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

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Abstract:

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

Capsule Abstract:

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

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

1. Introduction

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

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

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

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

2. Remote Sensing Measurements

In Hong Kong, Remote sensing measurements are carried out periodically by the Hong Kong Environmental Protection Department on different roadways within the city. Highway on-ramps, toll booths, and roadways with gentle uphill inclines are frequently selected as remote sensing measurement sites. Measurements are carried out on weekdays. At the measurement sites, the majority of vehicles are undergoing acceleration. The vehicles travelling past the remote sensing site are assumed to be sufficiently warmed up, thus it is assumed that no vehicles operated under cold-start conditions, under which vehicles running on different types of fuels have higher emissions (Mazzoleni et al., 2004b; Mazzoleni et al., 2007).

Measurements are gathered using a model ETC-S420 remote sensing system, developed by a local environmental testing centre. The instruments release non-dispersive infrared (NDIR) and non-dispersive ultraviolet (NDUV) beams. Concentrations of carbon monoxide (CO), carbon dioxide (CO_2), and hydrocarbons (HC) are measured with the NDIR beam while concentration of nitric oxide (NO) is measured using the NDUV beam, which has been shown to have a positive bias (Popp et al., 1999). The two beams are released from a source detector module, located on one side of a traffic lane, and reflected back to the module by a reflector located on the other side of the lane. The strength of the beams is measured continuously. When a vehicle travels past the test site, its exhaust absorbs some of the light emitted. Concentrations of gaseous emissions are determined by comparing the strength and waveform of the beams exiting and returning to the source detector module. A vehicle's emission is determined based on gaseous concentration measurements immediately before and after the vehicle's passage through the remote sensing site. Measurement instruments are calibrated every two hours at a minimum (Ko and Cho, 2006). HC is calibrated with propane. To increase data capture rate, two sets of instruments are deployed in series during testing.

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

3. Collation of remote sensing data

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

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

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

$$FC_{Fuel} = \left(\frac{EF_{CO2}}{44} + \frac{EF_{CO}}{28} + \frac{EF_{HC}}{MW_{Fuel}} \right) \cdot \left(\frac{MW_{Fuel}}{D_{Fuel}} \right) \quad (5)$$

The relationship between fuel consumption and instantaneous speed and acceleration rates are derived using regression analysis. Fuel consumption rates, expressed in terms of vehicle speed and acceleration, for petrol, diesel, and LPG are written as Eq. 6. The fuel consumption equation for petrol vehicles (Eq. 6a) is derived from dynamometer measurements of a passenger car's fuel consumption (Post et al., 1984). The R^2 value of the equation is 0.844. Fuel consumption equations of diesel and LPG vehicles (Eqs. 6b and c) are derived from instantaneous CO_2, CO, and HC emission factors (Eq. 5), which are computed from on-board emission measurements, whose results are discussed elsewhere (Lau, 2011). The R^2 values of the equations are 0.662 and 0.948 respectively. Fuel consumption rate of heavy-duty diesel vehicles is assumed to be 3.3 times higher than that of light-duty diesel vehicles (Pierson et al., 1996).

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

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

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

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

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

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

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

4. Emissions from On-road Vehicles

4.1 Fuel effect on emissions

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

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

Insert Fig. 1

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

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

	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

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

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

Insert Fig. 2

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

The percentage of vehicles whose emission exceeds the 90th percentile value for multiple gaseous pollutants is shown in Table 3. While Figs. 1 and 2 show that the pattern of HC emission is similar to that of NO, Table 3 shows that vehicles, diesel and LPG vehicles in particular, are more likely to emit high levels of CO and HC, but not NO, at the same time. Meanwhile, very few vehicles emit high levels of CO and NO simultaneously. Compared to diesel and LPG vehicles, it is more likely for a petrol vehicle to be a high emitter of CO, NO, and HC. The results are similar to those 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

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

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

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

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

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

Table 4 shows a decreasing trend in CO and NO emissions from petrol vehicles between 2004 and 2008. No clear trend in gaseous emissions can be observed from LPG vehicles. CO emissions of 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

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

c) Petrol	*N*	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

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

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

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

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

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

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

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

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

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

4.2 Vehicle model year and emissions

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

Insert Fig. 4

Insert Fig. 5

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

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

Insert Fig. 6

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

5. Conclusions

In this study on-road gaseous emissions of vehicles under urban driving conditions are investigated using remote sensing measurements collected from three different periods. Measurement results show that gaseous emission from petrol vehicles is more skewed by heavy emitters. Petrol vehicles have higher CO and HC emissions and lower NO emissions compared to diesel vehicles. 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.

