A remote sensing emissions monitoring programme reduces emissions of gasoline and LPG vehicles

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Abstract

Vehicle emissions are a major source of air pollution in Hong Kong affecting human health. A ‘strengthened emissions control of gasoline and liquefied petroleum gas (LPG) vehicles’ programme has been operating in Hong Kong since September 2014 utilising remote sensing (RS) technology. RS has provided measurement data to successfully identify high emitting gasoline and LPG vehicles which then need to be repaired or removed from the on-road vehicle fleet. This paper aims to evaluate the effectiveness of this globally unique RS monitoring programme. A large RS dataset of 2,144,422 records was obtained covering the period from 6th January 2012 to 30th December 2016, of which 1,206,762 records were valid and suitable for further investigation. The results show that there have been significant reductions of emissions factors (EF) for 40.5% HC, 45.3% CO and 29.6% NO for gasoline vehicles. Additionally, EF reductions of 48.4% HC, 41.1% CO and 58.7% NO were achieved for LPG vehicles. For the combined vehicle fleet, the reductions for HC, CO and NO were 55.9%, 50.5% and 60.9% respectively during this survey period. The findings demonstrate that the strengthened emissions control programme utilising RS has been very effective in identifying high emitting vehicles for repair so as to reduce the emissions from gasoline and LPG vehicles under real driving.

Keywords: Remote sensing; Gasoline vehicles; LPG vehicles; High emitting vehicles; Strengthened emissions control programme

Abbreviations

AFR	Air Fuel Ratio
AQO	Air Quality Objectives
BAR	California Bureau of Automotive Repair
CARB	California Air Resources Board
CNx	China National Emission Regulation (x = UNECE regulation level)
CO	Carbon Monoxide
CO_2	Carbon Dioxide
conc.	concentration
EF	Emission Factor
ETN	Emissions Test Notice
HC	Hydrocarbons
HKEPD	Hong Kong Environmental Protection Department
HKTET	Hong Kong Transient Emissions Test
IM240	Inspection Maintenance 240 second chassis dynamometer emissions test
LPG	Liquefied Petroleum Gas
Nm	Newton Metres
NO	Nitrogen Monoxide
NO_2	Nitrogen Dioxide
O_3	Ozone
OBD	On Board Diagnostics
PLB	Public Light Bus
Q_P	Concentration ratio of pollutant P over CO_2
rpm	Revolutions per minute
RS	Remote Sensing
UNECE	United Nations Economic Commission for Europe
USEPA	United States Environmental Protection Department

1. Introduction

Air pollution control measures for motor vehicles were first developed in the US in the 1950s (US Public Law, 1955) after motor vehicles were identified as major contributors to the problem of air quality (Giechaskiel *et al.*, 2018b; Requia *et al.*, 2016). Today the control of toxic vehicle emissions worldwide is by the primary regulatory instruments. In Europe this is managed with the United Nations Economic Commission for Europe (UNECE) (Giechaskiel *et al.*, 2018a; Suarez-Bertoa and Astorga, 2018) regulations for vehicles. In the US federal standards are established by the United States Environmental Protection Agency (USEPA) and further more stringent regulations are imposed by California Air Resources Board (CARB) (Perugu *et al.*, 2018). The Ministry of Environment in Japan issues its motor vehicle exhaust emission standards. Many countries around the world follow the UNECE regulations either directly or with some level of testing variation pending local conditions. The US and Japanese regulations may also be accepted in lieu of the UNECE regulations in some countries as well. In Asia, China has one of the largest and fastest growing vehicle fleets and Chinese regulations, denoted as CN followed the UNECE regulation level (number), currently CN5. In addition, China has started to implement CN6 initially in some cities and later for the whole country in July 2020 (Tang *et al.*, 2019). Locally in Hong Kong the vehicle regulations follow the UNECE regulations, currently Euro 6 except those for diesel private cars which are based on CARB's requirements, currently LEV 3.

Each of these regulatory instruments have reduced new vehicle emissions limits to achieve Air Quality Objectives (AQO) in respective countries and cities. In Hong Kong, the AQOs (Hong Kong Environment Protection Department, 2013) are based on the World Health Organization (WHO) guidelines (World Health Organisation, 2018). The latest published data for compliance to these targets in Hong Kong showed a significant number of exceedances for nitrogen dioxide (NO_2) at the roadside in 2017 (Hong Kong Environment Protection Department, 2018), although the NO_2 concentration had been reduced by 30% compared with that of 2013.

Vehicle emissions are a major source of roadside air pollution. Whilst the air quality issues vary between country, region or city, the systems for controlling and reducing vehicle emissions lie with the vehicle design and hardware installed. The vehicle manufacturers are utilising a combination of the latest range of engine and exhaust/emissions control hardware (Huang *et al.*, 2019a; Huang *et al.*, 2019b; Zheng *et al.*, 2018) combined with calibrated engine management software to alert drivers to check faulty emissions control systems. Such measures are essential in order to achieve compliance with the regulations of each market where vehicles are being sold. Once a vehicle has been sold and is in use on the road, factors which influence the emissions performance of each vehicle begin to vary significantly. Determining factors influencing long term emissions are individual vehicle usage patterns and loading, road and traffic conditions and vehicle maintenance (Fontaras *et al.*, 2017; O'Driscoll *et al.*, 2018). The capability of each vehicle to continue to meet their respective emissions regulation limits is not guaranteed if the required vehicle maintenance is not performed.

The reality of gasoline and LPG in-use vehicle emissions differs from the desired outcome of these successive regulatory steps. Each new regulation step has progressively lowered the allowable level of on road vehicle emissions. If the vehicle fleet is properly maintained, the results should be showing over time the impact of vehicle emissions on air quality is reducing, in line with successive reducing regulatory emissions limits. The improvements in emissions control technology and the increased durability requirements (refer Table S2) reflect this for all vehicles. For many vehicles which are maintained correctly this is the case, but a portion of the vehicle fleet has little or no maintenance or have their emissions control systems tampered with (Borken-Kleefeld and Chen, 2015; He *et al.*, 2019; Wenzel, 2001). It is these vehicles which have accumulated high mileage that show significant deterioration and in turn contribute a disproportionate amount of emissions that impacts local air quality (Bishop *et al.*, 2016; Popp *et al.*, 1999; Pujadas *et al.*, 2017). In Hong Kong, the Environment Bureau issued 'A Clean Air Plan for Hong Kong' (Hong Kong Environment Bureau, 2013) that outlined the problems of local roadside pollution. It highlighted that a high mileage LPG vehicle with worn out emissions control hardware emitted ten times more NO_x, CO and VOC than when these devices were in good condition. Identifying this problem, the Government allocated HK $150 million to provide a one-off subsidy to replace worn out catalytic converters and oxygen sensors in LPG/gasoline taxis and light buses to assist the transport sector to improve vehicle maintenance (Government, 2012). This ran between August 2013 to April 2014 during which vehicle owners could on a voluntarily basis choose to have a new catalytic converter and oxygen sensor installed in their vehicle. A total of 13,942 taxis and 2,881 light buses received a replacement emissions catalyst and oxygen sensor (approximately 80% of the LPG vehicles). This was then followed by a strengthened emission control plan to identify high emitting vehicles which the owners would then need to repair and maintain.

