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“Assessment of urban passenger fleet emissions to quantify climate and air quality co-benefits resulting from potential interventions”

Nguyen Thi Kim Oanh, Lai Nguyen Huy, Didin Agustian Permadi, Eric Zusman, Ryoko Nakano, Sudarmanto Budi Nugroho, Puji Lestari & Asep Sofyan

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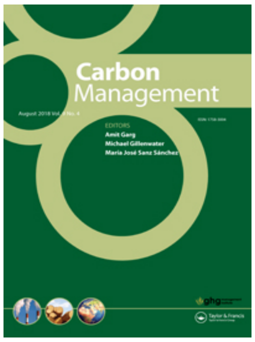

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Assessment of urban passenger fleet emissions to quantify climate and air quality co-benefits resulting from potential interventions

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ABSTRACT
Lack of robust data to assess the effects of different policies may hamper the design and implementation of effective solutions to reduce traffic emissions. This study analyzed the emissions of passenger fleets in Bandung, Indonesia, illustrated with three emission scenarios against the 2015 baseline. Local surveys were conducted to get traffic activity data for International Vehicle Emissions (IVE) modeling to generate emission factors (EFs) relevant to actual fleets and driving conditions in the city. EFs obtained for gasoline fleets that could have been affected by the leaded gasoline used prior 2006 were adjusted for the catalyst deactivation effect. Annual emissions (Gg/year) for CO, VOC, NOx, PM, BC, OC, NH_3, air toxics and SO_2 were 168, 36, 16, 1.8, 0.68, 0.72, 0.68, 4.7 and 0.42, respectively. Emissions of CO_2, N_2O and CH_4 were 2679; 0.07 and 5.8 Gg/year, respectively. Collectively, the 20-year global warming potential (GWP) of the emissions was 6770 Gg/year CO_2 eq. Analysis of potential interventions of technology intrusion of Euro3 (S1) and Euro4 (S2), and catalyst revamping (S3) showed potential co-benefits to air quality improvement and climate forcing mitigation. S1 would reduce the toxic pollutants emissions by 62% and GWP by 29%; corresponding reductions would be 68% and 45% for S2 and 47% and 16% for S3. Actual measurements are required to validate the potential emission reductions by catalyst revamping.

KEYWORDS
Passenger vehicle; emission inventory; technology intrusion; catalyst deactivation; Bandung

Introduction

Many rapidly motorizing cities in Asia suffer from worsening air quality [1–3]. Transport-related emissions, such as particulate matter (PM), CO, VOC, NOx among others, as well as greenhouse gases (GHGs) of CO_2, N_2O and CH_4 adversely affect the environment while contributing to near- and long-term climate change [4]. Urban people especially those living or working in heavy traffic areas would suffer more from the exposure to these toxic pollutants. In particular, PM emitted from vehicles pose a serious risk to human health due to their high levels, high toxicity and tendency to lodge deeply in the respiratory system [5–7]. Black carbon (BC) particles, a prominent PM component of diesel fueled vehicular exhaust, have been shown to be the most significant short-lived climate forcing pollutant (SLCP). BC is recognized as the second largest warming agent after CO_2 [8]. Other toxic pollutants emitted from vehicles also have climate effects. For example, toxic gases of VOC and NOx released from vehicles are key precursors of tropospheric ozone which itself is a strong GHG, a toxic pollutant to human health and to plants. Thus, clean traffic fleets can bring in multiple benefits to air quality, human health and climate [9].

Bandung, the capital of West Java Province, with 2.4 million people, is approximately 180 km from Jakarta (Figure S1, Supplementary information, SI). Bandung's high elevation (790 m above the sea level), narrow roads and hilly topography would principally cause high vehicle exhaust emissions. The implementation of the national low-cost green cars policy since May 2013 has boosted domestic vehicle sales in Indonesia, leading to a significant growth in the passenger car (PC) fleet in the city [101]. The total cumulative passenger fleet registered in Bandung in 2015 was nearly 1.5 million vehicles [10]. This comprised mostly of private vehicles: motorcycles (MC), 76% and PC, 23%. The public transport system, including buses (both inner city and inter-provincial bus fleets), paratransit vehicles and taxis, made up only small parts of the total city passenger fleets, i.e. of 0.39,

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0.38 and 0.13%, respectively. The average annual growth rate of the passenger fleet in Bandung is 11% [102]. Heavy traffic flows between Bandung and Jakarta, the capital city of Indonesia, during weekends and holidays induce additional traffic congestion. Traffic emissions are expected to contribute significantly to air pollution in the city. Previous studies reported high levels of fine particles measured at a mixed traffic site in Bandung [11], where the traffic emission contributed 22% to the $PM_{2.5}$ mass in the dry season and 35% in the wet season [12].

To address the situation, Bandung's government has initiated several campaigns to control air pollution. The Blue Sky Program, a national program initiated by the Ministry of Environment of Indonesia that was introduced in Bandung in 1997, is one such example [13]. Other examples include the phase-out of leaded gasoline in 2006 that significantly cut lead concentrations in the ambient air [14]. The Bandung government has launched several programs to reduce the traffic density such as car free night and day in several parts of the city [103]. However, the city continued to rely heavily on the paratransit vehicles (microbuses and vans) to shuttle people on fixed routes across the city. These paratransit vehicles did not have fixed stop locations/stations hence they often caused traffic jams, especially when they parked along narrow streets waiting for passengers.

It is hypothesized that well-designed multi-benefit strategies in traffic management can be identified for Bandung and these can provide multi-benefit solutions for the city to improve air quality and environmental health while mitigating climate forcer emissions. The first step to design such solutions is the development of a comprehensive emission inventory (EI) to understand the air emissions load from the traffic in the city during recent years [15, 16].

The accuracy of any traffic EI depends upon estimates of vehicle activity data and emissions factors (EFs). Previous EI studies in Bandung mainly employed secondary EFs, i.e. based on proxies from other countries [17], with only limited measurement data generated for Bandung [18]. Further, the shares of vehicle technologies in the existing fleets and the activity data were generally derived from rough estimations without a detail survey.

This study therefore analyzed the potential emission reduction scenarios related to engine technology and revamping lead-deactivated catalysts. The potential air quality and climate co-benefits were quantified to inform transport policies in Bandung. Bottom-up local data were collected to develop EI for various passenger fleets including PC, MC, taxi, paratransit vehicles (vans with 12–14 seats privately owned and used for public transport) and buses in Bandung in 2015. The EI incorporates technology-based EFs generated using the International Vehicle Emission (IVE) model and detailed activity data generated from several bottom-up local surveys. The co-benefits from reduction in emissions of toxic pollutants and climate forcing agents (SLCPs and GHGs) were estimated for three scenarios: accelerated/faster engine technology intrusion of Euro3 (S1), and Euro4 (S2); and catalyst revamping (S3: replacement of lead deactivated catalysts for existing vehicles that operated before unleaded gasoline was mandated in 2006).

Methodology

The methodological framework of this study is illustrated in Figure S2, SI. The local surveys were conducted from 15 October to 15 November 2015. Secondary data including the meteorological conditions, fuel characteristics [19], vehicle registration information (Department of Transportation of Bandung) were also collected. A previous study conducted the traffic counting at 30 road segments and 30 road junctions in Bandung intermittently for about one month but back in 2012 [20] hence could not be directly used for our IVE modeling because we aimed to develop the EI for 2015.

Data collection and processing for IVE modeling

The IVE model, 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 [104], has been successfully applied for mobile source EI in several Asian cities, e.g. Shanghai [21], Hanoi [22, 23], and Kathmandu Valley [24]. The model covers a wide array of fuel types (gasoline, diesel, natural gas, etc.), fuel quality (lead content, sulfur content and benzene content) and vehicle engine technologies extending from pre-Euro to Euro5 [104]. IVE produces local specific EFs of 14 emission species for both running (g/km) and engine startup (g/start). These EFs are then used together with the activity data, i.e. vehicle kilometers travelled (VKT) and the numbers of starts over one year, to calculate annual emissions.

