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## Traffic emission inventory for estimation of air quality and climate co-benefits of faster vehicle technology intrusion in Hanoi, Vietnam

Tran Thu Trang<sup>†</sup>, Huynh Hai Van and Nguyen Thi Kim Oanh

Environmental Engineering and Management, Asian Institute of Technology (AIT), Pathumthani 12120, Thailand

### ABSTRACT

Traffic emission contributes significantly to air pollution in Hanoi. This study estimated emissions from passenger fleets of cars, taxis and buses in Hanoi in 2010 using International Vehicle Emission (IVE) model for 14 species of air pollutants and greenhouse gases (GHGs). Surveys were conducted to gather information on fleet technology distribution and driving activities. Results showed that the 2010 annual emission from three fleets for CO, volatile organic compounds (VOC), NO<sub>x</sub>, SO<sub>x</sub> and particulate matter (PM) were 39.5, 5.9, 3.8, 0.6 and 0.22 Gg, respectively. Gasoline-fueled taxis and cars had the major shares of CO and VOC, while diesel-fueled buses contributed mainly to PM and black carbon (BC) emissions. If all vehicles of three fleets conformed to Euro3 and Euro4, air pollution emissions would collectively reduce by 85 and 88%, respectively. Concurrently, emissions of climate forcing agents, both GHGs and short-lived climate pollutants, in CO<sub>2</sub> eq. would reduce by 28 and 12%, respectively. Incorporation of emission from motorcycles (MC), vans and trucks showed that MC contributed the highest shares in total emission of every species, from 36% for CO<sub>2</sub> to above 90% for air toxics. The MC fleet should be prioritized for traffic emission control. Faster Euro technology intrusion in Hanoi would bring in significant co-benefits.

### KEYWORDS

road traffic; emission inventory; short-lived climate pollutants; co-benefits; Hanoi

### Introduction

Traffic air pollution is a serious challenge for environmental quality management in Hanoi, the capital city of Vietnam. Rapid urbanization and economic development in the city are accompanied by a fast increase in the vehicle fleet to meet the increasing transport demand of the growing population. Motorcycles (MC) dominate the urban traffic fleet population in Hanoi. A survey conducted in 2008 showed a 2 million MC fleet operating in Hanoi, and 35% of the fleet did not meet any Euro emission standards [1]. In 2013, the MC fleet in the Hanoi Capital Region reached 4.7 million [2] and this large increase was caused by both the physical expansion of the Hanoi territory that took place in 2008 [3] and the annual growth rate of the MC fleet of around 16%. Other on-road vehicle types, such as bus, taxi and personal car, have also significantly grown in numbers in recent years. For example, the average annual growth rate for the personal car fleet was about 20% during the 2001–2012 period, as seen from the registration data provided by the Vietnam Register [2]. The number of taxis increased fast; hence, the density of taxis in the Hanoi streets was high: on average, about 20 taxis per kilometer on a total of 600 kilometers of six urban districts in Hanoi [101]. Public buses, which are recently becoming a popular means


of mass transport in Hanoi, increased by nearly 2.5 times during the period from 2001 to 2009, and this trend is expected to continue in accordance with the policy supporting the public transport system [4]. By 2012, the number of public buses in Hanoi had reached 1425 vehicles [102].

Road traffic was reported to be the largest air pollution source in cities of Vietnam including Hanoi [103]. Traffic jams are often observed in the city, especially during rush hours, and cause serious air pollution problems. Low speeds and the stop-and-go driving mode lead to huge emission amounts from the traffic in Hanoi, in particular toxic air pollutants such as fine particles, volatile organic compounds (VOC) and carbon monoxide (CO). These toxic exhaust fumes are released at the breathing level and in populated urban areas, and therefore can lead to a high risk of human exposure. The vehicles also emit greenhouse gases (GHGs) including carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O), along with acid rain precursors (SO<sub>2</sub> and NO<sub>x</sub>).

Presently, short-lived climate pollutants (SLCPs) attract wide attention because of their multiple adverse effects. Emission control for SLCPs would bring in co-benefits in improving air quality and reducing the rate of climate warming in the near term [106]. The most

**CONTACT** Nguyen Thi Kim Oanh ✉ [kimoanh@ait.asia](mailto:kimoanh@ait.asia)

<sup>†</sup> Current address: Department of Environmental Technology and Management, Van Lang University, Ho Chi Minh City, Vietnam

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important SLCP is black carbon (BC) particles, which have recently been considered the second largest warming agent after CO<sub>2</sub> [5]. About 20% of the globally emitted BC is generated by diesel-powered vehicles, on-road and off-road, including trucks, buses, ships, construction machinery and so on [5]; hence, a cleaner diesel fleet can reduce BC emissions substantially. For illustration, Bahner et al. [6] projected that the BC emissions in the United States would be reduced by 42% from 2001 to 2020, primarily as a result of diesel vehicle regulations. Tropospheric ozone, being a strong GHG and a toxic pollutant to both human health and the ecosystem, is another important SLCP. Measures that lower tropospheric ozone levels would bring in multiple benefits to climate, human health and crop production [104]. Ozone is not directly released from a source but is formed in the atmosphere through photochemical reactions involving precursors of NO<sub>x</sub>, VOC and CO, which are released in large amounts from traffic fleets. Therefore, measures for emission reduction of vehicle fleets are expected to provide win–win solutions. However, to assess the effectiveness of these measures, a detailed analysis of emission of current fleets and projection of emission according to various emission control strategies is required.

This study was designed to provide an emission inventory (EI) for the passenger transport fleet in Hanoi, and assess the benefits of scenarios of a faster intrusion of the Euro3 and Euro4 vehicle technologies in the city. The EI was done using the International Vehicle Emission (IVE) model which was developed jointly by the University of California at Riverside, College of Engineering – Center for Environmental Research and Technology (CE-CERT), Global Sustainable System Research and the International Sustainable System Research Center [105]. Using the input files generated from survey data, the IVE model produces the pollutant emission factors (EFs) that are relevant to the local driving conditions and local fleet composition. IVE has been successfully used to generate emission data for several cities in developing countries [105]. It was also previously applied for estimating EI for the MC fleet in Hanoi for the year of 2009 by our research group [1]. The present study focused on other types of passenger vehicles, including personal cars, taxis and buses, that were surveyed in Hanoi in 2010. Our results were compiled with the MC emission produced for Hanoi [1] and rough estimates of emissions for other on-road fleets of vans and trucks to develop an EI for the entire on-road vehicle fleet in the city.

## Methodology

### Research design

IVE modeling requires a large amount of local data to generate the input files for producing relevant EFs for the driving conditions in each study area. IVE has three

types of input files of which two files, the location and fleet files, are mandatory. The third file, the base adjustment, is an optional file and is prepared only when the local measurement data for EFs are available. Such measurement data was not sufficiently available for the considered vehicle fleets of Hanoi in 2010; hence, the base adjustment file was not used in this study.

