Supplementary Information (SI)

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

Text box S1. Survey design and data collection for IVE modeling

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Text Box S1 Survey design and data collection for IVE modeling

1. Questionnaire survey and VKT estimation

The parking lot survey was used to acquire data on five passenger fleets (PC, MC, bus, taxi, and paratransit), including the vehicle model years, odometer readings, fuel types, fuel delivery systems, exhaust control devices and evaporative control systems. The survey was conducted in parking lots in commercial areas, gasoline stations and bus terminals. The sample size (number of questionnaires) was determined using the simple Taro formula (Taro, 1967) with an acceptable error of <5-10%. The cumulative population of registered fleets in Bandung by the time of the survey was used to distribute the number of questionnaires for each vehicle category. Out of the delivered 1350 questionnaires, there were 1315 completed responses. The final number of responses obtained for each passenger fleet type (Table S1, SI) was adjusted to account for the actual fleet population, e.g. the number of questionnaires for MC was increased to 450 (larger than the size of 400 at 5% error by Taro's formula) as MC made up a large share of the Bandung's vehicle population. On other side, the number of questionnaires for other fleets with smaller populations were adjusted from the estimated sample size by Taro's formula with an acceptable error below 10% (about 7%). Further, the number of questionnaires for a fleet were distributed over the six zones of the city, i.e. Bojonegara, Tegalega, Cibeunying, Karees (city center), Ujung Berung and Gedebage (Fig. S1, SI), using the total number of inhabitants in the zone (Table S2, SI). Note that 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.

The parking lot survey provided information on the vehicle technologies; this information is essential for the EI and is a required input for the IVE model. The survey results were used to develop a regression equation between the odometer readings and the vehicle age (years) to calculate the annual VKT following the same approach used in several previous studies (Wang et al., 2008; Kim Oanh et al., 2012; Shrestha et al., 2013; Trang et al., 2015).

Total annual VKT for each type of fleet was calculated by multiplying the annual VKT per fleet (obtained from the regression line of age vs. odometer readings) with the number of active vehicles for the city, as detailed in Section 3.1.2.5 of the main text.

2. Traffic video recording

Three categories of roads in Bandung were considered in the traffic video recording: highway, arterial road and residential road which were selected to obtain a representative sample of driving activities in Bandung. Totally, six points were selected for the traffic flow survey (Fig. S1, SI) with two points per road category (one point in urban and sub-urban area per road category). We scrutinized the results reported by a previous study to select the road segments that were driven by the representative fleet in the city (LPPM, 2012) to get the representative vehicle composition. To record the traffic volume for both rush and non-rush hours, monitoring was carried out from 6:00 am to 8:00 pm (only daytime recording was possible because of limited light during the evening). The camera was operated for 30 minutes over every two hours during the monitoring period at each point. The traffic recording was done for two days on the weekday and two days on the weekend at every monitoring point. The video camera was then replayed for a manual counting of vehicles to get the average hourly traffic volume on different road categories, separately for weekend and weekday and used for IVE modeling.

3. GPS monitoring

Similar to the previous studies (Trang et al., 2015; Kim Oanh et al., 2012), the GlobalSat DG-100 GPS Data Loggers were used to record the time, speed and location (including longitude, latitude, and altitude) of each monitored vehicle on the second-by-second basis for 24 hr of a monitoring day.

In total, 12 vehicles were monitored on both weekday and weekend, including 3 MCs (a governmental officer, a student and a MC taxi), 3 passenger cars (a governmental officer, a private worker and a student), 2 buses (Leuwipanjang-Ledeng and Cicaheum-Cibeureum routes), 2 paratransit vehicles (Antapani-Ciroyom and Gedebage-Dago routes) and 2 taxis (Fig. S2, SI). The bus and paratransit routes were selected to be the longest routes to cover large areas in the city. Two selected taxis included one standing by at the airport/train station taxi and general taxi which usually picks up passenger on-road. The GPS records were used to generate hourly average vehicle speed and the vehicle specific power (VSP) information. IVE incorporates 20 VSP categories and three engine stress modes: low (-1.6 to 3.1), medium (3.1 to 7.8) and high (>7.8) that makes for a total of 60 bins (Jimenez, 1999).

The GPS records also provide information on the numbers of engine starts (startups) and soak time distribution that helps to distinguish emission-intensive cold starts (after an engine rests for 18 hr or more) from lower emission warm starts (ISSRC, 2008).