The question that followed was how to implement a strengthened emissions control programme to determine if a vehicles emissions control system/hardware is functioning correctly. Mechanisms for effectively checking and testing of vehicle hardware condition are short cycle transient dynamometer tests like the USEPA IM240 (Wenzel, 2001) or the utilisation of On Board Diagnostic (OBD) systems. The dynamometer test is effective, but has the limitation that it can only be applied to a small number of vehicles. Whilst OBD is effective for determining serious vehicle failures, it became apparent that moderate and slow deterioration of catalytic converter systems was not being detected and aging vehicles were becoming high emitters and contributing significantly to roadside air quality deterioration without being detected. It is also known that OBD systems can be prone to tampering so that malfunction alerts or reporting of emissions equipment failures are not reported or acted upon with the result of high emitting vehicles remaining on road without proper maintenance (USEPA, 2014). Other monitoring and enforcement capabilities available to check the on road vehicle fleet are roadside spot checks or time consuming testing using tools such as portable emissions monitoring systems (PEMS), plume chasing (Borken-Kleefeld, 2013; Franco *et al.*, 2013; Ropkins *et al.*, 2009), and testing at vehicle inspection centres. Each of these options have not been able to keep pace with the growth of vehicle ownership and usage in Hong Kong.

It was determined that remote sensing (RS) could be used for effectively measuring emissions of passing vehicles. It has gained popularity as such a tool for the rapid detection of vehicle engine emissions (Huang *el al.*, 2018b). It was selected for the purpose and has been used in the strengthened vehicle emissions control programme in Hong Kong since the 1st September 2014 (Hong Kong Government, 2014). By using the RS tool, the HKEPD has the means to identify individual gasoline and LPG vehicles which are high emitters. Emissions limit cut points have been determined for all gasoline and LPG vehicle classes (Table S3). When identified, the vehicle owner is sent an Emissions Test Notice (ETN) which informs them their vehicle has been identified as having high emissions. They then have 12 working days to have the vehicle repaired and tested to prove its compliance with its respective emissions limit. Otherwise the owner will have their vehicle registration cancelled, and the vehicle will be removed from the on-road vehicle fleet. There are no fines applied when an ETN is issued to a vehicle owner. However, the owner is responsible for all costs related to the necessary maintenance/repairs and the subsequent emissions test.

This strengthened emissions control programme in Hong Kong is pioneering in utilising RS technology in this manner. This study aims to evaluate the effectiveness of using RS emissions monitoring in reducing vehicle emissions in Hong Kong. A large dataset of 2,144,422 gasoline and LPG vehicle emissions records was collected in five years from 6th January 2012 to 30th December 2016. Analysis to select valid RS data and determine EFs was performed to assess the effect of the strengthened emissions control programme on the overall emissions trends of gasoline and LPG vehicles as well as the dominant vehicle models.

2. Methods and data analysis

2.1. Data collection

The RS survey data has been collected using the dual RS techniques developed and employed by the HKEPD across 148 measurement sites (Figure S1 in the Supplementary Section) in the Hong Kong Special Administrative Region. The measurement sites encompass significant areas where heavy traffic conditions prevail and there are a sufficient number of passing vehicles available for measurement. The RS equipment consists of 14 different units of the ETC-S420 RS system, which utilises specialised light sources to detect specific types of emissions gases. Non-dispersive infrared is used for detecting HC, CO and CO_2, whilst ultraviolet is used for NO detection. The RS equipment is set up with the unit containing all light sources on one side of the road. The light beams are directed across the road to a retro reflector which reflects them back to the detectors in the RS unit. A measurement begins when a vehicle passes into the first light beam for speed and acceleration measurement. When the speed measurement system detects the vehicle has passed the RS unit the emissions gases are then recorded and photo of the vehicle license plate is taken. The vehicle emissions are recorded for approximately 0.5 s. The emissions data, speed, acceleration and license plate number are recorded in a database which is subsequently transmitted to the HKEPD survey database for assessment. For verification purposes, vehicle data is made available to HKEPD from the Transport Department so that vehicle class, make, model, year of manufacture, engine size and fuel type are available to correctly identify the vehicle emissions limits that need to be applied per the appropriate UNECE emission regulations (Table S2).

Selection of which measurement site RS equipment is deployed to is determined by the HKEPD pending the vehicle makeup at each site and evaluation of the air quality. On any day up to 100 sites may be considered for selection. No prior notification to the public is made of daily RS measurement site section. The RS measurement sites have a 5-m wide single lane of traffic with a slight uphill gradient, between 2 to 5°, so vehicles are under load whilst driving. They are ideally located away from traffic lights or intersections to avoid off cycle emissions from hard acceleration or deceleration. Traffic volumes are significant, free flowing and the range of vehicle speeds for assessment need to be between 7 to 90 km/h for repeatability (Huang *et al.*, 2018a). The site needs to allow for sufficient space to lay out the RS equipment including batteries, cameras and cabling. Staff and the support vehicle must also be safely stationed whilst undertaking the measurements. The two RS systems are to be set up so there is approximately 1 s travel distance between them. This distance between the units can range from between 3 to 20 m pending on the average vehicle speeds for each individual site. The data from the 2nd RS unit is utilised to confirm the validity and repeatability of the measurement. This is necessary for quality assurance as the survey data is to be used for issuing an ETN to the vehicle owner. Equipment calibration for each RS unit is checked to be satisfactory onsite with a puff of High Range BAR-97 with NO span gas (3200 ppm HC, 8.0% CO, 12.0% CO2 & 3000 ppm NO). Stable weather conditions are also desirable for consistency and quality of measurements. Temperature conditions in Hong Kong are relatively aseasonal with the difference in daily average high and low temperatures ranges being around 5°C (Hong Kong Observatory, 2019a). This stable temperature range combined with relatively low average wind speeds (Hong Kong Observatory, 2019b) allows for year round utilisation of the RS systems. The RS survey measurements are halted when there is either heavy rainfall or typhoon weather signals are raised. Measurements are conducted for a shift typically between 9:00am and 4:00pm. The measurements are taken at the site throughout the day, but the data during peak periods may not be used if the speed validity is poor (i.e. heavy traffic conditions). Since every site has different characteristics so the number of RS measurements taken at each site varies as well. Information relating to the variations of number of measurements and make of vehicles at each site is included in Table S1.

Figure 1. Setup of a typical remote sensing measurement site.

2.2. Data analysis

Assessment of the RS data applies the methodology that was developed by the University of Denver (Bishop *et al.*, 1989; Bishop and Stedman, 2014; Burgard *et al.*, 2006; Huang *et al.*, 2018b) to assess turbulent exhaust gas plumes. In every measurement the magnitude or volume of gas that will be measured varies. This combined with measurement uncertainties which are about ±15% (Huang *et al.*, 2018c), requires some consideration on how to optimise the measurements. To mitigate this variability, the measured gas concentrations are used to determine ratios of individual pollutant gases in respect to the dominant/major exhaust gas in the plume i.e. CO_2. The resultant ratios of HC/CO_2, CO/CO_2 and NO/CO_2 are determined, which can be used to calculate the vehicle emissions factors (EFs, in grams of pollutant/kg of fuel) and possibly identify a vehicle as a high emitter.