In principle, with the location and fleet files prepared from the local survey data, the IVE model produces EFs for Hanoi by using a range of correction factors applied to adjust the base EFs for every identified vehicle technology index. The resulting EFs are used together with vehicle driving activities (driving distance and number of starts) to produce the emission – for example, the annual emission in Hanoi for 2010. This study covered the following emission species: CO, VOC (exhaust and evaporative), NO<sub>x</sub>, SO<sub>2</sub>, PM<sub>10</sub>, CO<sub>2</sub>, N<sub>2</sub>O, CH<sub>4</sub>, 1,3-Butadiene, acetaldehyde, formaldehyde, ammonia (NH<sub>3</sub>) and benzene. Lead (Pb) was excluded from this EI study because the leaded gasoline has been successfully phased out in Vietnam since July 2001 [106].

The data collection generally followed the IVE method as described in IVE field data collection activities documents [105]. This study included three road types, namely highways, and arterial and residential roads, that run through three zones representing the Hanoi urban area – higher income (zone A, city center), commercial (zone B, city center) and lower income (zone C, peri-urban) – as shown in Figure S1 of the Supplementary information.

### Data collection and processing

The data collection was done in Hanoi during the period from July 2010 to January 2011. A summary of primary and secondary data collected for the IVE modeling in this study is shown in Table S1. The required data were collected following the IVE data collection method and are detailed below.

### Questionnaire survey

The survey for three passenger transport fleets (bus, taxi and personal car) was conducted at parking lots, gasoline refilling stations and bus terminals (for buses) in all three zones (A, B, C) of the city. As of 2009, there were 1020 buses, 11,533 taxis and 84,578 personal cars in Hanoi [4]. The sample size, estimated using the Taro Yamane table for the acceptable error of 0.10, was 94 for buses, 99 for taxis and 100 for personal cars; hence, the final survey was done for 100 vehicles of each vehicle fleet. The questionnaire survey was done in July–August 2010 which provided data on the vehicle types, model years, vehicle sizes, fuel types, fuel delivery systems, exhaust control devices and evaporative control systems. The collected information was used to identify the vehicle technologies to match with the IVE default technology indexes.

### Estimation of vehicle kilometers traveled

This study estimated the annual average vehicle kilometers traveled (VKT) using the relationship between odometer readings and vehicle ages [7], which was also used in our earlier studies [1,8]. A regression equation between the vehicle age (years) and the vehicle odometer reading (km), both collected in the questionnaire survey, was developed for the three considered fleets (bus, taxi, personal car). The average VKT for a given fleet was then calculated using Equation S1.

### Vehicle flow monitoring

Vehicle counting was done manually at nine selected roads, one location per road (Figure S1), for three time periods in a monitoring day: 07:00–09:00 and 17:00–19:00 to cover rush hours, and 10:00–11:00 and 13:00–15:00 to cover normal hours. The counting was done for 1 day at each road in December 2010. Thus, for every selected road, a total of 180 minutes of vehicle counting was obtained (continuously counting over 15 minutes followed by a 10-minute break) which yielded a total of  $9 \times 180 = 1620$  minutes of vehicle data.

### Global positioning system survey

This survey was conducted to obtain the vehicle driving and startup patterns. A global positioning system (GPS; GlobalSat DG-100 model) was attached on each surveyed vehicle on every monitoring day. The GPS had an accuracy in velocity recording of 0.1 m/sec, and of 1–5 m in horizontal position. The longitude, altitude, latitude, speed and time were recorded second by second. The Hanoi urban area is quite flat; hence, information on altitude was not necessary as the road grade was close to zero. The GPS survey was done on both weekdays and weekends. In total, six buses on two fixed routes in Hanoi (in their normal operating period), six taxis (non-fixed routes) and six personal cars of office workers were monitored (Table S2), with the routes shown in Figure S1.

Vehicular tailpipe emissions are affected by a number of factors, such as driving speed, acceleration and deceleration. In the IVE model, driving patterns are characterized by two parameters: vehicle specific power (VSP) and engine stress. The obtained second-by-second GPS data were used to calculate VSP using Equation S2, while the engine stress was calculated using Equation S3 [105]. There are 20 VSP categories and three engine stress categories which yield a total of 60 VSP bins for every monitoring hour.

The GPS data were also used to determine the vehicle startup pattern. A cold start generates high exhaust emission; hence, the predominant factor is the soak period before an engine starts. In IVE, the term “engine soak” is defined as the length of time that an engine has been shut off before starting again [105]. A cold start is referred to as a start when the engine has been completely cooled off – that is, after resting for

18 hours or more. A completely warm start is when a warm engine is shut off for 5 minutes or less before starting again. In this study, a stop of a monitored vehicle was recognized if its speed (shown by GPS data) was less than 1 km/h for more than 4 minutes and a start was then counted after the stop.

### Secondary data collection

Hourly temperature and humidity in Hanoi were collected from the Weather Underground website [www.wunderground.com](http://www.wunderground.com) [107]. The data on fuel characteristics were extracted from the information by the standards, metrology and quality of Viet Nam (STAMEQ) [108] and the Vietnam National Petroleum Corporation (VNPC) [109]. All of the data were used in the location input file of IVE.

### Emission reduction scenario and co-benefit quantification

The EI for the three passenger vehicle fleets was produced for the base case of 2010. Further, two optimistic, faster technology-intrusion scenarios were considered which assumed that all buses, taxis and cars in Hanoi would at least conform to Euro3 (Scenario 1) and Euro4 (Scenario 2), respectively. These scenarios were intended to provide a simple image of what could have happened in 2010 had there been a greater penetration level of Euro3 and Euro4, whereas the driving activities of these passenger vehicle fleets remained unchanged. To construct the scenarios, this study simply assumed that all vehicles with lower engine standards than Euro3 and Euro4, respectively, presented in the 2010 fleets would be scrapped and their VKT would be provided by new Euro3 and Euro4 vehicles, respectively. The emissions of toxic air pollutants and associated global warming potential (GWP) in CO<sub>2</sub> equivalent (CO<sub>2</sub> eq.) under these scenarios and the base case were compared. The CO<sub>2</sub> equivalent of an emission was calculated using Equation (1):

$$\text{GWP of a scenario (CO}_2 \text{ eq.)} = \sum E_i \times \text{GWPI} \quad (1)$$

where  $E_i$  = emission amount of species  $i$  (mass, tonne/year) and  $\text{GWPI}$  = global warming (+) or cooling (–) potential of species  $i$ .

Only GWP for the 20-year horizon was estimated because the impacts of SLCPs should be more pronounced over this shorter period. The GWPs for GHGs and SLCPs used in this study are those considered relevant for Southeast Asia (SEA), and listed in Table S3. Most of the species in Table S3 have warming effects, except for OC and sulfates (transformed particulate products of SO<sub>x</sub> in the atmosphere) which have cooling effects. Because the IVE model does not produce OC and BC emissions directly, this study estimated the OC

and elemental carbon (EC) emissions as the fractions of exhaust PM emitted from diesel and gasoline vehicles. For diesel vehicles, the values used in this study were based on the measurements for the diesel fleet in Bangkok, Thailand [9]: EC = 0.46 PM and OC = 0.2 PM. The OC and BC fractions in the PM emission from gasoline vehicle exhaust were estimated using the data provided by the United States Environmental Protection Agency (US EPA) [110]: OC = 0.78 PM and BC = 0.19 PM.