4. Vehicle technology index determination

Vehicle technologies and shares of different technologies are a key input for the IVE modeling. The IVE model v.2.0.2 (http://www.issrc.org/ive/) used in this study has over 1,300 technology index defaults, ranging from pre-Euro to Euro5 engine standards (ISSRC, 2008). It is essential to assign the current technologies in the Bandung fleets to the right IVE default technologies indices and determine their shares. However, often drivers interviewed during the parking lot survey of this study could not provide detailed information on the vehicle engine (Euro standards) and the emission control devices. Therefore, additional information was collected by visiting vehicle showrooms and maintenance stations, and interviewing technicians in the public garages. The survey data was analyzed by the local vehicle/engine experts to match with the IVE defaulted technology indices.

5. IVE modeling

The IVE model v.2.0.2 (http://www.issrc.org/ive/) incorporates different types of fuels, i.e. gasoline, diesel, natural gas, propane, ethanol, compressed natural gas (CNG) and liquefied petroleum gas (LPG). The model allows for inputting a wide range of lead (0 - 0.02 g/L), benzene (0.2 – 3%), sulfur (S) content in gasoline (15 - 600 ppm) and sulfur in diesel (15 - 5,000 ppm). Based on the research octane number (RON), there were four possible types of gasoline (RON88, RON90, RON91 and RON95).

In Indonesia, the government regulation set a standard of maximum S of 3,500 ppm for diesel transport fuel (diesel 48) but field monitoring for fuel quality in several cities in Java Island conducted by the Ministry of Environment showed lower contents of 350-2,100 ppm (Safrudin, 2016). In addition, some cleaner diesel has already been introduced in the market, such as diesel fuel 51 (S=300 ppm) and PETRADEX (S=500 ppm) as reported by Palguna and Safrudin (2010).

Table S1. Number of questionnaires for parking lot survey.

Vehicle category	Accumulative vehicle number (2015)	Taro's sample size		Delivered questionnaires
		10%	5%	
PC	340,082	100	400	350
MC†	1,143,316	100	400	450
Taxi	1906	95	333	150
Bus‡	5918	98	375	150
Paratransit	5721	98	375	250
Total	1,496,943	491	1883	1350

Note:

† Including common MC and MC taxi

‡ Including both inter-city and inner-city bus

Table S2. Allocation of questionnaires to the city zones for parking lot survey.

Vehicle category	Bojonegara	Tegalega	Karees	Cibeunying	Ujung Berung	Gede Bage	Total
PC	70	70	70	70	35	35	350
MC	90	90	90	90	45	45	450
Taxi	30	30	30	30	15	15	150
Bus	30	30	30	30	15	15	150
Paratransit	50	50	50	50	25	25	250
Total	270	270	270	270	135	135	1350

Table S3. GWP values used in this study relative to CO_2 emission mass (where available the values relevant for Southeast Asia were used).

Pollutants	GWP	References
	20-yr horizon	
CO_2	1	
CH_4	72	Fuglestvedt et al., 2010
N_2O	289	Fuglestvedt et al., 2010
NO_x, per kg N	43	Fuglestvedt et al., 2010
Sulfate (as SO_4^{2-})	-57	Fuglestvedt et al., 2010
VOC	14	Collins et al., 2002
CO	7.2	Derwent et al., 2001
BC	3200	Bond et al., 2013
OC	-540	Fuglestvedt et al., 2010

Table S4. Passenger vehicle fleet technologies matched with default IVE indexes.

