m. This trend was similar to the daily vehicle number in Ho Chi Minh city (two peaks: 7-8 a.m. and 5-6 p.m.) [26]. In Hanoi city, a large number of motorcycles was also observed during 6-8 a.m. and 4-6 p.m. [25]. Besides, the vehicle number in Vinh Phuc province, Ho Chi Minh city and Hanoi city also showed a small peak over the period of 11 a.m.-1 p.m., which was probably due to residents going out or coming back home at lunch time. HDVs

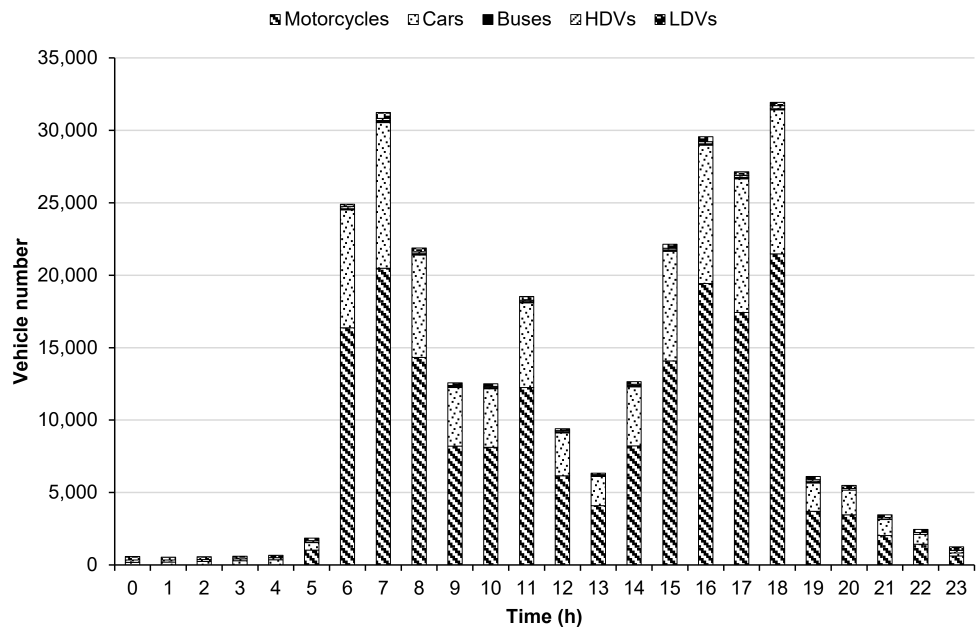

Figure 3. Daily variation of vehicle numbers on urban streets (HDVs: Heavy-duty vehicles; LDVs: Light-duty vehicles)

mostly travel at night-time and in early morning as HDVs are not allowed on urban streets during the daytime. Hanoi city also had a similar result while Ho Chi Minh city was observed a certain number of motorcycles and cars during night-time [25, 26]. Bus operation time was regulated by local schedule (5 a.m.-8 p.m.). It can be understood from the obtained data of this study and other studies in Hanoi and Ho Chi Minh city that traffic flow distribution reflects local residential lifestyle and traffic regulation.

3.3 Emissions from on-road vehicles

Table 4 summarizes hot emissions, cold emissions, and evaporation emissions by vehicle type. It shows that the main emission source was hot emissions except for NMVOC. NMVOC was mostly released via evaporation emissions from cars (471 tons/year), LDVs (109 tons/year), and HDVs (66 tons/year). Motorcycles also contributed a large proportion to NMVOC emissions (4,307 tons/year). Cold emissions (which occur during engine warmup) of NO_x and CO from motorcycles were quite high. Buses showed low levels of cold emissions for most pollutants except for CO. Cold emissions of CO from buses were 32 tons/year, which constituted approx. 30% of total CO emissions from buses. LDVs and HDVs released almost no cold emissions. LDVs released small amounts of cold emissions of CO (11 tons/year) and VOC (0.03 tons/year). HDVs released about 0.03 tons/year of CH_4 cold emissions.

