Supplementary Information

Emission Inventory of Traffic Fleet in Hanoi for Estimation of Air Quality and Climate Co-Benefits of Faster Technology Intrusion

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Figure S1. Map of Hanoi urban area showing 3 study zones with GPS survey routes and 9 vehicle survey/counting points (dark dots)

Figure S2. Regression analysis of odometer readings vs. vehicle age

Figure S3a. Emission factors of selected pollutants by bus technology types

Figure S3b. Emission factors of selected pollutants by taxi technology types

Figure S3c. Emission factors of selected pollutants by personal car technology types

Figure S4a. Diurnal emission of bus fleet in Hanoi

Figure S4b. Diurnal emission of taxi fleet in Hanoi

Figure S4c. Diurnal emission of personal car fleet in Hanoi

Equations for calculation

1) Daily VKT calculation:

$$T_v = (O_{v,a+0.5} - O_{v,a-0.5})/365 \quad (\text{Equation S1})$$

Where,

- N_v : Population of vehicle interested
 T_v : Average usage of vehicle interested, (km day⁻¹ vehicle⁻¹)
 f_v : Fraction of vehicle type observed in fleet
 $O_{v,a+0.5}$, $O_{v,a-0.5}$: Average accumulated mileage of vehicle (km), taken from Fig. S2
 a : Average age of vehicle interested (years)

2) VSP and engine stress calculation

$$\text{VSP} = v [1.1a + 9.81 (\arctan(\sin(\text{grade}))) + 0.132] + 0.000302v^3 \quad (\text{Equation S2})$$

Where, grade = $(h_{t=0} - h_{t=-1}) / d_{(t=-1 \text{ to } 0 \text{ seconds})}$

v = velocity (m s⁻¹)

a = acceleration (m s⁻²)

h = Altitude (m)

$d_{(t=-1 \text{ to } 0 \text{ seconds})}$ = the length of the link or roadway from beginning to end (m)

$h_{t=0}$ = the altitude at the beginning of the roadway (m)

$h_{t=-1}$ = the altitude at the end of the roadway (m)

(Grade numbers from 0 to 1 is accepted in the model. However, actual road grades rarely exceed 0.15)

$$\text{Engine Stress (unitless)} = \text{RPMIndex} + (0.08 \text{ ton kW}^{-1}) * (\text{Pre average Power})$$

(Equation S3)

Where, Pre average Power = Average (VSP_{t=-5sec to -25 sec}) (kW/ton)

RPM Index = Velocity_{t=0}/SpeedDivider (unitless), Minimum RPMIndex = 0.9

Table S1. Summary of data collection in Hanoi (December 2010 - February 2011)

Type of data		Method	Data use in IVE model	Description
Primary	Parking lots and fuel stations survey	Questionnaire	Location file and Fleet input file	300 vehicles
	Vehicle count	Manually	Fleet input file	Counting 180 minutes per location for 9 roads
	Vehicle activity (driving patterns, start patterns)	GPS logger	Bin distribution and soak distribution for fleet input file	GPS (2 units) installed in 6 buses, 6 taxis and 6 personal cars to collect data in both weekdays and weekends.
Secondary	Meteorology data, vehicle count (available at some locations)	Public information, website of government or organizations	Location file and fleet input file	For example: registered vehicles, temperature and humidity, reports of various projects, etc.

Table S2. Details of vehicles surveyed by GPS

Vehicle Type	Number of Vehicles	Survey time	Date
Taxi	6 vehicles - 4 for weekdays - 2 for weekend days	5:00-15:00 15:00-21:00	17 – 23 Jan, 2011
Personal car	6 vehicles - 4 for weekdays - 2 for weekend days	5:00-15:00 15:00-22:00	24 – 30 Jan, 2011
Bus	6 vehicles - 4 weekdays - 2 weekend days	5:00-15:00 15:00-22:00	3 – 9 Jan, 2011

