ATMOSPHERIC SCIENCE

Rapid detection of high-emitting vehicles by on-road remote sensing technology improves urban air quality

Yuhan Huang[1]*, Casey K. C. Lee[2], Yat-Shing Yam[2], Wai-Chuen Mok[1], John L. Zhou[1]*, Yuan Zhuang[3], Nic C. Surawski[1], Bruce Organ[1,4], Edward F. C. Chan[1,5]

Vehicle emissions are the most important source of air pollution in the urban environment worldwide, and their detection and control are critical for protecting public health. Here, we report the use of on-road remote sensing (RS) technology for fast, accurate, and cost-effective identification of high-emitting vehicles as an enforcement program for improving urban air quality. Using large emission datasets from chassis dynamometer testing, RS, and air quality monitoring, we found that significant percentages of in-use petrol and LPG vehicles failed the emission standards, particularly the high-mileage fleets. The RS enforcement program greatly cleaned these fleets, in terms of high-emitter percentages, fleet average emissions, roadside and ambient pollutant concentrations, and emission inventory. The challenges of the current enforcement program are conservative setting of cut points, single-lane measurement sites, and lack of application experience in diesel vehicles. Developing more accurate and vertical RS systems will improve and extend their applications.

INTRODUCTION

Road transport is the most important source of air pollution in cities globally and has caused significant health and economic losses to the public (*1*–*4*). The International Council on Clean Transportation estimated that global transport emissions were linked to 385,000 premature deaths in 2015, causing 7.8 million years of life lost and approximately US$1 trillion of health damages (*2*). Spark ignition engine–powered vehicles such as petrol and liquefied petroleum gas (LPG) vehicles are the dominating vehicles on roads, accounting for more than 80% of total vehicles worldwide except for the European Union, India, and South Korea where diesel vehicles account for significant shares (39 to 52%) (*5*–*7*). As a result, spark ignition engine–powered vehicles also account for a substantial share of pollutant emissions, particularly when many of them are not properly maintained. Regulations (e.g., Euro 6) are becoming increasingly stringent to curb vehicle emissions, in terms of limit values, regulated pollutant species, and testing methods (*8*).

Although vehicles are type-approved to meet the emission standards before entering the market, their emissions will deteriorate or even fail as mileage accumulates. Each in-use vehicle has different operation intensity, driving behaviors of its driver, and maintenance levels. Some vehicles may even be modified or tampered to improve power performance or to reduce operation cost, such as removing the three-way catalysts (TWCs) or exhaust gas recirculation (EGR) systems (*9*–*11*). All these factors influence the emission performance of in-use vehicles. Therefore, a proportion of the total fleet, in particular the high-mileage vehicles, will emit substantially higher emissions than the standard limits and thus contribute to a disproportionally large percentage of the total emissions (*12*). Urban air quality can be effectively improved if these high-emitting vehicles are rapidly identified for repair or deregistration to reduce the source of vehicle pollutants (*13*, *14*). Intuitively, targeting such small portion of high emitters is a highly cost-effective method for vehicle emission control, which significantly reduces the cost and time for both the government and vehicle owners in comparison with other methods such as passive sampling or periodic inspections. It can also help vehicle owners detect premature failure of emission-related components of their vehicles for early rectification to prevent major failures and high emissions. In addition, such screening has the potential of identifying vehicles with defeat devices (*15*) that help them pass laboratory tests but emit much higher emissions in real driving. The control of in-use vehicle emissions is critical in solving the urban air pollution problem (*16*) and is gaining worldwide attention in recent years (*17*–*20*).

Among different methods of vehicle emission measurement, on-road remote sensing (RS) technology has the advantages of fast detection, noninvasive, in situ, and cost-effective (*21*, *22*) features. For a government enforcement program, the identification of high emitters must be highly accurate and precise. However, RS only measures the snapshot emissions when a vehicle passes by. The instantaneous vehicle emissions under real-world driving are very dynamic and influenced by many factors such as driving speed, acceleration, and load (*14*, *23*). Therefore, a successful high-emitter enforcement program using on-road RS technology requires careful policy design and significant research.