## Results and discussion

### Vehicle fleet and driving activities in Hanoi

#### Vehicle flow

The results (detailed in Table S4) show that the hourly average flow on each road of a particular type of vehicle did not vary much during a day (small standard deviations, SD). However, the fluctuations between the road types and zones were significant, which is seen in the large SD of average hourly flows in the city:  $74 \pm 44$  buses,  $463 \pm 343$  taxis and  $768 \pm 527$  personal cars. In fact, the shares of bus, taxi and personal car fleets were quite small in the active traffic fleet in Hanoi as compared to motorcycles. Using the data from the Vehicle Registration (VR) office [4] and with the assumption of a retirement rate of 2% per year of buses and cars and 12% of the taxi fleet, the share of the active fleets was estimated at 0.04% for buses, 0.47% for cars and 3.44% for taxis (Table S4). The MC had the predominant proportion in the operating traffic fleet in Hanoi – that is, a share of 93–97% [10] with an average hourly flow of 8000 in 2009 [1]. The results of hourly vehicle counts on nine roads for weekdays and weekends obtained in this study were used in the IVE location files for the EI of bus, taxi and car fleets on the respective roads.

#### Vehicle technology distribution

The questionnaire survey results are summarized in Table 1, and show that diesel and gasoline were the only two fuel types used for on-road transportation in Hanoi during the study period (2009–2010). Other types of cleaner fuels, such as compressed natural gas

(CNG) and liquefied petroleum gas (LPG), were not observed. The bus fleet was 100% diesel powered, while the taxi fleet was 100% gasoline powered. Only a small portion of the personal car fleet, about 7% (e.g., Ford Everest brand), used diesel. This finding agrees with Tung et al. [11] who reported that 95% of the light-duty vehicles in Hanoi in 2008–2009 were gasoline powered.

Our study also showed that Euro3 was the most advanced engine standard observed in Hanoi as of 2010, and it was only seen in the car fleet (34%). The most advanced technologies found in the bus and taxi fleets only conformed to Euro2 (74 and 80%, respectively). Substantial shares of pre-Euro vehicles were still observed in these fleets: 16–26%. Most vehicles were relatively new; the weighted average age was about 2 years for taxis and personal cars but was 6.3 years for buses.

The vehicle technologies obtained in the survey were matched with the default IVE indexes, and results are presented in Table S5. The bus fleet had four IVE technology indexes, with index number 1130 being the most popular at 53% (diesel fuel, Euro2, mileage >161,000 km). The taxi fleet was matched with five IVE technology indexes, with index number 182 having the highest share at 38% (petrol fuel, Euro2, >161,000 km). The personal car fleet was matched with seven IVE indexes, with index number 183 being the most popular at 31% (petrol fuel, Euro2, <71,000 km).

#### Vehicle kilometers traveled

The non-linear regression equations between the odometer readings (km) and vehicle ages (years) produced higher coefficients of determination –  $R^2 = 0.93$  for buses, 0.99 for taxis and 0.99 for the personal car fleet (Figure S2) – than the linear ones. The average annual VKT of a vehicle was calculated as the difference in odometer readings ( $\Delta Y$ ) for  $X \pm 0.5$  years ( $X$  = fleet average age, given in Table 1). The annual usage of a vehicle was 77,380 km/yr for buses, 57,305 km/yr for taxis and 15,330 km/yr for personal cars.

As a way of checking, the daily VKT was also determined using the GPS survey data, and the results are

**Table 1.** Summary of vehicle questionnaire survey and GPS survey.

Parameters	Bus	Taxi	Personal car
Accumulative fleet, 2010 <sup>†</sup>	1020	13,850	101,500
Number of IVE technology indexes	4	5	7
Average age (span), years	6.3 (1–11)	2.4 (1–6)	2.1 (1–8)
Fuel used	Diesel: 100%	Petrol: 100%	Diesel: 7% Petrol: 93%
Engine standards (%)	Euro2: 74% Pre-Euro: 26%	Euro2: 80% Pre-Euro: 20%	Euro3: 34% Euro2: 50% Pre-Euro: 16%
Number of startups per day (based on GPS survey)	16.6	26	6.9
Daily VKT (km)	GPS survey 239 ± 10 Odometer regression 212	227 ± 41 157	52 ± 12 42

<sup>†</sup>Source: [4].

Note: GPS - global positioning system; IVE - international vehicle emission; VKT - vehicle kilometers traveled.



mostly comparable, better for buses and cars (Table 1). For taxis, the GPS survey showed a higher daily VKT, which may reflect the fact that in the past people used taxi services less than during the survey period. However, due to a smaller number of taxis covered by the GPS survey (six vehicles) as compared to the parking lot survey (100 vehicles), the VKT for taxis was also estimated using the regression equation.

### Vehicle speed

The vehicle speeds, determined based on the GPS survey, showed diurnal variations with lower speeds during rush hours, especially on weekdays (Figure 1a) due to the larger traffic volume and, hence, more traffic jams. There were differences in vehicle speeds between weekdays and weekends (Figure 1a, b). Apparently, during rush hours the bus speed on the fixed routes on weekdays was lower than on weekends. The speeds of taxis and personal cars at rush hours, however, were not much different between weekdays and weekends, owing to their flexibility in selection of routes. Taxis had generally higher speeds, especially at midday on weekdays, reaching 50 km/h. Note that bus daily operation time was from 05:00 to 22:00, while taxis and personal cars were observed at all times but more during the daytime. The average speed in km/h of buses and personal cars was almost the same on weekdays and weekends:  $13.3 \pm 7.4$  and