Using the principle of carbon balance, EFs can be calculated for each of the target pollutant gases using the method of Bishop and Stedman (1996, 2014) and Burgard et al. (2006). The emissions ratio of pollutant P relative to total carbon emitted (C) is given by.

$$\frac{moles\ P}{moles\ C} = \frac{P}{CO_2+CO+3HC} = \frac{Q_P}{1+Q_{CO}+3\times2\times Q_{HC}} \qquad [1]$$

The EFs are calculated utilising equations 2-4 (Bishop and Stedman, 1996, 2014; Burgard *et al.*, 2006;) where Q_P (P= pollutant) is the emission volume ratio of the target gas divided by CO_2:

$$EF_{HC} = \frac{2\cdot 44}{0.014} \cdot \frac{Q_{HC}}{1+Q_{CO}+6Q_{HC}} \left[g/kg_{fuel}\right] \qquad [2]$$

$$EF_{CO} = \frac{28}{0.014} \cdot \frac{Q_{CO}}{1+Q_{CO}+6Q_{HC}} \left[g/kg_{fuel}\right] \qquad [3]$$

$$EF_{NO} = \frac{30}{0.014} \cdot \frac{Q_{NO}}{1+Q_{CO}+6Q_{HC}} \left[g/kg_{fuel}\right] \qquad [4]$$

Prior to undertaking EF calculations, the RS survey data collected needs to be assessed for validity before it can be used for purposes such as general air quality impact assessments or identification of individual high emitting vehicles for the purpose of issuing ETNs. The following criteria (Huang *et al.*, 2018c) have been utilised to filter and select data for analysis:

- Speed range between 7 to 90 km/h
- Acceleration range between -5.0 to 3.0 km/h/s
- Sufficient gas plume for measurement

The amount of CO_2 present in the measurement must be checked to ensure that a sufficient gas plume is available to determine quantitative emissions ratios of target gases to CO_2 (Borken-Kleefeld and Dallmann, 2018; Carslaw *et al.*, 2011). The vehicle speed is checked to be valid for each individual measurement and between the two RS units used for the measurement. Additionally the speed and acceleration ranges to be analysed are selected to match the actual ranges within the Hong Kong Transient Emissions Test (HKTET) used at designated emissions testing centres for providing vehicle emissions compliance certificates (Commissioner for Transport, 2012).

Only valid RS measurement data has been used for this assessment. Applying the criteria above there were 937,696 out of the 2,144,422 records deemed to be invalid. Once the data has been filtered and calculations are completed the resultant EF values for each measurement can be used to characterise the on-road vehicle fleet.

3. Results and discussion

3.1. Survey data characteristics

After filtering and selection criteria have been applied, the breakdown of the number of vehicles analysed for each survey year and fuel type are shown in Table 1. To ensure statistical validity of EFs for survey and model year assessment of results, there is a minimum of 100 records are used for each point (Bernard *et al.*, 2018; Chen and Borken-Kleefeld, 2016). The distribution of vehicle makes and models across each year of the survey period varies pending on the fuel type. For gasoline fuelled vehicles there is a broad range of many makes and models making up the sample population. There are some 157 different vehicle makes alone recorded in the gasoline samples. Table 2 shows the sample distribution for the top 20 most dominant vehicles representing 52.3% of all the gasoline RS samples.

Table 1. Number of valid vehicle emission measurements by remote sensing during 2012-2016.

Survey year	Gasoline	LPG	Combined
2012	40,188	39,666	79,854
2013	108,132	165,937	274,069
2014	148,052	100,454	248,506
2015	177,855	166,429	344,284
2016	169,065	90,984	260,049
Total	643,292	563,470	1,206,762

Table 2. Most frequently measured gasoline vehicles in the RS database.

Category	Vehicle make code*	Engine size (cc)	No. of samples	% of total samples	Manufacture year	European standard
1	1	3456	52,260	8.12%	2006-2016	Euro 4-5
2	1	2362	47,625	7.40%	1997-2016	Euro 2-5

3	2	3498	19,498	3.03%	2004-2015	Euro 3-5
4	1	1497	19,492	3.03%	1994-2016	Euro 1-5
5	2	1796	17,716	2.75%	2001-2014	Euro 3-5
6	1	2994	17,114	2.66%	1996-2008	Euro 1-4
7	1	1998	16,866	2.62%	1986-2015	Pre Euro to Euro 5
8	1	1987	15,105	2.35%	2008-2011	Euro 4-5
9	3	1997	15,001	2.33%	2004-2016	Euro 3-5
10	4	2979	12,939	2.01%	2000-2016	Euro 2-5
11	5	1984	11,098	1.72%	1994-2016	Euro 1-5
12	4	1997	11,088	1.72%	2011-2016	Euro 4-5
13	4	2497	11,087	1.72%	2004-2011	Euro 3-4
14	2	3199	10,828	1.68%	1992-2007	Pre Euro to Euro 4
15	6	2354	10,555	1.64%	2002-2015	Euro 3-5
16	5	1390	10,357	1.61%	2002-2016	Euro 3-5
17	6	1998	10,137	1.58%	1997-2011	Euro 2-4
18	3	3498	9,799	1.52%	2000-2016	Euro 3-5
19	6	1997	9,676	1.50%	1991-2015	Pre Euro to Euro 5
20	6	1339	8,704	1.35%	2001-2014	Euro 3-5

**Note: 'Vehicle make code' refers to a sequentially assigned number to identify makes in the data set provided by HKEPD*

The distribution of vehicle makes and models for LPG is significantly different. The use of LPG fuel in Hong Kong is limited to taxis, Public Light Buses (PLB), Special Purpose Vehicles (SPV) and Private Light Buses (PrivLB). In this study the dominant vehicle model for taxis is the Toyota Crown Comfort Sedan and the dominant vehicle model for PLBs is the Toyota Coaster 16-seat minibus. They make up 72.2% and 27.6% respectively of the LPG RS sample population in the dataset. Table 3 shows the sample distribution for the major analysed LPG vehicles measured by RS. These distributions of make and models for each fuel type present a significantly different picture for analysis of the subsequent EFs when compared to the gasoline RS sample data.

Table 3. Number of LPG vehicles and associated RS measurements

Vehicle make	Engine size (cc)	No. of records	% of total records	Manufacture year	European standard	Vehicle class
Toyota	1998	406,716	72.18%	1997-2016	Euro 2-5	Taxi
Toyota	4104	155,231	27.55%	2001-2016	Euro II-V	PLB, SPV
Nissan	1998	997	0.18%	1999-2001	Euro 2	Taxi
Nissan	1597	417	0.07%	2014-2015	Euro 5	Taxi
Ford	2488	106	0.02%	2014-2015	Euro 5	SPV

For the strengthened emissions control programme, the number of ETNs issued for vehicle classes, the pass rate for the HKTET and license cancellations are shown in Table 4. It should be noted that an ETN is issued only when a vehicle is measured and exceeded either Co, HC or NO cut points on both RS units.

Table 4. Statistics on the number of ETNs issued (1/9/2014 to 31/12/2016)

Vehicle Type	Number of vehicles	%
Private Car	2168	28.6
Taxi	5005	65.9
Light Bus	398	5.2
Light Goods Vehicle	22	0.3
Total number of ETNs	7593	
Repaired and passed HKTET	7258	95.6
Vehicle license cancellations	335	4.4

3.2. Overall emissions trends

Figure 2 shows EFs for all gasoline and LPG vehicles by survey year for EF_{HC} (a), EF_{CO} (b) and EF_{NO} (c). For the combined dataset the general trend for EFs in 2012 and 2013 shows an increase of 24% EF_{HC} and 5% EF_{CO} (Figure 2a-2b) and a decrease of 18% EF_{NO} (Figure 2c). From 2014 onwards there is an average decrease for all EFs which continues for EF_{HC} and EF_{NO}

through to 2016. The EF_{CO} begins to increase in 2015 by 18% and then decreases again in 2016 by 23%. Overall EF magnitudes for all pollutant gases have decreased from the beginning of the survey data period by 55.9%, 50.5% and 60.9% for HC, CO and NO respectively. Considering the fuel types separately the gasoline EFs are noted to be significantly lower in most instances than the LPG EFs throughout the survey period. Early in the survey period the LPG EFs are in the range of 2.7 to 5.3 times higher than the gasoline EFs. As the survey period progresses, the absolute EF values decrease and the magnitude of difference between the EFs changes to 2.9 to 3.7 times higher for LPG. The 2014 EF reductions can be directly linked to the government subsidised LPG emissions catalyst and oxygen sensor replacement scheme. Gasoline EFs are noted to be relatively stable or overall decreasing for each pollutant gas between the years from 2012 to 2015, with a reduction of 37% EF_{HC}, 52% EF_{CO} and 38% EF_{NO}, after which EF_{HC} continues to decrease by 5% whilst there is an increase of EF_{CO} (14%) and EF_{NO} (13%). Overall, EF magnitudes for all pollutant gases have decreased from the beginning of the survey data period by 40.5% HC, 45.3% CO and 29.6% NO for gasoline and by 48.4% HC, 41.1% CO and 58.7% NO for LPG. The government subsidised LPG catalyst and oxygen sensor replacement programme combined with the strengthened emissions control programme have reduced vehicle emissions, and through the ETN process, continue to reduce the number of high emitting vehicles on the road.

