

1 **Observation of increases in emission from modern vehicles over time in Hong Kong using**
2 **remote sensing**

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7 **Abstract:**

8 In this study on-road gaseous emissions of vehicles are investigated using remote sensing
9 measurements collected over three different periods. The results show that a high percentage of
10 gaseous pollutants were emitted from a small percentage of vehicles. Liquefied Petroleum Gas
11 (LPG) vehicles generally have higher gaseous emissions compared to other vehicles, particularly
12 among higher-emitting vehicles. Vehicles with high VSP values tend to have lower CO and HC
13 emissions while petrol and LPG vehicles tend to have higher NO emissions when engine load is
14 high. It can be observed that gaseous emission factors of petrol and LPG vehicles increase greatly
15 within 2 years of being introduced to the vehicle fleet, suggesting that engine performance of such
16 vehicles deteriorate rapidly. It can be observed that LPG vehicles have higher levels of gaseous
17 emissions than petrol vehicles, suggesting that proper maintenance of LPG vehicles is essential in
18 reducing gaseous emissions from vehicles.

19 **Capsule Abstract:**

20 Remote sensing measurements show large increases in gaseous emissions from vehicles in Hong
21 Kong after 2 years of operation, indicating that engine and catalyst performance deteriorate rapidly.

22 **Keywords:** vehicle emission; remote sensing; gaseous emission factor; model year

23 **1. Introduction**

24 In many cities, measurement of emissions from vehicles travelling under typical driving conditions
25 is carried out using remote sensing techniques, originally developed by the University of Denver
26 (Stedman and Bishop, 1990; Mazzoleni et al., 2004a; Ko and Cho, 2006). Often such measurements
27 are carried out to identify high-emitting vehicles within the vehicle fleet and thus the effectiveness
28 of vehicle inspection and maintenance programs. The time needed to measure emissions of a
29 vehicle is shorter using remote sensing compared to other methods. This enables measurement of
30 emissions from a large number of vehicles without obstructing traffic flow.

31 In addition the exhaust emissions, image of the vehicles can be captured. With the captured
32 image, information associated to each vehicle, such as model year, fuel type, and vehicle type can
33 be found through matching the database of the Transport Authority. Thus remote sensing enables
34 examination of emission factors of vehicles with different model years. In many cities, Liquefied
35 Petroleum Gas (LPG) vehicles have been introduced to reduce fleet emissions (Ning and Chan,
36 2007; Yang et al., 2007). By comparing on-road emissions of LPG vehicles and vehicles fuelled by
37 conventional fuels operating under similar conditions, the effectiveness of alternatively-fuelled
38 vehicles in reducing vehicle emissions can be examined.

39 Remote sensing can be used to investigate emissions of vehicles over a single time period. By
40 measuring emissions at the same road segment over several years, this technique can also be applied
41 to investigate changes in vehicle emissions over time (Sjödin and Andréasson, 2000; Kuhns et al.,
42 2004; Schifter et al., 2005; Bishop et al., 2007). By examining emission measurements collected
43 using remote sensing equipment over consecutive years, changes in vehicle fleet emission factors
44 over time can be investigated.

45 In this study, remote sensing techniques are employed to investigate gaseous emissions from a wide
46 range of vehicles in Hong Kong. Gaseous emission from different vehicle and fuel types are
47 examined. Emission factors of vehicles with different model years in relation to emission standards
48 of the time are investigated. Vehicle emission factors are derived from measurements collected in
49 three different periods to examine the effect of vehicle emission control measures.

50 **2. Remote Sensing Measurements**

51 In Hong Kong, Remote sensing measurements are carried out periodically by the Hong Kong
52 Environmental Protection Department on different roadways within the city. Highway on-ramps,
53 toll booths, and roadways with gentle uphill inclines are frequently selected as remote sensing
54 measurement sites. Measurements are carried out on weekdays. At the measurement sites, the
55 majority of vehicles are undergoing acceleration. The vehicles travelling past the remote sensing

56 site are assumed to be sufficiently warmed up, thus it is assumed that no vehicles operated under
57 cold-start conditions, under which vehicles running on different types of fuels have higher
58 emissions (Mazzoleni et al., 2004b; Mazzoleni et al., 2007).

59 Measurements are gathered using a model ETC-S420 remote sensing system, developed by a local
60 environmental testing centre. The instruments release non-dispersive infrared (NDIR) and
61 non-dispersive ultraviolet (NDUV) beams. Concentrations of carbon monoxide (CO), carbon
62 dioxide (CO₂), and hydrocarbons (HC) are measured with the NDIR beam while concentration of
63 nitric oxide (NO) is measured using the NDUV beam, which has been shown to have a positive bias
64 (Popp et al., 1999). The two beams are released from a source detector module, located on one side
65 of a traffic lane, and reflected back to the module by a reflector located on the other side of the lane.
66 The strength of the beams is measured continuously. When a vehicle travels past the test site, its
67 exhaust absorbs some of the light emitted. Concentrations of gaseous emissions are determined by
68 comparing the strength and waveform of the beams exiting and returning to the source detector
69 module. A vehicle's emission is determined based on gaseous concentration measurements
70 immediately before and after the vehicle's passage through the remote sensing site. Measurement
71 instruments are calibrated every two hours at a minimum (Ko and Cho, 2006). HC is calibrated with
72 propane. To increase data capture rate, two sets of instruments are deployed in series during testing.

73 Speed measurements are collected from a speed sensor, which contains a detector bar and an emitter
74 bar that emits two lasers. The two lasers are separated by a fixed distance. As a vehicle travels past
75 the measurement site, the beam's path is obstructed. The vehicle's speed at the time when the
76 vehicle passes each of the laser beams is derived and the acceleration, defined to be the difference
77 between the speeds measured by the two lasers, of the vehicle are recorded. The license plate
78 information of each vehicle travelling past the test site is recorded by a video camera. The vehicles'
79 model year, vehicle type, and fuel type are retrieved from the vehicle registration database. If a
80 vehicle's emission is detected by both sets of remote sensing instruments and the vehicle's speed
81 and license plate information are successfully captured, the vehicle's information is recorded to a
82 database. On average, emission measurements and vehicle information are successfully captured for
83 75% of vehicles travelling past measurement sites.

84 **3. Collation of remote sensing data**

85 In this study, remote sensing measurements collected in 2004, 2006, and 2008 are investigated,
86 specifically measurements that are collected from sites visited in all three periods. In total there are
87 10 such sites. Each of these sites is located in the urban area while some sites are located in close
88 proximity to residential areas. Road grade at different measurement sites ranges between 0 and 9%.
89 Measurements mostly took place between January and April of each year. On each day of testing,
90 measurements take place at one single site.

Linear relations between different pollutants are established. Measurements that deviate from the relationship large degrees (above 20%) are considered invalid. HC measurements are expressed as equivalent propane. The detection ranges for CO, NO, and HC are -0.5~20%, -500~8000ppm, and -500~20000ppm respectively. Any measurement that is out of the respective detection range is deemed invalid. A set of measurements is considered valid if measurement of every pollutant is valid. These are similar to the guidelines given by Bishop and Stedman (2006). Approximately 90% of the data is considered valid. The CO, NO, and HC emission indices of each vehicle are derived from remote sensing measurements using the following equations (Ning and Chan, 2007):

$$EI_{CO} = \frac{[CO]}{[CO] + [CO_2] + 3 \cdot 2 \cdot [HC]} \cdot \frac{28}{MW_{Fuel}} \cdot D_{Fuel} \quad (1)$$

$$EI_{NO} = \frac{[NO]}{[CO] + [CO_2] + 3 \cdot 2 \cdot [HC]} \cdot \frac{30}{MW_{Fuel}} \cdot D_{Fuel} \quad (2)$$

$$EI_{HC} = \frac{2 \cdot [HC]}{[CO] + [CO_2] + 3 \cdot 2 \cdot [HC]} \cdot \frac{44}{MW_{Fuel}} \cdot D_{Fuel} \quad (3)$$

where $[P]$ is the measured concentration of a pollutant P , expressed in terms of %, MW_{fuel} and D_{fuel} are the molecular weight and density of the fuel, respectively. The molecular weight of petrol, diesel, and LPG fuels are 13.86g/(mol C), 13.85g/(mol C), and 14.54g/(mol C) respectively while the density of petrol, diesel, and LPG fuels are 750g/L, 850g/L, and 558.6g/L respectively (Holmén and Niemeier, 1998; Kean et al., 2001; Ning and Chan, 2007). HC measurements are multiplied by a factor of 2 as it has been observed that HC measurements obtained from a flame ionization detector and those obtained from NDIR differ by this factor (Unal et al., 2004).