In this study, the EI species included CO, VOC (exhaust and evaporative), NOx, SO_2, PM_{10}, CO_2, N_2O, CH_4, 1,3-Butadiene, acetaldehyde, formaldehyde, ammonia (NH_3) and benzene. Lead (Pb) was not included because the leaded gasoline was phased out back in 2006. The key IVE input data consisted of vehicle and fuel technology distributions, driving activities of second-by-second speeds on selected routes, numbers of engine startups, and hourly traffic density in the routes. The information was collected from three types of local surveys following the general framework of IVE data collection as summarized below. More details on the survey designing and collected data are presented in Text box S1, SI. First, the six zones in the city were considered as six strata in the statistical sampling design. These included Bojonegara, Tegalega, Cibeunying, Karees, Ujung Berung and Gedebage as seen in Figure S1, SI. The Karees zone is the commercial center where government buildings are located while other zones are mixed land use areas with varying levels of commercial, industrial and residential activity.

Parking lot survey

A total of 1315 questionnaires were delivered to acquire data on five passenger fleets (PC, MC, bus, taxi, and paratransit) to analyze for the total annual VKT and the IVE technology distribution for the city. The data collected in this survey included the vehicle model years, odometer readings, fuel types, fuel delivery systems, exhaust control devices and evaporative control systems. The sample size (number of questionnaires) was determined using the simple Taro formula [25] with an acceptable error of <5–10%. The final number of responses obtained for each passenger fleet type (Table S1, SI) was adjusted to account for the actual fleet population. Further, the number of questionnaires for a given fleet was distributed over the six zones of the city using the total number of inhabitants in each zone (Table S2, SI).

The information on the vehicle technologies and shares of different technologies, key input for the IVE modeling, was the most challenging to generate. We relied not only on the information obtained from the parking lot survey for the vehicle engine (Euro standards) and the emission control devices but also on the information obtained from the visits to vehicle showrooms and maintenance stations, and interviewing technicians in the public garages.

Traffic video recording and vehicle counting

The video recording was conducted at six points representing three categories of roads in Bandung, including highway, arterial road and residential road, crossing both urban and sub-urban areas to get representative flows and composition of vehicle fleets in the city. Two points were selected per road category (one point in urban and sub-urban area per road category), as shown in Figure S1, SI. The monitoring was carried out from 6:00 am to 8:00 pm to collect the data of both rush and non-rush hours. However, only daytime recording was possible because of limited light during the evening. The video camera was then replayed for manual counting of vehicles of different types, separately for weekend and weekday, and used as the input for IVE modeling.

Global positioning system (GPS) survey

GlobalSat DG-100 GPS Data Loggers were attached on 12 selected vehicles over 24 hours of each monitoring day (one weekday and one weekend day) to record the time, speed and location on the second-by-second basis. The selected vehicles included three MCs (a governmental officer, a student and a MC taxi), three PCs (a governmental officer, a private worker and a student), two buses and two taxis with the routes shown in Figure S3, SI. The GPS records were used to generate hourly average vehicle speed and the vehicle specific power (VSP) information required for IVE modeling. These records also provided information on the number of engine starts (startups) and soak time distribution to distinguish emission-intensive cold starts (after an engine rests for 18 hours or more) from lower emission warm starts (Text box S1, SI).

IVE modeling

The IVE model v.2.0.2 was used in this study. The input files were prepared from the survey results, including the location input file (driving and startup pattern, hourly average speed, VKT, numbers of starts, meteorological parameters, fuel characteristics and altitude) and fleet input file (technology indices and shares). The base adjustment file [104] was not used in this study due to the lack of locally measured EFs. This study used the representative characteristics of fuels for 2015, namely: S = 300 ppm, Pb = 0, benzene = 3% and oxygenate = 2.5% for gasoline, and average sulfur content of S = 500 ppm for diesel. The inspection and maintenance (I/M) was set to zero in the input location file due to the actual low level of inspection and maintenance. Meteorological input data (relative humidity and temperature) for 2015 were taken from the Husein Sastranegara airport meteorological station [105].

The model was run for each vehicle fleet, e.g. PC or MC, and for every selected route on weekdays and weekends separately. Outputs of the IVE model were the hourly emissions of every technology index of a vehicle fleet, both for startup and running activities. The composite weekly EFs of all considered pollutants were calculated as the weighted average EFs for five weekdays and two weekend days per week and used in the EI.

Scenario development and climate co-benefit assessment

Three scenarios affecting traffic emissions in Bandung were considered. These are "what if" scenarios which have been developed using the current policy on the vehicle engine technology implementation (S1 and S2) as well as the potential improvement in the vehicle control technology (S3) suggested by the survey results.

Technology intrusion scenarios (S1 and S2)

The Euro3 scenario (S1) assuming all current fleets in Bandung would at least comply with Euro3, while Euro4 scenario (S2) assuming all current fleets would at least comply with Euro4. The vehicle technology distributions in the fleets were accordingly modified while the driving activities (VKT, speeds and number of starts) were kept the same as 2015. In scenario S2, the sulfur content of the fuel was adjusted to match the Euro4 engine standard, i.e. 50 ppm for both diesel and gasoline. The current fractions of technologies above Euro3 remained at S1 while those of above Euro4 remained at S2 scenario. The scenarios were developed to analyze the benefits of faster intrusion of the vehicle emission standard as compared to the road map of Indonesia. The country has implemented a road map since 2005 to enforce at least Euro2 standards for all PCs, heavy duty vehicles (HDV) and light duty vehicles (LDV) by 2018. For MCs, the target was set higher, i.e. in 2013 all new MCs should already comply with Euro3 [106]. Draft Euro4 standards for all vehicles by 2018 have been discussed at high-level meetings [19].

Catalyst revamping (S3)

Leaded gasoline was phased out in Indonesia in 2006 [107] which cut down lead emissions and reduced lead levels measured in the ambient air and in human blood [13, 14]. The leaded gasoline used before 2006 would deactivate catalysts hence they may not function as expected to remove the designated pollutants [26]. This scenario analyzed what could be the potential emission reduction if the lead deactivated catalysts in existing gasoline vehicles in Bandung (those operated prior to the phase-out of leaded gasoline in 2006) were replaced by new ones. Our survey results showed that considerable portions of the gasoline fueled fleets in Bandung registered before 2006 were equipped with catalysts that would have been permanently deactivated by the high lead content. The IVE model by default produced EFs based on the technology indices (with the full removal efficiency of catalysts). Therefore, the leaded gasoline effects on the catalyst efficiency should be manually adjusted for the EFs of these aged gasoline vehicles. The fraction of gasoline fueled fleets which had catalysts deactivated by leaded gasoline was determined using the regression analysis of vehicle ages on odometer readings as detailed below.

Estimation of co-benefits

These scenarios could result in the emission reduction of toxic air pollutants and global warming potential (GWP). We considered the climate effects of GHGs (CO_2, N_2O and CH_4) and SLCPs that in turn include both warming (BC) and cooling agents of OC, secondary sulfates (SO_4^{-2}) and nitrates (NO_3^-) particles. Some pollutants, such as NOx, CO or VOC, also have climate effects, for example, through the formation of tropospheric O_3. GWPs in terms of CO_2 equivalent of different emission species are listed in Table S3, SI. The GWP calculation method, i.e. converting the emission in mass unit to CO_2 equivalent, has been detailed in our previous study [22–24]. Briefly, the mass emissions of different species were converted to CO_2 equivalent (CO_2 eq) using Equation (1):

$$CO_2 \text{ equivalent } = \sum E_i \times GWP_i \tag{1}$$

where, E_i is the annual emission of pollutant i (mass unit/year) and GWP_i is the global warming/cooling potential of pollutant i.