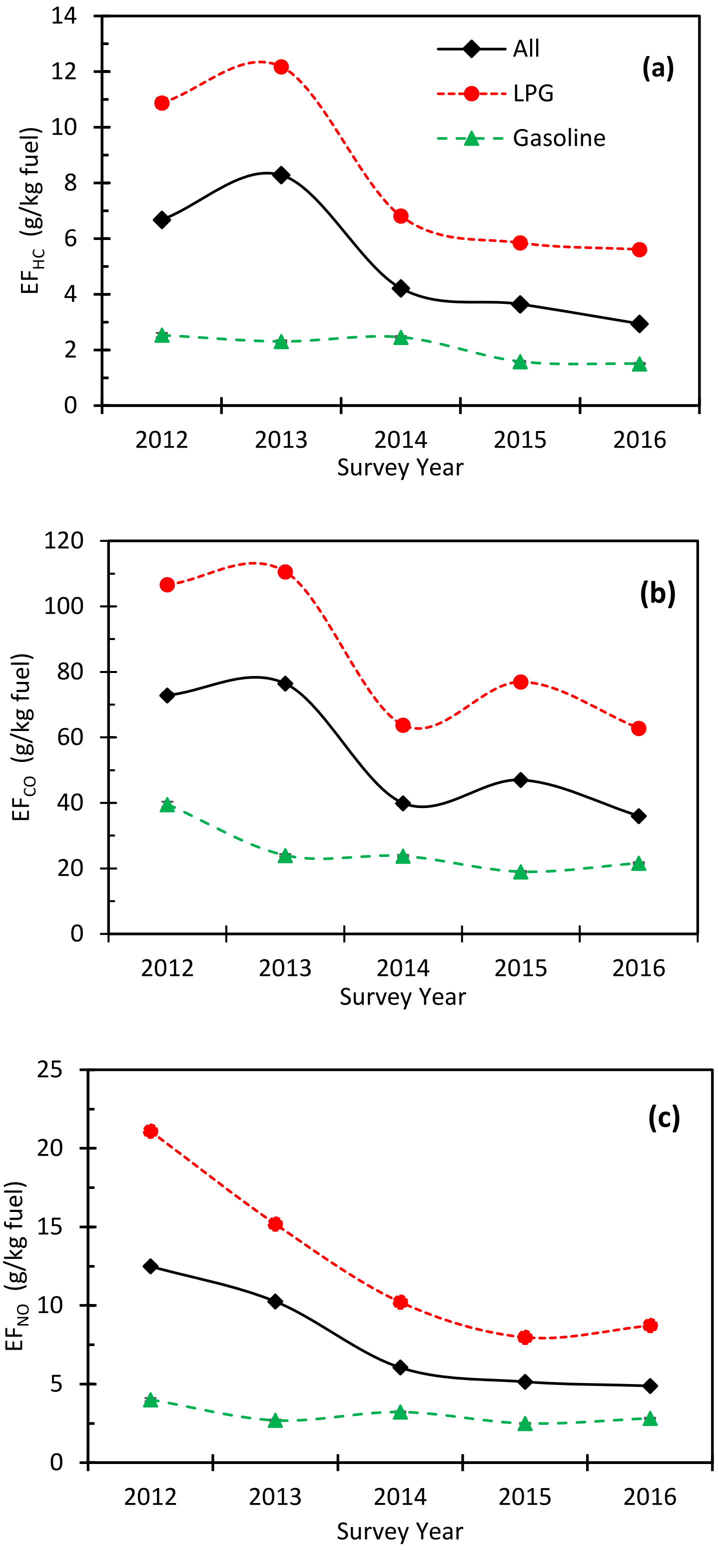

Figure 2. Emission factors of HC (a), CO (b) and NO (c) for gasoline and LPG vehicles during 2012-2016.

The RS data for LPG covers vehicles manufactured between 1997 and 2016. Figure 3 shows EFs for LPG vehicles breaking the data down further by survey and manufacture year for EF_{HC} (a), EF_{CO} (b) and EF_{NO} (c). It also shows EFs for taxis separately further by survey and manufacture year for EF_{HC} (d), EF_{CO} (e) and EF_{NO} (f). LPG EFs increase from the 2012 to 2013 survey years for EF_{HC} by 12% and EF_{CO} by 4% (Figure 3a-3b) whilst the EF_{NO} (Figure 3c) is decreasing by 28%. In 2014 all LPG EFs show dramatic improvement with significant decreases (from 33% to 50%) in EFs across all pollutant gases. The trend for EF_{HC} and EF_{NO} continues to decrease over the period by 18% and 15% respectively. The EF_{CO} on the other hand increases in 2015 by 21% and then decreases in 2016 by 18%.

This significant drop in EF values from 2013 to 2014 for LPG vehicles can be directly linked to the government subsidised programme to provide a free replacement catalytic converter and oxygen sensor per registered taxi and PLB/minibus, as mentioned earlier. The 2013 to 2014 reductions for EF_{HC}, EF_{CO} and EF_{NO} were 44.0%, 42.4% and 32.7% respectively for the LPG vehicle fleet. This improvement in reduced emissions is in line with the effect of other catalytic converter replacement programmes (Brezny and Kubsh, 2013).

The EF results for LPG vehicles can be further investigated to determine the influence of the two dominant vehicle classes, i.e. taxis and PLBs in the results data. Comparing the combined LPG vehicle result against the taxi results (Figures 3d-3f) some distinct characteristics are observed. The survey years 2012 and 2013 show higher or increasing EFs for each pollutant. The 2014 EF data shows the impact of the catalytic and oxygen sensor replacement programme as mentioned previously. As the survey years progress from 2015 to 2016 the EFs increase (Lau *et al.*, 2012) as the taxis and PLBs accumulate mileage at a high rate with daily usage (up to 20 hours driving a day for a taxi and 17 hours driving a day for the PLBs). Mileage in excess of 100,000 km annually (Bishop *et al.*, 2016; Lau *et al.*, 2012) is not unexpected. It should be noted in Figure 3 charts that the EF deterioration described for vehicles manufactured after 2008 is present, but it can be obscured by size of the EF scale for the charts. The findings indicate the crucial importance in maintaining the performance of exhaust control systems (Zachariadis *et al.*, 2001). Within Figure 3 EF chart curves, it can be observed that for individual vehicle classes (taxis or PLBs) or models particular vehicle emissions characteristics can be identified and investigated. The characteristics may relate to individual years of vehicle manufacture or relevant European emissions regulations for the vehicle class or model in question.