Since its development in the late 1980s (*24*), RS has been extensively used for characterizing real-driving vehicle emissions worldwide (*25*–*27*), although it has rarely been used to identify high-emitting vehicles for enforcement purposes, the most important application of RS to realize emission reduction benefits. Hong Kong, under its Environmental Protection Department (HKEPD), was among the first cities to pioneer extensive research on RS since 1993 (*22*, *28*). Since 1 September 2014, HKEPD started using RS as a regulatory tool to detect high-emitting petrol and LPG vehicles for enforcement (*29*), which is one of the few such applications worldwide that are actively using RS technology (*30*). There is therefore a wealth of

[1]Centre for Green Technology, School of Civil and Environmental Engineering, University of Technology Sydney, NSW 2007, Australia. [2]Environmental Protection Department, Hong Kong Special Administrative Region Government, Hong Kong, China. [3]School of Automotive and Transportation Engineering, Hefei University of Technology, Hefei, China. [4]Jockey Club Heavy Vehicle Emissions Testing and Research Centre, Vocational Training Council, Hong Kong, China. [5]Faculty of Science and Technology, Technological and Higher Education Institute of Hong Kong, Hong Kong, China.
*Corresponding author. Email: yuhan.huang@uts.edu.au (Y.H.); junliang.zhou@uts.edu.au (J.L.Z.)

unique research and emissions data from Hong Kong, which should be highly valuable for the research community and policy-makers, to learn the progress of on-road RS technology for catching high-emitting vehicles and combating transport-related urban air pollution. However, its accuracy in detecting high-emitting vehicles and effectiveness in mitigating urban air pollution remain unknown to the public.

We systematically evaluate the unique RS enforcement program in Hong Kong, including its development, preparation, implementation, effectiveness, and challenges and future perspectives. The conceptual advance offered by our study is that the complex policy and technical considerations in the development of an emission-focused enforcement program are thoroughly discussed. It is expected that researchers and policy-makers can comprehensively learn how to develop a high-emitter enforcement program using RS and thus establish their own vehicle emission control programs quickly and accurately for protecting public health. These results could also help consolidate stakeholder acceptance under the enforcement program, which is critically important with global implications for vehicle emission control.

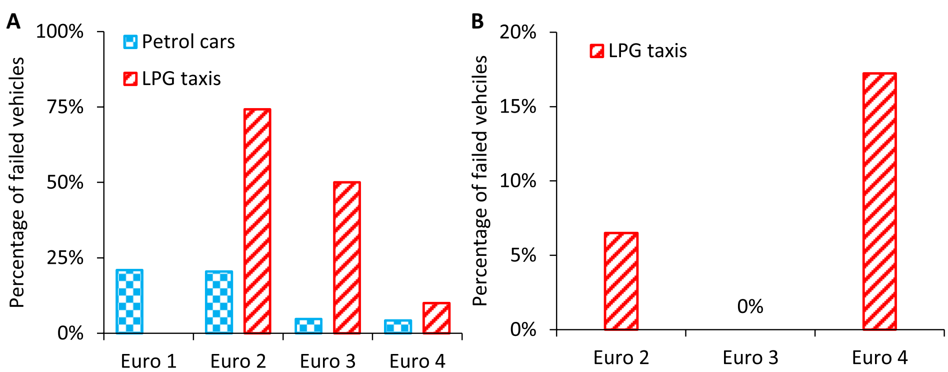
The hypotheses of this research are therefore that (i) old vehicles are more polluting, (ii) RS is an effective tool for the rapid detection of high emitters, and (iii) urban air pollution can be effectively mitigated if high-emitting vehicles are repaired/removed. The hypotheses are tested by systematically evaluating the unique Hong Kong RS enforcement program. The large emission datasets collected from RS, chassis dynamometer testing, and air quality monitoring are analyzed.