Index	Technological configuration	Euro standard	Share (%)
Bus			
1077	De: Hv: Pre-chamber Inject.: None: None: <79K km	Pre-Euro	1.45
1078	De: Hv: Pre-chamber Inject.: None: None: 80-161K km	Pre-Euro	0.72
1079	De: Hv: Pre-chamber Inject.: None: None: >161K km	Pre-Euro	1.45
1086	De: Hv: DI: Improved: None: <79K km	Pre-Euro	0.72
1087	De: Hv: DI: Improved: None: 80-161K km	Pre-Euro	2.17
1088	De: Hv: DI: Improved: None: >161K km	Pre-Euro	11.59
1131	De: Hv: FI: Euro2: None: <79K km	II	18.84
1132	De: Hv: FI: Euro2: None: 80-161K km	II	7.97
1133	De: Hv: FI: Euro2: None: >161K km	II	23.91
1140	De: Hv: FI: Euro3: None: <79K km	III	6.52
1141	De: Hv: FI: Euro3: None: 80-161K km	III	4.35
1142	De: Hv: FI: Euro3: None: >161K km	III	15.22
1150	De: Hv: FI: Euro4: None: 80-161K km	IV	1.45
1151	De: Hv: FI: Euro4: None: >161K km	IV	1.45
1159	De: Hv: FI: Euro5: None: 80-161K km	V	1.45
1160	De: Hv: FI: Euro5: None: >161K km	V	0.72
Motorcycle			
1170	Pt: Lt: 2-Cycle: None: None: 0-25K km	Pre-Euro	0.21
1171	Pt: Lt: 2-Cycle: None: None: 26-50K km	Pre-Euro	0.21
1172	Pt: Lt: 2-Cycle: None: None: >50K km	Pre-Euro	0.21
1207	Pt: Lt: 4-Cycle, Carb: None: None: 26-50K km	Pre-Euro	0.42
1208	Pt: Lt: 4-Cycle, Carb: None: None: >50K km	Pre-Euro	0.84
1233	Pt: Lt: 4-Cycle, Carb: Catalyst: None: 0-25K km	II	2.53
1234	Pt: Lt: 4-Cycle, Carb: Catalyst: None: 26-50K km	II	4.85
1235	Pt: Lt: 4-Cycle, Carb: Catalyst: None: >50K km	II	6.54
1242	Pt: Lt: 4-Cycle, FI: Catalyst: PCV: 0-25K km	III	47.89
1243	Pt: Lt: 4-Cycle, FI: Catalyst: PCV: 26-50K km	III	23.21
1244	Pt: Lt: 4-Cycle, FI: Catalyst: PCV: >50K km	III	13.08
Paratransit			
9	Pt: Lt: Carb: 2-way: PCV: <79K km	Pre-Euro	9.66
10	Pt: Lt: Carb: 2-way: PCV: 80-161K km	Pre-Euro	2.52
11	Pt: Lt: Carb: 2-way: PCV: >161K km	Pre-Euro	5.46
18	Pt: Lt: Carb: 2-way/EGR: PCV: <79K km	Pre-Euro	1.26
63	Pt: Lt: Single-Pt FI: 2-way: PCV: <79K km	Pre-Euro	14.29
64	Pt: Lt: Single-Pt FI: 2-way: PCV: 80-161K km	Pre-Euro	8.40
65	Pt: Lt: Single-Pt FI: 2-way: PCV: >161K km	Pre-Euro	8.82
180	Pt: Lt: Multi-Pt FI: Euro2: PCV/Tank: <79K km	II	20.59
181	Pt: Lt: Multi-Pt FI: Euro2: PCV/Tank: 80-161K km	II	6.30
182	Pt: Lt: Multi-Pt FI: Euro2: PCV/Tank: >161K km	II	1.26
183	Pt: Md: Multi-Pt FI: Euro2: PCV/Tank: <79K km	II	5.88
Paratransit (cont'd)			

Index	Technological configuration	Euro standard	Share (%)
184	Pt: Md: Multi-Pt FI: Euro2: PCV/Tank: 80-161K km	II	0.42
757	De: Lt: DI: EGR+Improve: None: 80-161K km	Pre-Euro	1.68
758	De: Lt: DI: EGR+Improve: None: >161K km	Pre-Euro	0.84
792	De: Lt: FI: Euro2: None: <79K km	II	10.50
793	De: Lt: FI: Euro2: None: 80-161K km	II	1.68
794	De: Lt: FI: Euro2: None: >161K km	II	0.42
Passenger Car			
9	Pt: Lt: Carb: 2-way: PCV: <79K km	Pre-Euro	2.35
10	Pt: Lt: Carb: 2-way: PCV: 80-161K km	Pre-Euro	1.47
11	Pt: Lt: Carb: 2-way: PCV: >161K km	Pre-Euro	2.06
36	Pt: Lt: Carb: 3-way/EGR: PCV: <79K km	Pre-Euro	2.35
37	Pt: Lt: Carb: 3-way/EGR: PCV: 80-161K km	Pre-Euro	1.18
38	Pt: Lt: Carb: 3-way/EGR: PCV: >161K km	Pre-Euro	0.88
63	Pt: Lt: Single-Pt FI: 2-way: PCV: <79K km	Pre-Euro	5.00
64	Pt: Lt: Single-Pt FI: 2-way: PCV: 80-161K km	Pre-Euro	0.29
65	Pt: Lt: Single-Pt FI: 2-way: PCV: >161K km	Pre-Euro	3.24
180	Pt: Lt: Multi-Pt FI: Euro2: PCV/Tank: <79K km	II	50.0
181	Pt: Lt: Multi-Pt FI: Euro2: PCV/Tank: 80-161K km	II	11.47
182	Pt: Lt: Multi-Pt FI: Euro2: PCV/Tank: >161K km	II	9.12
189	Pt: Lt: Multi-Pt FI: Euro3: PCV/Tank: <79K km	III	2.35
190	Pt: Lt: Multi-Pt FI: Euro3: PCV/Tank: 80-161K km	III	0.29
191	Pt: Lt: Multi-Pt FI: Euro3: PCV/Tank: >161K km	III	0.59
747	De: Lt: Pre-Chamber Inject.: Improved: None: <79K km	Pre-Euro	0.59
748	De: Lt: Pre-Chamber Inject.: Improved: None: 80-161K km	Pre-Euro	0.29
749	De: Lt: Pre-Chamber Inject.: Improved: None: >161K km	Pre-Euro	0.88
756	De: Lt: DI.: EGR+Improve: None: <79K km	Pre-Euro	0.88
792	De: Lt: FI.: Euro2: None: <79K km	II	2.35
793	De: Lt: FI.: Euro2: None: 80-161K km	II	1.18
794	De: Lt: FI.: Euro2: None: >161K km	II	1.18
Taxi			
2	Pt: Lt: Carb: None: PCV: >161K km	Pre-Euro	0.75
110	Pt: Lt: Multi-Pt-FI: none/EGR: PCV: >161K km	Pre-Euro	27.0
126	Pt: Lt: Multi-Pt-FI: 3-Way/EGR: PCV: <79K km	At least II	2.99
127	Pt: Lt: Multi-Pt-FI: 3-Way/EGR: PCV: 80-161K km	At least II	5.22
128	Pt: Lt: Multi-Pt-FI: 3-Way/EGR: PCV: >161K km	At least II	29.7
180	Pt: Lt: Multi-Pt-FI: Euro2: PCV/Tank: <79K km	II	0.75
181	Pt: Lt: Multi-Pt-FI: Euro2: PCV/Tank: 80-161K km	II	28.4
182	Pt: Lt: Multi-Pt-FI: Euro2: PCV/Tank: >161K km	II	5.22