The vehicles are classified into the following vehicle types: passenger cars (petrol/diesel), light buses (diesel/LPG), light goods vehicles (petrol/diesel), heavy goods vehicles (diesel), taxis (LPG), non-franchised buses (diesel), and franchised buses (diesel). Diesel vehicles are also classified into two classes by vehicle weight—light-duty (passenger cars, light buses, and light goods vehicles) and heavy-duty (heavy goods vehicles and buses). All petrol and LPG vehicles are considered light-duty. In Hong Kong the hydrogen-carbon ratios (H-C ratio) of petrol and diesel fuels are approximately 1.86 and 1.85 respectively. LPG fuel consists of approximately 30% propane and 70% butane. Thus it has a H-C ratio of approximately 2.54.

Gaseous emission factors of a vehicle are computed from its emission indices using the following:

$$EF_{P,fuel} = EI_{P,fuel} \cdot FC_{fuel} \quad (4)$$

119 where FC_{fuel} is the fuel consumption rate in l/km (Ning and Chan, 2007). A vehicle's fuel
 120 consumption rate can be expressed as a function of speed and acceleration (Kent and Mudford,
 121 1979; Panis et al., 2006). Fuel consumption can be estimated from instantaneous gaseous emission
 122 factors that are derived from dynamometer and on-board measurements using the following (Kent
 123 and Mudford, 1979; Song et al., 2009):

$$124 \quad FC_{Fuel} = \left(\frac{EF_{CO_2}}{44} + \frac{EF_{CO}}{28} + \frac{EF_{HC}}{MW_{Fuel}} \right) \cdot \left(\frac{MW_{Fuel}}{D_{Fuel}} \right) \quad (5)$$

125 The relationship between fuel consumption and instantaneous speed and acceleration rates are
 126 derived using regression analysis. Fuel consumption rates, expressed in terms of vehicle speed and
 127 acceleration, for petrol, diesel, and LPG are written as Eq. 6. The fuel consumption equation for
 128 petrol vehicles (Eq. 6a) is derived from dynamometer measurements of a passenger car's fuel
 129 consumption (Post et al., 1984). The R^2 value of the equation is 0.844. Fuel consumption equations
 130 of diesel and LPG vehicles (Eqs. 6b and c) are derived from instantaneous CO₂, CO, and HC
 131 emission factors (Eq. 5), which are computed from on-board emission measurements, whose results
 132 are discussed elsewhere (Lau, 2011). The R^2 values of the equations are 0.662 and 0.948
 133 respectively. Fuel consumption rate of heavy-duty diesel vehicles is assumed to be 3.3 times higher
 134 than that of light-duty diesel vehicles (Pierson et al., 1996).

$$135 \quad FC_{Petrol} = 0.135 + \frac{2.017}{v} + 0.029 \cdot a \quad (6a)$$

$$136 \quad FC_{Diesel} = 0.066 + \frac{1.034}{v} + 0.042 \cdot a \quad (6b)$$

$$137 \quad FC_{LPG} = 0.153 + \frac{3.296}{v} + 0.025 \cdot a \quad (6c)$$

138 The vehicle specific power (VSP), defined as the power required to operate a vehicle at a given speed
 139 and acceleration divided by the mass of the vehicle, of each vehicle passing through the remote
 140 sensing site is computed. The VSP of a passing vehicle, expressed in terms of kW/tonne, is computed
 141 from remote sensing measurements using the following:

$$142 \quad VSP = 2.73 \cdot v \cdot \sin(\text{grade}) + 0.14 \cdot v \cdot a + 0.0593 \cdot v + 0.0000169 \cdot v^3 \quad (7)$$

143 where v is the vehicle's speed in km/h, a is the vehicle's acceleration in km/(h.s), and $grade$ is the
 144 slope gradient of the road segment (Jimenez, 1999; Bishop and Stedman, 2006). In the following,
 145 measurements are classified by VSP in increments of 5 and emissions of vehicles operated at different

146 VSP levels are compared to examine emissions of vehicles operating at different conditions.

147 **4. Emissions from On-road Vehicles**

148 4.1 Fuel effect on emissions

149 To study the emission distribution of various types of vehicles, remote sensing measurements of
150 each vehicle type are sorted by increasing concentration. They are then classified into ten classes of
151 equal size, or deciles, each representing 10% of the vehicles. The number of vehicles in each decile
152 ranged between 2200 and 5800. Decile 1 consists of vehicles emitting the lowest amount of a
153 pollutant and decile 10 consists of vehicles emitting the highest amount of a pollutant. The
154 contribution of each decile towards gaseous emissions of petrol, light-duty diesel, and LPG vehicles
155 in 2008 is shown in Fig. 1. Each bar represents the contribution of a pollutant from one decile of
156 vehicles running on one type of fuel (Mazzoleni et al., 2004a; Ko and Cho, 2006). The distribution
157 for other years is similar.

158 Fig. 1 shows that distribution in gaseous emissions of diesel and LPG vehicles are generally similar.
159 Contribution from high-emitters (vehicles belonging to decile 10) is slightly larger among diesel
160 vehicles compared to LPG vehicles, while gaseous emissions of petrol vehicles are more skewed
161 towards high-emitting vehicles (decile 10) than diesel and LPG vehicles.

162 Insert Fig. 1

163 Table 1 shows the contribution from the highest 10% of emitters towards vehicle emissions in
164 different cities. It shows that, among petrol vehicles, contribution to gaseous emissions from the
165 highest 10% of emitters is generally similar to other cities. Meanwhile, high-emitting diesel and
166 LPG vehicles tend to contribute less towards vehicle fleet emissions. While contribution from
167 high-emitters in other cities is derived from the total vehicle fleet, Table 1 suggests that, in Hong
168 Kong, there is a large number of diesel and LPG vehicles emitting high levels of gaseous pollutants.
169 Meanwhile, emission distribution of petrol vehicles suggests that emissions from such vehicles can
170 be improved greatly through proper vehicle maintenance.

171 Fig. 2 shows various percentile values of emissions from petrol, diesel, and LPG vehicles, based on
172 remote sensing measurements collected in 2004, 2006 and 2008. The plots show that, in different
173 years, CO emissions of petrol and LPG vehicles are greater than diesel vehicles. NO exhaust
174 emissions of diesel vehicles are generally higher than those of petrol vehicles while HC exhaust
175 emissions from petrol and diesel vehicles are generally similar. Meanwhile, NO and HC emissions
176 of LPG vehicles are vastly higher than those of petrol and diesel vehicles.

177

	CO	NO	HC	Fuel Type	Source
Taiwan	60	45	40	All	Ko and Cho (2006)
Las Vegas	77	47	47	All	Mazzoleni et al. (2004a)
Hangzhou	35	45	50	All	Guo et al. (2007)
Hong Kong	59	47	56	Petrol	HKEPD
Hong Kong	45	24	39	Diesel	HKEPD
Hong Kong	37	22	35	LPG	HKEPD

179 Table 1 Contribution (in terms of % of total emissions) from high emitting vehicles (top 10% of
180 emitters) in different cities

181 Comparing percentile values of emissions collected in 2004, 2006 and 2008 shows that there is a
182 slight reduction in CO and NO emissions from diesel and LPG vehicles between 2004 and 2008.
183 This may be the result of introduction of vehicles containing more advanced emission control to the
184 vehicle fleet. However, no such decrease can be observed from petrol vehicles. Meanwhile, a large
185 increase in HC emissions from petrol and LPG vehicles can be observed between 2004 and 2006.
186 HC emissions from such vehicles in 2006 and 2008 are similar. A smaller increase in HC emission
187 from diesel vehicles can also be observed between 2004 and 2006. The higher level of emissions
188 observed from LPG vehicles, shown in Fig. 2, indicate the engines of these vehicles may be less
189 efficient compared to those of petrol and diesel vehicles.