In the combined LPG EF_{HC} results (Figure 3a), there are some emission peaks in 2012 and 2013 survey years before the impact of the Government subsidised LPG catalytic converter and oxygen sensor replacement programme is observed. The results become more consistent (considering age and vehicle emissions standards) until 2016 when the EF_{HC} level begins to increase. Reviewing the taxi EF_{HC} data (Figure 3d), the magnitude of these characteristics is less pronounced in comparison the combined chart (Figure 3a). This would suggest the peaks in the manufacture years 2003-2005 in 2012 and 2013 were from PLBs.

In the combined LPG EF_{CO} results (Figure 3b), there are two periods where the values are significantly higher, in the manufacturing years 2003 to 2005 range and in 2009 to 2010. The effect of the HKEPD replacement programme is variable for EF_{CO} across the years of manufacture for all LPG vehicles. The taxi EF_{CO} values (Figure 3e) show significant reductions from survey years 2013 to 2014 when compared to the combined LPG results. The taxi EF_{CO} did not show any significantly higher results until the survey year 2016 and it is especially pronounced for vehicles manufactured in 2009 and 2010. This suggests that a problem has arisen for vehicles built in these two model years which is impacting the emissions performance. These vehicles are of Euro 4 emissions standards, but not representative of all Euro 4 vehicles.

The peaks in the 2003-2005 range are identified as coming from the PLBs are the source of the higher EFs, which can be traced to the Euro III standard vehicles. It would suggest that the Euro III PLBs have emissions problems with either the oxidation related emissions control or other engine issues which impact emissions, specifically CO

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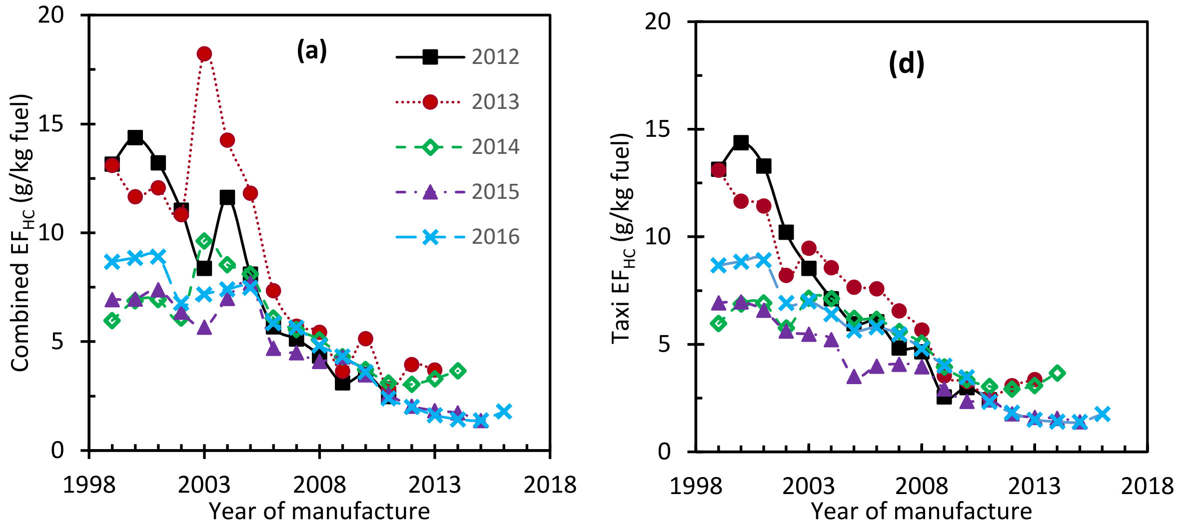
The EF_{NO} (Figure 3c and 3f) practically follow the same patterns for the combined and the taxi results. The EF_{NO} reduction in magnitude in 2014 can be linked to the Government subsidised LPG catalytic converter and oxygen sensor replacement programme. The subsequent survey years show EF_{NO} deterioration to be slowly increasing and at levels which are respective to the particular Euro emissions standards for the manufacture year of the vehicles. This indicates the higher EF_{NO} are from the taxis, not the PLBs. The PLB EF_{NO} are lower, but not significantly so that they affect the overall LPG results. Furthermore, it is observed from these results that RS data has been very effectively utilised in identifying high emitters so they can be issued an ETN to be repaired and in turn helping to maintaining significantly lower EF_{NO} for the older taxis manufactured before 2006.

What is evident from reviewing the charts in Figure 3 is how effective the combination of the Government subsidised LPG catalytic converter and oxygen sensor replacement programme (Lyu *et al.*, 2016; Yao *et al.*, 2019) and the introduction of the strengthened emissions control programme have been for improving the emissions performance of high mileage accumulating LPG vehicles.



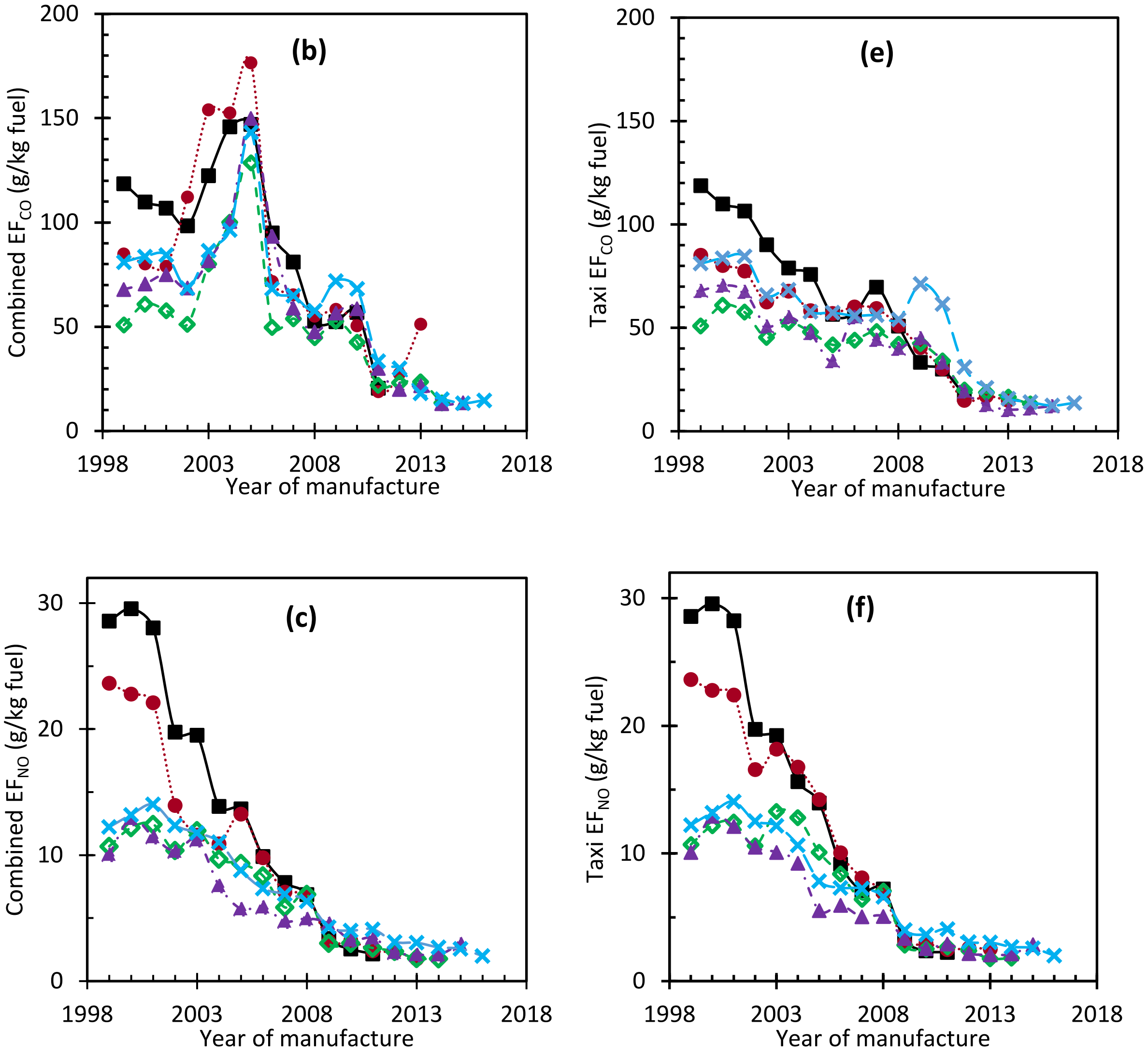


Figure 3. Emission factors for all LPG vehicle and taxi measurements.