Table S3. GWP values used in this study relative to CO₂ emission mass

Pollutants	GWP	Remark
	20-year horizon	
CO ₂	1	
CH ₄	72	Fuglestvedt et al., 2010
N ₂ O	289	Fuglestvedt et al., 2010
NO _x , per kg N	43	Fuglestvedt et al., 2010
VOC	14	Collins et al., 2002
Sulfate	-140	Fuglestvedt et al., 2010
CO	6	Derwent et al., 2001
BC	3,200	Bond et al., 2013
OC	-240	Fuglestvedt et al., 2010

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Table S4. Hourly average vehicle flows at nine selected roads in Hanoi, 2010

Road name	Road types	Hourly flow (veh h ⁻¹)		
		Bus	Taxi	Personal car
Nguyen Thai Hoc	Arterial	53 ± 3	514 ± 21	943 ± 19
Nguyen Van Cu	Highway	159 ± 5	544 ± 10	1416 ± 64
Pham Hung	Highway	89 ± 3	735 ± 44	1679 ± 31
Nguyen Quy Duc	Residential	-	72 ± 4	96 ± 7
Truong Chinh	Arterial	34 ± 2	355 ± 22	617 ± 14
Phuong Mai	Residential	15 ± 1	201 ± 14	214 ± 17
Nguyen Trai	Arterial	73 ± 3	386 ± 23	1023 ± 38
Giai Phong	Highway	96 ± 1	1247 ± 41	768 ± 59
Nha Chung	Residential	-	112 ± 6	155 ± 20
Average hourly flow (veh h ⁻¹)		74 ± 44	463 ± 343	768 ± 527
Average fraction (%) [*]		0.04	0.47	3.44

* based on registration data of different vehicle types, estimated for active number using retirement rate (VR, 2010).

Table S5. Shares of IVE technology indexes for Hanoi under the base case and considered scenarios

IVE technology	Share, %		
	Base case	Euro3	Euro4
Bus fleet			
1076 Ds: Tk/Bus: Med: Pre-Inj: None: None: >161K km	26		
1128 Ds: Tk/Bus: Med: FI : EuroII: None: <79K km	20	100	100
1129 Ds: Tk/Bus: Med: FI : EuroII: None: 80-161K km	1		
1130 Ds: Tk/Bus: Med: FI : EuroII: None: >161K km	53		
Taxi fleet			
100 Pt: Auto/SmTk : Lt : MPFI: none : PCV : 80-161K km	8		
101 Pt: Auto/SmTk : Lt : MPFI: none : PCV : >161K km	12		
180 Pt: Auto/SmTk : Lt : MPFI: EuroII : PCV/Tank : <79K km	18	100	100
181 Pt: Auto/SmTk : Lt : MPFI: EuroII : PCV/Tank : 80-161K km	24		
182 Pt: Auto/SmTk : Lt : MPFI: EuroII : PCV/Tank : >161K km	38		
Personal car fleet			
99 Pt: Auto/SmTk : Lt : MPFI: none : PCV : <79K km	9		
100 Pt: Auto/SmTk : Lt : MPFI: none : PCV : 80-161K km	6		
101 Pt: Auto/SmTk : Lt : MPFI: none : PCV : >161K km	1		
180 Pt: Auto/SmTk : Lt : MPFI: EuroII : PCV/Tank : <79K km	19	33.3	33.3
183 Pt: Auto/SmTk : Med : MPFI: EuroII : PCV/Tank : <79K km	31		
192 Pt: Auto/SmTk : Med : MPFI: EuroIII : PCV/Tank : <79K km	27	33.3	33.3
804 Ds: Auto/SmTk : Med : FI : EuroIII : None : <79K km	7	33.3	33.3

Note: the technology description following the order: 1) fuel (DS: diesel, Pt: petroleum); vehicle types (bus, auto; Tk:); engine size (Sm: small; Med: medium; Tk: Truck)

The scenarios were constructed assuming that all vehicles which were Euro2 and pre-Euro2 in the base case would be converted to Euro3 and Euro4 in Scenario 1 and Scenario 2, respectively. The total VKT of a fleet would be covered by the Euro3 and Euro4 vehicles, respectively, in these two scenarios.