The emission of SO_2 was 100% from hot emissions. Particulate matter (PM) including TSP, PM_{10}, and $PM_{2.5}$ are released as hot emissions, and are associated with friction between the wheel and the road surface, and vehicle brake [27]. The hot emissions of PM from motorcycles and cars were 377 tons/year and 250 tons/year, respectively. Motorcycles and cars generated PM from hot emission and cold emission whereas other vehicles released PM from only hot emission. The

Table 4. Emissions from on-road vehicles in Vinh Phuc province

Vehicle Type	Emission Type	Pollutants (tons/year)						
		NO_X	CO	SO_2	VOC	CH_4	NMVOC	PM
Motorcycles	Hot emissions	1,437.08	144,150.00	186.00	11,532.28	2,299.07	5,382.49	377.23
	Cold emissions	2,056.92	82,822.08	0.00	1,922.72	814.93	651.48	233.77
	Evaporation emissions	0.00	0.00	0.00	0.00	0.00	4,307.03	0.00
	Total	3,494.00	226,972.00	186.00	13,455.00	3,114.00	10,341.00	611.00
Cars	Hot emissions	1,199.15	5,448.51	264.00	506.23	10.09	30.87	250.44
	Cold emissions	26.85	44.49	0.00	6.77	0.91	0.40	1.56
	Evaporation emissions	0.00	0.00	0.00	0.00	0.00	470.73	0.00
	Total	1,226.00	5,493.00	264.00	513.00	11.00	502.00	252.00
Buses	Hot emissions	900.93	72.69	4.00	21.66	5.39	0.04	755.08
	Cold emissions	4.07	32.31	0.00	2.34	0.61	0.00	0.00
	Evaporation emissions	0.00	0.00	0.00	0.00	0.00	17.96	0.00
	Total	905.00	105.00	4.00	24.00	6.00	18.00	755.08
HDVs	Hot emission	2,433.00	1,199.00	15.00	75.00	8.97	0.59	368.00
	Cold emission	0.00	0.00	0.00	0.00	0.03	0.00	0.00
	Evaporation emission	0.00	0.00	0.00	0.00	0.00	66.41	0.00
	Total	2,433.00	1,199.00	15.00	75.00	9.00	67.00	368.00
LDVs	Hot emission	663.00	775.59	45.00	113.97	3.00	1.61	435.00
	Cold emission	0.00	11.41	0.00	0.03	0.00	0.00	0.00
	Evaporation emission	0.00	0.00	0.00	0.00	0.00	109.39	0.00
	Total	663.00	787.00	45.00	114.00	3.00	111.00	435.00
Total		8,721.00	234,556.00	514.00	14,181.00	3,143.00	11,039.00	2,421.08

Notes: HDVs: Heavy-duty vehicles; LDVs: Light-duty vehicles, PM: Particulate matter including TSP, PM_{10} and $PM_{2.5}$

results also indicated that CO was mainly released from the hot and cold emissions of vehicles other than HDVs. CO emissions from HDVs happened only via hot emission. Motorcycles released 226,972 tons/year of CO, accounting for 88% of total emissions from motorcycles and 67% (5,493 tons/year) of total emissions from cars was CO. LDVs and HDVs released 787 tons/year and 1,199 tons/year of CO, contributing to 34% and 29% of the total emissions from LDVs and HDVs, respectively. CO emission from buses was 105 tons/year, which was only 6% of the total emissions from this vehicle. Buses also released a large amount of NO_x and 58% (2,433 tons/year) of the total emissions of HDVs was contributed by NO_x. Half of the total emissions of buses was NO_x (905 tons/year). The contributions of NO_x to the total emissions of LDVs and cars were 31% and 15%, respectively. A small proportion (about 1%) of the total emissions from motorcycles was NO_x (3,494 tons/year). The other pollutants (SO_2, VOC, CH_4 and NMVOC) contributed a small amount to the total emissions from all vehicle types. Particularly, PM was the second largest contributor to the total emissions from buses (the largest contributor was NO_x). In Figure 4, the total emissions from road vehicles are presented. The results show that motorcycles were a major contributor to air pollutants, and this was especially for CO, CH_4, VOC and NMVOC, for which motorcycles contributed more than 90% of emissions (93% of the total vehicle numbers). Cars were the main source of SO_2, contributing 51% of total SO_2 emissions. Besides, cars also contributed a large proportion of NO_x and particulate matter emissions. The emissions of TSP, PM_{10} and $PM_{2.5}$ mainly came from buses (about 32%), followed by motorcycles (about 25%). LDVs and HDVs were also the contributors to TSP, PM_{10} and $PM_{2.5}$ emissions. The largest emission from HDVs was NO_x and this vehicle type was the second largest contributor to total NO_x emissions.