190 Insert Fig. 2

191 Vehicles whose emissions exceed the 90th percentile value is often considered high-emitters in
192 remote sensing studies (Ko and Cho, 2006; Ning and Chan, 2007). Meanwhile, screening standards
193 have been established in some cities to determine whether concentrations of gaseous pollutants
194 within a vehicle's emissions are high—in Taiwan, vehicles with CO and HC emissions exceeding
195 3% and 500 ppm respectively are considered high emitters (Chen et al., 2009). The percentage of
196 vehicles exceeding such standards in Hong Kong is shown in Table 2. The table shows that more
197 petrol vehicles exceed CO screening standards while LPG vehicles are more likely to exceed HC
198 screening standards. This suggests that higher amount of fuel is un-burnt within engines of LPG
199 vehicles, resulting in higher HC emissions from LPG vehicles compared to petrol and diesel
200 vehicles.

201 The percentage of vehicles whose emission exceeds the 90th percentile value for multiple gaseous
202 pollutants is shown in Table 3. While Figs. 1 and 2 show that the pattern of HC emission is similar to
203 that of NO, Table 3 shows that vehicles, diesel and LPG vehicles in particular, are more likely to

204 emit high levels of CO and HC, but not NO, at the same time. Meanwhile, very few vehicles emit
 205 high levels of CO and NO simultaneously. Compared to diesel and LPG vehicles, it is more likely
 206 for a petrol vehicle to be a high emitter of CO, NO, and HC. The results are similar to those
 207 reported in Mazzoleni et al. (2004b).

Year	2004			2006			2008		
Fuel Type	Petrol	Diesel	LPG	Petrol	Diesel	LPG	Petrol	Diesel	LPG
CO	1.7	0.2	0.8	1.3	0.1	1.1	2.3	0.1	0.9
HC	0.7	1.6	3.1	2.4	0.7	15.8	3.8	1.2	14.3

208 Table 2 Percentage of vehicles exceeding CO and HC screening standards in different years

Petrol	None	CO	NO	HC	CO/NO	CO/HC	NO/HC	All
2004	79.7	4.5	5.3	2.9	0.6	2.9	2.2	2.0
2006	81.1	3.9	4.6	2.2	0.4	2.9	2.4	2.6
2008	81.6	3.6	4.3	2.1	0.5	2.6	2.2	3.1
Diesel								
2004	77.6	4.1	7.8	3.8	0.5	4.5	1.0	0.6
2006	78.1	4.3	7.1	4.6	0.5	3.0	1.6	0.8
2008	76.9	5.6	6.9	4.5	0.6	3.0	1.7	0.8
LPG								
2004	74.4	6.1	9.5	5.8	0.0	3.7	0.4	0.0
2006	75.2	5.7	8.9	5.2	0.1	3.9	0.8	0.1
2008	74.3	6.9	8.7	5.8	0.1	2.9	1.2	0.1

209 Table 3 Percentage of vehicles of different fuel types whose emission exceeds respective 90th
 210 percentile values

211 The gaseous emission factors of various vehicle types in 2004, 2006, and 2008 are shown in Table
 212 4. It shows that, across different years, diesel light buses tend to have lower CO and HC emissions
 213 and higher NO emission compared to LPG light buses. LPG taxis have higher emission factors
 214 compared to petrol passenger cars, which generally have similar engine size and power as taxis.
 215 Petrol LGVs have higher CO and HC emissions compared to diesel LGVs.

216 The differences between emissions of vehicles operating on different fuels are likely due to
 217 operating characteristics of different engines—petrol and LPG engines typically operate at rich
 218 conditions, under which CO and HC emissions are increased and NO emission is decreased, while
 219 diesel engines typically operate at lean conditions, under which higher level of NO and lower levels
 220 of CO and HC are emitted (Ceviz and Yüksel, 2005). Result showing that petrol vehicles emit less
 221 NO than LPG vehicles agrees with previous work (Ceviz and Yüksel, 2005; Yang et al., 2007).

222 However, results showing that LPG taxis emitting higher levels of HC compared to petrol passenger
 223 cars are opposite of the conclusion found in previous work (Ning and Chan, 2007; Yang et al.,
 224 2007). LPG vehicles having high emissions may be a result of their high mileage—Table 5 shows
 225 that, on average, a LPG vehicle travelled 110,000km per year, compared to 11,500km for a petrol
 226 vehicle and 33,000km for a diesel vehicle. This can result in deterioration in engine performance
 227 and efficiency of catalytic converters equipped in LPG vehicles.

228 Table 4 shows a decreasing trend in CO and NO emissions from petrol vehicles between 2004 and
 229 2008. No clear trend in gaseous emissions can be observed from LPG vehicles. CO emissions of
 230 various types of diesel vehicles generally exhibit a decreasing trend between 2004 and 2008.

a) Petrol	N	CO	NO	HC
PC	57629	5.37±0.06	0.93±0.01	0.25±0.01
LGV	482	21.65±1.49	1.71±0.12	0.55±0.04
MC	0	N.A.	N.A.	N.A.
Diesel				
PC	428	1.15±0.27	0.87±0.04	0.25±0.03
LGV	16603	0.76±0.02	1.05±0.01	0.21±0.01
HGV	320	3.53±0.52	6.88±0.38	2.15±0.28
LB	2739	1.02±0.04	1.79±0.03	0.37±0.01
NFB	2132	4.09±0.28	6.58±0.12	1.16±0.04
FB	201	2.45±0.36	7.70±0.53	0.56±0.07
LPG				
Taxi	32493	7.64±0.05	3.19±0.02	0.77±0.01
LB	391	12.60±0.90	0.53±0.07	0.43±0.04

231

b) Petrol	N	CO	NO	HC
PC	45296	4.33±0.05	0.58±0.01	0.27±0.01
LGV	471	11.55±0.84	1.31±0.09	0.58±0.05
MC	0	N.A.	N.A.	N.A.
Diesel				
PC	319	0.42±0.07	0.69±0.03	0.33±0.03
LGV	19476	0.40±0.01	1.02±0.01	0.34±0.01
HGV	1155	3.40±0.26	9.50±0.24	2.80±0.09
LB	1675	0.72±0.04	1.86±0.04	0.57±0.02
NFB	2100	2.54±0.11	6.75±0.12	1.85±0.05
FB	963	2.97±0.14	8.94±0.21	1.38±0.05
LPG				
Taxi	28534	8.34±0.05	2.83±0.01	1.72±0.01
LB	697	8.50±0.45	0.62±0.08	0.63±0.05

232

233

c) Petrol	<i>N</i>	CO	NO	HC
PC	51553	2.96±0.04	0.47±0.01	0.23±0.01
LGV	290	8.69±1.10	0.88±0.08	0.41±0.06
MC	251	5.39±1.07	1.38±0.11	0.66±0.07
Diesel				
PC	239	0.41±0.11	0.63±0.04	0.24±0.03
LGV	18675	0.39±0.01	1.05±0.01	0.26±0.01
HGV	2237	2.41±0.17	6.58±0.14	1.94±0.05
LB	2555	0.39±0.02	1.47±0.02	0.32±0.01
NFB	2381	1.68±0.08	5.12±0.09	1.20±0.03
FB	531	1.85±0.21	8.26±0.35	1.03±0.05
LPG				
Taxi	36033	6.52±0.04	2.95±0.01	1.47±0.01
LB	1330	9.65±0.36	0.83±0.05	0.67±0.03

235 Table 4 Emissions factors of major vehicles types in a) 2004, b) 2006, and c) 2008 (*N*—number of
236 valid readings, PC—passenger car, LGV—light goods vehicle, HGV—heavy goods vehicle,
237 MC—motorcycle, LB—light bus, NFB—non-franchised bus, FB—franchised bus). Uncertainties
238 represent standard errors.

VKT per vehicle	2004	2006	2008
Petrol	11,900	11,500	11,500
Diesel	32,400	33,500	34,100
LPG	99,200	110,500	118,100

239 Table 5 Annual vehicle kilometre travelled (VKT) of petrol, diesel, and LPG vehicles (HKTD,
240 2011)

241 The table shows that, in 2008, motorcycles have higher emissions than passenger cars, indicating
242 that emissions from motorcycles are released directly into the atmosphere without any treatment
243 (Tsai et al., 2000). Meanwhile, petrol LGVs emit higher amounts of gaseous pollutants than
244 passenger cars.

245 In different years, light buses have higher NO and HC emissions compared to other types of
246 light-duty diesel vehicles. Heavy goods vehicles have higher HC emissions than buses while it is
247 not clear whether one type of heavy-duty diesel vehicles has higher CO and HC emissions
248 compared to others.