Further, the climate benefit was quantified as the difference in GWP of the emissions (CO_2 eq.) between the scenario and the base case. Similarly, the air quality benefit was the difference between the scenario emissions of toxic air pollutants and that of the base case.

The IVE model produced only the total PM_{10} mass emission, hence the fractions of BC and OC in PM_{10} mass should be estimated. For the emissions from diesel vehicles, we used the fraction of elemental carbon (EC) of 0.46 PM mass and organic carbon of 0.20 PM mass based on the measurements in Bangkok [2]. For the emissions from gasoline vehicles, the fractions of OC = 0.78 PM and BC = 0.19 PM mass were applied using the values reported by the United States Environmental Protection Agency [27].

Results and discussion

Vehicle technologies and driving activities

This section presents key findings based on the survey results. These include the local vehicle technologies, fuel consumptions, driving activities (VSP and start-up distribution, average speed, hourly vehicle flow), and catalyst deactivation effects by leaded gasoline for vehicles operated prior 2006. All these parameters are required for IVE modeling and EI calculations for the city.

Vehicle technologies

The survey fleets were matched with the IVE default technology indices. The results are presented in Table S4, SI and summarized in Table 1 along with other information obtained from the surveys.

Bus. All buses used diesel fuel with the majority of the surveyed buses conforming to different Euro standards, i.e. 50.7% Euro2, 26.1% Euro3, 2.9% Euro4 and 2.2% Euro5, but a substantial share of pre-Euro (18.1%) remained. The bus fleet was matched with 16 IVE technology indices (Table S4, SI). The largest share was by the index 1133 (23.9%) which is Euro2 with high mileage >161,000 km. The bus age range was 1–22 years with the weighted average age, weighted against the shares in the bus fleet, of 6.4 years. Above 30% of the fleet was older than 6 years and 15% older than 10 years.

Motorcycles. All MCs in Bandung were gasoline fueled and the majority (99.4%) had four-stroke engines. The MC fleet in Bandung were matched with 11 default IVE indices (Table S4, SI). Most MCs conformed Euro3 (84.2%), followed by Euro2 (13.9%), and only a small share of pre-Euro (1.9%). The MC fleet was quite new with the weighted average age of 3.6 years and more than 77.7% were less than 5 years old. Most (98%) of the MC fleet were equipped with catalysts (2-way) hence with the age span of 1–12 years. There was a potential for lead deactivation of catalysts used in MC operated before 2006.

Paratransit. A small fraction (15%) used diesel and the rest (85%) of the fleet used gasoline. Only pre-Euro (53%) and Euro2 (47%) engines were found in the fleet and these were matched with 17 IVE technology indices. The age range of the fleet was 1–17 years with the weighted average of 5 years. All gasoline fueled paratransit vehicles were equipped with 2- or 3-way catalysts (Table S4, SI), hence those started operation before 2006 were likely to be affected by the catalyst deactivation.

Passenger cars. The PC fleet used either gasoline (93%) or diesel (7%, Table 1). The fleet was matched with 22 IVE technology indices with index 180 being the most common (50%). The majority

Table 1. Summary of the survey results for Bandung.

	Bus	MC	Paratransit	PC	Taxi
Cumulative number, 2015	5,918	1,143,316	5,721	340,082	1,906
Questionnaire survey					
No. of IVE technology indexes	16	11	17	22	8
Average age and span, years	6.4 (1–22)	3.6 (1–12)	5.0 (1–17)	5.2 (1–15)	7.5 (1–10)
Fuel usage, %	Diesel: 100	Gasoline: 100	Gasoline: 85 Diesel: 15	Gasoline: 93 Diesel: 7	Gasoline: 100
Share of Euro standard, %	Euro5: 2.2 Euro4: 2.9 Euro3: 26.1 Euro2: 50.7 Pre-Euro: 18.1	Euro3: 84.18 Euro2: 13.9 Pre-Euro: 1.9	Euro2: 47.1 Pre-Euro: 52.9	Euro3: 3.2 Euro2: 75.3 Pre-Euro: 21.5	Euro2: 72.2 Pre-Euro: 27.8
GPS survey					
Average speed (km/ hr)	11.2 ± 2.9	15.8 ± 2.3	13.5 ± 2.4	16.5 ± 4.9	17.0 ± 2.9
No. of daily startups	11	9	11	5	12
Daily VKT, km[†]	88.6 ± 27.6 (117)	20.1 ± 8 (25)	109.1 ± 23.3 (91)	35.3 ± 7.4 (37)	144.4 ± 21.7 (70)
Traffic counting survey					
Share of vehicle types in the traffic fleet, %	0.4	73.7	2.9	22.7	0.3
Highway	38 ± 13	4,564 ± 1,614	165 ± 37	1,949 ± 454	21 ± 8
Arterial	39 ± 9	5,479 ± 1,472	372 ± 148	1,862 ± 700	25 ± 7
Residential	0 (not allowed)	1,262 ± 610	7 ± 3	253 ± 171	6 ± 4

[†]In brackets are the daily VKT obtained from the regression analysis

of PCs were Euro2 (75.5%) followed by pre-Euro (21.3%), while Euro3 had a small share of 3.2%. The fleet age range was 1–15 years with the weighted average age of 5.2 years. All gasoline fueled PCs were equipped with 2- or 3-way catalysts (Table S4, SI) hence those started operation before 2006 were also likely affected by the catalyst deactivation effects.

Taxi. The entire taxi fleet was light duty and gasoline fueled, and most of them had high mileage, i.e. about 62.7% had mileage above 161,000 km. The fleet was matched with eight technology indices with index 128 being the most common (29.7%). The majority of the fleet complied with at least Euro2 (72.2%). The age range of 1 to 10 years with the weighted average age of 7.5 years of the fleet suggested that most of the taxis started operation after 2006. In addition, the higher age pre-Euro fraction (27.8%) was not equipped with any catalysts. Therefore, the revamping catalyst scenario was not considered for the taxi fleet in Bandung.

Driving activities

VSP Bin distribution. The engine stress is correlated to the vehicle specific power (VSP) load requirements over the past 20 seconds of operation in the IVE modeling [104]. The IVE incorporates 20 VSP categories in combination with three engine stress modes (low, medium and high) to produce 60 possible bins representing hourly distribution for a vehicle fleet [28]. The bin distribution for Bandung (Figure 1) showed the most frequently observed bins of 11 (VSP = −2.9 to 1.2 kW/t) and bin 12 (VSP =1.2 to 5.3 kW/t) which belong to the low engine stress conditions, i.e. when vehicles operate at low speeds and less acceleration during the last 20 seconds of operation and low revolutions per minute of engines. In practice, these are the conditions when vehicles operated with frequent stops, i.e. with traffic jams or waiting for traffic light signals, and idling. Medium and high engine stress (bin 13 and higher) occurred with lower shares, i.e. 13.2% for bus, 18.8% for MC, 14.3% for paratransit, 15.8% for PC and 15.8% for taxi. The driving activities in bin 13 (VSP =5.3 to 9.4 kW/t) and higher bins would correspond to the conditions when vehicles operated at constant speeds and accelerating [104]. Our findings of a high frequency of bin 11 and 12 suggested that improvement in the driving pattern, e.g. with higher speed and less idling, may help to reduce vehicle emissions in the city.

Engine startup distribution pattern. A bus usually stopped engines at the terminal after finishing a scheduled round, while taxis would stop the engines when waiting for passengers. Paratransit vehicles had fixed routes but no terminals or fixed stations, hence they stopped the engines when waiting for passengers along the routes. The numbers of daily starts of each surveyed vehicle were determined using the GPS records. In IVE, the term "engine soak" is defined as the length of time period that an engine has been shut off before starting again. A cold start is defined as a start with the soak time ≥18 hours while a warm start is when the soak time ≤5 minutes. Cold starts generate higher exhaust emissions than warm starts; hence, the soak time is a predominant factor for the emission calculation. Among the ten IVE default groups of the engine soak time, the most dominant observed in Bandung was 15-minute, i.e. the engine stops for a period of less than 15 minutes, followed by the 30 minutes (a stop for a period between 15 minutes and 30 minutes), as seen in Figure 2.