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Figure Captions

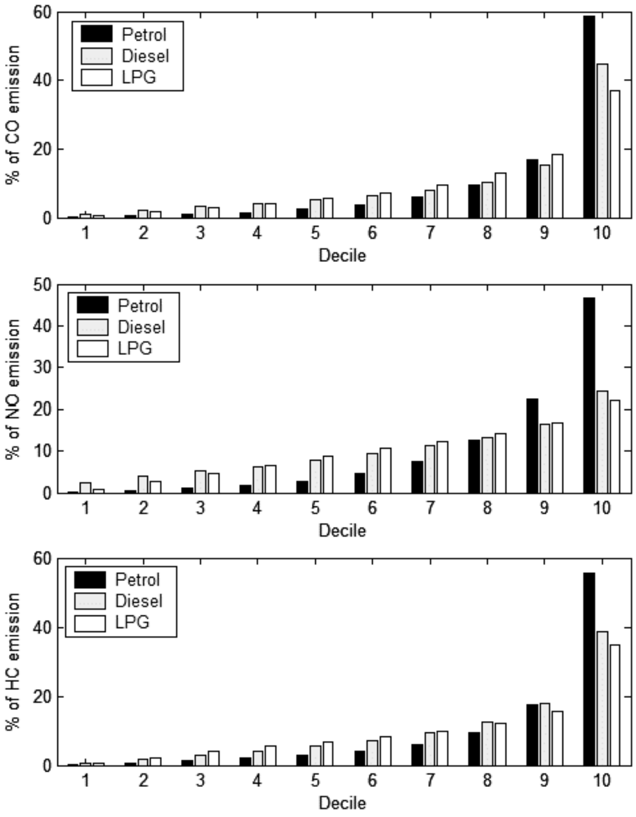