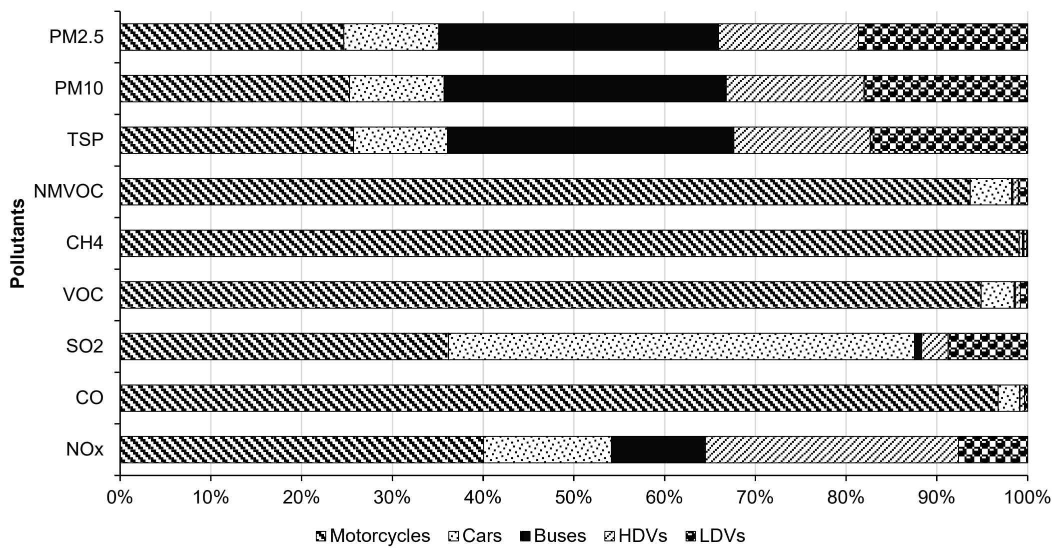

Figure 4. Total emissions from on-road traffic by vehicle type

3.4 Spatial distributions of CO, NO_x, SO_2, TSP, NMVOC and $PM_{2.5}$ from road traffic emissions

Figure 5 presents the spatial emissions of CO, NO_x, SO_2, TSP, NMVOC, and $PM_{2.5}$ (ton/year/cell) in Vinh Phuc province. The results show that the highest emission of pollutants from road traffic was concentrated in Vinh Yen city, which is one of the two cities of Vinh Phuc province that belongs to urban street group, and was high traffic density as previously discussed in section 3.2 and 3.3. The CO emissions ranged from 0.29 to 3,158 ton/year/2.25 km^2. The highest CO emission was at Vinh Yen city (2,190-3,158 ton/year/2.25 km^2), which was probably due to more than 90% of emissions being contributed from motorcycles (Figure 4). As the urban street group was dominant with motorcycles, CO emission must be highest in the urban areas.