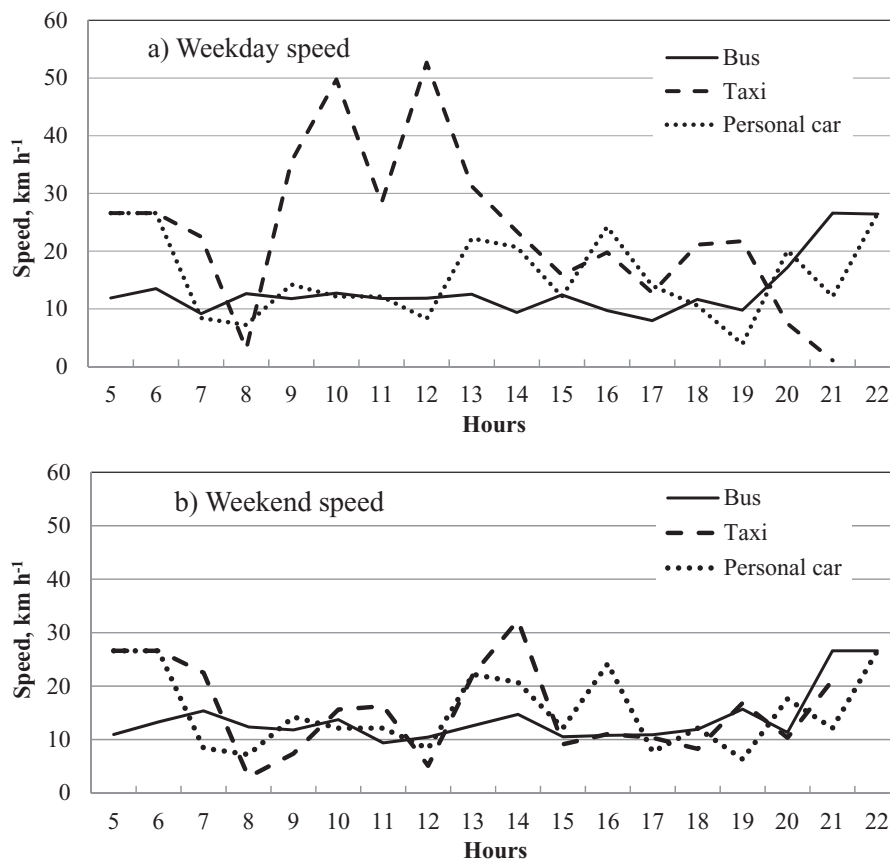
$18.4 \pm 8.0$  vs.  $13.8 \pm 7.5$  and  $17.3 \pm 8.7$ , respectively. Taxis, however, had higher speeds on weekdays ( $20.2 \pm 14.6$  km/h) than weekends ( $17.0 \pm 9.8$  km/h).

### Vehicle specific power

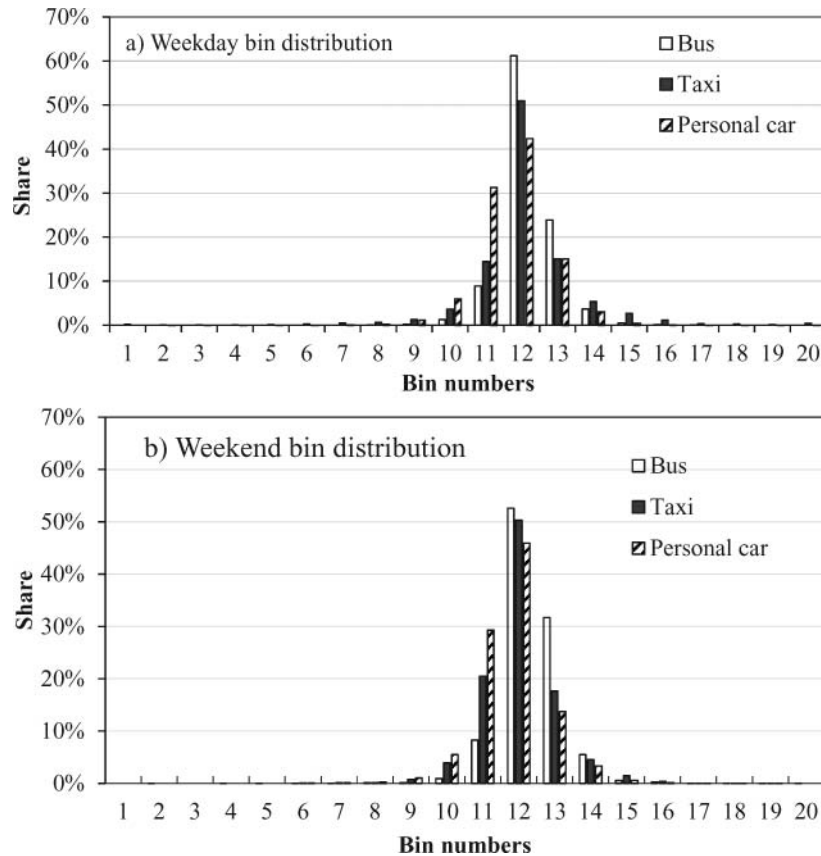
The results of the bin distribution, averaged for 24 hours of the monitoring days, showed quite similar patterns on both weekdays and weekends (Figure 2a, b). Most common bins found were within numbers 9 to 17. Bin number 12 had the highest share for all fleets – that is, >50% for buses and taxis, and >42% for personal cars. Bin 11 and bin 13 also had significant shares for all vehicle types, above 15%, respectively. In fact, bins 11 and 12 characterize the low vehicle speeds with stops (i.e., at traffic signal) or the idling conditions in traffic jams, while bin 13 presents the driving pattern with slight accelerations and constant speed [105]. Buses and personal cars operated only in bins 0 to 20, inclusively, which corresponded to a low power usage. For taxis, some small shares (0.01 to 0.87%) of higher bin numbers (20 to 40; not shown in Figure 2) that correspond to medium engine stress were also obtained, and this is consistent with the higher speeds of taxis.

### Engine startup distribution

The numbers of starts and soak time (the time interval between two consecutive starts) directly affect the vehicle emission. Generally, buses in Hanoi arrived at



**Figure 1.** Diurnal variations of vehicle speeds in Hanoi, 2010. (A) weekdays; (B) weekends. Survey time was 05:00–21:00 for taxis; 05:00–22:00 for personal cars, and 05:00–22:00 for buses (entire bus daily operation period).



**Figure 2. Daily average power bin distribution.** (a) Weekdays and (b) weekends. Bins are used to characterize driving patterns. In total there are 60 bins, which combine 20 categories of the Vehicle Specific Power (VSP) and three engine stress categories. Bin numbers 21–60 are not shown because they had minor shares (0.01 to 0.87%) for taxis and were not observed for buses and personal cars.

terminal depots when finished a service round, and the drivers stopped the engine before continuing on the next service. The taxi engine was stopped while waiting for customers. Private cars normally stopped at the final destination of a trip, for example office or home. The number of engine starts in a day of each vehicle type was obtained from the GPS survey and also checked by direct observations. On average, a bus had 16 starts on a weekday and 18 starts on weekend (more service rounds because of fewer traffic jams), which corresponds to a weighted average of 16.6 times per day. The daily number of startups for a taxi was 30 on a weekday and 16 on weekend day, yielding a weighted average of 26 times per day. Likewise, the daily number of startups for a personal car was eight on a weekday and four on a weekend; hence, the weighted average was 6.9 times per day (Table 1).