The daily operation of buses in Bandung was from 5:00 to 20:00. Thus the 9-hour interval

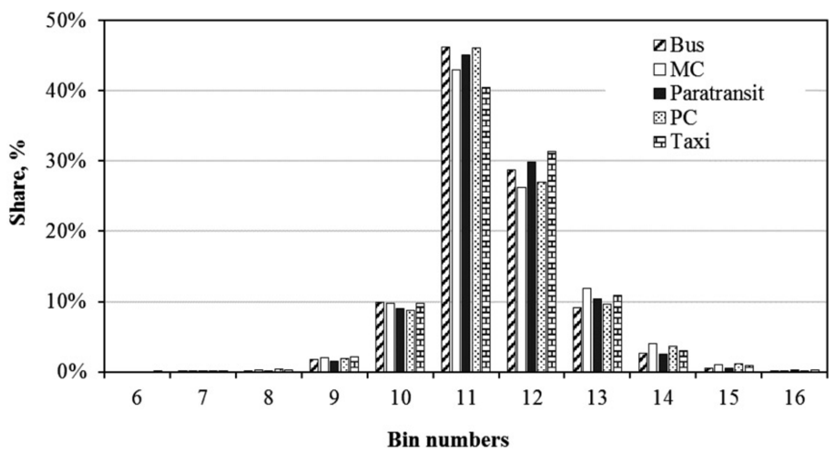

Figure 1. VSP bin distribution of all vehicle fleets in Bandung.

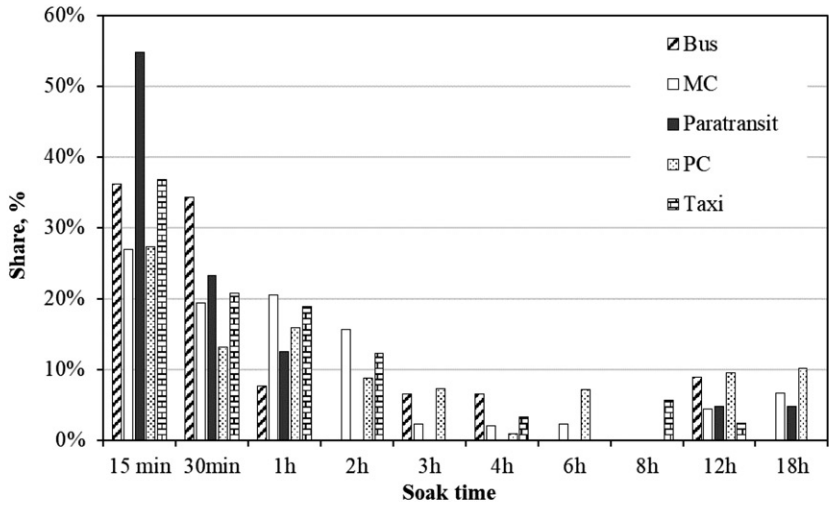

Figure 2. Soak bin distribution of different vehicle fleets in Bandung.

between two consecutive operation days contributed to the 12-hour soak bin (a rest of 8 hours to 12 hours). The high shares of 15-minute and 30-minute soak bins for buses reflected the amount of time buses rested at the terminals. The paratransit vehicles had high shares of short soak bins, 15-minute, 30-minute and 1-hour and this suggested an effective use of this public transport in Bandung. The soak time distributions for taxis were similar with paratransit vehicles but with a lower frequency of 15-minute soak and a higher frequency of 2-hour soak. The private MCs and PCs had similar soak time distribution patterns with 15-minute and 30-minute being the most common but due to the needs for personal use, MCs and PCs had soak time distributions cutting across all categories.

On average, a bus had 11 startups per day, a figure that was lower than Hanoi (16.6 times) [23] and somewhat higher than the Kathmandu Valley (nine times) [24]. Similar to buses, the paratransit vehicles in Bandung had 11 startups per day. The daily number of startups for a taxi in Bandung was 12, which was comparable with 15 times per day in Kathmandu Valley [24]. Trang *et al.* [23] reported a considerably higher startup number for taxis in Hanoi with 26 times per day. The average number of startups for a PC in Bandung was 5, which was slightly lower than Hanoi (6.9 times per day) [23]. On average, one MC in Bandung had a daily number of startups of nine times per day, that is well above that for Hanoi of 4.9 times [22] or Kathmandu Valley (3.8 times) [24] but close to the 7.2 startups reported for Pune [104]. Generally, public transport vehicles had a higher number of startups than private vehicles, as anticipated.

Average speed. The second-by-second speeds recorded by GPS for the monitored vehicles on the selected routes were used to calculate hourly average speeds. Figure 3 shows diurnal variations of hourly average speeds, ranging from 5.1 to 33.1 km/h for different vehicle types, with lower speeds during rush hours. Taxis had the highest daily average speed of 16.6 km/h, followed by PCs (15.6 km/h), MCs (15.4 km/h), paratransit vehicles (14.0 km/h) and buses (11.9 km/h). Buses, MCs and paratransit vehicles had slightly higher speeds during weekends than weekdays. PCs and taxis exhibited the opposite pattern, with slightly higher speeds on weekdays than weekends; this may be attributed to their relatively greater flexibility in selecting routes and using highways during weekdays.

Vehicle flow. The arterial roads were the busiest roads with a total 7780 vehicle/h, followed by the highway with a total 6740 vehicle/h, while the residential roads had the lowest flow of 1530 vehicle/h (the sum of all vehicle categories given in Table 1). The composition of the traffic also varied by road types; MCs dominated the traffic in all three road types but were most prominent on residential roads (83%), followed by arterial roads (70%) and highways (68%). The PC fleet was the second most dominant but more on highways (29%), and arterial (24%) than on residential roads (17%). Buses were not allowed in residential areas (0%) and accounted for only a small share of vehicles on other roads (<0.6%). Taxis operated on all road types but with small shares (<0.3%) so as the paratransit vehicles on their routes (<3%). The compositions of the traffic fleet in Bandung varied between weekend and weekday and reflected the actual uses of the vehicles in the city (Figure 4). During weekdays, the diurnal variations were clearly seen with the highest densities of private vehicles (MC and PC) and paratransit in the morning rush hours (7:00–8:00 am) followed by

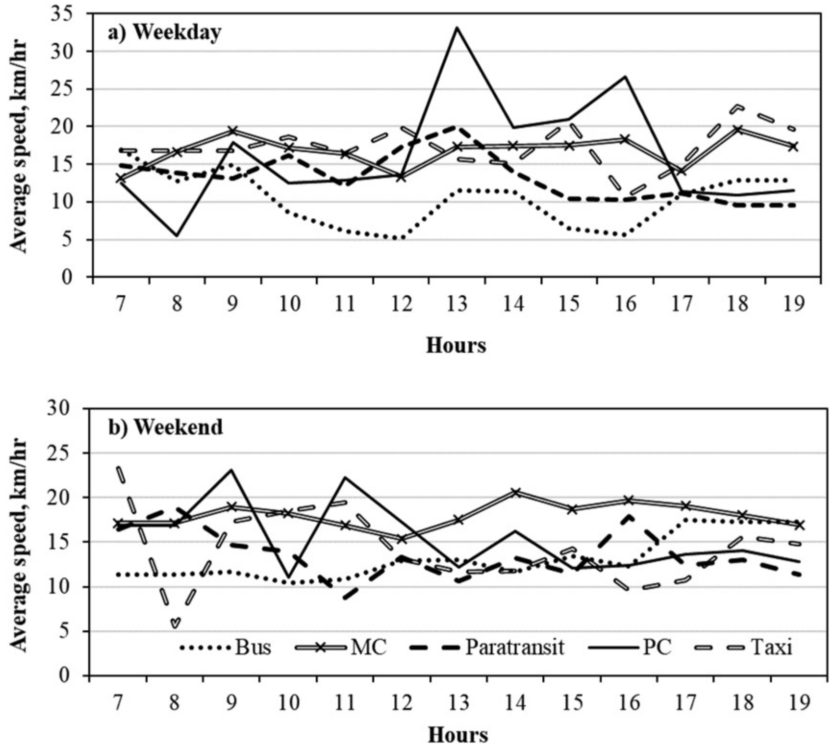

Figure 3. Hourly average speeds (km/h) of all fleets for a) weekday and b) weekend.