249 Among LPG vehicles, light buses emit the higher amount of CO while taxis emit the higher
250 amounts of NO and HC. Since light buses have higher vehicle load and engine size than taxis, this
251 suggests that gaseous emissions from taxis may be the result of their heavy usage, as taxis are often
252 on-road throughout the day. The long operation period and high mileage of taxis may result in faster
253 deterioration of engine performance and effectiveness of emission control devices such as catalytic

254 converters. The operational period of taxis also prevents proper maintenance from taking place.

255 Fig. 3 shows gaseous emissions of petrol, diesel, and LPG vehicles under different VSP bins in
256 2004, 2006, and 2008. Between 2004 and 2008, a decrease in CO emissions can be observed from
257 petrol and diesel vehicles belonging to different VSP bins. A smaller decrease can be observed from
258 LPG vehicles. NO emissions from petrol vehicles exhibit a decrease trend between 2004 and 2008.
259 LPG vehicles belonging to different VSP bins have the lowest NO emissions in 2006.

260 Fig. 3 shows that, in different years, HC emissions of vehicles fuelled by different fuels generally
261 decrease as VSP increases. Similar results have been reported elsewhere (Mazzoleni et al., 2004b,
262 Bishop and Stedman, 2006; Bishop et al., 2007). Negative VSP mainly corresponds to periods when
263 a vehicle undergoes deceleration or travels downhill. When vehicles operate in such modes, lower
264 amount of fuel injected to the engine is being burnt, which results in higher amounts of unburnt fuel
265 within the exhaust and thus higher HC emissions.

266 NO emissions of petrol and LPG vehicles are the lowest when VSP is approximately 0 while
267 highest NO emissions are observed from such vehicles when their VSP is high. High VSP
268 corresponds to periods when a vehicle travels uphill or accelerates aggressively, during which the
269 engine consumes higher amounts of fuel. This is similar to results observed elsewhere (Bishop and
270 Stedman, 2006; Bishop et al., 2007). In 2004 and 2006, NO emissions from diesel vehicles with a
271 VSP of approximately 0 are the highest while low emissions are observed from vehicles with high
272 VSP. This is opposite of what is observed from petrol and LPG vehicles. In 2008, NO emissions of
273 diesel vehicles with different VSP tend to be similar.

274 In different years, low level of CO is emitted by petrol vehicles with a VSP of 10-15 while vehicles
275 with extreme VSP values tend to have high CO emissions. In 2004, CO emissions of diesel and
276 LPG vehicles with negative VSP tend to be the highest. CO emissions of diesel vehicles with
277 different VSP tend to be similar in 2006 and 2008 while the relationship between LPG vehicles'
278 VSP and CO emissions in different years tends to be similar. Similar relationship between VSP of
279 vehicles and CO emissions has also been observed elsewhere (Kuhns et al., 2004; Bishop and
280 Stedman, 2006).

281 4.2 Vehicle model year and emissions

282 To examine the relationship between a vehicle's model year and gaseous emission, vehicles are
283 classified by their model year and emissions of petrol and LPG vehicles of different model years,
284 collected in the years 2004, 2006, and 2008, are shown in Figs. 4 and 5 respectively. The emission
285 standards of vehicles of different years of model are listed on Table 6, which shows that newer
286 model vehicles are subject to increasingly stringent emission standards. Emission factors of

light-duty diesel vehicles of different model years, collected in 2008, are shown in Fig. 6. Model year information of diesel vehicles is not available from the 2004 and 2006 data.

a)	Pre-Euro	Euro	Euro 2	Euro 3	Euro 4
Petrol	Before 1992	1992	1997	2001	2006
Diesel	Before 1995	1995	1998	2001	2006
LPG	N.A.	N.A.	2001	2003	2006

b)	Euro 1	Euro 2	Euro 3	Euro 4
CO (g/km)	2.7	2.2	2.3	1.0
NO (g/km)	0.52	0.28	0.19	0.10
HC (g/km)	0.42	0.21	0.15	0.08

c)	Euro 1	Euro 2	Euro 3	Euro 4
CO (g/km)	8.82	7.84	4.12	2.94
NO (g/km)	14.91	13.04	9.31	6.52
HC (g/km)	2.16	2.16	1.29	0.90

Table 6 a) Emission standards of vehicles of different model years; b) Emission standards of petrol and LPG vehicles (Li et al., 2008); c) Emission standards of diesel LGVs. Emission standards are converted from g/kWh by a factor of 1.96kWh/km (Lenaers, 1996). NO standards are converted from NO_x standards assuming NO_x consists of 95% NO by mass (Carslaw and Beevers, 2004)

Fig. 4 shows that newer model petrol vehicles have lower gaseous emission factors compared to older model vehicles. This is similar to results reported in Sjödin and Andréasson (2000) and Kuhns et al. (2004). The reduction in gaseous emissions from vehicles as model year increases may be due to the increasingly stringent emission standards imposed on vehicles. Emission control devices such as catalytic converters are installed to newer-model vehicles in order to meet such standards (Tables 6b and c).

Fig. 4 shows that emission factors of petrol vehicles of different model years generally are higher than the corresponding emission standard values. It can also be observed that gaseous emission factors of later model vehicles are higher the longer such vehicles are on road. For instance, CO and HC emission factors of vehicles with model year of 2004 are 54% and 50% higher in 2006 compared to in 2004, when such vehicles enters the vehicle fleet, respectively. Similarly, CO and HC emission factors of vehicles with model year of 2006 are 96% and 185% higher in 2008 compared to in 2006 respectively. There is little change in NO emissions from petrol vehicles after two years of operation. This indicates regular vehicle operation can result in large deterioration of engine performance.

310 Insert Fig. 4

311 Insert Fig. 5

312 Fig. 5 shows gaseous emission factors of LPG vehicles, derived from remote sensing measurements
313 collected in different years. Similar to petrol vehicles, emission factors of newer vehicles are
314 generally lower compared to those of older model vehicles. Such results are similar to those
315 reported in Ning and Chan (2007). Emission factors of LPG vehicles generally exceed values
316 outlined by emission standards. In 2006 and 2008, gaseous emissions from new vehicles, or
317 vehicles introduced to the vehicle fleet on the same year as the measurements, satisfy emission
318 standards. Among vehicles adhering to Euro 3 and 4 emission standards, NO and HC emission
319 factors derived from measurements collected in 2008 are higher compared to those derived from
320 measurements collected in 2004 and 2006. CO, NO, and HC emission factors of vehicles with
321 model year of 2004 are 73%, 21%, and 113% higher in 2006 compared to in 2004, when such
322 vehicles enter the vehicle fleet, respectively. Meanwhile, CO, NO, and HC emission factors LPG
323 vehicles with model year 2006 are 2.5, 3.0, and 5.1 times higher in 2008 compared to 2006
324 respectively. This suggests that engine performance and catalyst efficiency of modern LPG vehicles
325 deteriorate at a rapid rate, due to high mileage of such vehicles (Table 5).

326 Comparing Figs. 4 and 5 shows that LPG vehicles generally have higher gaseous emission factors
327 compared to petrol vehicles of similar age. This may be due to that LPG vehicles, which consist
328 mainly of public transport vehicles, are on the road for long consecutive periods each day, which
329 can hasten engine wear and deterioration of engine performance and catalyst efficiency (Riveros et
330 al., 2002).

331 Insert Fig. 6

332 Gaseous emission factors of light-duty diesel vehicles mostly comply with emission standard values
333 (Table 5c). From Fig. 6 it can be observed that, unlike petrol and LPG vehicles, newer model diesel
334 vehicles do not necessarily have lower CO and NO emissions factors compared to older vehicles.
335 Meanwhile, new vehicles tend to have lower HC emission factors compared to older vehicles.

336 5. Conclusions

337 In this study on-road gaseous emissions of vehicles under urban driving conditions are investigated
338 using remote sensing measurements collected from three different periods. Measurement results
339 show that gaseous emission from petrol vehicles is more skewed by heavy emitters. Petrol vehicles
340 have higher CO and HC emissions and lower NO emissions compared to diesel vehicles.
341 Meanwhile, LPG vehicles, introduced to reduce vehicle fleet emissions, emit more gaseous

pollutants compared to light-duty petrol and diesel vehicles. CO and HC emissions of vehicles, particularly petrol and LPG vehicles, and engine load tend to be negatively correlated. Meanwhile, vehicles emit more NO when the engine undergoes heavy work. In general, newer vehicles have lower emission factors compared to older vehicles, likely due to better emission control within new vehicles. LPG vehicles generally have higher emission factors compared to petrol vehicles with the same model year, indicating that LPG vehicles deteriorate at a rapid rate due to heavy vehicle operation. Emission factors of vehicles mostly exceed emission standards and large increases in emission factors can be observed from modern petrol and LPG vehicles after 2 years of operation. Meanwhile, CO and NO emissions of modern diesel vehicles are similar to those of older model vehicles. These observations indicate that urban driving conditions can hasten deterioration of engine performance and catalyst efficiency.