RESULTS AND DISCUSSION

Emissions profiling of in-use vehicles

HKEPD conducted vehicle emission baseline survey using a portable dynamometer to test vehicles on as-received basis (Fig. 1A). The overall failure rates for petrol cars and LPG taxis are 13 and 63%, respectively. The failure rate for taxis is significantly higher. Older vehicles are more likely to fail the standards, indicating that emission deterioration during mileage accumulation is the key element in the high failure rate. Therefore, it is expected that vehicle repair would yield high emission reduction benefit. However, failed vehicles are not all from older vehicles. In this study, 4 and 10% of the Euro 4 cars and taxis fail the Hong Kong Transient Emission Test (HKTET), respectively, although they are relatively new when tested (1 to 3 years old). In particular, the worst high emitters were emitting significantly over the limits of in-use vehicles by over 10 times for CO and NO. Therefore, it is crucial to develop an enforcement program to curb the emissions from these high emitters.

To evaluate the emission reduction benefit arising from an enforcement program, a pilot repair demonstration program was carried out on 600 selected LPG taxis that had been reported by owners of having operation problems (mostly engine stall and lacking in power). Severe damage of TWC converters had been reported upon inspection of some taxis. This program was to demonstrate the benefit of replacing the TWC converters and oxygen sensors to the transport trade, so no other engine repair was performed on these taxis. After the repair, the emissions of 563 in-use LPG taxis were tested on transient chassis dynamometers under the HKTET cycle (Fig. 1B). The overall percentage of failed vehicles



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Emission control scenarios		Emission reductions		
		HC	CO	NO
1	All (100%) of the failed vehicles are repaired	22%	47%	39%
2	50% of the worst failed vehicles are repaired	20%	45%	38%
3	25% of the worst failed vehicles are repaired	14%	37%	29%

Fig. 1. Emission profiles of in-use vehicles and potential benefits of strengthened emission control. (**A**) Percentages of failed vehicles in the emission baseline survey program in which 340 petrol cars and 121 LPG taxis were sampled for HKTETs. (**B**) Percentages of failed vehicles in the pilot repair demonstration program in which 563 LPG taxis were sampled for HKTETs. The criteria of failed in-use vehicles are twice their respective type-approval limits in Hong Kong, which have considered normal deterioration of engine combustion and emission after-treatment systems. (**C**) Potential fleet-wide emission reductions of different emission control scenarios.

has been greatly reduced from 63% (Fig. 1A) in the emission survey program to only 7% (Fig. 1B) after the pilot repair program. This demonstration program shows that nearly 90% of the repairs needed were TWC and oxygen sensor related. It also helped establish the acceptance of proper emission repair by the industry. Subsequently, the Hong Kong government fully subsidized taxis and light buses to replace their TWCs and oxygen sensors in 2013, which will be further discussed later.

However, Fig. 1B shows that some vehicles still failed the emission limits after the pilot repair program, indicating that there were other engine faults that could increase vehicle emissions greatly (Table 1). Besides, some vehicles may fail again sometime later as their mileages accumulate quickly. Therefore, an RS enforcement program is highly valuable in constantly checking the fleet. Figure 1C estimates the potential emission reduction benefits of three enforcement scenarios, namely, the worst emitting 100, 50, and 25% of the failed vehicles (after the pilot repair program) are repaired. It is assumed that failed vehicles are repaired to achieve the average emission level of passed vehicles in the same Euro standard. In addition, it is assumed that all vehicles are used equally, i.e., having the same kilometers traveled each year. Figure 1C shows that the fleet-wide total CO and NO emissions could be largely reduced, while hydrocarbon (HC) emissions could be moderately reduced by only targeting the high-emitting vehicles. This is because some of the CO and NO high emitters are greatly over the emission limits. In an ideal scenario that all high emitters are repaired, the total HC, CO, and NO emissions can be reduced by 22, 47, and 39%, respectively. The emission reduction benefits decrease with smaller coverage of enforcement program. However, total CO and NO emissions can still be reduced noticeably by 37 and 29%, respectively, even in a low-coverage enforcement program of 25%. These estimates are reasonable as RS targets the worst high emitters that exceed the cut points more often for enforcement. When deployed for long-term continuous monitoring, a high emitter will eventually be caught after it passes by an RS site for many times. This means that not only the failed vehicles after the pilot repair program but also many newly failed vehicles in the following years will be identified and repaired in an RS enforcement program. The projections in Fig. 1C imply that an RS enforcement program for LPG high-emitting vehicles should be a very cost-effective method to control the fleet-wide emissions.