Figure 4 shows EFs for gasoline vehicles by survey and manufacture year for HC (a), CO (b) and NO (c). The gasoline EF results present a summary of a diverse range of vehicles which are on the whole not accumulating mileage at the same rate as the LPG taxis and PLBs (Bishop *et al.*, 2016; Lau *et al.*, 2012) and in turn present lower EFs. The RS data for gasoline covers vehicles manufactured from 1926 through to 2016. Vehicles with emissions controls were introduced from 1975 in Hong Kong. Reviewing the distribution of the RS data it shows that the majority of all results are for vehicles with a year of manufacture since the mid-1990s. The sample size of data before 1994 is small and presents a large variation in results. For effective analysis purposes detailed analysis has focussed on vehicles with a year of manufacture from

1994 to 2016. The trends of EFs for all of the gases show reducing values which reflect the progress of emissions standards and new technological innovations in emissions controls (Bishop and Haugen, 2018).

The EF_{HC} results (Figure 4a) show the highest values in the survey years 2012 to 2014. In 2015 there is an average decrease of 30.3% in EF_{HC} values for the survey year. This overall reduction shows the impact of the strengthened emissions control programme which began in 2014. The EF_{CO} results (Figure 4b) show that the 2012 survey year has the highest EF_{CO} values for the survey period, being 27% higher than in 2013 and 2016. The EF_{CO} values start decreasing in 2013 and continue to decrease through to 2015 when they are at their lowest. In the 2016 survey year the trend reverses indicating deterioration of EF_{CO} values, which is partly due to mileage accumulation/fleet aging. Further to this for later model vehicles (manufacture year 2007 and newer), the EF values are starting to returning to levels approaching those from the 2012 survey year. The trends of EF_{NO} values (Figure 4c) from survey years 2012-2014 show the values for vehicles manufactured before 2000 to be on average 3.4 times higher and with greater variability in comparison to post 2000 vehicles. In the 2015 survey year there is a 12% decrease in average EF_{NO} values. For vehicles manufactured before 2000 the EF_{NO} values on average have reduced by 22% in comparison to the 2014 survey year. These results show the effective impact of the strengthened emissions control programme after its first full year of operation. In the 2016 survey year, EF_{NO} values are observed to increase on average by 16%. These increases are noted for 86% of the years of manufacture for the vehicles.

The gasoline EF results show the strengthened emissions control programme to have positive impacts for all measured pollutant gases for all vehicle years of manufacture in the 2015 survey data. The reductions achieved in 2015 were 35.6% for HC, 20.16% for CO and 22.5% for NO. In 2016 some deterioration is noted, for HC the changes are minor and just noticeable. For CO and NO the deteriorations are more significant for older vehicles manufactured before 2000. This EF deterioration is affected by the effort made for RS measurements and the resulting number of ETNs issued. It is noted that the HKEPD has stepped up the roadside measurements since 2018 after reviewing the programme data.

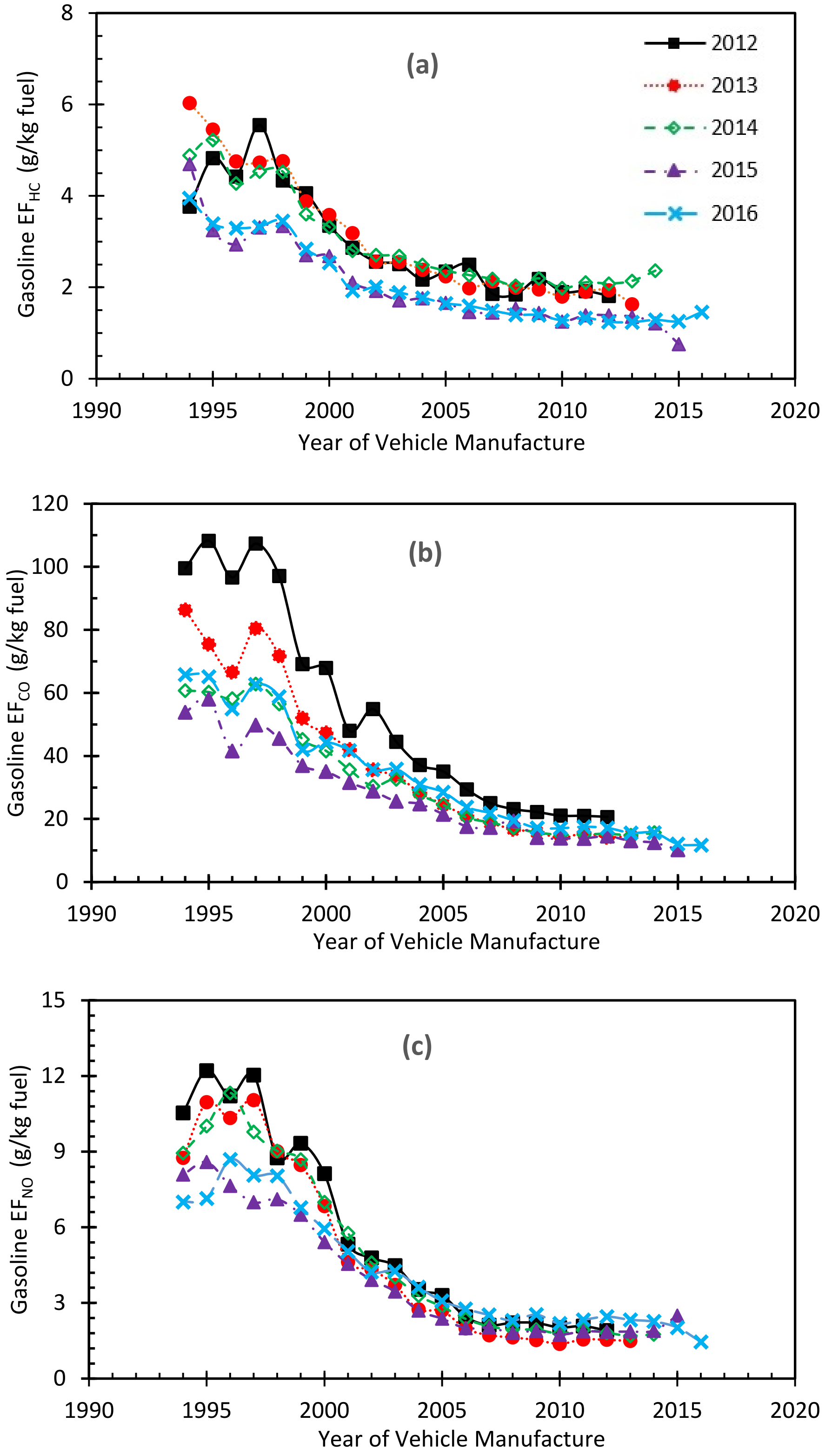
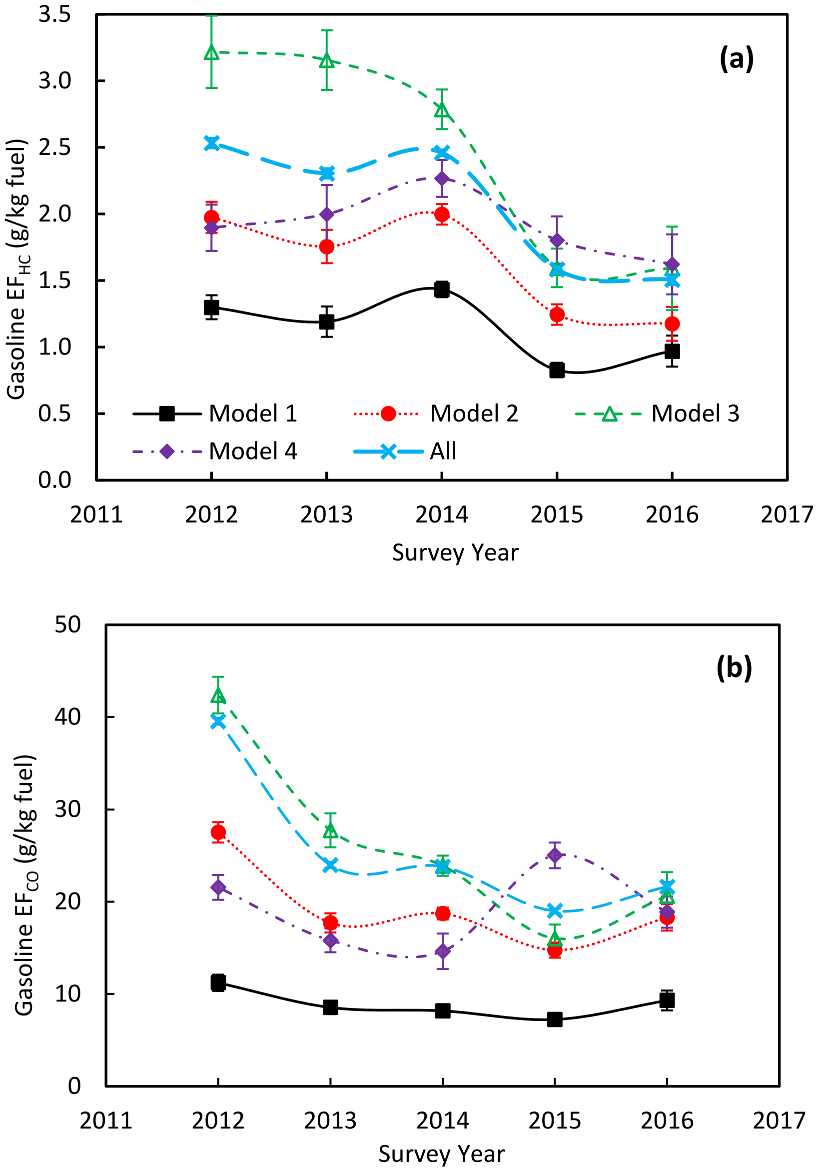