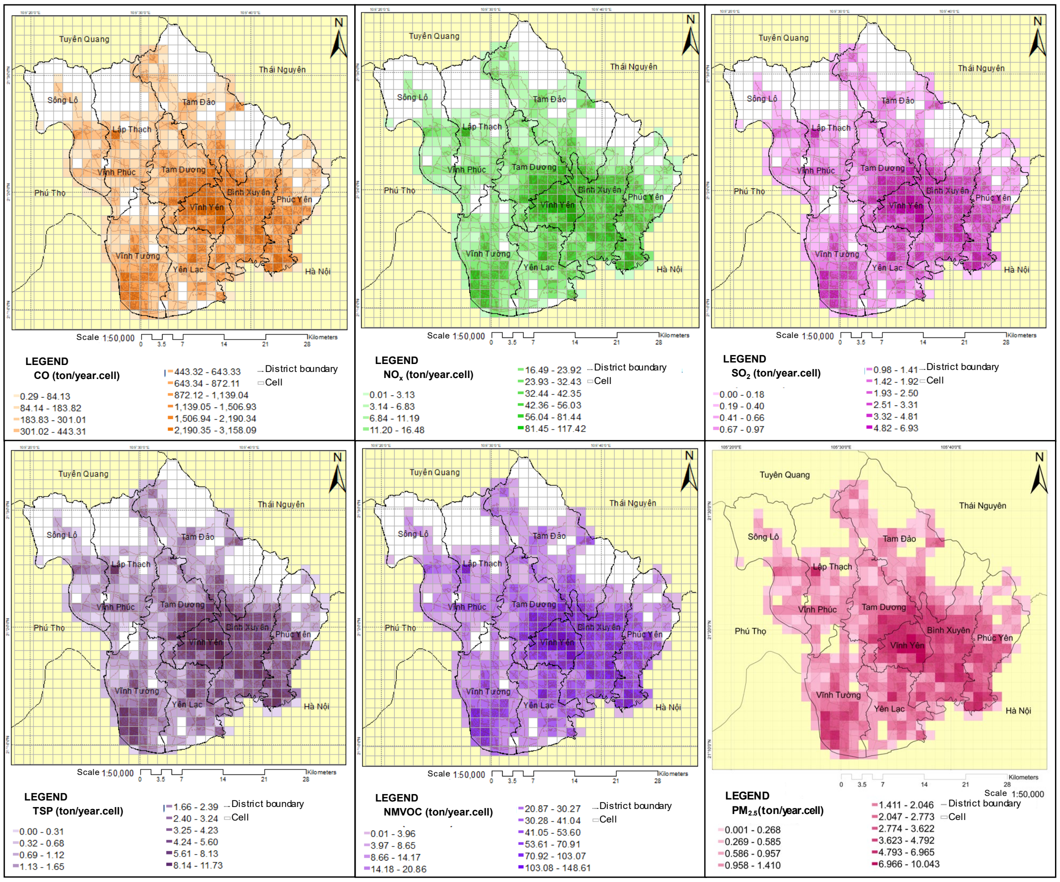

Figure 5. Spatial distribution of CO, NO_x, SO_2, TSP, NMVOC, and $PM_{2.5}$ from road vehicles in Vinh Phuc province

Emissions of NO_x were from 0.01 to 117 ton/year/2.25 km^2. The NO_x spatial distribution also indicated that the highest NO_x emissions were at Vinh Yen city (81-117 ton/year/2.25 km^2). Emissions of SO_2 were not at a high level (4-6 ton/year/2.25 km^2) and concentrated at Vinh Yen city. High TSP emissions occurred at Vinh Yen city and the surrounding areas such as Binh Xuyen district and Phuc Yen city. NMVOC emissions of Vinh Phuc province ranged from 3 to 150 ton/year/2.25 km^2 and were high in Vinh Yen city, Binh Xuyen district and Phuc Yen city with the emissions ranged from 70 to 150 ton/year/2.25 km^2. $PM_{2.5}$ emissions were also concentrated mainly at Vinh Yen city, Binh Xuyen district and Phuc Yen city (3.6-10 ton/year/2.25 km^2). Generally, the spatial distribution of the pollutants illustrates that high emissions occurred in the southeast part of Vinh Phuc province. Some locations of Song Lo, Lap Thach and Tam Dao district had no air emission from road traffic activities as there were no road system in these areas (Figure 1). The highest average yearly emissions of CO, NO_x, SO_2, TSP, NMVOC, and $PM_{2.5}$ were 3,150 ton/year/2.25 km^2, 117 ton/year/2.25 km^2, 6.93 ton/year/2.25 km^2, 11.71 ton/year/2.25 km^2, 148.61 ton/year/2.25 km^2, and 10.04 ton/year/2.25 km^2, respectively.

4. Conclusions

Traffic counts were performed and a total 1134 questionnaires (800 motorcycles, 200 cars, 58 HDVs, 51 LDVs, and 25 buses) were analyzed to estimate the emissions from road vehicles. The emission results were then spatially distributed in a map by the application of ArcGIS software. The questionnaire survey showed that most motorcycles (84%) in Vinh Phuc province met the Euro II and the Euro III standards. Sixteen percent of motorcycles was manufactured before 2007, which meant they met Euro I and previous standards; these were quite old vehicles. Seventy percent of cars met the Euro VI standard, and 15% met the Euro V standard. Buses, HDVs, and LDVs mostly met the Euro VI standard with the respective proportions of 92%, 76%, and 57%. Motorcycles were the most common means of transportation, accounting for 93% of total vehicles and this vehicle type was also the major contributor to CO, CH_4, VOC and NMVOC emissions. Cars were the main source of SO_2, contributing 51% of total SO_2 emissions. The emissions of TSP, PM_{10} and $PM_{2.5}$ mainly came from buses (32%), followed by motorcycles (25%), LDVs (18%) and HDVs (15%). HDVs were also the second largest source of NOx emissions after motorcycles. The total emissions were 8,721; 234,556; 514; 14,181; 3,143; 11,039; 2,421 tons/year of NO_x, CO, SO_2, VOC, CH_4, NMVOC, and PM. respectively.