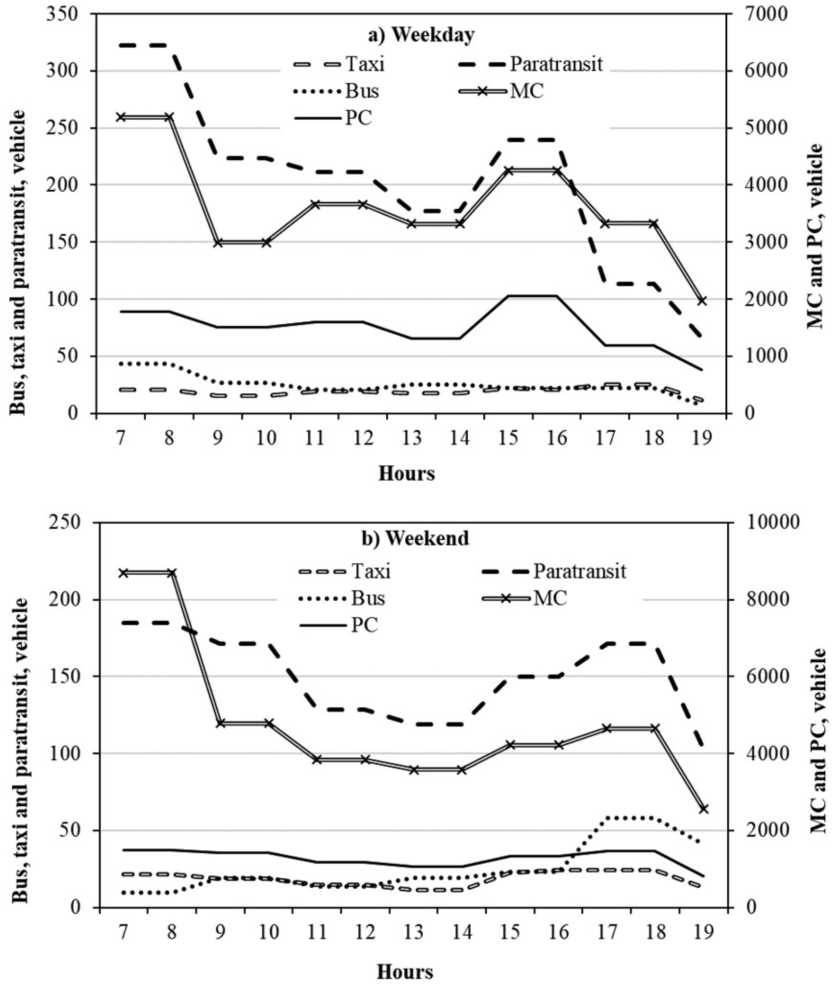

Figure 4. Hourly flows of the vehicle fleets on: a) weekday and b) weekend.

afternoon rush hours (3:00–4:00 pm). At weekends, less diurnal variations were observed with lower peaks in rush hours and more activities during midday. Buses and taxis did not exhibit a considerable variation in hourly density. The hourly average vehicle flow is required for the IVE modeling

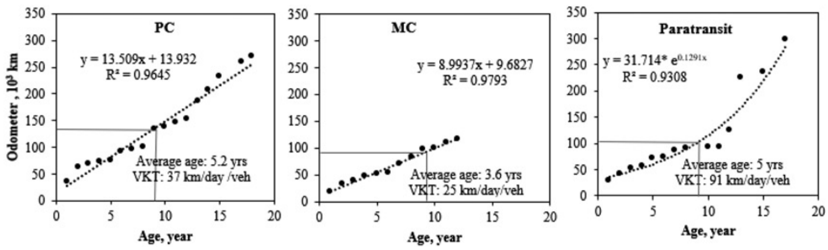

Figure 5. Age vs. odometer readings of selected vehicle fleets in Bandung. (The leaded gasoline was phased out in 2006, 9 years before the survey)

and this information was also used to estimate diurnal variations in traffic emissions in our study.

Vehicle kilometers travelled. Regression equations between the odometer readings and the average age of surveyed vehicles were developed which showed the coefficients of determination (R^2) between 0.93 and 0.98 for MCs, PCs and paratransit vehicles (Figure 5), and somewhat lower R^2 values for taxis (0.92) and buses (0.88; Figure S4, SI). These equations were used to calculate the annual VKT of the corresponding fleet type [21, 22].

The average daily VKT in Bandung obtained from the GPS survey for a bus, MC, paratransit, PC and taxi was 89, 20, 109, 35 and 144 km, respectively (Table 1). The corresponding daily VKT estimated from the regression analysis was 117, 25, 91, 37 and 70 km which are given in brackets along with the GPS survey results in Table 1. The VKT results by the GPS survey and regression analysis were in similar ranges for all vehicle types except for taxis, which differed by a factor of 2. Note that the GPS monitoring was done only for a limited number of vehicles in each fleet, e.g. two taxis (Figure S3), while the regression analysis was done using the data of a few hundred vehicles in each fleet, e.g. 150 taxis (Table S1 and S2). The large difference between the two VKT results for taxis may be due to the selection of long routes for the monitored taxis (to get more representative data on the VSP distributions) as seen in Figure S3, SI. Therefore, the VKT obtained from the regression analysis for each fleet was used in our EI. Future studies should include more vehicles in the GPS survey, especially for the taxi fleet, to obtain better representative VKT values.

The daily VKT of a bus in Bandung was higher than that in Kathmandu Valley (96 km) [24], but much lower than Hanoi (212 km) [23]. The daily VKT of a MC in Bandung was comparable to that (20 km) of Hanoi and the Kathmandu Valley. A taxi in Bandung travelled less than that in Hanoi (157 km) and Kathmandu Valley (109 km). A PC in Bandung also traveled less than that in Hanoi (42 km).

Effects of the deactivated catalysts on exhaust emissions. High fractions of in-use gasoline fueled fleets of MC, PC and paratransit in Bandung were found to be equipped with catalysts (Table S4, SI). The lead poisoning/deactivation effects on the catalysts should be considered for those vehicles which started operation before 2006 when leaded gasoline was still in use. The IVE modeling requires the input of Pb content in gasoline by the time of the survey to calculate Pb emissions. The common perception is that as leaded gasoline has been phased out the lead emission would be low. There is no direct way in IVE to include the effects resulting from the permanent deactivation of catalysts due to the past use of leaded gasoline on the exhaust emissions of CO, NOx and VOC. Therefore, the IVE produced EFs applicable for the exhaust emissions after the treatment by catalysts need to be adjusted to account for the catalyst deactivation. The challenge was to find the fractions of the vehicles with deactivated catalysts in the corresponding IVE fleet technology indices so that the EF adjustment can be made.