Figure 4. Gasoline Emission Factors by survey year and vehicle year of manufacture

3.3. Emissions trends of dominant gasoline vehicle models

The four most commonly measured gasoline vehicles in the survey period comprise 138,875 RS measurements or 21.6% of the results. Figure 5 shows EFs for the dominant gasoline vehicles breaking the data down by survey and manufacture year for EF_{HC} (a), EF_{CO} (b) and EF_{NO} (c). In the survey period the results for all EFs show what could be model to model variation in the years 2012 and 2013 with values being both higher or lower than the average result for 'all gasoline' vehicles. The exception here is the no. 1 dominant vehicle which has lower EFs for all gases in all years of the survey than the average result and also each of the other dominant vehicles as well. For EF_{HC} (Figure 5a) the trend for the dominant vehicles shows vehicles 1, 2 and 4 having lower EFs than the average result in 2012 and 2013. This changes in the years from 2014 to 2015. For all of the dominant vehicles there is a noted decrease compared to the average result which is generally maintained in 2016. The EF_{CO} (Figure 5b) is decreasing in 2012 and 2013 in line with the average result. This continues in 2014 and 2015 except for vehicle no. 4 which increases above the average result before decreasing to a lower value in 2016. The lowest values for all of the EFs occurs in 2015. The average result and the results for vehicles 1, 2 and 3 then begin to increase in 2016. The EF_{NO} values (Figure 5c) are lower than the average result except for vehicle no. 3 from 2012 to 2014. In 2015 this is the only time all vehicles have a lower EF than the average result. From 2016 the EFs for each vehicle begin to increase whilst the average for the whole vehicle fleet result lowers.

The gasoline vehicles which have been measured by RS during the survey period are predominantly private vehicles. Some of them are used by businesses for company transport or commercial purposes such as limousine or private shuttle services, but this comprises only < 1% of the gasoline vehicle fleet (Hong Kong Government, 2018; Transport Department, 2017). For gasoline vehicles there have been no programmes such as the catalyst and oxygen sensor replacement that was undertaken in the LPG fleet which would influence reductions in the EF values. Influencing factors for improving emissions trends of gasoline vehicles would include regular vehicle maintenance, annual roadworthy inspection for vehicles older than 6 years, replacement of older vehicles by new ones (fleet renewal) and since September 2014 the introduction of the RS programme to strengthen emissions controls.



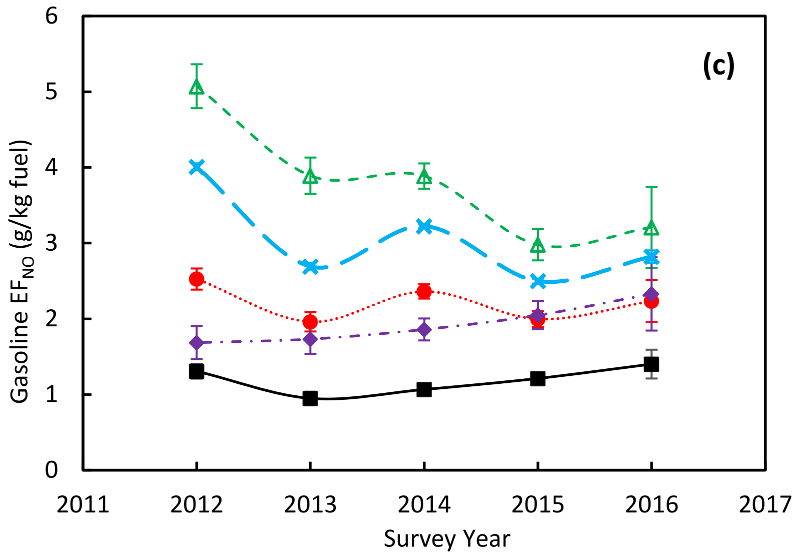


Figure 5. Gasoline emission factors for dominant measured vehicle models during 2012-2016. The error bars represent the 95% confidence interval over the mean.