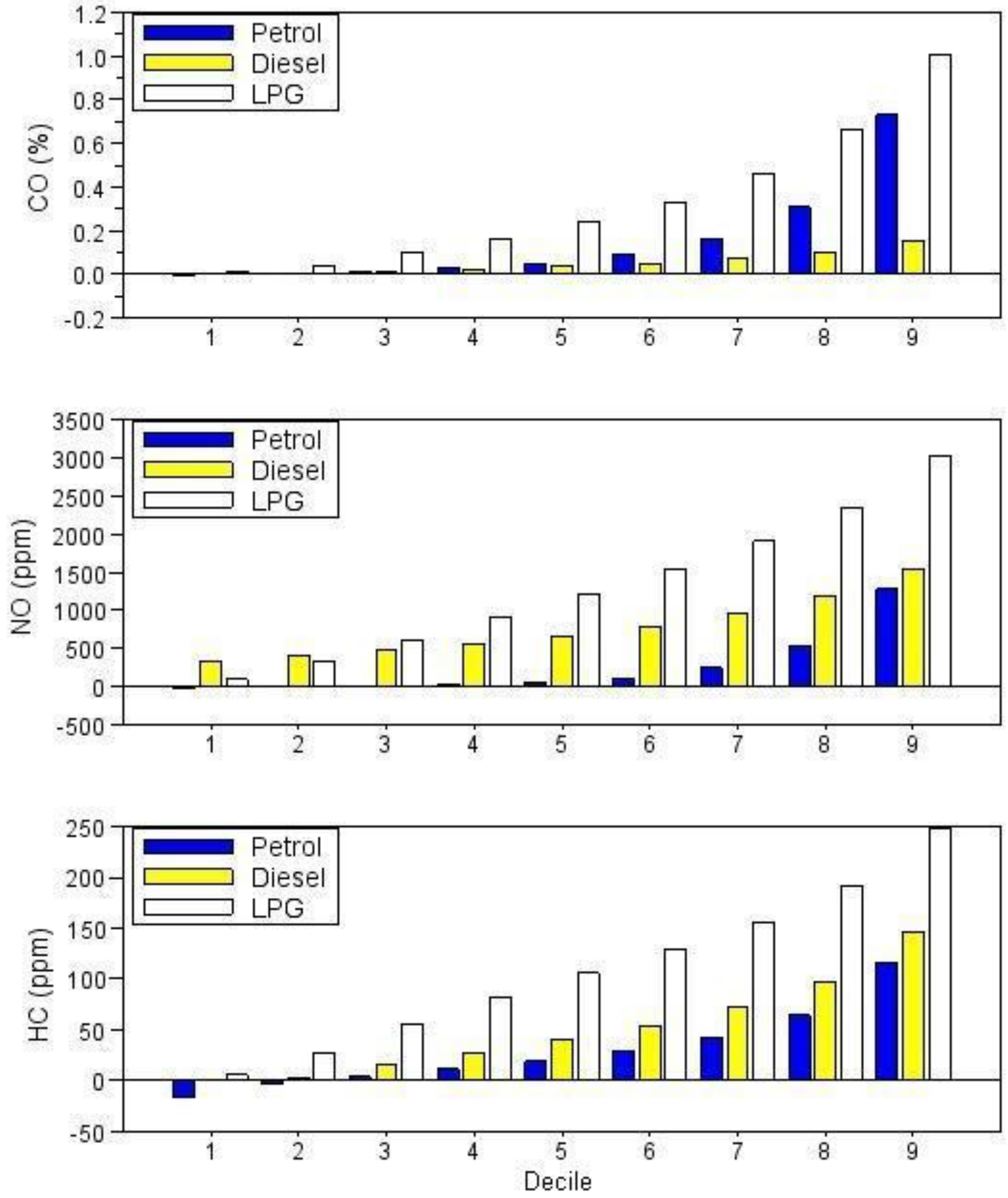
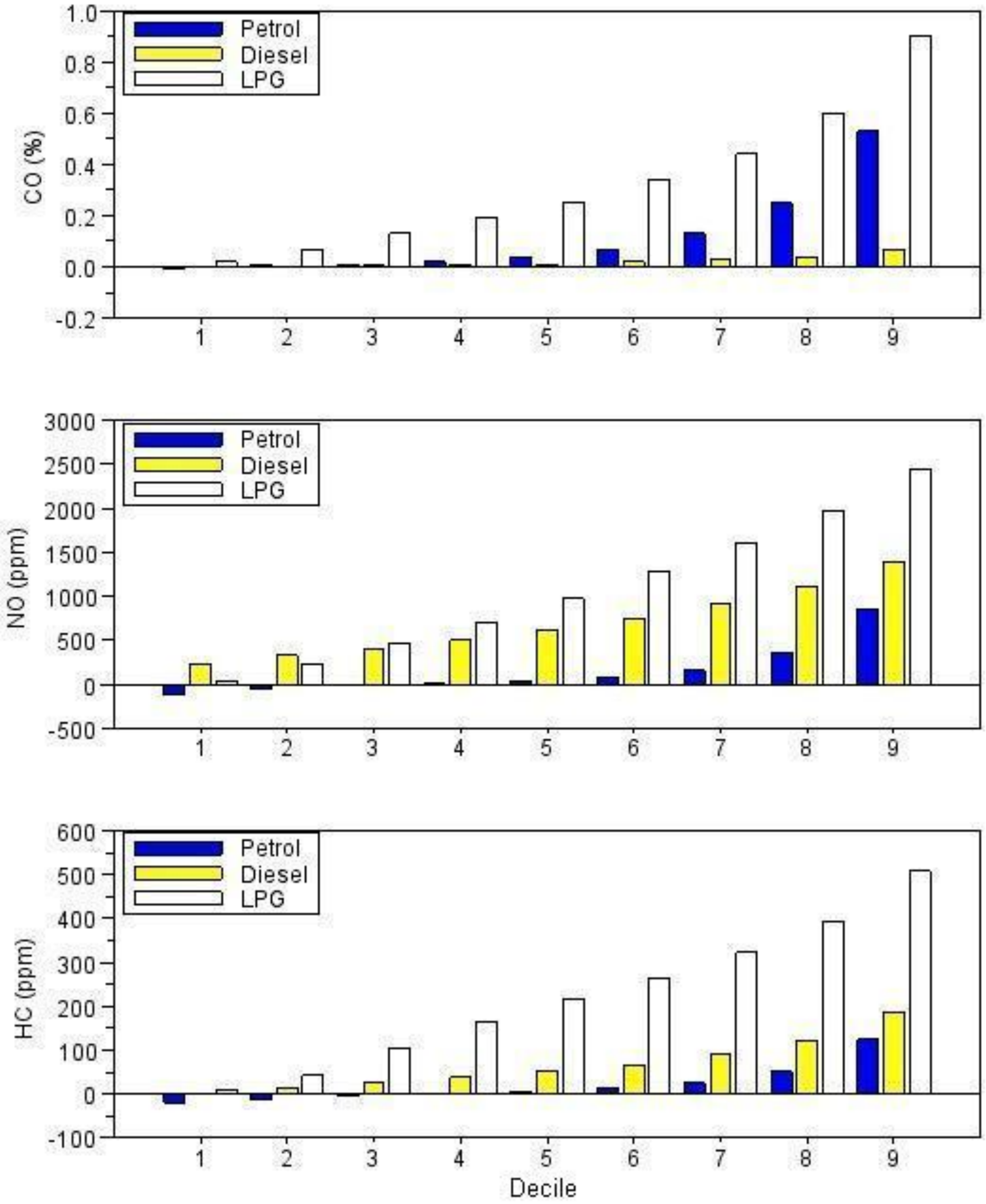