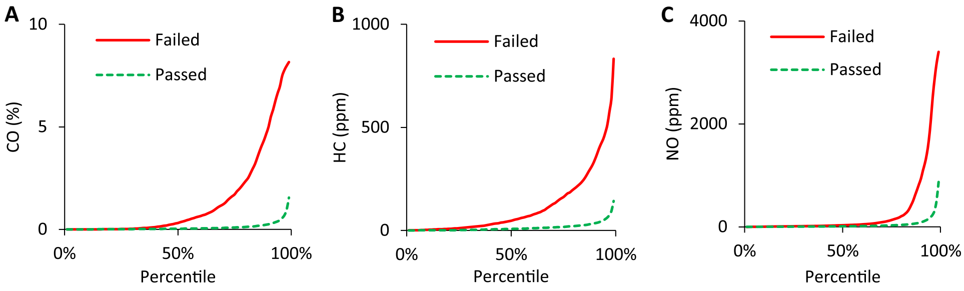
Development and validation of RS enforcement program

It is challenging to determine whether a vehicle is high-emitting or not on the basis of one RS measurement when it passes by, considering that instantaneous vehicle emissions are highly dynamic. Those detected as high emitters are required to undertake an HKTET cycle test in the laboratory to officially examine their emission levels and retain their licenses. RS only measures the instantaneous emissions of a vehicle under one driving condition, while HKTET includes various driving conditions. Therefore, RS cut points must be chosen with due consideration to avoid any false detections.

First of all, the characteristics of instantaneous emissions of both clean and high-emitting vehicles in HKTETs were investigated. Figure 2 (A to C) shows the percentiles of instantaneous emissions of both passed and failed Euro 2 taxis (Euro 3 and 4 are shown in fig. S3). As shown in Fig. 2 (A to C), there are obvious differences between the percentile curves of passed and failed vehicles. The instantaneous emissions of passed vehicles remain very clean (almost zero) for most the time, and the 99th percentiles are 1.6% for CO, 143 parts per million (ppm) for HC, and 871 ppm for NO. Therefore, using these concentrations as RS cut points could effectively avoid false positives while still capturing failed vehicles. On the basis of this concept, RS cut points for Euro 1 to 5 petrol and LPG high emitters are developed (Fig. 2D), which have considered vehicle classes, fuel types, and Euro standards.

Table 1. Emission and fuel consumption performance with various engine faults. Positive and negative percentages indicate emission increases and reductions comparing with the baseline test (i.e., all engine components are functioning properly after thorough maintenance), respectively.

Systems	Faulty components	HC	CO	NO	Fuel consumption
Intake system	Throttle-body butterfly valve	31%	218%	–40%	16%
	Throttle-body mixture control valve	168%	782%	–86%	3%
	Throttle-body idle control valve	–28%	–51%	151%	11%
Fuel system	Vaporizer (rich)	17%	276%	–5%	5%
	Vaporizer (lean)	–32%	–38%	–41%	5%
	Main fuel supply line	49%	–5%	352%	8%
	Idle fuel supply line	30%	294%	–6%	6%
	Fuel cut solenoid valve	–39%	–43%	–50%	10%
Ignition system	Spark plug	0%	60%	–40%	6%
	Distributor cap and rotor	–13%	–29%	–20%	6%
Exhaust system	TWC	131%	211%	178%	7%
	Oxygen sensor (0.1 V)	249%	150%	33%	11%
	Oxygen sensor (0.9 V)	317%	410%	61%	9%
	EGR valve (open)	169%	34%	3%	11%
	EGR valve (closed)	–45%	–39%	72%	5%
Baseline test (all components functioning properly)		0.15 g/km	0.61 g/km	0.26 g/km	11.01 liters/100 km