We used the regressions between odometer readings and vehicle ages to identify the fractions of gasoline fueled fleets which had lead deactivated catalysts. The year of 2006 corresponded to the vehicle age of nine years at the survey time of 2015. The regressions for MCs, PCs and paratransit vehicles (Figure 5) showed that the odometer readings for the nine-year old vehicles would be 90,000 km for MCs and above 100,000 km for both PCs and paratransit vehicles. These approximately correspond to the mileage of the IVE technology indices (Table S4, SI) of >50,000 km for MC and >80, 000 km for the PC and paratransit fleets. Note that the lower cut-off values of mileage (than the results obtained for the nine-year age from the regression lines in Figure 5) would bring in larger numbers of the technology indices subjected to the adjustment; hence it would be a conservative approach that produces higher emissions results. There was no need to consider the lead deactivation effects for taxis because they were quite new (1–10 years) and the high mileage pre-Euro fractions had no catalysts equipped as mentioned above. Likewise, the whole bus fleet in the city was diesel fueled; hence no adjustment was needed.

The emissions of related pollutants (depending on the use of two- or three-way catalyst) from these vehicles were adjusted back to the original untreated levels. The removal efficiencies of catalysts varied with the engine conditions, vehicle mileage and technologies, but for simplicity this study assumed an average removal efficiency of 80%, i.e. lower than the expected efficiency of catalysts in new vehicles of around 90% [29]. Accordingly, a three-way catalyst device was assumed to have the removal efficiency for the exhaust emission of 80% for each of CO, VOC and NOx, while a two-way catalyst would have a removal efficiency of 80% of CO and VOC, respectively. The MC fleet had only the two-way catalyst while PC and paratransit vehicles may have either two-way or three-way catalyst (Table S4, SI). The adjustment was done only for the running exhaust emissions, i.e. the lead deactivation effects (on catalysts) on the startup emission were neglected. For VOC emissions, only exhaust (not evaporative) emissions were adjusted and the adjustment was made for the total VOCs as well as individual VOC species (i.e. benzene, 1,3 butadiene, acetaldehydes, formaldehydes, and CH_4). The adjustment was made by dividing the EFs of the pollutants obtained for corresponding IVE technology indices by 0.2 to return to the original (100%) uncontrolled levels. The EFs of other exhaust species of PM, SO_2, and N_2O were not adjusted. It worth mentioning that the N_2O emission, in particular, may be affected by catalysts; this effect should be considered in future studies, for example, when focusing on GHG emissions.

Table 2 shows the adjusted and unadjusted EFs for the gasoline fueled MCs, PCs and paratransit vehicles. There were significant differences between these two sets of EF values which are attributable to the lead deactivation effects. In fact, the unadjusted EFs were unrealistically low which are well below the EFs of similar fleets in Asian cities, while the adjusted EFs are comparable (Table S5, SI). The adjusted EFs were used in the EI of 2015 while the difference between the two EFs sets was used for the analysis of the potential emission reduction in scenario S3.

Emission factors

Composite emission factors

IVE produced hourly emissions of each fleet with its compositional technology indices (Table S4, SI) on each considered route. The composite EFs are the weighted average of EFs produced on weekdays and weekend (5 weekdays and 2 weekend days) for each pollutant for running and startup conditions, respectively. The composite EFs (adjusted for MC, PC and paratransit vehicles) for startup and running, respectively, of 14 species for the passenger fleets in Bandung are presented in Table 3. These EFs present the average emissions of the fleets operating in the Bandung city in 2015 hence they were used in our EI.

The paratransit vehicles, taxis and PCs had comparably high running EFs of CO and VOC. The highest EFs (CO: 25.1 g/km; VOC: 2.6 g/start) found for the paratransit fleet could be explained by its high proportion of pre-Euro vehicles (~53%). The low running PM_{10} EF of paratransit, i.e. comparable to that emitted by the PC fleet (0.04 g/km) and significantly lower than diesel bus (4.7 g/km), was because the paratransit fleet mainly used gasoline (85%). The taxi fleet had the second highest EF of CO (22.9 g/km) and the highest EF of VOC (2.6 g/km, same as the paratransit) due to its high mileage and a large fraction of pre-Euro vehicles. The startup EFs of the paratransit, taxi and PC fleets were, however, quite different. PC had the highest startup EF of CO (17.5 g/start) and VOC (2.1 g/start) followed by taxi, and the lowest were

Table 2. Comparison of adjusted (for lead deactivated catalysts) and unadjusted (IVE output) running EFs.

	MC (g/km)		PC (g/km)		Paratransit (g/km)	
Pollutants	Adjusted	Unadjusted	Adjusted	Unadjusted	Adjusted	Unadjusted
CO	6.39	3.20	22.39	6.03	25.12	7.32
VOC	1.89	1.00	2.04	0.58	2.64	0.78
NOx	0.17	0.17	1.79	1.14	1.92	1.79
CH_4	0.41	0.21	0.43	0.12	0.58	0.16
1,3 Butadiene	0.01	0.00	0.02	0.00	0.01	0.00
Acetaldehyde	0.04	0.02	0.04	0.01	0.03	0.01
Formaldehyde	0.14	0.07	0.09	0.02	0.07	0.01
Benzene	0.04	0.02	0.21	0.06	0.28	0.08

Note: The adjusted EFs were used for the baseline EI. The difference between adjusted and unadjusted EFs was used in the catalyst revamping scenario analysis. MC had only 2-way catalysts hence NOx was not affected.

Table 3. Composite emission factors of air pollutants and greenhouse gases for the passenger fleets in Bandung.

	Vehicle category									
	Bus		MC		Paratransit		PC		Taxi	
Species	Start (g/start)	Running (g/km)	Start (g/start)	Running (g/km)	Start (g/start)	Running (g/km)	Start (g/start)	Running (g/km)	Start (g/start)	Running (g/km)
CO	0.45	5.33	4.43	6.39	7.76	25.1	17.4	22.4	14.0	22.9
VOC (exh.)	0.04	1.41	1.08	1.89	0.74	2.64	2.10	2.04	1.39	2.64
VOC (evap.)	0.00	0.00	0.14	0.33	0.17	0.27	0.42	0.31	0.71	0.72
NO_x	1.12	23.9	0.39	0.17	0.31	1.92	0.67	1.79	0.83	1.09
SO_2	0.014	0.65	0.0002	0.01	0.0015	0.059	0.0036	0.054	0.003	0.03
PM_{10}	1.82	4.67	0.04	0.03	0.02	0.04	0.05	0.04	0.01	0.01
CO_2	37.8	1,789	1.86	69.4	4.79	406	11.9	434	8.93	288
N_2O	0.01	0.09	0.0005	0.00	0.001	0.01	0.004	0.01	0.002	0.01
CH_4	0.00	0.00	0.0005	0.41	0.15	0.58	0.42	0.43	0.28	0.54
1,3-Butadiene	0.002	0.01	0.23	0.01	0.002	0.01	0.01	0.02	0.01	0.01
Acetaldehyde	0.01	0.03	0.003	0.04	0.004	0.03	0.01	0.04	0.02	0.02
Formaldehyde	0.02	0.08	0.06	0.14	0.01	0.07	0.03	0.09	0.04	0.05
Benzene	0.0005	0.01	0.02	0.04	0.08	0.28	0.22	0.21	0.15	0.28
NH_3	0.001	0.04	0.01	0.02	0.001	0.10	0.003	0.13	0.003	0.11

Note: VOC (exh.): VOC exhaust emissions
VOC (evap.): VOC evaporative emissions

found for the paratransit. The differences in the fleet startup or soak distribution patterns were the major reason for the difference in the startup EFs: the shorter soak time of the paratransit (higher number of daily startups, mainly warm starts) reduced the emissions per startup as compared to PC, for example. The evaporative VOC EFs from the gasoline fueled vehicles were the highest for the taxi fleet (0.71 g/start and 0.72 g/km). The bus fleet (100% diesel fueled) was found to have the highest EFs of CO_2, SO_2, NOx and PM, both running and startup. The composite PM EFs of the bus fleet were 4.7 g/km and 1.1 g/start which were two orders of magnitude higher than the gasoline fueled fleets (Table 3).