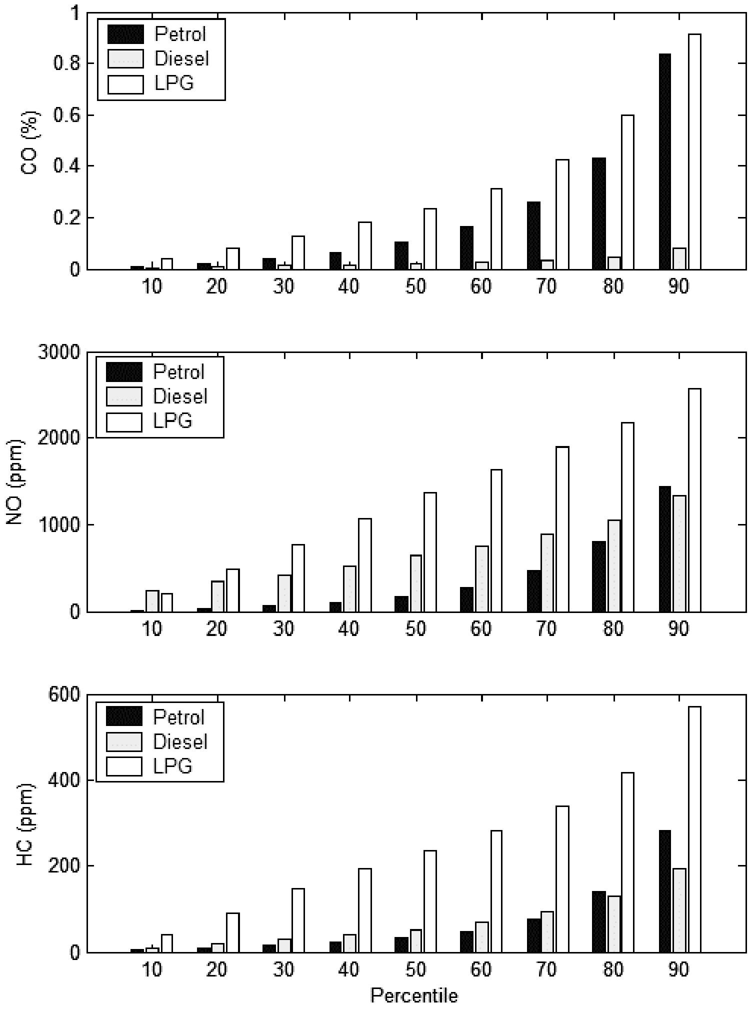
Fig. 1 Distribution of gaseous emissions from petrol, diesel and LPG vehicles in 2008