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Vehicle classes	Pollutants	Pre-Euro	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5
Private cars (petrol)	CO (%)	5	2	2	2	2	2
	HC (ppm)	500	500	500	500	500	500
	NO (ppm)	4000	2000	1500	750	750	750
Taxis (LPG)	CO (%)			2	2	2	2
	HC (ppm)			500	500	500	500
	NO (ppm)			1500	750	750	750
Light buses (LPG)	CO (%)			5	5	5	5
	HC (ppm)			700	700	700	700
	NO (ppm)			2000	2000	2000	2000

Fig. 2. Determination of RS cut points for high emitters. (**A** to **C**) Percentiles of instantaneous CO, HC, and NO emissions of Euro 2 passed and failed vehicles. Passed and failed vehicles are classified using twice the Euro limits as the thresholds. The percentiles are calculated from the second-by-second HKTET cycle test results. (**D**) RS high-emitting cut points for Euro 0 to 5 petrol and LPG vehicles.

Figure 2D shows that the final Euro 2 cut points adopted by HKEPD are 2% for CO, 500 ppm for HC, and 1500 ppm for NO, which are higher than the 99th percentile values in Fig. 2 (A to C). This is because RS cut points are conservatively defined to achieve zero false positives but not to avoid zero false negatives, which is critical for a government enforcement program. Note that an ideal zero-error cut point is not possible because of the snapshot measurement nature of RS and the high variations of instantaneous real-driving emissions. Trade-offs have to be made between missing true high emitters (i.e., false negatives) and avoiding false high emitters (i.e., false positives). The RS equipment serves to screen out the high emitters among the tremendous number of vehicles with zero false positives. The HKEPD high-emitter enforcement program imposes no punishment on vehicle owners but requests them to bring the vehicles to be tested on chassis dynamometers. RS screening and dynamometer testing play different roles in the enforcement program. Figure 2D also shows that the cut points are unchanged after certain Euro stages. This is mainly due to the same conservative definitions and the detection limits of RS, as well as the fact that Euro limits for some pollutants have not been further reduced in recent years. The high-emitting cut points for newer Euro standard vehicles could be tightened when more precise RS equipment is available.

In addition to the conservative definitions of cut points, a dual RS technique (fig. S2A) has been developed to further increase the accuracy of high-emitter identification. This means that only those vehicles emitting pollutants exceeding the cut points at both the upstream and downstream RS systems (i.e., dual RS setup; fig. S2A) simultaneously are considered as high emitters. In the dual RS setup, the two RS systems are placed in 1-s separation distance under the average driving speed of a given measurement site so as to ensure that two different engine combustion conditions are measured. This is because most modern petrol and LPG vehicles use oxygen sensors and TWC convertors in a closed-loop control to achieve the emission standards. The air/fuel ratio shall be maintained at unity to keep high conversion efficiency of TWC converters, except under hard acceleration or cruising down the slope.

The closed-loop control on air/fuel ratio is relatively simple. An oxygen sensor measures the oxygen content upstream of the TWC in the exhaust manifold. It generates a high/low-voltage signal when the exhaust is rich/lean, which is used to adjust the quantity of fuel injection. Such control is a negative feedback so that engine operation oscillates between rich and lean alternatively to achieve a stoichiometric combustion on average. Meanwhile, normal operation of a TWC also oscillates between oxidation and reduction modes. In the oxidation mode, CO and HC are oxidized to CO_2 and H_2O using O_2 as the oxidizing agent. In the reduction mode, NO is reduced to N_2 and O_2 using CO as the reducing agent. The O_2 generated in the NO reduction is essential for the oxidation of the CO and HC. TWC functions normally only under the lean-rich oscillating mode. The response time of oxygen sensor switching from high to low output voltage has to be very fast, at a frequency higher than 1 Hz. Our research showed that the two emission factors measured by dual RS technique demonstrated little correlation (*31*), which proved the ability of the 1-s separation distance to capture exhaust emissions under different engine combustion conditions. Therefore, if both RS readings exceed the cut points, there is a high probability of failure from oxygen sensor and/or TWC, leading to a persistent high emitter. This justifies the necessity of a dual RS technique in achieving the aim of zero false positive in a government enforcement program.