A distribution map was used to visually identified the emission areas. High emissions were observed in the southeast part of Vinh Phuc province, and the most polluted areas were Vinh Yen city, followed by Binh Xuyen district and Phuc Yen city. Since the main air pollutants were CO, VOC, NMVOC, NO_x, which were emitted from motorcycles, local governments are advised to provide solutions to control and reduce emissions from motorcycles. Together with inspection of emissions from motorcycles, alternative transportation means such as public transportation or bicycles should be promoted. The use of alternative energy sources such as some biofuels and electricity should also be promoted to help to reduce vehicle emissions. Finally, public awareness about air quality should be raised to enhance the roles and responsibilities of local residents.

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References

[1] World Health Organization, 2022. *Ambient (Outdoor) Air Pollution*. [online] Available at: https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health?gclid=EAIaIQobChMIxJeqtoq4gQMV4pDCCh3wTgjiEAAYAS AAEgLeY_D_BwE.

[2] World Health Organization, 2018. *More than 60000 Deaths in Viet Nam Each Year Linked to Air Pollution.* [online] Available at: https://www.who.int/vietnam/news/detail/02-05-2018-more-than-60-000-deaths-in-viet-nam-each-year-linked-to-air-pollution.

[3] MONRE, 2016. *National Environmental Status Report - Urban Environment*. Vietnam Ministry of Natural Resources and Environment. (in Vietnamese)

[4] Vinh Phuc Statistical Office, 2019. *Number of Administrative Units as of 31 Dec. 2019 by District*. [online] Available at: http://niengiam2019.thongkevinhphuc.gov.vn/.

[5] Vinh Phuc Department of Transport, 2019. *Number of Registered Vehicles.* (Local report - unpublished).

[6] Vinh Phuc Department of Natural Resources and Environment, 2018. *Current State of Environmental Quality*. (in Vietnamese)

[7] Cornet, B. and Bang, Q.H., 2017. Air emission inventories for smaller cities in ASEAN region: findings and sensitivities. *Air Quality, Atmosphere and Health*, 10(7), 897-906, https://doi.org/10.1007/s11869-017-0479-7.

[8] Ho, B.Q., Vu, H.N.K., Nguyen, T.T., Nguyen, T.T.H. and Nguyen, T.T.T., 2019. A combination of bottom-up and top-down approaches for calculating of air emission for developing countries: a case of Ho Chi Minh City, Vietnam. *Air Quality, Atmosphere and Health*, 12(9), 1059-1072, https://doi.org/10.1007/s11869-019-00722-8.

[9] Ho, B.Q. and Clappier, A., 2011. Road traffic emission inventory for air quality modelling and to evaluate the abatement strategies: A case of Ho Chi Minh City, Vietnam. *Atmospheric Environment*, 45(21), 3584-3593, https://doi.org/10.1016/j.atmosenv.2011.03.073.

[10] Tran, T.T., Huynh, H.V. and Nguyen, T.K.O., 2015. Traffic emission inventory for estimation of air quality and climate co-benefits of faster vehicle technology intrusion in Hanoi, Vietnam. *Carbon Management*, 6(3-4), 117-128, https://doi.org/10.1080/17583004.2015.1093694.

[11] Ho, B.Q., Vu, H.N.K., Nguyen, T.T., Lasko, K., 2018. Air pollution emission inventory and air quality modeling for Can Tho City, Mekong Delta, Vietnam. *Air Quality, Atmosphere and Health*, 11(1), 35-47, https://doi.org/10.1007/s11869-017-0512-x.

[12] Ho, B.Q., Tran, T.D.H., Tran, T.H.H., Huynh, T.M.D., Nguyen,T.T., Nguyen. T.T.H., Nguyen, V.V. and Vu, H.N.K., 2022. Air emission inventory for industry activities in Hanoi city. *VNUHCM Journal of Earth Science and Environment*, 5(S3), 13-24.