1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
CO (%)
Petrol
Diesel
LPG
1
2
3
4
5
6
7
8
9
3500
3000
2500
2000
1500
1000
500
0
-500
NO (ppm)
Petrol
Diesel
LPG
1
2
3
4
5
6
7
8
9
250
200
150
100
50
0
-50
HC (ppm)
Petrol
Diesel
LPG
1
2
3
4
5
6
7
8
9
Decile

a)

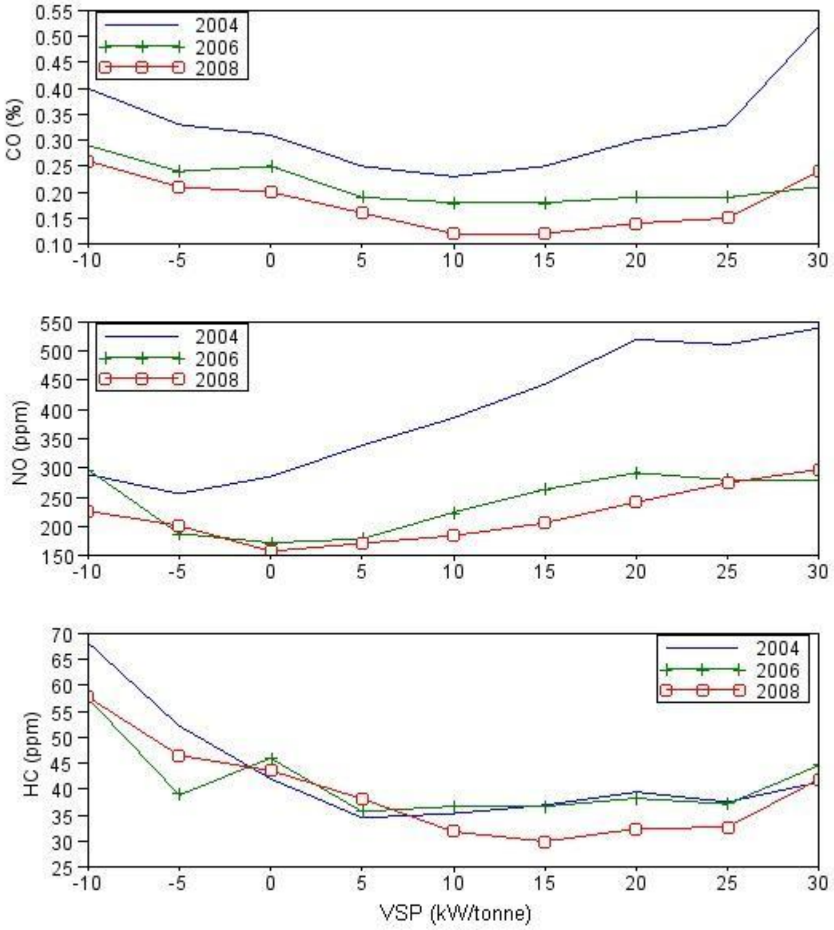

Petrol
Diesel
LPG
CO (%)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
NO (ppm)
3000
2500
2000
1500
1000
500
0
-500
HC (ppm)
600
500
400
300
200
100
0
-100
1
2
3
4
5
6
7
8
9
Decile

b)

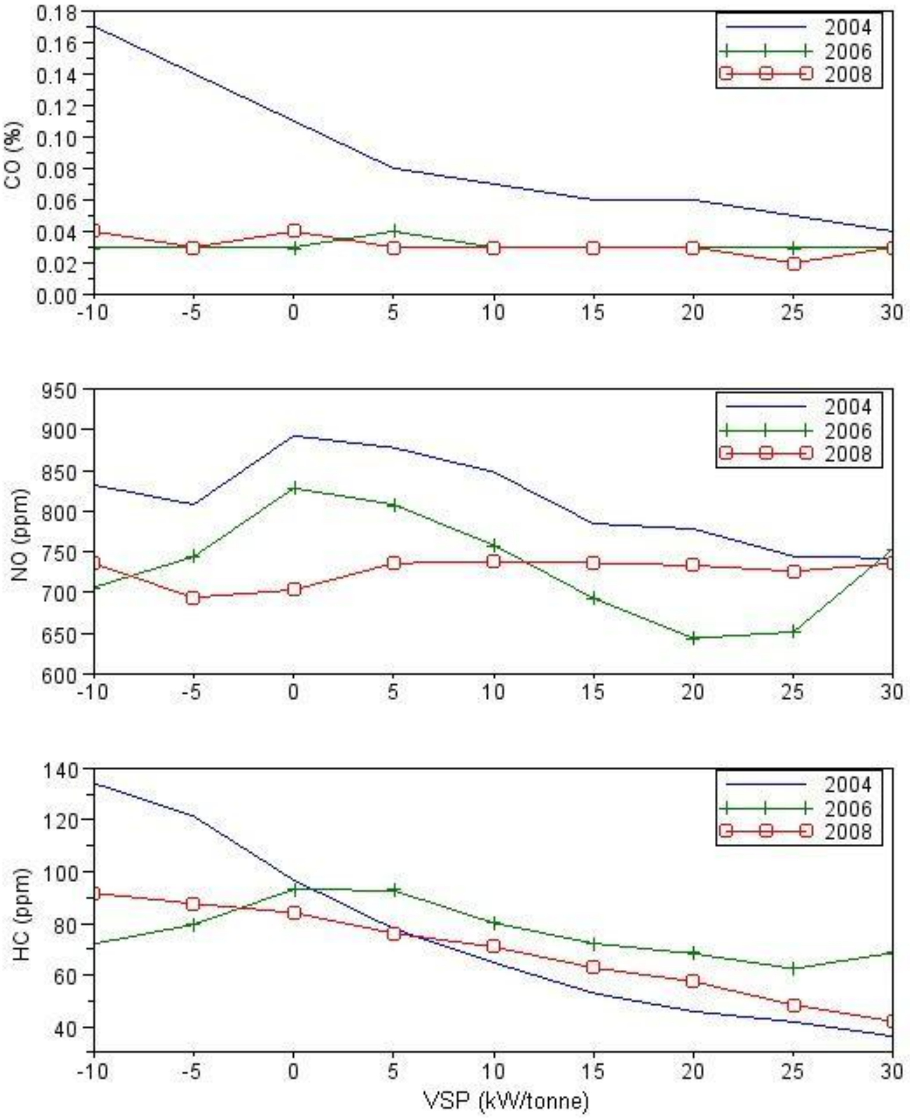


c)