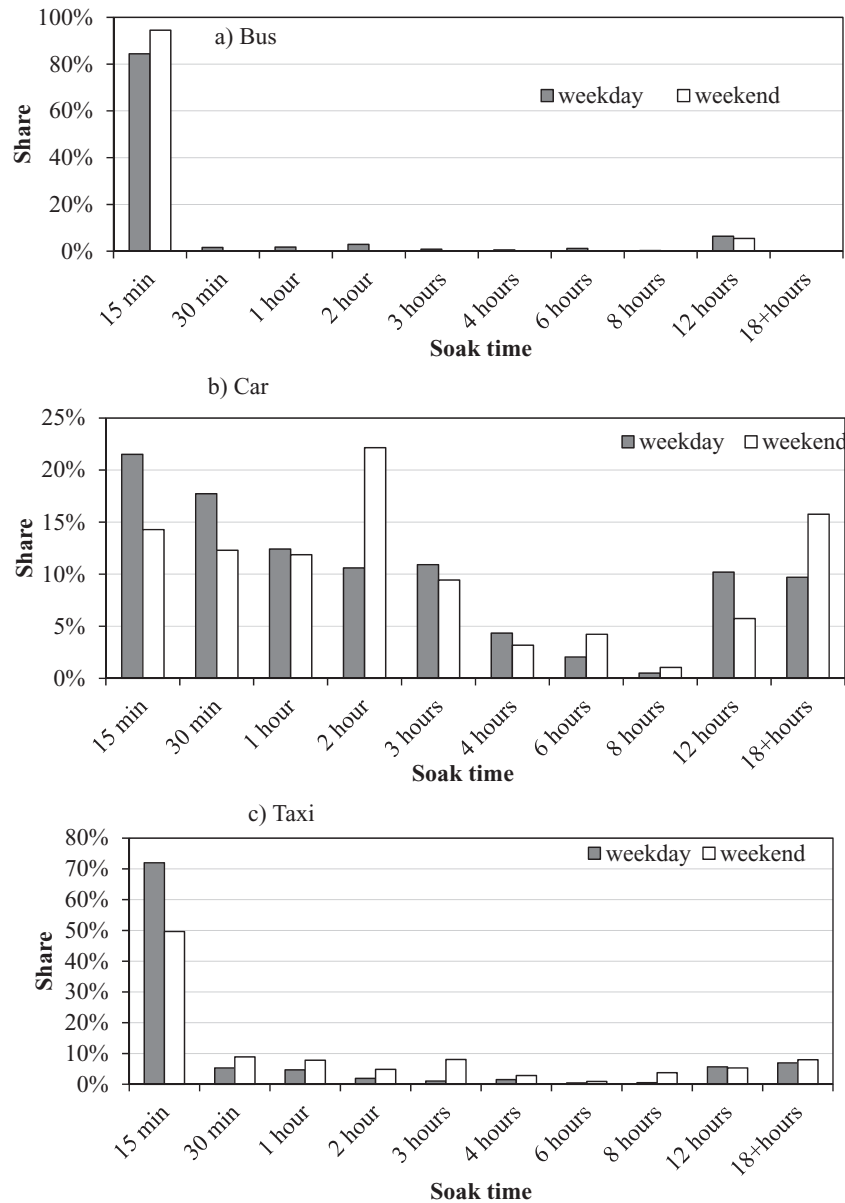
The startup distribution patterns of three vehicle types are shown in Figure 3a–c. The soak time bins on the x-axis indicate the time period between two consecutive engine starts. The “15 min” bin means the soaks were between 0 and 15 minutes, whereas “30 min” means the soaks were between 16 and 30 minutes, and so on [105]. For buses, the 15-minute soak bin was the most predominant (85–95%), which corresponds to the short stop at depots. The second most common soak bin was 12 hours (engine rest time for 8–12

hours), reflecting the bus daily operation period which ended at 22:00 and started at 05:00 the next day. For taxis, the 15-minute soak bin was also the most common, 72% on weekday and >50% on weekend, but other soak bins from 30 minutes to 18+ hours were also observed with a share of <10% each. The long soak periods of taxis, 12 or 18+ hours, were the rest time between two consecutive working days. The soak bin distribution for personal cars was markedly different from buses and taxis with the bins distributed rather evenly, each generally having a share of <15%. There were also differences in the soak bin distribution between weekdays and weekends for cars, with weekdays having a higher share of 15-minute bins and weekends having more shares of 2-hour and 18-hour soak bins. This reflected the fact that on weekdays the cars were mainly used by owners to go to work, while on weekends other driving activities (for shopping, sightseeing, etc.) were involved.

### Emission factors

#### Emission factors by vehicle type

IVE was run to provide hourly emissions from each vehicle fleet on a considered road, separately on weekdays and weekends. The emission results were produced for every technology index (of bus, taxi or car



**Figure 3.** Daily distribution of soak times. (a) Buses; (b) personal cars; (c) taxis.

fleet), which were used to calculate the corresponding running EF (g/km) and startup EF (g/start).  $\text{SO}_2$  emission produced by IVE is for a range of S content (not for a specific S value); hence,  $\text{SO}_2$  emission results in this study are only indicative. For example, the S content in diesel and gasoline of 0.05% in Vietnam [109] belonged to the S input range of 350–600 ppm of IVE.

Details of running and startup EFs for different vehicle technology indexes in Hanoi are given in Table S6 for all pollutants, while Figure S3 visually illustrates EFs for selected pollutants. The results show that the indexes of old technologies, i.e. pre-Euro, and high mileage (>161,000 km), had higher EFs in every fleet – that is, index 1076 for buses, indexes 100 and 101 for taxis, and indexes 99, 100 and 101 for personal cars. The EFs from these polluting vehicles were generally several times (2–10 or more) higher than the corresponding Euro2 vehicles in the same fleet type.

IVE emission results for a fleet (with the observed shares of technology indexes) were used to calculate the fleet composite EFs (for all road types in three zones of Hanoi). The average EFs of selected pollutants are presented in Table 2, separately for weekdays and weekends, while for other pollutants, weighted average EFs (5 weekdays and 2 weekend days) are presented in Table S6. The EFs of toxic pollutants for the taxi fleet were higher than those for the car fleet, which may be explained by the higher mileage and less advanced engine technologies – that is, no Euro3 was observed for taxis (Table 1). Buses, all diesel powered, as expected released larger amounts of  $\text{NO}_x$  and PM than the gasoline-powered taxis and cars. It is noted that the startup EFs of all vehicle types were also considerable, especially for the products of incomplete combustion – that is, CO, PM and air toxics. The EFs were comparable between weekdays and weekends for buses and cars. For taxis, however, running EFs on



**Table 2.** Emission factors of selected pollutants for vehicles in Hanoi, 2010.

	Vehicle types	States	CO	VOC	VOC evap.	NOx	Benzene	PM <sub>10</sub>
Bus	Weekday	Start (g/start)	0.628	0.054	–	0.791	0.001	1.133
		Running (g/km)	7.031	1.764	–	17.266	0.019	2.118
	Weekend	Start (g/start)	0.622	0.053	–	0.787	0.001	1.121
		Running (g/km)	6.592	1.644	–	16.173	0.017	1.986
	Average	Start (g/start)	0.626	0.053	–	0.790	0.001	1.129
		Running (g/km)	6.905	1.730	–	16.954	0.018	2.080
Taxi	Weekday	Start (g/start)	23.947	1.981	0.403	0.553	0.005	0.013
		Running (g/km)	20.842	1.715	0.380	0.798	0.047	0.009
	Weekend	Start (g/start)	23.621	1.850	0.316	0.521	0.005	0.011
		Running (g/km)	32.661	5.584	1.365	1.249	0.132	0.020
	Average	Start (g/start)	23.854	1.944	0.378	0.544	0.005	0.012
		Running (g/km)	24.219	2.820	0.661	0.927	0.071	0.012
Car	Weekday	Start (g/start)	10.445	0.998	0.066	0.606	0.005	0.011
		Running (g/km)	9.825	1.448	0.179	0.871	0.083	0.011
	Weekend	Start (g/start)	11.614	1.113	0.073	0.617	0.007	0.013
		Running (g/km)	13.296	2.004	0.245	1.130	0.113	0.015
	Average	Start (g/start)	10.779	1.031	0.068	0.610	0.006	0.012
		Running (g/km)	10.816	1.607	0.198	0.945	0.092	0.012

Note: VOC - volatile organic compounds; PM - particulate matter.

weekends were higher, which may be explained by their lower speeds as compared to weekdays, discussed above.