The EFs found in previous IVE studies for the fleets in Asia [22–24, 30] are presented in Table S5, SI along with the Bandung results. There are relatively wide ranges of the EFs, differing by a factor of 2–4, and those found for Bandung appeared to be in the middle range of the presented values for different pollutants. Several factors may explain the difference, for example, the higher elevation of Bandung and lower bus speeds can be the reason for its higher EFs of NOx and PM as compared to Hanoi. The high mileage of the Kathmandu bus fleet coupled with the extremely low speeds brought about its higher EFs. Note that, as compared to other quoted cities, only the bus fleet of Bandung was found to have Euro5 vehicles even though still with only a 2% share.

Emission factors by technology indices

The EFs, both running (g/km) and startup (g/start), of each technology index for every fleet type were obtained from IVE results. In each fleet, the indices with the low technology levels (e.g. pre-Euro) and more mileage had higher EFs. Diesel fueled vehicles had higher EFs for PM and NOx than the gasoline fueled vehicles while the opposite was generally true for VOC and CO.

The EFs for the paratransit fleet by technology indices were also affected by the fuel type as expected. The gasoline fueled paratransit vehicles had higher EFs of CO and VOC while diesel fueled vehicles had higher EFs for PM. The diesel fueled technology indices that were equipped with the exhaust gas recirculation (EGR) for NOx emission control or with Euro2 engine produced lower NOx emissions. Similarly, in the bus fleet, the highest EFs were from the high mileage of pre-Euro engine indices and the index with the highest EFs (number 1079) was with diesel fueled engine, heavy duty, pre-chamber injection without exhaust and evaporative control, and having a high mileage (>161,000 km). The lowest EFs were associated with advanced Euro4 and Euro5 technologies, but their share in the bus fleet was only 5.1% collectively.

For the MC fleet, the running and startup EFs for different technology indices were higher for two-stroke engines with carburetor combustion and a high mileage (>50,000 km). The newer MCs with more advanced technologies and catalyst emission control (not affected by Pb deactivation) had the lowest EFs. In the PC fleet, the indices with high mileage (>80,000 km) also had high EFs. The highest EFs of PM were for pre-Euro diesel fueled PCs while gasoline fueled Euro3 engines had the lowest EFs for most pollutants. In the taxi fleet, the pre-Euro engine indices had the highest EFs of all pollutants, while the Euro2 index with lower mileage (<79,000 km) had the lowest EFs.

Table 4. Annual emission and global warming potential (in Gg/year) for baseline 2015 and different scenarios.

Species	Baseline (2015) Emission	Baseline (2015) 20-year CO_2 eq	Scenario 1 (Euro3) Emission	Scenario 1 (Euro3) 20-year CO_2 eq	Scenario 1 (Euro3) Reduction (%)	Scenario 2 (Euro4) Emission	Scenario 2 (Euro4) 20-year CO_2 eq	Scenario 2 (Euro4) Reduction (%)	Scenario 3 (Revamping catalyst) Emission	Scenario 3 (Revamping catalyst) 20-year CO_2 eq	Scenario 3 (Revamping catalyst) Reduction (%)
CO	168	1,210	56.35	406	66.5	46.45	334	72.4	79.15	570	52. 9
VOC	35.70	500	17.19	241	51.9	16.82	235	52.9	21.97	308	38. 5
NO_x	15.79	207	8.45	111	46.5	6.58	86.1	58.4	13.57	178	14.1
SO_2†	0.42	−48.17	0.26	−29.16	39.5	0.26	−29.49	38.8	0.42	−48.17	–
PM_{10}	1.83	–	1.32	–	28.0	0.55	–	69.8	1.83	–	–
BC	*0.68*	*2,176*	*0.49*	*1,568*	*27.9*	*0.15*	*491*	*77.4*	*0.68*	*2,176*	-
OC	*0.72*	*−387*	*0.51*	*-278*	*28.2*	*0.33*	*−177*	*54.1*	*0.72*	*-387*	-
Air toxics‡	4.66	–	1.91	–	59.1	1.68	–	63.9	2.68	–	42.6
CO_2	2,679	2,679	2,591	2,591	3.3	2,619	2,619	2.3	2,679	2,679	–
N_2O	0.07	18.82	0.10	29.96	−59.2	0.10	27.96	−48.6	0.07	18.82	–
CH_4	5.76	415	1.86	134	67.7	1.83	132	68.3	2.71	195	53.1
NH_3	0.68	–	0.64	–	6.0	0.63	–	7.5	0.68	–	–
Total AP§	227.1		86.1		62%	72.9		68%	119.6		47%
Total CO_2 eq		6,770		4,773	29%		3,719	45%		5,689	16%

Note: - not applicable/not considered
†Calculated for sulfates (∼2 times of SO_2)
‡Air toxics include benzene, acetaldehyde, formaldehyde and 1,3-butadiene.
§Total toxic air pollutants, excluding GHGs as well as BC & OC (to avoid double counting with PM)

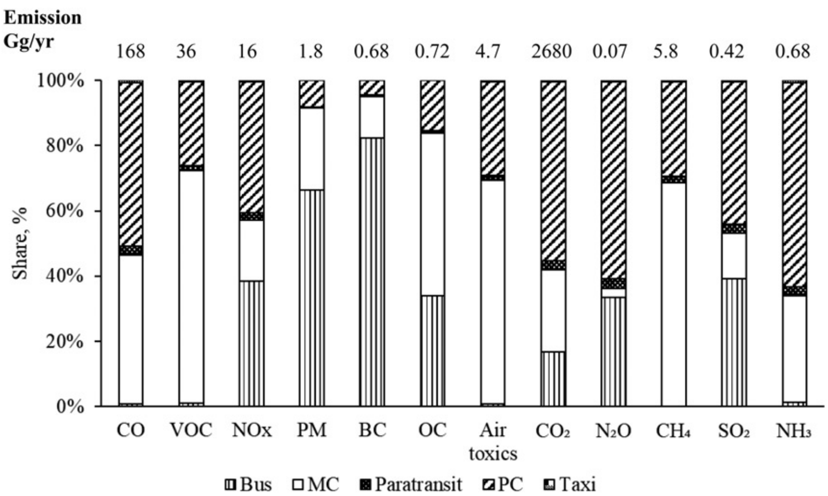

Figure 6. Total emission (Gg/year) and emission share (%) by different vehicle fleets in Bandung, 2015. (Air toxics include 1,3-Butadiene, acetaldehyde, formaldehyde and benzene)

Emission inventory for Bandung

Total emission and emission shares by vehicle categories

Figure 6 presents the total annual emissions in Gg and emission shares (%) by vehicle fleet in Bandung for the base year 2015. Collectively, the emissions from all traffic passenger fleets in Bandung in Gg/year of CO, VOC (exhaust plus evaporative), NOx, PM, BC, OC, NH_3, air toxics (1,3-butadiene, acetaldehyde, formaldehyde and benzene), SO_2 and GHGs of CO_2, N_2O, CH_4 were 168; 36; 16; 1.8; 0.68; 0.72; 0.68; 4.7; 0.42; and 2679; 0.07; 5.8, respectively.

The large fleet of MCs (1,143,316 vehicles) and PCs (340,082 vehicles) were the greatest contributors to the total emissions. The MC fleet was also the greatest contributor to VOC, air toxics, OC and CH_4 emissions with the share of 71%, 69%, 50% and 69%, respectively, but the PC fleet contributed more to CO emissions (50%) than MC (46%). The PC fleet in Bandung was also the main source of NOx, CO_2, N_2O and SO_2 with a share of 40%, 55%, 60% and 57%, respectively. As expected, PM_{10} and BC emissions came chiefly from diesel fueled buses with a share of 66% and 82%, respectively.