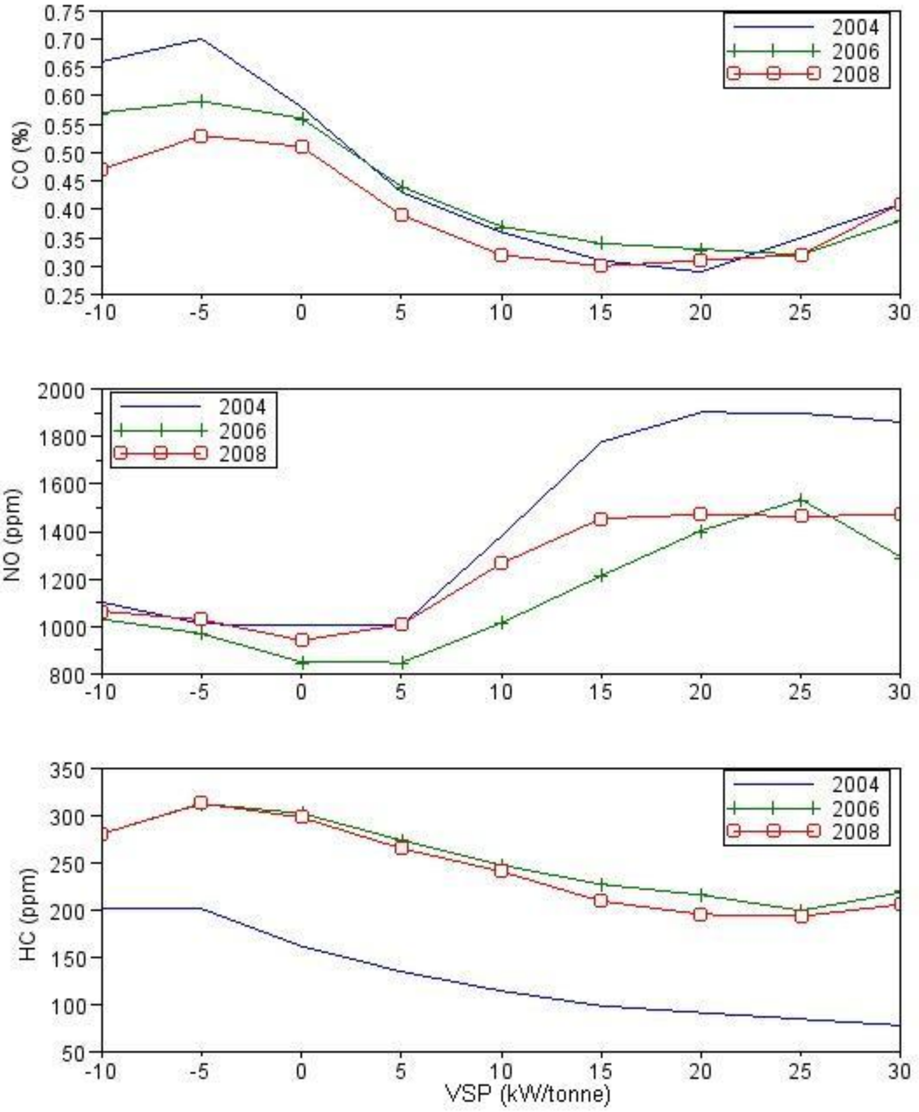
Fig. 2 Decile values of emissions from light-duty petrol, diesel, and LPG vehicles in a) 2004, b) 2006, and c) 2008


CO (%)
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
2004
2006
2008
-10
-5
0
5
10
15
20
25
30
NO (ppm)
550
500
450
400
350
300
250
200
150
2004
2006
2008
-10
-5
0
5
10
15
20
25
30
HC (ppm)
70
65
60
55
50
45
40
35
30
25
2004
2006
2008
-10
-5
0
5
10
15
20
25
30
VSP (kW/tonne)

a)

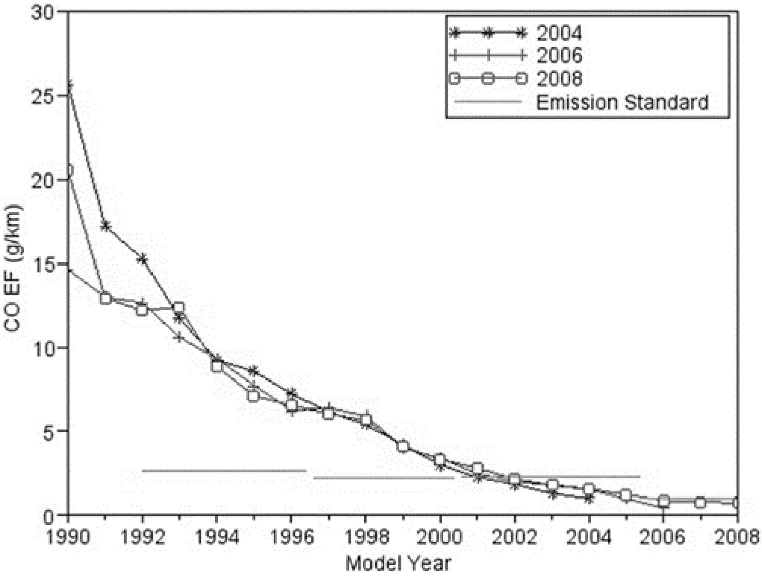

0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
CO (%)
2004
2006
2008
950
900
850
800
750
700
650
600
NO (ppm)
140
120
100
80
60
40
HC (ppm)
-10
-5
0
5
10
15
20
25
30
VSP (kW/tonne)