[13] Ho, B.Q., Nguyen, T.T., Nguyen, T.T.H, Vu, H.N.K., Tran, T.H.H., Ngo, D.N.D. and Nguyen, N.T.N., 2022. Air emission inventory for area source in Hanoi city and mitigation measures. *Vietnam Journal of Environment*, 1, 8-15, https://sti.vista.gov.vn/tw/Lists/TaiLieuKHCN/Attachments/334753/C Vv359SCD12022008.pdf. (in Vietnamese)

[14] Shrestha, S R., Nguyen, T.K.O., Xu, Q., Rupakheti, M. and Lawrence, M. G., 2013. Analysis of the vehicle fleet in the Kathmandu Valley for estimation of environment and climate co-benefits of technology intrusions., *Atmospheric Environment*, 81, 579-590, https://doi.org/10.1016/j.atmosenv.2013.09.050.

[15] Nguyen, T.K.O. and Huynh, H.V., 2015. Comparative assessment of traffic fleets in Asian cities for emission inventory and analysis of co-benefit from faster vehicle technology intrusion. *Proceedings of the International Emission Inventory Conference "Air Quality Challenges: Tackling the Changing Face of Emissions"*, California, USA, April 13-16, 2015, pp. 1-10.

[16] Rahal, F., Benharrats, N., Blond, N., Clappier, A. and Ponche, J.L., 2014. Modelling of air pollution in the area of Algiers City, Algeria. *International Journal of Environment and Pollution*, 54(1), 32-58, https://doi.org/10.1504/IJEP.2014.064049.

[17] Clappier, A. and Madrazo, J., 2016. *Emission Inventories over Cuba and La Havana*. [online] Available at: https://aqm.jrc.ec.europa.eu/fairmode/document/event/presentation/20150624-Aveiro/WG2/WG2_FAIRMODE_EmissionTool_Cuba.pdf.

[18] Ho, B.Q., 2010. *Optimal Methodology to Generate Road Traffic Emissions for Air Quality Modeling: Application to Ho Chi Minh city.* Ph.D. Ecole Polytechnique Fédérale de Lausanne, Switzerland.

[19] Ntziachristos, L., Samaras, Z.G.D. and Kouridis, C., 2007. *COPERT IV Computer Programme to Calculate Emissions from Road Transport. User Manual (Version 5.0),* EEA.

[20] Eggleston, S., Gorißen, N., Hassel, D., Hickman, A.-J., Joumard, R., Rijkeboer, R., White, L. and Zierock, K.-H., 2000. *COPERT III Computer Programme to Calculate Emissions from Road Transport Methodology and Emission Factors (Version 2.1)*. [online] Available: https://www.eea.europa. eu/publications/Technical_report_No_49.

[21] Yamane, T., 1967. *Statistics: An Introductory Analysis*. New York: Harper and Row.
[22] Ho, M.D. and Dinh, X.T., 2008. Estimation of emission factors of air pollutants from the road traffic in Ho Chi Minh City. *VNU Journal of Science, Earth Sciences*, 24, 184-192.
[23] Belalcazar, L.C., Fuhrer, O., Ho, M.D., Zarate, E. and Clappier, A., 2009. Estimation of road traffic emission factors from a long term tracer study. *Atmospheric Environment*, 43(36), 5830-5837, https://doi.org/10.1016/j.atmosenv.2009.07.059.
[24] Department of Science, Technology and Environment of Ho Chi Minh City, 2001. *Urban Transport Energy Demand and Emission Analysis - Case Study of Ho Chi Minh City. No.1 (Phase II).*
[25] Ngo, T.H., Ketzel, M., Jensen, S.S. and Nguyen, T.K.O., 2010. Air pollution modeling at road sides using the operational street pollution model—A case study in Hanoi, Vietnam. *Journal of the Air and Waste Management Association*, 60(11), 1315-1326, https://doi.org/10.3155/1047-3289.60.11.1315.
[26] Phùng, N.K., Long, N.Q. and Tín, N.V., 2017. Xây dự'ng bộ số liệu phát thải phục vụ mô hình dự báo chất lượng không khí ở Thành phố Hồ Chí Minh. *Tạp chí Khí tượng Thủy văn*, 682, 1-6. (in Vietnamese)
[27] Oroumiyeh, F. and Zhu, Y., 2021. Brake and tire particles measured from on-road vehicles: Effects of vehicle mass and braking intensity. *Atmospheric Environment: X*, 12, https://doi.org/10.1016/j.aeaoa.2021.100121.