A comparison between EFs produced in this study and other studies for Hanoi and several other Asian cities is presented in Table S7. Hung et al. [10] applied the back calculation method using the Operational Street Pollution Model (OSPM) to produce running EFs (g/km) for buses in Hanoi, and the results were quite close to ours for PM. EFs of taxis in Hanoi were in similar ranges to those reported for Shanghai [111]. In Kathmandu, however, higher EFs for buses and taxis were obtained, which is explained by the extremely low vehicle speeds in the city as well as the high mileage of the bus fleet [8]. The EFs determined, using the chassis dynamometer method, for four light-duty vehicles in Hanoi [13] were similar to our results for NOx but lower for CO. However, the small number of vehicles tested and the narrow span of age (3–7 years) in their study may not have yet produced EF results to be fully comparable to the fleet composite values obtained in our study.

### Annual emission of vehicle fleets in Hanoi

#### Annual emission by vehicle types

The daily vehicle activities (Table 3) and the fleet composite EFs were used to produce the 2010 annual emissions of bus, taxi and car fleets, respectively. The running and startup emissions were calculated separately and summed up to produce the total annual emission for each of 14 considered species.

In order to get a more comprehensive overview of the traffic emission in Hanoi, we also present in this section the emissions estimated for other vehicle types in the city. The MC annual emission for 2010 was calculated using the EFs produced by IVE based on survey data of 2009 [1] and the active MC population of 2010. The emissions by the van and truck fleets in Hanoi

were roughly estimated using the survey data available in Bangkok for vans and in Ho Chi Minh City (HCMC) for trucks. First, based on the survey results for vans in HCMC [14], the van fleet in Hanoi was assumed to be 50% gasoline fueled and 50% diesel fueled. The EFs for vans were roughly estimated as the average of EFs for gasoline and diesel vans produced by IVE for Bangkok [15]. The number of startups and daily VKT of vans were assumed to be the same as those obtained by survey for Bangkok – startups of 20.3 times per day [15], and a VKT of 89 km per day [16]. For trucks, the survey results in HCMC reported by Van [17] were used: 7% gasoline fueled (mainly light duty) and 93% diesel fueled; 6.9 startups per day and 31.4 km per day of VKT. The EFs used for emission estimation of all vehicle types considered in this study are shown in Table S8. Further studies should conduct a detailed survey for van and truck fleets in Hanoi to gather local data for IVE modeling to produce relevant EFs.

The large MC fleet in Hanoi contributed predominantly to the driving activities (VKT) and startup number (Table 3) which explain its predominant contribution to the overall traffic emission (Figure 4; Table S9). The MC fleet shared 35–47% of SOx, NOx and CO<sub>2</sub>, while for other pollutants its proportions were above 70%. The total traffic CO emission in Hanoi in 2010 was 221 Gg, of which 77% was from MC and about 9% each from taxi and car fleet, while the other fleets collectively contributed about 5%. MC also contributed over 88% of the total VOC emission (62.4 Gg) and above 80% of air toxics emissions. The large MC fleet also contributed predominantly to PM, about 70% of the total emission of 3.7 Gg/year. It is noted that the PM EFs from MC, 0.094 g/km and 0.23 g/start [1], were higher than those from other gasoline-fueled vehicles of personal cars (PC) and taxis obtained in this study, but as expected were lower than the EFs of diesel-powered vehicles (Table S8). The diesel fleets,

**Table 3.** Daily vehicle activities in Hanoi, 2010.

Vehicle type	Number of active vehicles <sup>†</sup>	Daily VKT		Daily number of startups	
		Per vehicle (km/veh)	Per fleet (*1000 km)	Per vehicle (Number)	Per fleet (*1000 times)
Motorcycle <sup>‡</sup>	2,339,519	20.2	47,258	4.9	11,463
Bus	1118	212	237	16.6	18.6
Taxi	12,189	157	1914	26	316.9
Personal car	100,359	42	4215	6.9	686.9
Van <sup>§</sup>	15,680	89	1396	20.3	318
Truck <sup>¶</sup>	67,399	31.4	2116	6.9	465

<sup>†</sup>Active vehicle number was estimated based on Vietnam Registration [4] data using retirement rate of 2% for buses and cars, and 12% for taxis.

<sup>‡</sup>The number of motorcycles in 2010 was used while the vehicle kilometers traveled (VKT) and number of startups per motorcycle were extracted from [1].

<sup>§</sup>For the van fleet emission, the VKT, startup number and emission factors (EFs) for Bangkok (2009–2013) [15,16] were used.

<sup>¶</sup>For the truck fleet emission, the VKT, startup number and EFs obtained for Ho Chi Minh City in 2013 [17] were used.

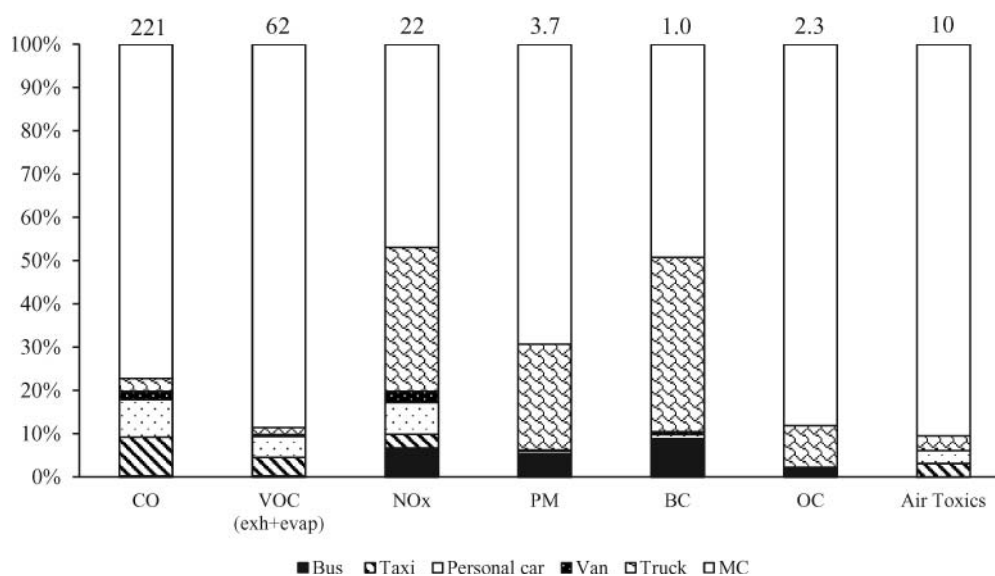
as expected, also made a significant contribution to PM emission, trucks 24% and buses 5%, that was lower than the MC contribution despite their higher PM EFs (Table S8). The emissions of BC and OC were estimated using their proportions in the PM emitted from diesel and gasoline exhaust, respectively. The total annual emissions of BC and OC from the entire traffic fleet in Hanoi were 1.0 Gg and 2.3 Gg, respectively. The MC fleet was also the largest contributor to BC (~50%) and OC (>87%), as seen in Figure 4. The truck and bus fleets, largely diesel powered, also had large shares of BC emissions, 41% by trucks and 9% by buses, and considerable OC emissions, 10% by trucks and 2% by buses, while other types of vehicles had only small emissions of BC and OC.