Pt: Petrol, De: Diesel, Lt: Light duty, Md: Medium duty, Hv: Heavy duty.

Table S5. Comparison of composite EFs obtained for Bandung (adjusted for Pb deactivation of catalysts) with other Asian cities.

Composite EFs (g/ km)	**CO**	**VOC**	**NOx**	**SOx**	**PM**	**CO_2**	**N_2O**	**CH_4**	**1,3 But.**	**Acet.**	**Formal.**	**NH_3**	**Benzene**
Bus													
HCMC (2014)[a]	5.242	1.083	12.418	0.089	1.383	900	0.010	0.071	0.002	0.009	0.024	0.028	0.011
Hanoi (2010)[b]	6.905	1.730	16.954	0.115	2.080	1131	0.008	-	0.003	0.014	0.039	0.035	0.018
Kathmandu (2010)[c]	12.300	3.100	36.900	0.300	10.900	2972	0.050	-	0.010	0.050	0.150	0.060	0.030
Bandung (2015)	5.327	1.415	23.908	0.654	4.666	1786	0.085	0.000	0.006	0.030	0.080	0.038	0.015
Taxi													
HCMC (2014)	23.660	2.225	0.738	0.058	0.014	277	0.038	0.266	0.014	0.047	0.088	0.104	0.133
Hanoi (2010)	10.577	1.573	0.525	0.042	0.006	190	0.009	0.311	0.006	0.013	0.034	0.075	0.166
Kathmandu (2010)	43.600	5.100	1.900	0.040	0.020	376	0.010	1.050	0.030	0.070	0.180	0.140	0.270
Bandung (2015)	22.932	3.358	1.092	0.032	0.009	288	0.007	0.535	0.008	0.018	0.046	0.109	0.278
MC													
HCMC (2014)	8.85	2.69	0.25	0.02	0.12	98	0.00	0.51	0.01	0.07	0.27	0.07	0.10
Hanoi (2008)[d]	5.50	1.80	0.20	0.01	0.09	58	-	0.38	0.01	0.05	0.21	-	0.09
Kathmandu (2010)	4.60	1.50	0.28	0.01	0.10	125	-	0.30	0.01	0.04	0.18	0.05	0.03
Bandung (2015)	6.39	2.22	0.17	0.01	0.03	69	0.00	0.41	0.01	0.04	0.14	0.02	0.04
PC													
HCMC (2014)	6.23	0.90	0.61	0.050	0.006	247	0.026	0.140	0.002	0.004	0.008	0.071	0.078
Hanoi (2010)	10.82	1.80	0.94	0.092	0.012	468	0.039	0.315	0.002	0.002	0.004	0.135	0.169
Kathmandu (2010)	43.60	5.10	1.90	0.040	0.020	376	0.010	1.050	0.030	0.070	0.180	0.140	0.270
Bandung (2015)	22.39	2.35	1.79	0.054	0.037	434	0.011	0.432	0.017	0.037	0.091	0.126	0.212

Sources:

[a] Van (2014); [b] Trang et al. (2015); [c] Shrestha et al. (2013); [d] Kim Oanh et al. (2012)

Table S6. Running and startup emission shares (in %) by vehicle category in each species emission (100%).