Last, it is important to estimate the impact of the proposed RS enforcement method on the existing on-road vehicles. Table S3 shows the number of vehicles that would be detected as high emitters by using the cut points (Fig. 2D) and dual RS method (fig. S2A). On average, 3, 45, and 16% of the total private cars, taxis, and light buses would be identified as high emitters, respectively, in the survey year of 2012 (i.e., 2 years before the introduction of the enforcement program). The percentages of high emitters in the taxi and light bus fleets are much higher than that in the private car fleet, which further demonstrates the seriousness of the excessive emission problem of the taxis and light buses due to their extensive usage.

A double-blind test on 34 petrol and LPG vehicles was conducted using dual RS and HKTET dynamometer test and found zero false positive, whereas the percentage of false negative was 40%. Comparing the potential RS screening (table S3) with the dynamometer baseline survey (Fig. 1A) results, it is noted that the false negative is comparable to the double-blind test for taxis but higher for petrol cars. This is due to the fact that petrol car utilization is much lower than taxis so that the RS scans per petrol car (1.6 scans/year) are much lower than for taxis (5.9 scans/year) (*31*). To reduce the false negatives, the intensity of the RS scanning per vehicle type needs to be increased in the design of the enforcement program. In the Hong Kong enforcement program, the scan intensity is optimized for taxis of up to three concurrent RS sites per day.

Identification and rectification of engine faults

To establish a successful enforcement program, it is crucial that the automotive industry is able to repair the detected high emitters, which would otherwise be deregistered and thus cause large resistance for introducing such an emission-focused enforcement program. Traditionally, however, it is common that vehicle owners and mechanics mostly only focus on faults that influence safety, drivability, and fuel consumption performance but lack knowledge or interests on emission-related faults. This is because emission-related faults do not necessarily affect safety or drivability and sometimes may even improve power or/and fuel consumption performance (e.g., removal of some exhaust after-treatment devices). In addition, most emission-related faults are not visible except for smoke problems, which are rare for modern vehicles, making them hard to be found by vehicle owners and mechanics without emission test equipment. Therefore, it is necessary to investigate which engine faults have the highest impact on each pollutant so that mechanics can identify the possible faulty parts and repair them quickly when a high-emitting vehicle is detected in the RS enforcement program. To address this issue, the effects of various engine faults on fuel consumption, emissions, and drivability of a Euro 2 LPG taxi were investigated on a chassis dynamometer, which represented the dominant model of LPG taxis on Hong Kong roads in 2014 before the introduction of the RS enforcement program. The fuel supply system of this vehicle is carburetor cum port injection with high accuracy air/fuel ratio control, which can achieve up to Euro 4 standard when combined with emission control technologies (i.e., EGR, TWC, and oxygen sensors). Such after-treatment technologies are still widely adopted in modern vehicles for gaseous emissions control.

Table 1 shows the relative changes of emissions and fuel consumption performance with various engine faults when comparing with the baseline test. It clearly shows that some engine faults can greatly increase vehicle emissions, demonstrating the importance of having a properly maintained engine to achieve optimal fuel economy and emission standards. The exhaust system faults generally have the highest impact on all emissions, except for the fault of a closed EGR valve (i.e., no EGR), which reduces CO by 39% and HC by 45% but increases NO by 72%. In particular, the two oxygen sensor faults (i.e., inaccurate air/fuel ratio control) greatly increase HC, CO, and NO emissions by 249 to 317%, 150 to 410%, and 33 to 61%, respectively, and a worn TWC (i.e., reduced catalyst efficiency) results in 131, 211, and 178% increases of HC, CO, and NO, respectively. The three intake system faults also greatly increase the emissions, although they usually show opposite variations in CO and HC versus NO. The faults in ignition and fuel supply systems generally have insignificant impacts on or could even reduce the emissions, except for three fuel system faults that increase one specific emission noticeably: Rich vaporizer (i.e., fuel oversupply) increases CO by 276%; restricted main fuel supply line (i.e., fuel undersupply) increases NO by 352%, and restricted idle fuel supply line (i.e., fuel undersupply during idling) increases CO by 294%.