Table S6. Emission factors by vehicle technologies

Index	Common pollutants													
	CO		VOC		VOC evap.		NOx		SOx		PM		NH ₃	
	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)	Start (g/start)	Running (g/km)	Start (g/start)	Running (g/km)
Bus														
1076	2.023	20.412	0.157	4.403	0.000	0.000	2.103	30.305	0.007	0.143	3.719	5.687	0.002	0.044
1128	0.125	2.332	0.016	0.839	0.000	0.000	0.320	12.860	0.001	0.112	0.071	0.300	0.0004	0.034
1129	0.132	2.398	0.017	0.848	0.000	0.000	0.327	12.787	0.001	0.110	0.143	0.587	0.0004	0.033
1130	0.140	2.620	0.017	0.904	0.000	0.000	0.332	13.326	0.001	0.112	0.277	1.171	0.0004	0.034
Taxi														
100	29.95	126.56	1.39	21.26	0.11	0.78	0.82	3.81	0.01	0.15	0.01	0.01	0.004	0.28
101	36.30	154.70	2.02	27.00	0.96	2.36	1.72	3.97	0.68	0.14	0.85	0.03	1.50	0.28
180	12.66	4.16	1.01	0.43	0.02	0.14	0.23	0.61	0.00	0.14	0.01	0.01	0.002	0.27
181	15.93	8.18	1.47	1.12	0.09	0.77	0.27	0.70	0.00	0.14	0.01	0.01	0.002	0.27
182	19.30	22.62	1.88	1.69	0.47	2.33	0.36	0.95	0.00	0.14	0.01	0.03	0.002	0.27
Personal car														
99	13.91	62.74	0.94	10.49	0.06	0.12	0.89	2.20	0.01	0.10	0.01	0.01	0.01	0.17
100	17.50	74.43	1.36	12.93	0.21	0.62	1.14	2.27	0.01	0.10	0.01	0.01	0.01	0.17
101	21.21	90.98	1.74	16.43	1.14	1.88	1.61	2.37	0.01	0.09	0.02	0.02	0.01	0.17
180	9.75	1.80	1.25	0.27	0.05	0.12	0.35	0.36	0.00	0.09	0.01	0.01	0.003	0.16
183	12.51	1.80	1.60	0.30	0.05	0.29	0.71	0.72	0.01	0.11	0.01	0.01	0.003	0.16
192	8.28	1.13	0.31	0.06	0.05	0.29	0.36	0.36	0.01	0.12	0.00	0.00	0.003	0.17
804	0.41	0.19	0.04	0.04	0.00	0.00	0.08	1.17	0.00	0.04	0.07	0.05	0.0005	0.01
Air toxics and GHGs														
Index	Acetaldehyde		Formaldehyde		1,3 Butadiene		Benzene		CO ₂		N ₂ O		CH ₄	
	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)	Start (g/start)	Running (g/km)	Start (g/start)	Running (g/km)
Bus														
1076	0.014	0.039	0.038	0.106	0.0029	0.0083	0.0016	0.0462	66.048	1400.097	0.004	0.009	0.000	0.000
1128	0.001	0.003	0.002	0.008	0.0001	0.0006	0.0002	0.0088	12.264	1102.249	0.001	0.007	0.000	0.000
1129	0.001	0.003	0.002	0.009	0.0001	0.0007	0.0002	0.0089	12.436	1077.226	0.001	0.008	0.000	0.000
1130	0.002	0.008	0.004	0.022	0.0003	0.0017	0.0002	0.0095	12.204	1096.854	0.001	0.009	0.000	0.000
Taxi														
100	0.003	0.01	0.005	0.02	0.002	0.01	0.15	2.24	16.95	562.36	0.0005	0.001	0.28	4.25
101	1.20	0.09	1.42	0.22	1.01	0.04	1.86	2.85	17.71	504.62	2.00	0.002	2.54	5.45
180	0.002	0.005	0.003	0.01	0.001	0.004	0.11	0.05	4.52	684.77	0.002	0.03	0.20	0.07
181	0.003	0.01	0.01	0.02	0.002	0.01	0.16	0.12	4.47	676.70	0.002	0.04	0.29	0.19
182	0.03	0.08	0.09	0.20	0.01	0.03	0.20	0.18	4.29	648.56	0.002	0.04	0.38	0.32
Personal car														
99	0.001	0.003	0.003	0.005	0.001	0.002	0.10	1.11	26.98	393.83	0.001	0.001	0.19	2.10
100	0.003	0.01	0.005	0.01	0.002	0.01	0.14	1.36	25.25	368.62	0.001	0.001	0.27	2.59
101	0.03	0.05	0.08	0.14	0.01	0.02	0.18	1.73	22.66	330.77	0.001	0.001	0.35	3.32
180	0.002	0.003	0.003	0.01	0.001	0.002	0.13	0.03	8.14	446.84	0.003	0.02	0.25	0.04
183	0.002	0.003	0.003	0.005	0.001	0.002	0.17	0.03	10.30	565.54	0.01	0.07	0.32	0.05
192	0.0003	0.0005	0.001	0.001	0.000	0.000	0.03	0.01	10.56	579.72	0.01	0.07	0.06	0.01
804	0.00001	0.00001	0.00003	0.00005	0.000	0.000	0.001	0.001	25.31	376.47	0.001	0.00	0	0