### Diurnal emissions

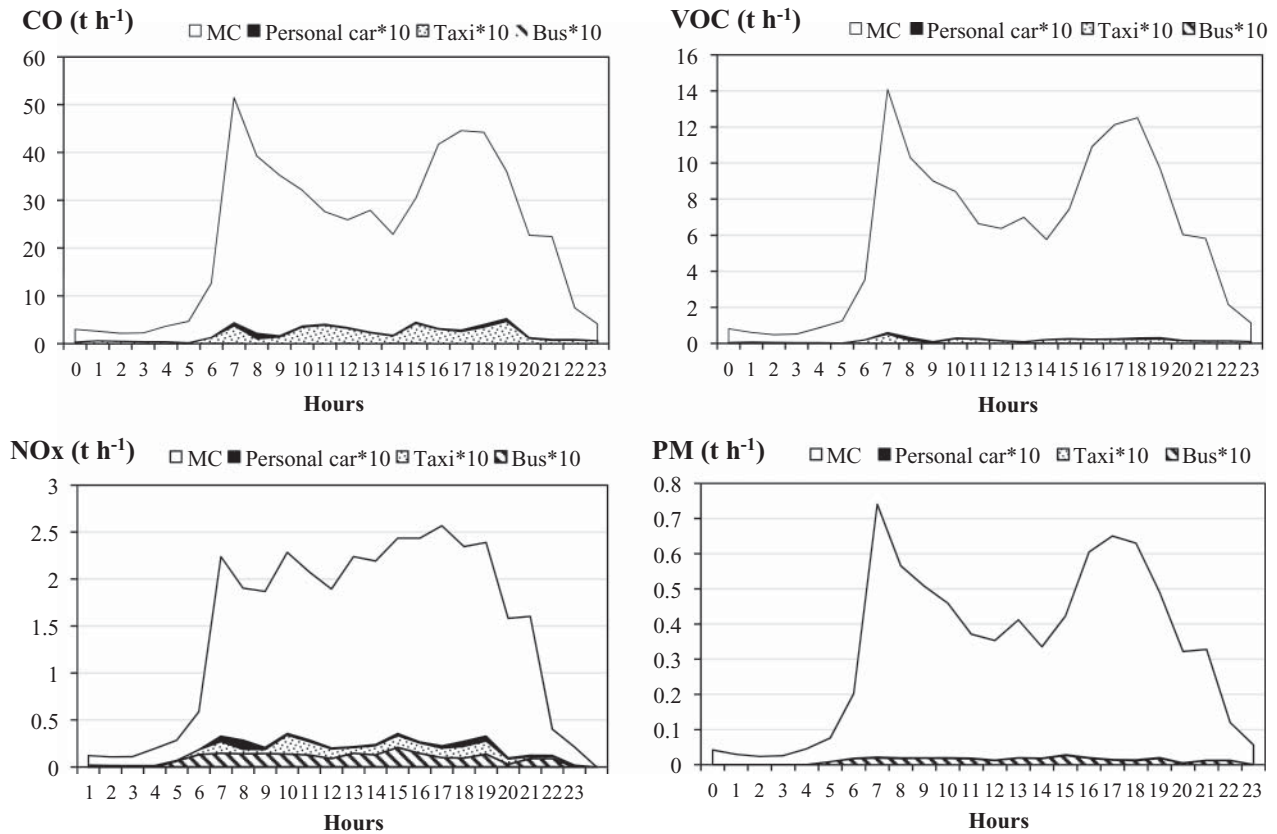
Diurnal emissions for a vehicle type were directly produced by IVE modeling, and the information is useful in the preparation of the emission input file for dispersion modeling studies. The hourly emissions (startup +

running) of the three fleets are presented in Figure 5 together with the estimated emissions from MC in Hanoi based on our previous study [1]. The diurnal emission variations of the total fleet were dominated by the MC fleet emission. The highest hourly emission was seen in the morning (06:00–08:00) and evening rush hours (18:00–20:00) for all pollutants. MC and car fleets had larger diurnal variations, with the peaks at 07:00–09:00 and 17:00–19:00, because they serve as the main transport means for people to move between homes and workplaces. Emissions from buses (moving on fixed routes, round by round) and from taxis (on customers' demand) did not show much daily variation.

Most of the emission was from the vehicle running activities. The startup emission of different pollutants shared about 0.2–4.1% of total emission for buses, 0.3–14% for taxis and 0.4–14% for the car fleet. More detail on the diurnal variations in running and startup emissions, separately, for selected pollutants is seen in Figure S4.



**Figure 4.** Total emissions (numbers, in Gg) and emission share of different vehicle fleets in Hanoi in 2010. Air toxics include 1,3-Butadiene, acetaldehyde, formaldehyde and benzene (VOC - volatile organic compounds; PM - particulate matter; BC - black carbon; OC - organic carbon; MC - motorcycle).



**Figure 5.** Diurnal variations of traffic emissions in Hanoi for motorcycles (MC), personal cars, taxis and buses (excluding vans and trucks). Values for other fleets are scaled up 10 times to be visible along with those for MC (VOC - volatile organic compounds; PM - particulate matter).

### Air quality and climate co-benefits of faster vehicle technology intrusion

The survey results showed that as of 2010, most of the bus, car and taxi fleets in Hanoi did not comply with Euro3 (Table 1). The current policy of Vietnam is to have the vehicle fleet conform to Euro4 by 2017 [112]. This study attempted to estimate how much emission of air pollution and climate forcers could be prevented if Euro standards, Euro3 and Euro4 respectively, could have been implemented as soon as 2010. As mentioned above, the Euro3 and Euro4 scenarios were constructed by assuming that all vehicles of lower engine standards would be scrapped and their VKT would be provided by new Euro3 and Euro4 vehicles, respectively (Table S5).