The breakdown of running and startup emissions by vehicle category are presented in Table S6, SI. The highest startup emission share was for benzene (41%) while for most other species the shares were <15%. Accordingly, the running activities contributed most of the emissions, 59%–100% of the total amount varying with pollutant.

Hourly emissions

The hourly emissions for major pollutants (CO, VOC, NOx and PM) of the passenger fleets, from 6:00 am to 8:00 pm, are presented in Figure S5, SI. The highest emissions occurred during morning rush hours (6:00–8:00 am) and afternoon rush hours (4:00–6:00 pm). The variations in hourly emissions were mainly influenced by the fleet types that had the dominant contributions to the emissions of the respective species. For example, the bus fleet had significant contributions to PM emissions hence also influenced the hourly emission distributions. A bus should have a regular number of the service rounds per day but the bus density appeared to be higher during weekday morning rush hours and weekend evening rush hours (Figure 4) that increased its PM and NOx emission contributions during these hours. The private passenger fleets, i.e. MC and PC, exhibited the most distinctive fluctuations since they were the main transport modes in the city. Note that the traffic flow data gathered in this study were for the daytime hence it was not possible to analyze the night time emissions.

Scenarios and air quality and climate co-benefits quantification

Scenario 1 and 2 (S1 & S2)

The survey results (Table 1) showed that the 2015 taxi and paratransit fleets in Bandung did not have vehicles conforming to Euro3 engine standards, the PC fleet had a negligible share of Euro3 (3%); while the bus fleet had a considerable fraction of Euro 3 (26%) and small fractions of Euro4 and Euro5. Only the MC fleet had a large Euro3 fraction (84%). Thus, majority of the fleets still did not comply with Euro3; hence the faster technology intrusion scenarios of S1 (at least Euro3) and even higher technology levels of S2 (at least Euro4 for other fleets and Euro3 for MC) would bring in significant emission reductions in toxic air pollutants (62% and 68%, respectively) and GWP (29% and 45%, respectively) as seen in Table 4. Note that MC fleet was assumed to be at most complying with Euro3 standard as this standard is the most advance MC technology defaulted in the IVE model. If the country follows the Euro standards road map [106] mentioned above the emission reductions by S1 and S1 would be realized by 2018. The Euro3 and Euro4 scenarios for Bandung brought about similar ranges of co-benefits for air quality and climate mitigation as compared to other cities. For example, the Euro3 implementation in Hanoi (for bus, taxi and PC) would reduce the toxic air pollution emissions by 85% and that of GWP by 28%) [23], while the corresponding emission reductions in Kathmandu (bus, van, three-wheeler, taxi and MC) would be 44% and 31% [24]. Note that the implementation of more stringent Euro standards, such as Euro4 and above, is contingent on availability of cleaner fuels, and depending on the national policy and economy, therefore may require some more time to realize.

Scenario 3 (S3)

The revamping catalyst scenario (S3) was specifically considered for Bandung due to the late implementation of unleaded gasoline (2006). It is shown that this measure potentially could reduce CO, VOC and NOx emissions, which would induce a reduction of 47% in the toxic air pollutants emissions and 16% of the GWP (Table 4). The replacement of lead deactivated catalysts was, for example, regulated by USEPA [31] and at the first look the measure appeared quite straightforward for Bandung. However, it is noted that S3 simply assumed an average of 80% removal efficiency of related pollutants by a revamped catalyst for an in-use gasoline vehicle. The removal efficiency expected for in-use vehicles in Bandung may not be exactly the same due to several technical issues such as existing high vehicle mileage, vehicle engine conditions and vehicle driving conditions [29]. The replacement of old catalysts with new ones for existing vehicles in Mexico City was found not to bring in the expected emission reduction due to the poor mechanical conditions of vehicles, i.e. none of the pollutants had a removal efficiency above 90% by the newly replaced catalysts (73% for CO, 83% for NOx, 90% for HC) [32]. The removal efficiency dropped with the mileage, faster after 60,000 km driving, and at 100,000 km odometer the removal efficiency of pollutants reduced to about 57% for CO, 67% for NOx and 83% for HC [30]. In our study we assumed that the lead deactivated catalysts in gasoline vehicles in Bandung would have removal efficiency close to zero hence the installation of new catalysts would bring in substantial emission reductions although not getting the full performance of the device. In addition, beside the catalysts, other vehicle control systems may be defected by leaded gasoline use; for example, the Pb deposits may also affect the performance of lambda sensors and fuel injectors that would reduce the removal efficiency of newly installed catalysts. Thus, further evaluation of the effectiveness of the catalyst revamping measure is required, e.g. by the exhaust emission measurements of the existing fleet before and after the catalyst revamping.

Moving forward, a cost–benefit analysis should be conducted to recommend the most cost-efficient scenario, i.e. in term of reduction of 1 ton of pollutants or of 1 ton of CO_2 eq. The faster technology intrusion scenarios require substantial financing but are already part of the existing national policy hence implementation is expected soon. Actual effectiveness of the lead deactivated catalysts in the existing gasoline fleets in Bandung should first be validated by measurements before a robust recommendation for policy making can be made. Other important considerations such as better traffic management to reduce congestion or introduction of rapid mass transport systems should be included in the future studies with detail analysis on co-benefits and cost–benefit.

Conclusions

Bandung's passenger vehicle fleets consisted of a wide range of technologies, with pre-Euro engines still existing in all vehicle types and sharing up to 51% in the paratransit fleet. The most advanced engine technologies, Euro4 and Euro5, were only observed in the bus fleet but with small shares. The most advanced technology of the PC and MC fleets was Euro3, while the taxi and paratransit vehicles were only at most complying with Euro2. The weighted average age of the bus, MC, paratransit, PC and taxi fleets was 6.4, 3.6, 5, 5.2 and 7.5 years, respectively. The low average speeds, 11 to 17 km/h, indicated heavy traffic in the city. Higher daily VKT (km/day/veh) were found for public buses (117), paratransit vehicles (91) and taxis (70) as compared to private vehicles of MCs (25) and PCs (37). Gasoline and diesel were the only fuels used by the passenger vehicles.

The city 100% diesel fueled bus fleet produced the highest running EFs for NOx (23.9 g/km), SO_2 (0.18 g/km) and PM_{10} (4.7 g/km). The large fraction of pre-Euro gasoline vehicles in the paratransit fleet produced high composite EFs for CO (25.1 g/km) and VOC (2.6 g/km). The large population of MC and PC fleets made them the major contributors to the emissions, only with exception for PM and BC which were contributed mainly by the bus fleet.

The consideration of the lead deactivation effects on the catalysts equipped in the gasoline vehicles operated prior to 2006 helped to produce more realistic pollutant emission factors that were comparable with other Asian cities. A preliminary estimation showed that replacement of these lead deactivated catalysts (catalyst revamping, S3) would bring in 47% reduction in toxic pollutants and 16% reduction in GWP in CO_2 eq. A faster intrusion of Euro3 (S1) and Euro4 (S2), according to the national road map, would bring in even more co-benefits with reductions of toxic air pollutants emissions by 62% and 67%, respectively, and reductions in CO_2 eq by 29% and 45%, respectively. These are, however, only "what if" scenarios; to make robust policy recommendations various social, technical and financial issues should be considered. The Euro standard progressive implementation is already in the national policy hence the implementation is expected. There are several technical considerations to justify the effectiveness of the catalyst revamping hence the emission reductions resulting from the replacement of the deactivated catalysts in the in-use gasoline fleets in Bandung should be first validated using the exhaust measurement data. Cost–benefit analyses that shed light upon the economic feasibility of these options are required in future studies to make robust policy recommendations.

Further studies should also cover other fleets, such as on-road trucks and non-road vehicles (construction, aviation, agricultural machinery, etc.), to obtain a more comprehensive EI for mobile sources in the Bandung area. Particularly, the inbound and outbound vehicle flows should be considered for Bandung because of its close connection with Jakarta.

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