455 b)

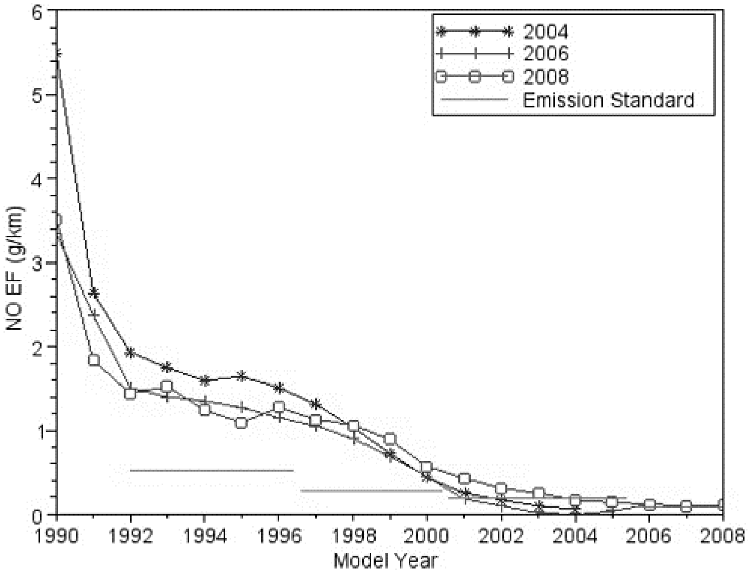


c)

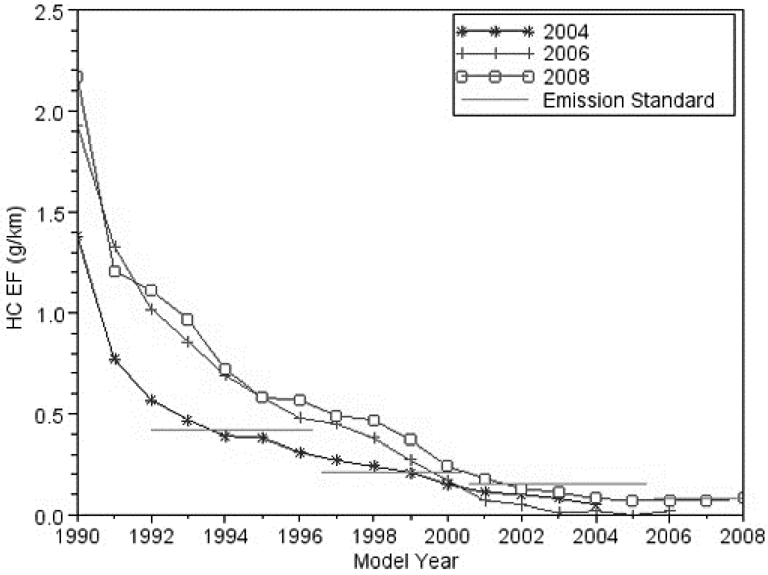
Fig. 3 Emissions of a) petrol; b) diesel; and c) LPG vehicles under different operating conditions


30
25
20
15
10
5
0
CO EF (g/km)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Model Year
2004
2006
2008
Emission Standard

458 a)

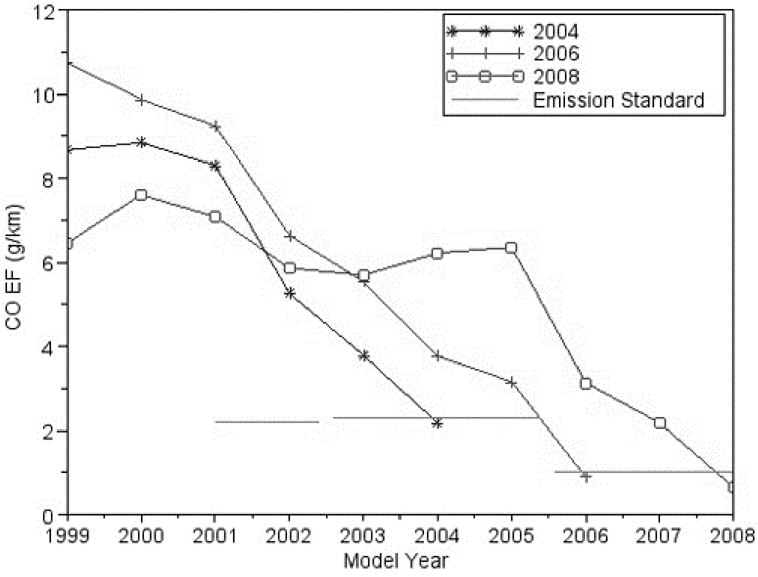

6
5
4
3
2
1
0
NO EF (g/km)
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
Model Year
2004
2006
2008
Emission Standard