The results show that, in major cities, replacing older vehicles with vehicles adhering to stringent emission standards cannot reduce vehicle emissions unless vehicles and their engines are kept in good condition. The high emissions observed from LPG vehicles, older vehicles in particular, indicate that there is an urgent need to improve the maintenance of such vehicles so that the environmental benefits of such vehicles can be realized.

Acknowledgements

The authors of this study would like to thank the Hong Kong Environmental Protection Department for providing the remote sensing measurements used for this study. The work described in this paper is supported by a research grant of The Hong Kong Polytechnic University (project GU708). Helpful comments from two anonymous reviewers are appreciated.

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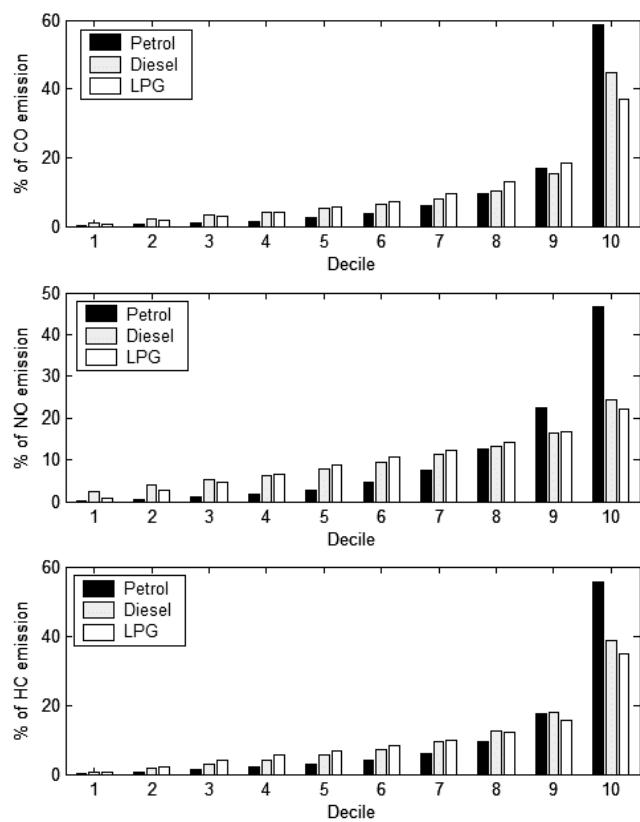
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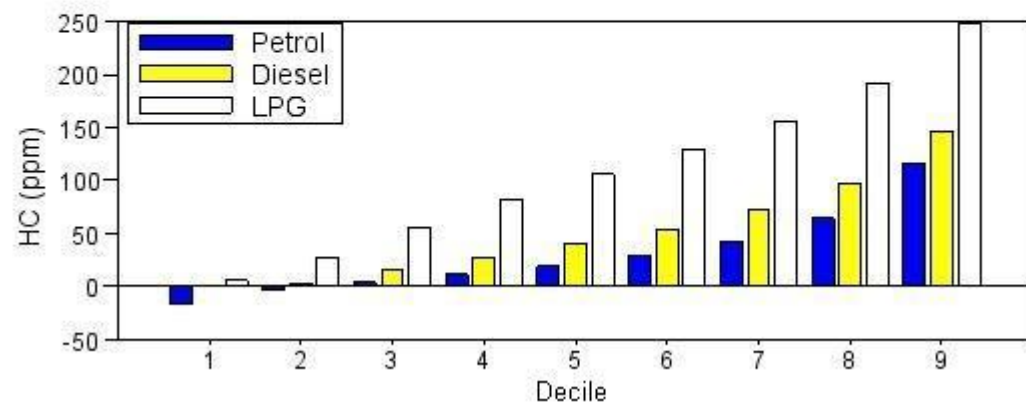
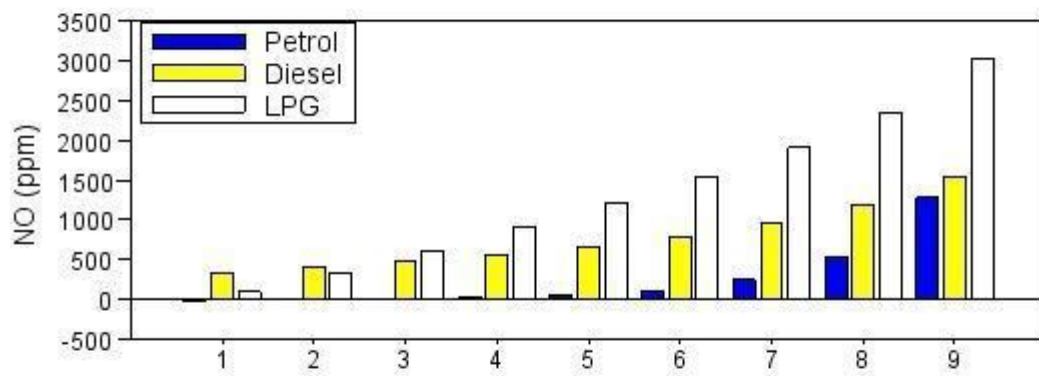
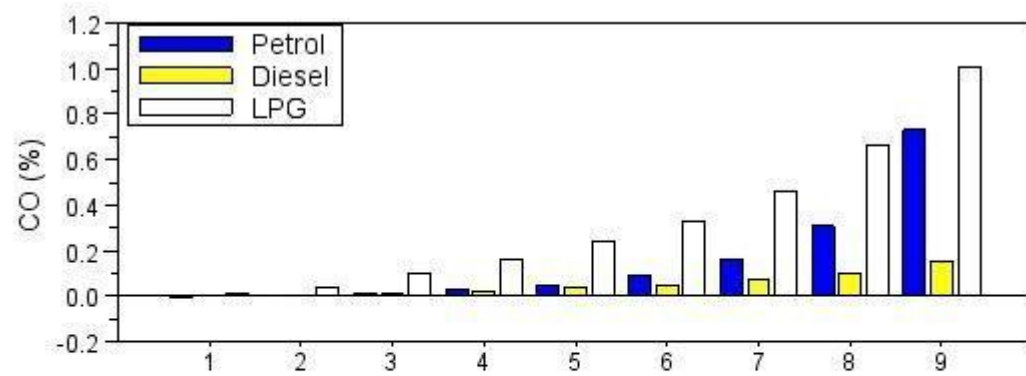
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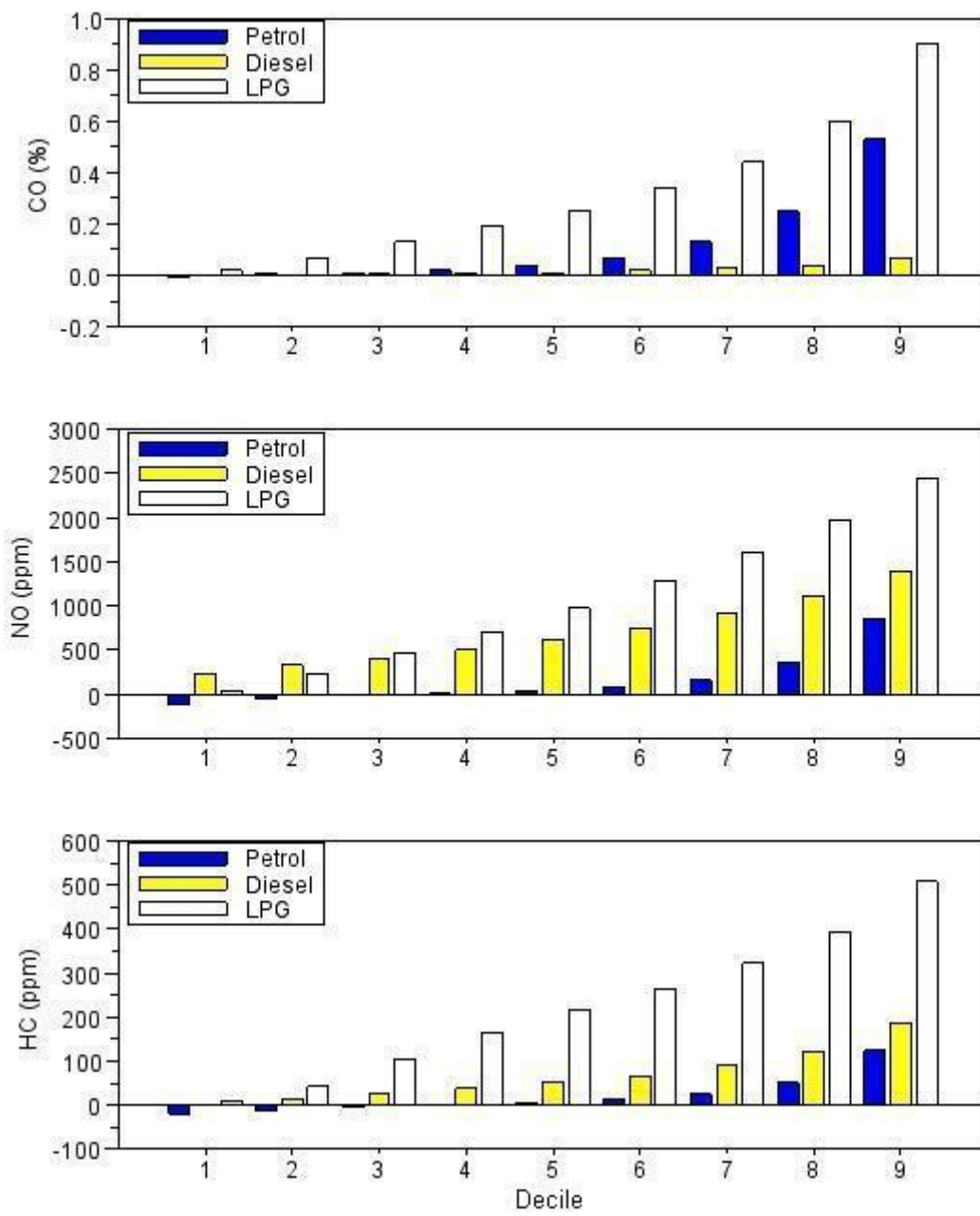
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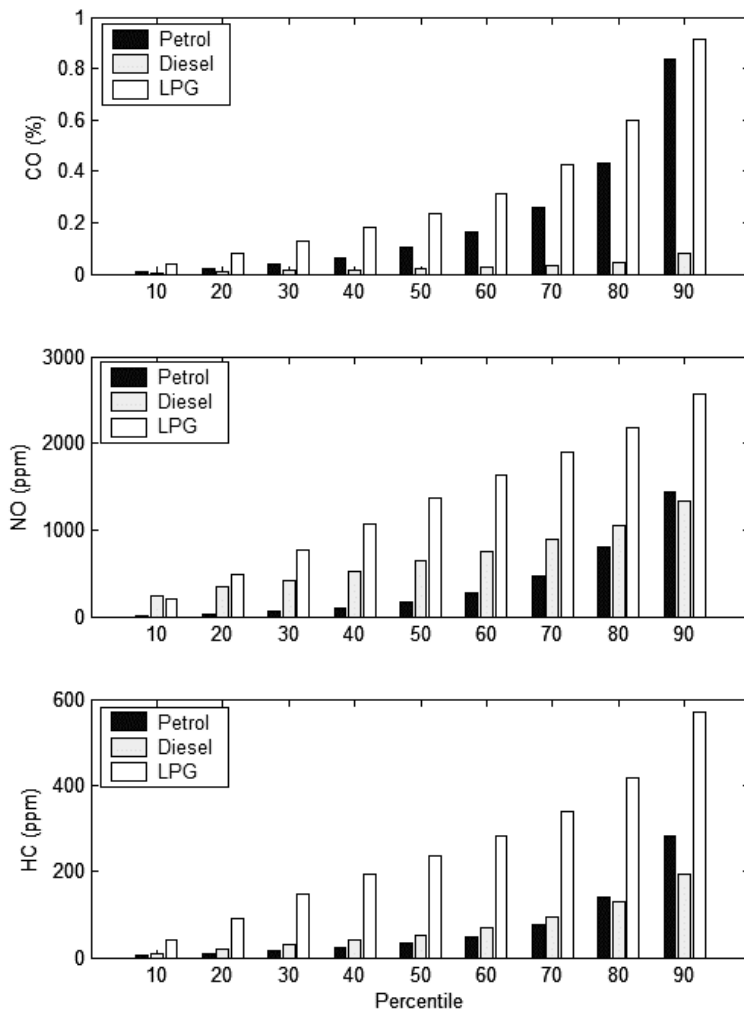
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448 Fig. 1 Distribution of gaseous emissions from petrol, diesel and LPG vehicles in 2008