Species	Emission	Bus	MC	Paratransit	PC	Taxi	Total of all fleets
CO	Startup	2	4	8	22	16	15
	Running	98	96	92	78	84	85
VOC	Startup	1	3	7	27	14	11
	Running	99	97	93	73	86	89
VOC (evp)	Startup	-	2	16	33	23	13
	Running	-	98	84	67	77	87
VOC (total)	Startup	1	3	8	28	16	11
	Running	99	97	92	72	84	89
NOx	Startup	1	6	2	7	19	6
	Running	99	94	98	93	81	94
SO_2	Startup	0	0	1	2	2	0
	Running	100	100	99	98	98	100
PM	Startup	11	6	15	32	28	14
	Running	89	94	85	68	72	86
CO_2	Startup	1	0	0	1	1	1
	Running	99	100	100	99	99	99
N_2O	Startup	4	100	4	12	6	11
	Running	96	0	96	88	94	89
CH_4	Startup	-	6	21	57	14	22
	Running	-	94	79	43	86	78
1,3 Butadiene	Startup	9	5	16	33	22	17
	Running	91	95	84	67	78	83
Acetaldehyde	Startup	9	5	17	33	22	11
	Running	91	95	83	67	78	89
Formaldehyde	Startup	9	5	17	34	23	9
	Running	91	95	83	66	77	91
NH_3	Startup	1	4	0	1	1	2
	Running	99	96	100	99	99	98
Benzene	Startup	1	6	22	57	14	41
	Running	99	94	78	43	86	59

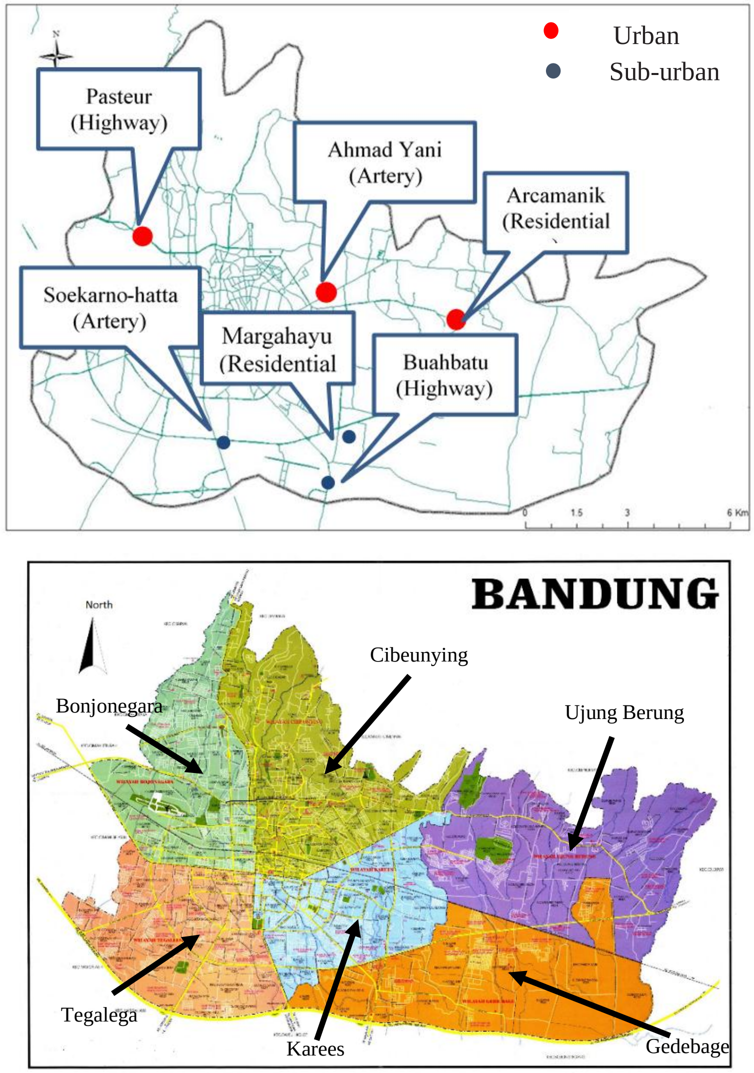

Figure S1. Map of study area with 6 traffic camera recording points, representing six urban and sub-urban zones of Bandung City.

Note: Bandung is located at about 790 m above sea level (ASL) and its meteorological conditions are influenced by Asian monsoon weather patterns. The winds in Bandung blow chiefly from the west (westerly) during the rainy season (November – April) while during the dry season (May – October) winds blow the east (Lestari and Permadi, 2014). The annual average air temperature is 23.4 °C; October has the highest monthly average temperature in a year of 24.2°C while January has the lowest of 22.5 °C (BPS, 2016). The highest rainfall intensity occurs in March (420 mm) while there is almost no rain in September.