Reviewing the dominant vehicle EF charts for each survey year, for EF_{HC} all dominant vehicle models show a decrease from 2014 to 2015. For EF_{CO} the trend is the same for all but one vehicle, model 4, which does not start to decrease until the 2015 to 2016 timeframe. For EF_{NO} model 2 and 3 decrease in 2014-2015, then in 2016 all models are seen to increase. It is safe to attribute these EF decreases to the introduction of the strengthened emissions control programme. The results for EF_{HC} (Figure 5a) show that there is a steep decrease from 2014 to 2015 when the initial impact of the programme would become measurable. EF_{HC} remains at values lower than before the programme began for each dominant vehicle model. The EF_{HC} results suggest all of the dominant vehicle models have responded to the identification of individual high emitting vehicles and the issuing of ETNs with the vehicles being repaired and pollutant emissions lowering in 2015. The EF_{CO} results (Figure 5b) show a steady decrease for each vehicle type with the lowest EF_{CO} values in 2015 except for vehicle model 4 which increases in 2015 after the programme has been put in place before having a delayed decrease in 2016 whilst the other vehicles EF values begin to increase in these years. These results suggest that vehicle model 1, 2 and 3 have responded to the influence of the programme in 2015 whilst vehicle model 4 did not until 2016. The EF_{NO} (Figure 5c) results differ from both EF_{HC} and EF_{CO}. For EF_{NO} vehicle 1 and 4 show no reduction after the programme begins. Whereas vehicle models 2 and 3 have lower EF_{NO} values in 2015. Further to this there is a steady increase in all vehicle models EF_{NO} values in 2016. This suggests there could be an apparent deterioration for all vehicles and/or especially those accumulating high mileage similar to that of taxis as the fleet is observed to age. These results suggest that for vehicle model 1 and 4 the average NO levels are generally low and on the whole lower than cut point limits for detection of high emitters. Vehicle models 2 and 3 have higher NO levels and with the implementation of the strengthened emissions control programme and the issuing of ETNs the high emitting vehicles of these models are repaired the NO values are reducing in their values from 2014 to 2015.

The overall results indicate that the gasoline vehicle fleet has some high emitting vehicles which are effectively being detected (Lau *et al.*, 2012) and having their emissions related defects repaired or they are removed from the on road fleet. The overall gasoline vehicle fleet EFs are much lower to begin with than the LPG fleet and as such the reductions appear incremental in comparison to the reductions being achieved with the LPG vehicle fleet.

The gasoline vehicle fleet differs considerably in size, composition and how it is utilised. The percentage of vehicles that are detected as high emitters is much lower than that for LPG vehicles, but the effect of ETNs being issued, repairs made and vehicles returning to the road with lower emissions is measurable as the progressive EF results show from RS data.

A review of the gasoline dominant model's information suggests that for any of these particular vehicle models, the percentage of vehicles needing to be identified as high emitters to be repaired before the EF average for the model decreases is around 5% of the valid RS measurements for that model. Verification of this would require confirmation of data from the HKEPD ETN process. This not possible due to confidentiality and privacy restrictions.

Table 5. Average vehicle age for main LPG and dominant gasoline models during RS survey.

	Average vehicle age (years)				
LPG	**2012**	**2013**	**2014**	**2015**	**2016**
Toyota Crown Comfort Taxi	9.6	10.4	10.8	10.2	9.7
Toyota Coaster Minibus	6.5	7.5	8.3	8.9	9.4
Gasoline					
Model 1	2.6	3.3	4.1	4.2	4.4
Model 2	5.1	5.9	7	7.3	8
Model 3	6.2	6.9	7.2	7.4	8
Model 4	3.8	4.4	5.2	5.7	6.5

A factor mentioned earlier that can affect the EFs for the vehicle fleet is fleet renewal. To determine if the influence of this has changed during the survey period, the average vehicle ages of the main LPG and dominant gasoline models for the survey period has been checked (Table 5).

For LPG vehicles the average age of taxis was 9.6 years at the beginning of the survey period, it rose to a high of 10.8 years in 2014 before beginning to reduce to 9.7 years by 2016. This data shows for taxis the strengthened emission control programme has been successful in accelerating the fleet renewal of LPG taxis, reducing the average fleet age and helping to reduce emissions. Further to support this observation it is noted that for LPG taxis in 2012 before the government sponsored catalytic converter and oxygen sensor replacement programme and then the strengthened emissions control programme implementation began, there were 300 new taxi registrations. By the end of 2015, after 16 months of the strengthened emissions control programme began, there were 2340 new taxi registrations. This is a change from 1.6% per annum to 12.9% per annum fleet renewal (Transport Department, 2013, 2016).

For the LPG minibuses/PLBs the average age has increased from 6.5 to 9.4 years over the survey period. Whilst the average has not reduced, its rate of increase is noted to be slowing after the beginning of the strengthened emission control programme which suggests that the rate renewal has also increased.

For the Gasoline dominant models, the average age for each model has been noted to be increasing over the survey period, none have reversed the trend. It is noted that for model 1, the increase of the average age has slowed down since 2015. For the other models it has been noted to decrease in 2015 but then increase in 2016. This suggests for Model 1 there is increased fleet renewal in in 2015 and 2016. For the other 3 models the rate of renewal has not consistently increased. It should also be considered that gasoline vehicle renewal rates will not show the same improvement as the LPG vehicles as these vehicles are predominantly private cars and utilised in a different manner when compared to vehicles used for commercial operation.

Overall these results clearly show that the strengthened emissions control programme is providing non-invasive on road monitoring data which is able to cover a significant proportion of the vehicle fleet. The ability to measure hundreds to thousands of vehicles at each measurement site on any day provides an amount of emissions data many times greater than any other individual vehicle measurement programme that has been utilised previously. The results over the 5 year period show that since September 2014 RS data has been successfully utilised to identify high emitting vehicles providing a new mechanism for the HKEPD to ensure the high emitting vehicles are repaired and pass the proscribed emissions test or be removed from the vehicle fleet.

4. Conclusions

This study analysed the effectiveness of a unique strengthened emissions control programme using RS technology. The large size of the unique dataset has allowed for analysis that shows there are high confidence levels in the resultant EFs calculated for each element of assessment undertaken. The following conclusions can be drawn.

- Due to poor maintenance practices where failed catalytic converters and oxygen sensors were not regularly replaced, the LPG vehicle fleet was shown to be emitting significantly higher amounts of regulated pollutants than the gasoline vehicle fleet. From 2013 to 2014 a government sponsored catalytic converter and oxygen sensor replacement programme for taxis and PLBs proved to be highly effective in reducing the EF_{HC}, EF_{CO} and EF_{NO} by 44.0%, 42.4% and 32.7% respectively for the LPG vehicle fleet. For the whole survey period (2012-2016), overall LPG EF reductions of 48.4% EF_{HC}, 41.1% EF_{CO} and 58.7% EF_{NO} have been achieved.

- Gasoline vehicles showed the lowest EFs throughout the survey period with the implementation of the strengthened emissions control programme. During 2014-2015, reductions of 35.6% HC, 20.16% CO and 22.5% NO were achieved. For the whole period (2012-2016), there were overall gasoline EF reductions of 40.5% HC, 45.3% CO and 29.6% NO.
- From January 2012 to December 2016, the overall EF reductions of 55.9%, 55.6% and 60.9% were achieved for HC, CO and NO, respectively.
- The results confirm that the government sponsored catalytic converter and oxygen sensor replacement programme then followed by the strengthened emissions control programme was effective in reducing emissions levels and identifying high gasoline and LPG emitters, allowing HKEPD to issue ETNs so these vehicles were able to be repaired and pass the proscribed emissions test or be removed from the vehicle fleet. The RS survey data was also effective in highlighting particular manufacture years and Euro emissions standards of taxis and PLBs which were the high emitters needing urgent maintenance.

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