Table S7. Comparison of averaged running EFs (g km⁻¹) obtained in this study for Hanoi with other studies

Vehicle type	CO	VOC	NO _x	PM ₁₀	Fleet characterization
Bus					
Hanoi (This study)	6.91	1.73	16.95	2.080	Diesel; Euro II: 74%, pre-Euro: 26%
Hanoi (2010) ^a	3.10	-	7.60	1.50	Diesel
Kathmandu (2013) ^b	12.3±4.6	3.1±1.1	36.9±2.0	10.9±0.7	Diesel; Euro II: 60%, Euro I: 22%, pre-Euro: 18%
Taxi					
Hanoi (This study)	24.22	3.62	0.93	0.0124	Gasoline; Euro II: 80%, pre-Euro: 20%
Kathmandu (2013) ^b	43.6±0.2	5.1±0.1	1.9	0.02	Gasoline; Euro II: 9%, Euro I: 60%, pre-Euro: 32%
Shanghai (2004) ^c	23.02	2.00	1.75	0.01	Gasoline: 73.5%, LPG: 26.5%; pre-Euro: 100%
Personal car					
Hanoi (This study)	10.82	1.8	0.95	0.0122	Gasoline: 93%; Diesel: 7% Euro III: 34%, Euro II: 50% pre-Euro: 16%
Hanoi (2011) ^d	2.21	-	1.05	-	Tested 4 light duty vehicles (3 gasoline, 1 diesel), aged 1- 7 years; no information on engine standard.

- Not available

^a – Hung et al. (2010) (back calculation using data from 2007); ^b – Shrestha et al. (2013); ^c – Wang et al. (2007);

^d – Tung et al. (2011) using chassis dynamometer, for light duty vehicles (not specifically cars)

Table S8. EFs of pollutants used for EI in this study for Hanoi, 2010 (average for weekdays and weekends)

Pollutants	Bus		Taxi		Car		Van ^a		Truck ^b	
	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	0.626	6.905	23.85	24.22	10.78	10.82	0.301	8.020	3.171	7.850
VOC	0.053	1.730	1.944	2.821	1.031	1.607	0.025	0.076	0.388	1.165
VOC evap.	-	-	0.378	0.662	0.068	0.198	0.053	0.398	0.075	0.060
NO _x	0.790	16.954	0.544	0.927	0.610	0.945	0.041	1.129	1.001	9.215
SO _x	0.003	0.115	0.005	0.071	0.006	0.092	0.000	0.040	0.005	0.078
PM ₁₀	1.129	2.080	0.0122	0.0124	0.0119	0.0122	0.003	0.029	0.861	0.990
1,3-Butadiene	0.001	0.003	0.010	0.011	0.001	0.002			0.002	0.003
Acetaldehyde	0.005	0.014	0.022	0.024	0.002	0.002			0.005	0.391
Formaldehyde	0.012	0.039	0.055	0.059	0.003	0.004			0.014	0.021
Benzene	0.001	0.035	0.205	0.297	0.108	0.169			0.022	0.021
NH ₃	0.001	0.018	0.003	0.147	0.003	0.135			0.001	0.034
CO ₂	26.219	1130.9	8.853	325.1	13.53	468.4	1.032	327.511	44.228	733.995
N ₂ O	0.002	0.008	0.002	0.016	0.007	0.039	0.001	0.021	0.002	0.005
CH ₄			0.391	0.558	0.206	0.315	0.015	0.375	0.034	0.015