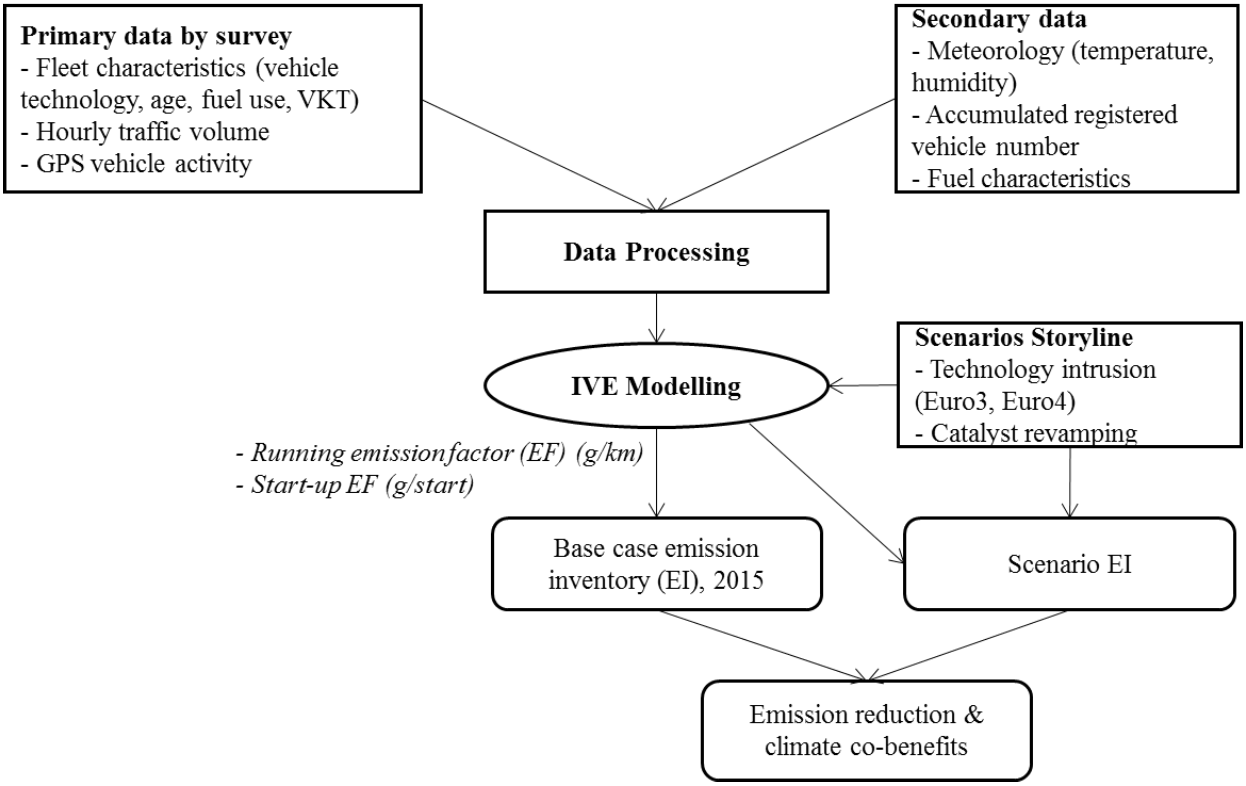

Figure S2. Methodological framework

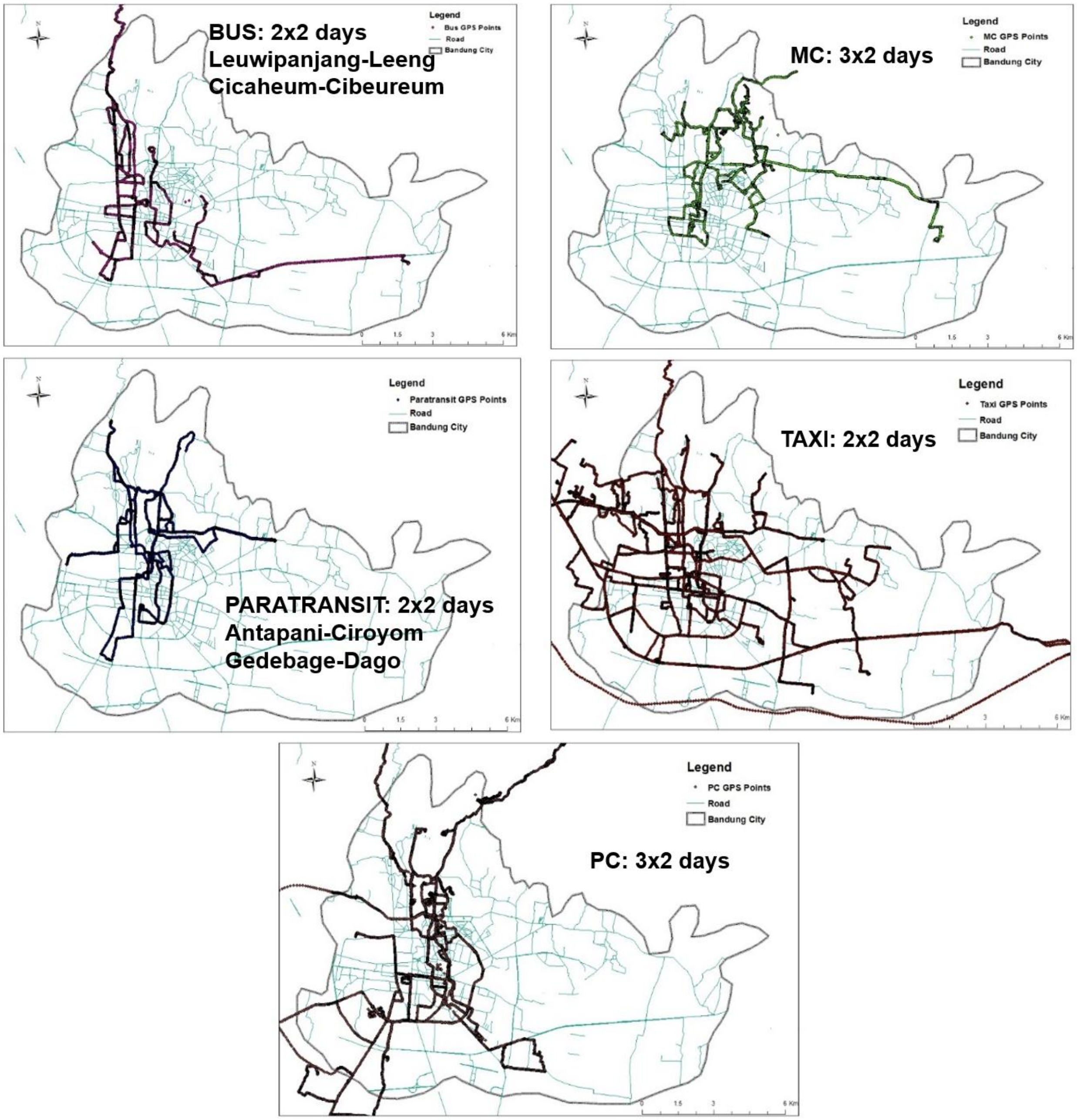