Table 4 presents a summary of the results of the emissions and emission reductions for bus, taxi and car fleets under the two Euro scenarios. Scenario 1 (Euro3) would induce significant reductions in emissions as compared to the base case – that is, by above 60% for most toxic air pollutants, with higher reductions seen for VOC (92%), CO (89%) and air toxics (87%). The PM emission reduction would be 61%, while NO<sub>x</sub> and SO<sub>x</sub> emission reductions would be 36 and 44%, respectively. The emission of GHGs N<sub>2</sub>O and CH<sub>4</sub> would reduce while CO<sub>2</sub> would increase (by 6.9%), which may be explained by better combustion, hence CO<sub>2</sub> instead of CO or VOC would be emitted. Collectively, under

Scenario 1, the emission reduction for the air pollutants (excluding BC/OC to avoid double counting with PM<sub>10</sub>) would be 85% while that of GWP (20-year horizon) would be 28%.

Further improvement of the vehicle technology to Euro4 under Scenario 2 would bring in additional emission reductions of all pollutants, but increases in emissions of NO<sub>x</sub>, CO<sub>2</sub> and N<sub>2</sub>O (Table 4). Note that SO<sub>x</sub> emission reduction under Scenario 2 is more significant than under Scenario 1 because a lower S content was used in IVE to satisfy the requirements of Euro4 vehicles. The overall emission reduction of air pollutants under the Euro4 scenario, compared to the base case, would be 87.9%, while the GWP of the emissions would reduce by 11.6%.

Our previous study for MC [1] also showed that if all MC in Hanoi conformed to Euro3 then the emission reduction, as compared to the base case of 2008, would be 70% for air pollutants and 16% for CO<sub>2</sub>, while the 20-year GWP of the emissions would reduce by 58.8%. Thus, faster technology intrusion for the vehicle fleets would bring in large co-benefits in air quality improvement and mitigation of climate forcer emissions in Hanoi.

Further studies should conduct comprehensive surveys for the van and truck fleets together with off-road vehicles to provide more detailed vehicle EI for Hanoi. Such EI should be regularly updated to provide a

**Table 4.** Annual emission of air pollutants and global warming potential (CO<sub>2</sub> eq 20-year horizon) in Gg for the base case (2010) and technology scenarios for bus, taxi and personal car fleets in Hanoi.

Species	Base case		Scenario 1 (Euro3)			Scenario 2 (Euro4)		
	Pollutants	CO <sub>2</sub> eq	Pollutants	CO <sub>2</sub> eq	Reduction (%)	Pollutants	CO <sub>2</sub> eq	Reduction (%)
CO	39.5	236.9	4.34	26.04	89.0	1.34	8.0	96.6
VOC (exh + evap)	5.9	82.3	0.45	6.24	92.4	0.31	4.4	94.7
NO <sub>x</sub>	3.8	49.4	2.42	31.66	35.9	4.42	57.9	-17.1
SO <sub>2</sub> /sulfate <sup>†</sup>	0.2	-56.4	0.11	-31.60	44.0	0.02	-5.3	90.7
PM <sub>10</sub>	0.22	—	0.09	—	60.51	0.05	—	77.83
BC diesel	0.09	285.18	0.03	80.34	71.83	0.01	42.91	84.95
OC diesel	0.04	-9.30	0.01	-2.62	71.83	0.01	-1.40	84.95
BC gasoline	0.01	28.76	0.01	19.45	32.37	0.004	13.30	53.74
OC gasoline	0.03	-7.56	0.02	-5.99	20.78	0.01	-3.40	54.98
CO <sub>2</sub>	1044	1044	1116	1116	-6.9	1400	1400	-34.0
N <sub>2</sub> O	0.072	20.9	0.04	11.77	43.7	0.09	25.6	-22.5
CH <sub>4</sub>	0.968	69.7	0.03	1.90	97.3	0.02	1.3	98.1
Air toxics <sup>‡</sup>	0.60	—	0.08	—	86.7	0.03	—	95.0
Total AP excluding BC, OC, and CO <sub>2</sub> , N <sub>2</sub> O	51.1	—	7.5	—	85.0	6.2	—	87.9
Total GWP	—	1744	—	1253	28	—	1541	11.6

<sup>†</sup>Amount of SO<sub>2</sub> is given in the column of "pollutants"; for estimation of CO<sub>2</sub> eq (GWP), sulfate (2 times SO<sub>2</sub> amount) [18] was used.

<sup>‡</sup>Air toxics include 1,3-Butadiene, acetaldehyde, formaldehyde and benzene.

Negative values of reduction mean an increase.

Note: VOC - volatile organic compounds; PM - particulate matter; BC - black carbon; OC - organic carbon; GWP - global warming potential.

relevant database for air quality management in general, and air quality modeling for the city in particular.

## Conclusions

As of 2010, the on-road vehicle fleets in Hanoi were mainly composed of old technologies, with only a small share of Euro3 being the most advanced technology observed in the personal car fleet. Diesel and gasoline were the only two fuel types used for transportation in the city. The average speeds were low, indicating traffic jams. On average, the daily driving activity of a bus resulted in 212 VKT and 17 startups, as compared to 157 km and 23 startups for a taxi, and 42 km and 6 startups for a personal car.

Within each surveyed fleet of buses, taxis and personal cars, the vehicles of higher mileage and older engine technologies produced EFs several times higher than those of newer vehicles. The total annual emission from the three surveyed fleets in 2010 for CO, VOC, NO<sub>x</sub>, PM, BC and OC were 39.5, 5.9, 3.8, 0.22, 0.10 and 0.07 Gg/yr, respectively.

The emission estimates for remaining traffic fleets of MC, vans and trucks in Hanoi provided a more comprehensive traffic emission in the city in 2010. The majority of the traffic emission in Hanoi, generally above 70% for the considered air pollutants, was from the large MC fleet. The MC fleet made the predominant contribution to PM emission (69%) as well as BC (49%) and OC (88%). The diesel fleets also made significant contributions to PM emissions, trucks 24% and buses 5%, which were lower than that of the MC fleet despite the higher PM EFs generated by the former.

Switching to Euro3 and Euro4 would bring in significant co-benefits by reducing emissions of both toxic air pollutants and climate forcers (SLCPs and GHGs). The results of this study indicated that co-benefits

should be considered in the evaluation of policies in order to justify the cost and benefit of various traffic pollution control strategies.

To reduce the traffic-induced air pollution in Hanoi, control of emissions from MC should be the main focus. Along with a progressive implementation of cleaner vehicle technologies, alternative public transport means should be promoted to reduce the reliance on MC of the urban commuters. Alternative fuels such as CNG, LPG and relevant biofuel should be promoted to further reduce the traffic fleet emission. Further studies should also conduct a detailed survey for trucks, vans and other off-road fleets to provide a more comprehensive and traceable traffic EI for the city.

## Research highlights

- Surveys were done on technology and driving activities of Hanoi passenger fleets;
- Annual emissions from bus, taxi and car fleets were estimated using the IVE model;
- Compiled annual emissions of 2010 showed the motorcycle emissions contributed the majority of all pollutants;
- Faster intrusion of Euro3 and Euro4 would bring in substantial co-benefits to air quality and climate.

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