^a – To estimate emission for vans, EF in Bangkok was used (Vilaiphorn, 2010); ^b – For truck, EF from Ho Chi Minh City in 2013 was used (Van, 2014).

Table S9. Annual emission of different types of vehicle in Hanoi for 2010, Gg yr⁻¹, and the share of total (percent in brackets)

Pollutants	Vehicle type						Total
	Bus ^a	Taxi ^a	Personal car ^a	Van ^b	Truck ^c	MC ^d	
CO	0.601 (0.3%)	19.68 (8.9%)	19.21 (8.7%)	4.12 (1.9%)	6.60 (3%)	171 (77%)	221
VOC (exh+evap)	0.150 (0.2%)	2.701 (4.3%)	3.029 (4.9%)	0.251 (0.4%)	1.026 (1.6%)	55.3 (88.5%)	62.4
NO _x	1.471 (6.7%)	0.710 (3.2%)	1.595 (7.3%)	0.580 (2.6%)	7.288 (33.2%)	10.3 (47%)	22.0
SO _x	0.01 (2.2%)	0.050 (11%)	0.141 (30.8%)	0.020 (4.4%)	0.061 (13.3%)	0.18 (38.5%)	0.46
PM ₁₀	0.187 (5%)	0.010 (0.3%)	0.022 (0.6%)	0.015 (0.4%)	0.911 (24.4%)	2.6 (69.3%)	3.73
<i>BC</i>	<i>0.086 (8.6%)</i>	<i>0.002 (0.2%)</i>	<i>0.01 (1.0%)</i>	<i>0.007 (0.7%)</i>	<i>0.402 (40.2%)</i>	<i>0.492 (49.2%)</i>	<i>1.00</i>
<i>OC</i>	<i>0.037 (1.6%)</i>	<i>0.008 (0.3%)</i>	<i>0.004 (0.2%)</i>	<i>0.003 (0.1%)</i>	<i>0.219 (9.6%)</i>	<i>2.019 (88.1%)</i>	<i>2.29</i>
1,3-Butadiene	0.0003 (0.1%)	0.009 (3.1%)	0.003 (0.9%)	-	0.002 (0.8%)	0.27 (95.1%)	0.29
Acetaldehyde	0.001 (0.1%)	0.019 (1.2%)	0.004 (0.2%)	-	0.303 (18.7%)	1.29 (79.8%)	1.62
Formaldehyde	0.003 (0.1%)	0.048 (0.9%)	0.008 (0.1%)	-	0.018 (0.4%)	5.19 (98.5%)	5.27
Benzene	0.002 (0.1%)	0.231 (8.1%)	0.285 (9.9%)	-	0.020 (0.7%)	2.33 (81.2%)	2.87
CO ₂	98 (3.5%)	228 (8.1%)	718 (25.5%)	167 (5.9%)	574 (20.4%)	1,027 (36.5%)	2,813
N ₂ O	0.001 (0.9%)	0.011 (12.8%)	0.060 (69.4%)	0.011 (12.6%)	0.004 (4.4%)	-	0.09
CH ₄	-	0.435 (3.8%)	0.533 (4.7%)	0.193 (1.7%)	0.017 (0.1%)	10.2 (89.6%)	11.4

^a – active vehicle number was estimated based on VR (2010) data using retirement rate of 2% for buses and cars, and 12% for taxis

^b – To estimate emission for vans, VKT obtained in a survey in Bangkok was used (Limanond et al., 2009);

^c – For truck, the survey data from Ho Chi Minh City in 2013 was used (Van, 2014);

^d – Number of motorcycles in 2010 was used with VKT and number of startups per MC extracted from (Kim Oanh et al., 2012).

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