Figure S3. GPS survey routes.

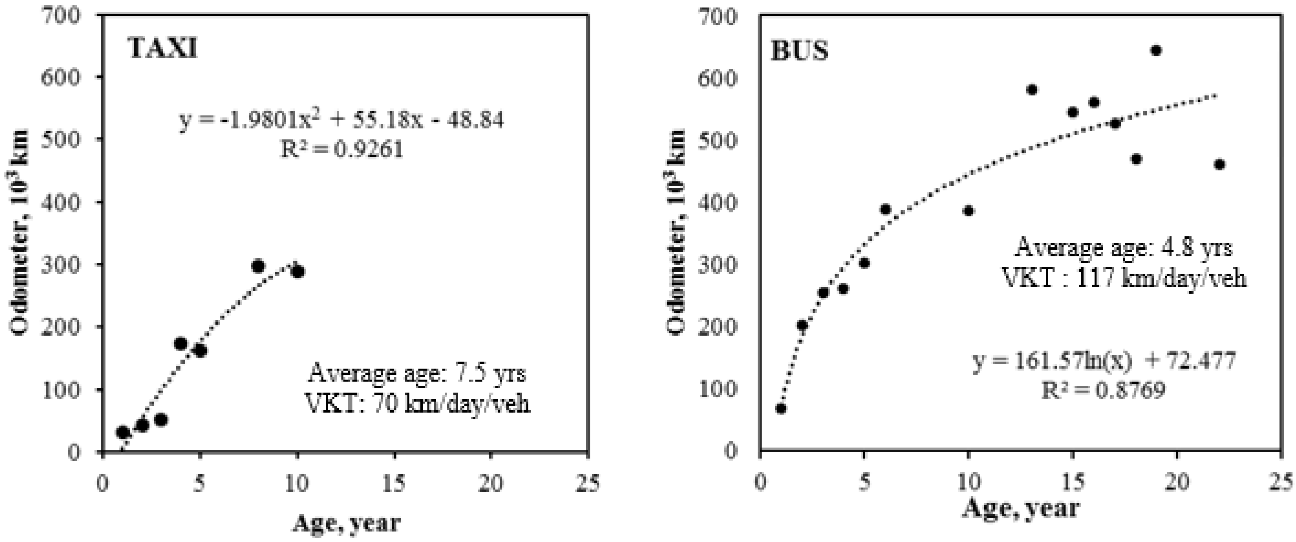

Figure S4. Age vs. odometer reading of bus and taxi fleets in Bandung 2015.