459 b)

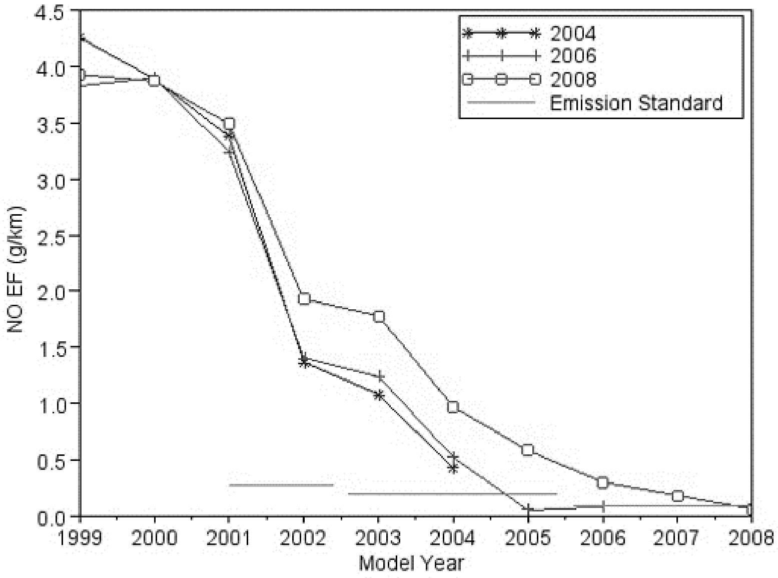


c)

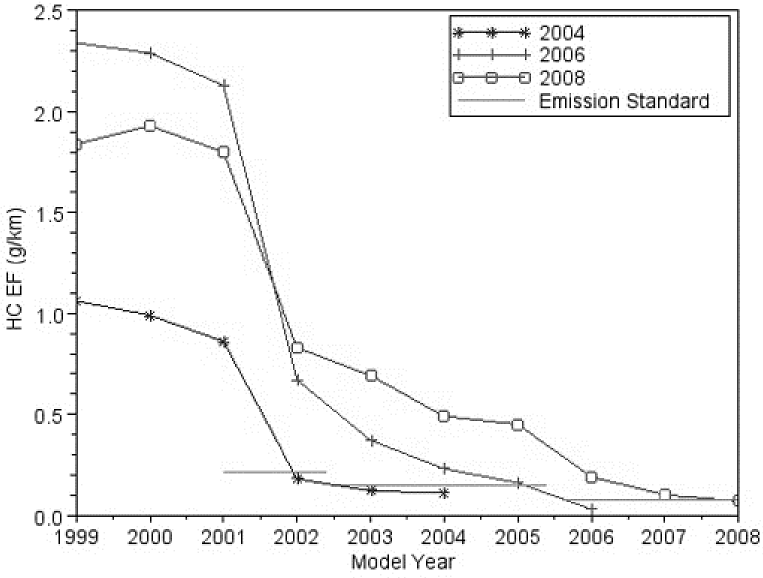
Fig. 4 a) CO, b) NO, and c) HC emission factors of petrol vehicles of different model years



a)



b)



c)

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

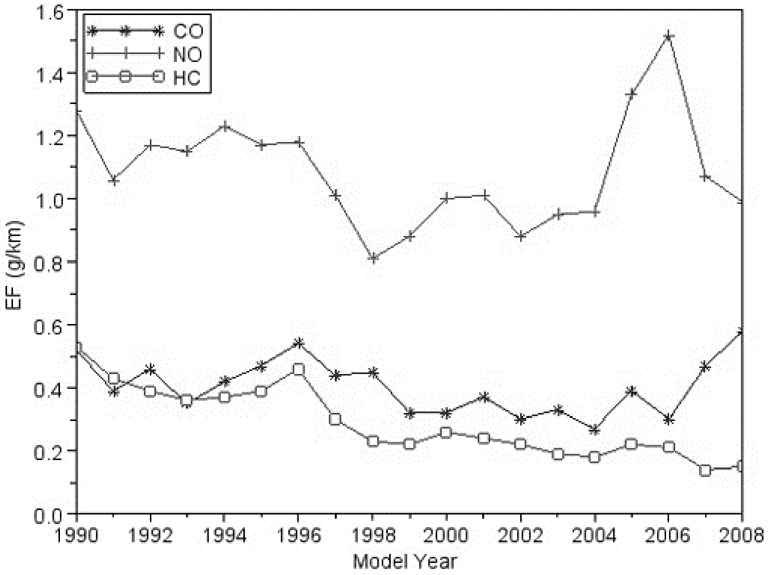


Fig. 6 Gaseous emission factors of light-duty diesel vehicles in 2008. Emission factors of vehicles of different model years satisfy corresponding emission standards (Table 6c)