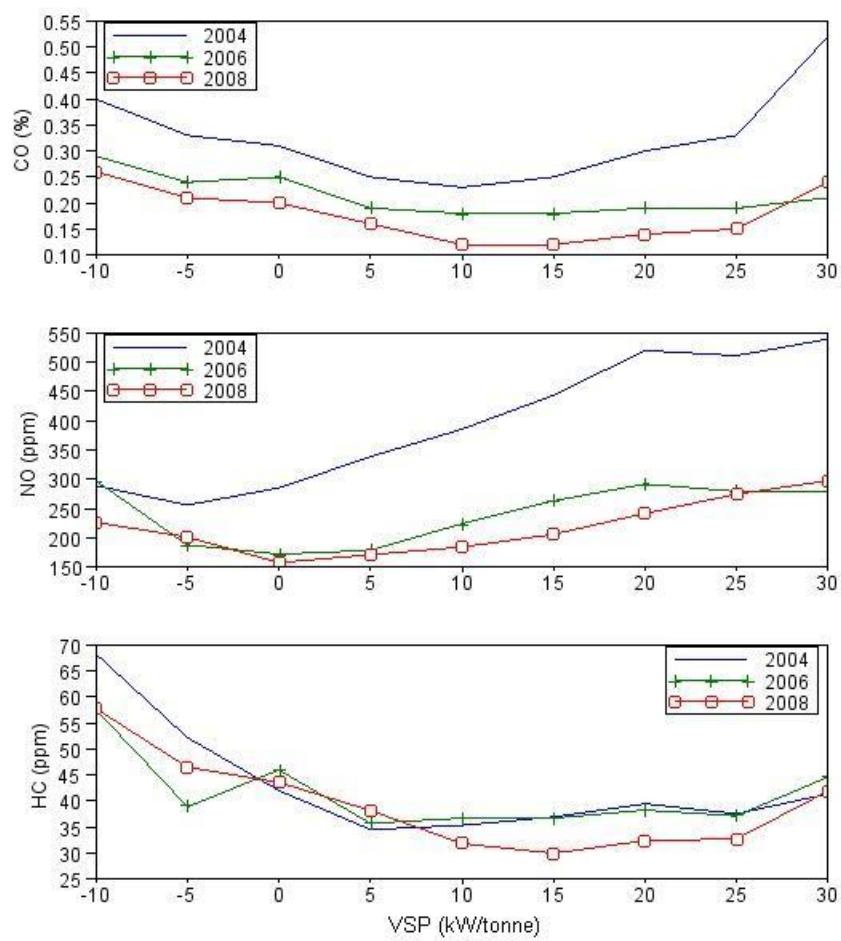


450 b)