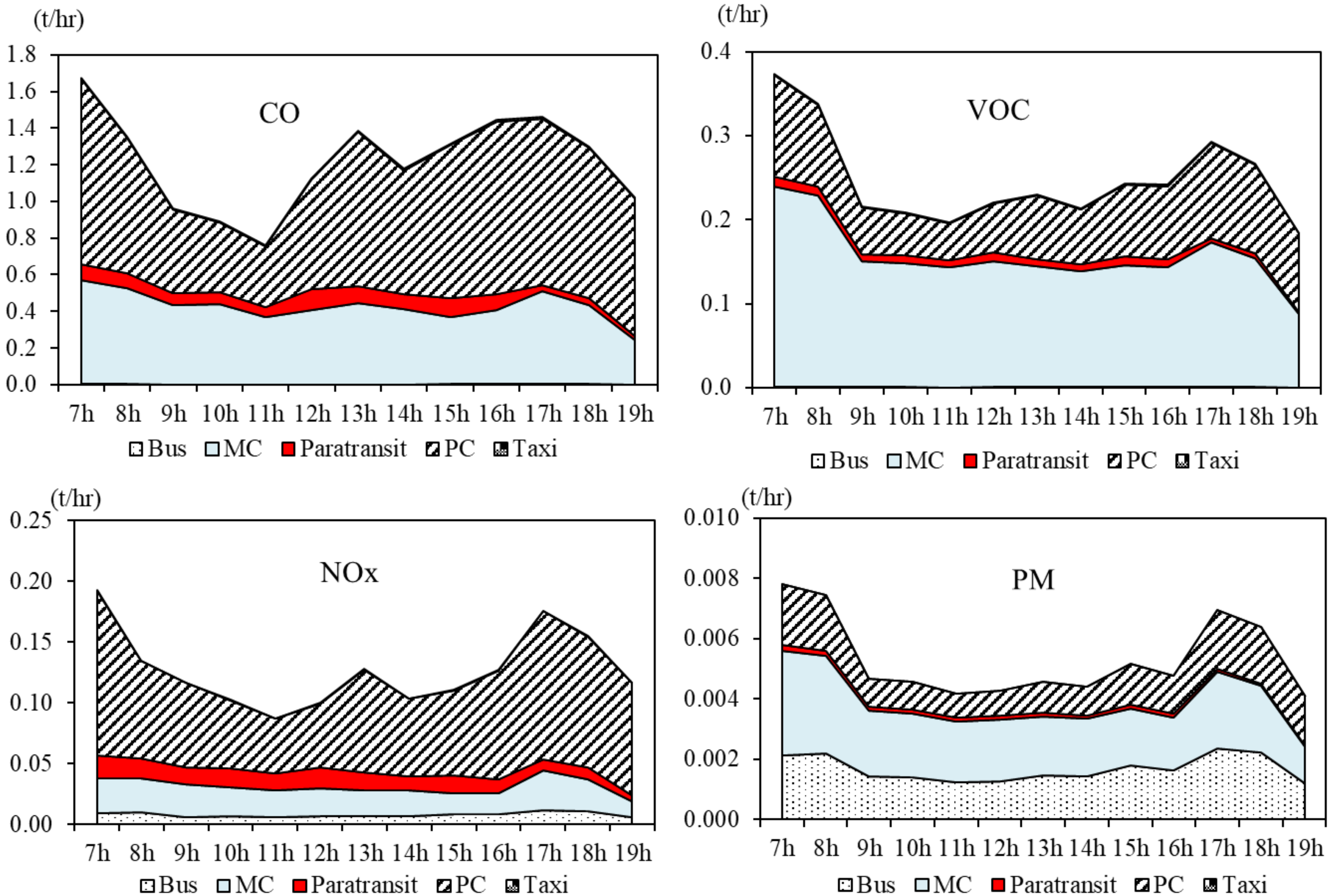

Figure S5. Hourly variation of emissions (running plus startup) of pollutants from passenger fleets of Bandung (hourly emissions are presented at the mid-point of 1 hr period, 7:00 am emissions are the mid-point of 6:00-7:00 period and so on