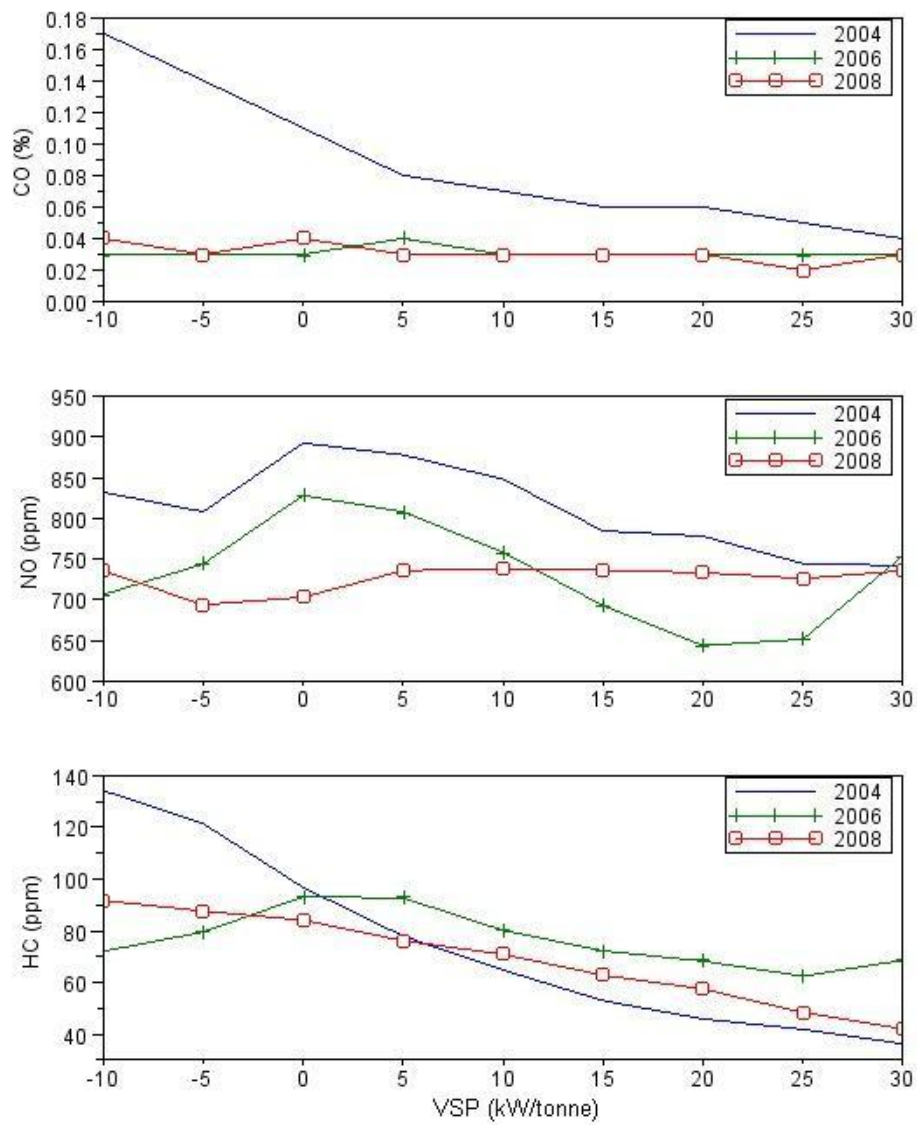


451 c)

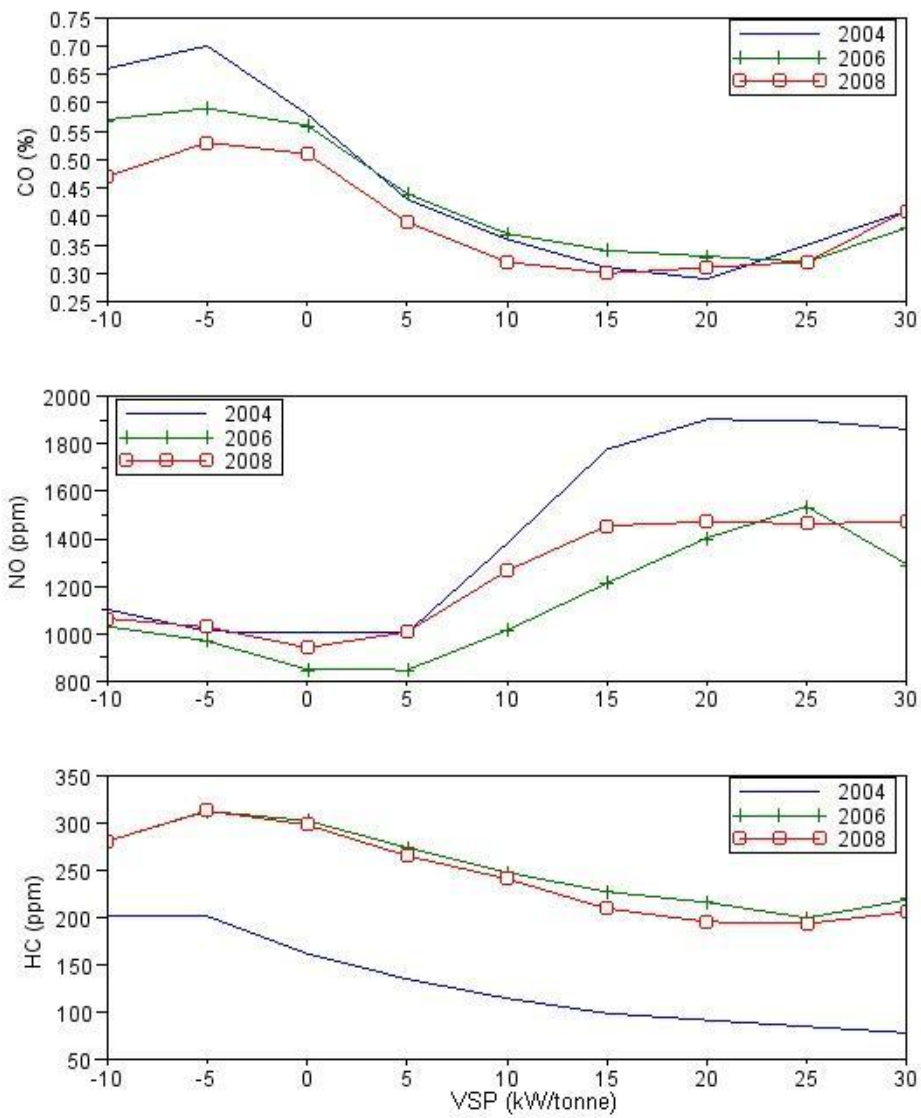
452 Fig. 2 Decile values of emissions from light-duty petrol, diesel, and LPG vehicles in a) 2004, b)
 453 2006, and c) 2008



454 a)

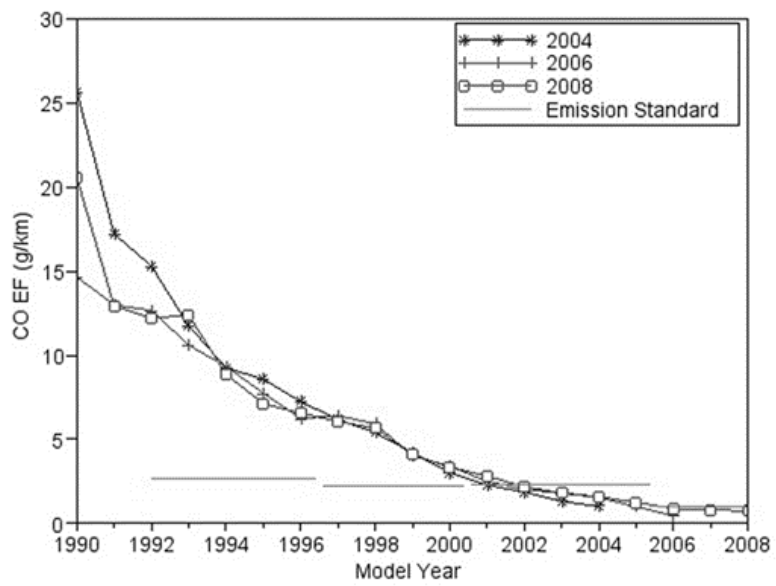


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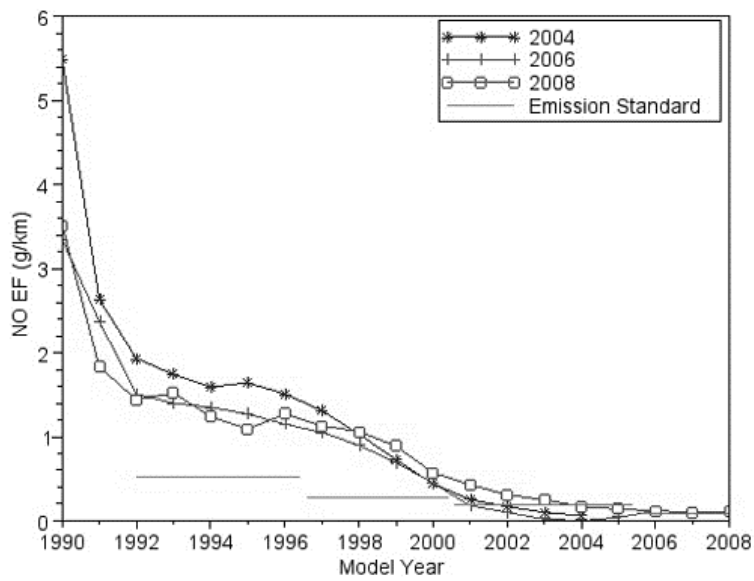


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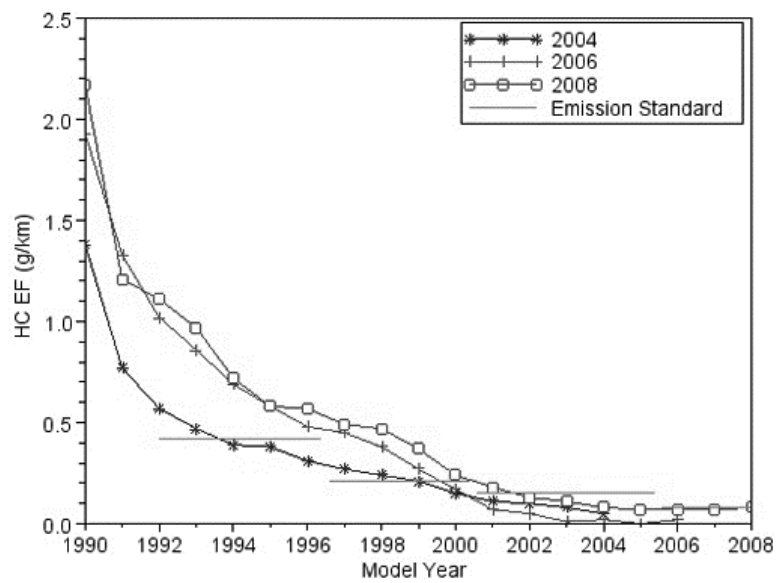
457 Fig. 3 Emissions of a) petrol; b) diesel; and c) LPG vehicles under different operating conditions



458 a)

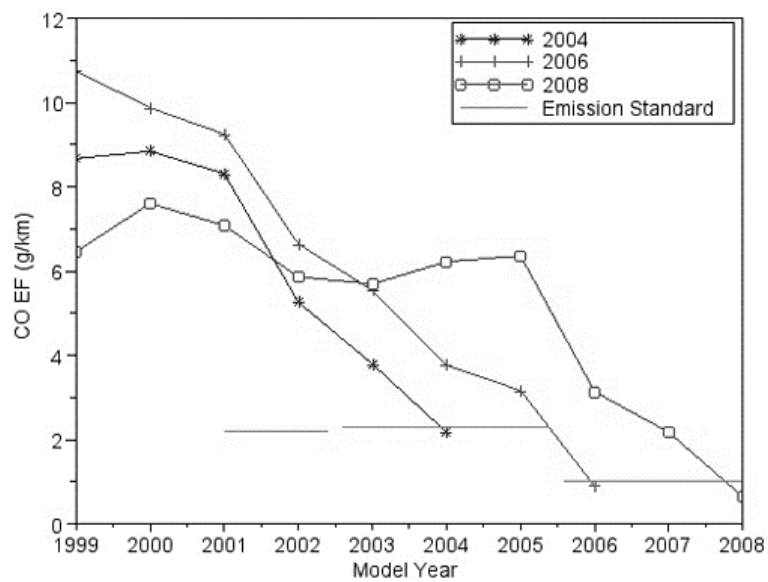


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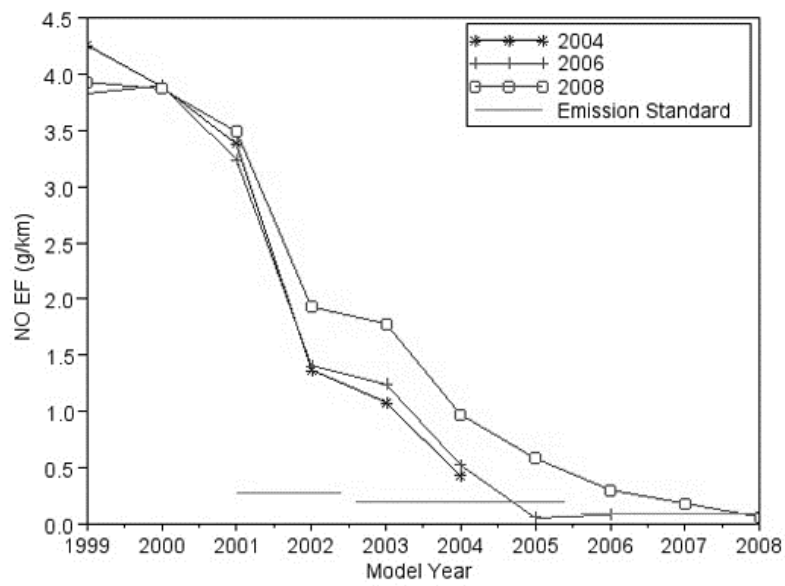


460 c)

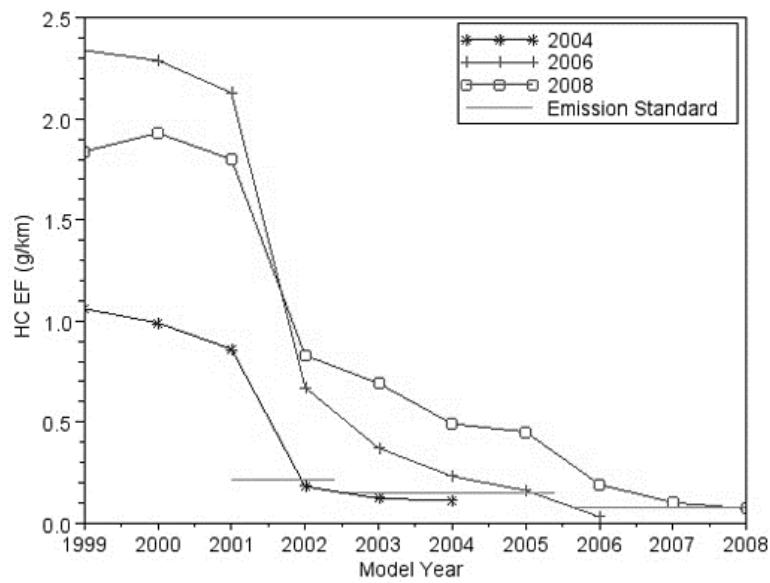
461 Fig. 4 a) CO, b) NO, and c) HC emission factors of petrol vehicles of different model years



462 a)

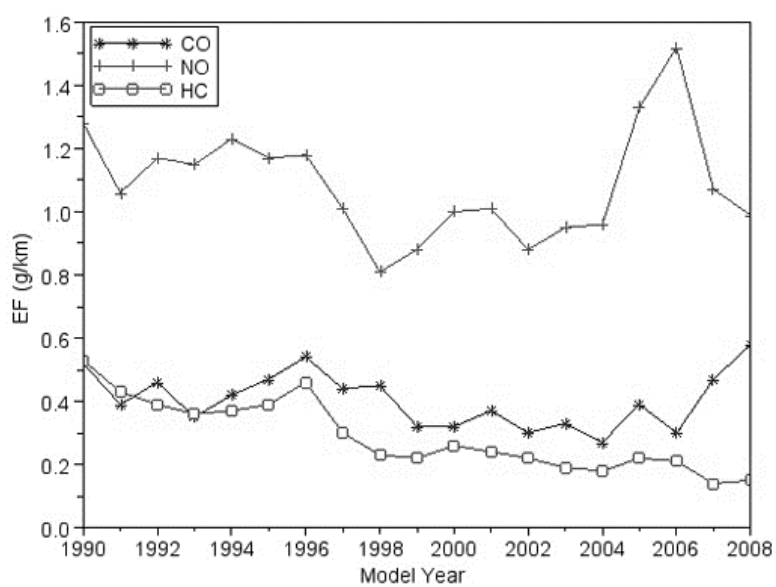


463 b)



464 c)

465 Fig. 5 a) CO, b) NO, and c) HC emission factors of LPG vehicles of different model years



466

467 Fig. 6 Gaseous emission factors of light-duty diesel vehicles in 2008. Emission factors of vehicles
 468 of different model years satisfy corresponding emission standards (Table 6c)