In terms of fuel economy performance, Table 1 shows that all the investigated engine faults increase fuel consumption rates, ranging from 3 to 16%. Last, the dynamometer tests demonstrate that vehicle drivability is not always negatively affected when emissions are increased by engine faults. The exhaust system faults generally have little impact on drivability, except for the fault of an open EGR valve (i.e., maximum EGR), which causes rough idle and acceleration. Two fuel system faults that affect drivability are the restricted main and idle fuel supply lines (i.e., fuel under-supply), which cause delayed acceleration response and rough idle, respectively. For the intake system, the fault of sticking throttle-body butterfly valve (i.e., delayed response of intake air) results in rough speed control, and the fault of sticking throttle-body idle control valve (i.e., delayed response of fuel supply during idling) produces rough idle. The ignition system faults cause misfire events and affect the drivability, while their impacts on emissions are moderate.

Table 1 clearly shows how different faults affect the vehicle emissions and fuel consumption. The results were used to develop research training workshops funded by HKEPD for the automotive industry groups and repair associations, including both technical seminars and laboratory demonstrations. They provided the industry with essential knowledge in repairing high-emitting vehicles that would be detected by an RS high-emitter enforcement program. Table 1 also proves that even a relatively old vehicle (>10 years old) could still achieve its emission standards if all engine components were functioning properly, which greatly enhanced the acceptance of an RS enforcement program.

In addition to the above industry training, it is possible that some high-mileage fleets may have large percentages of high emitters. This has been evidenced by the results in table S3 that 40 to 51% and 19 to 24% of the Euro 2 to 3 LPG taxis and light buses are considered as high emitters by using the proposed RS enforcement method. Therefore, great resistance would be expected from these fleet owners when introducing a high-emitter enforcement program. To address their concern, HKEPD acquired a HK$150 million budget from the Legislative Council to offer them a one-off subsidy for replacement of TWCs and oxygen sensors for all the taxis and light buses (*32*). The replacement program was carried out during August 2013 to April 2014. In total, 13,492 taxis and 2881 light buses participated in the program, reaching an overall coverage of 80%. These replacements received a 12-month warranty of the emissions performance and greatly eased the concern from the high-mileage fleet owners.

Implementation of RS enforcement program

HKEPD started implementing the RS enforcement program for petrol and LPG high emitters from 1 September 2014 (*29*). HKEPD chooses two to three measurement sites from more than 150 candidate sites (fig. S2B) for the enforcement program on each weekday when weather permits. This ensures a full coverage of the vehicles running in the city. Figure 3 shows the procedures of high-emitter identification in the enforcement program. The emissions and license plate number of a vehicle are measured twice when it passes by a dual RS site. The license plate number is used to obtain the registration information of the passing vehicle such as its fuel type, vehicle class, and emission standard, which are used to look up the RS high-emitter cut points (Fig. 2D). The measured emissions are compared with the cut points to determine whether the passing vehicle is high-emitting or not. Only those with two consecutive readings exceeding the cut points are considered as high emitters, which may fail only one pollutant or multiple pollutants simultaneously. Since the RS cut points are derived from the HKTET data, additional quality assurance measure is to only use measurements with speed and acceleration within the HKTET cycle conditions to avoid off-cycle high-emitting events (i.e., 7 to 90 km $hour^{-1}$ for speed and −5 to 3 km $hour^{-1}$ s^{-1} for acceleration). The owners of high-emitting vehicles identified by RS are notified with emission test notices (ETNs). The owners are required to repair and test/retest their vehicles at a designated vehicle emission test center within 12 workdays. The emissions of high-emitting vehicles are tested on a chassis dynamometer under the HKTET cycle and are required to meet the in-use vehicle emission limits, which are twice the type-approval limits. High-emitting vehicles that do not take or pass the HKTET within the 12-day limit will be delicensed and removed from roads.

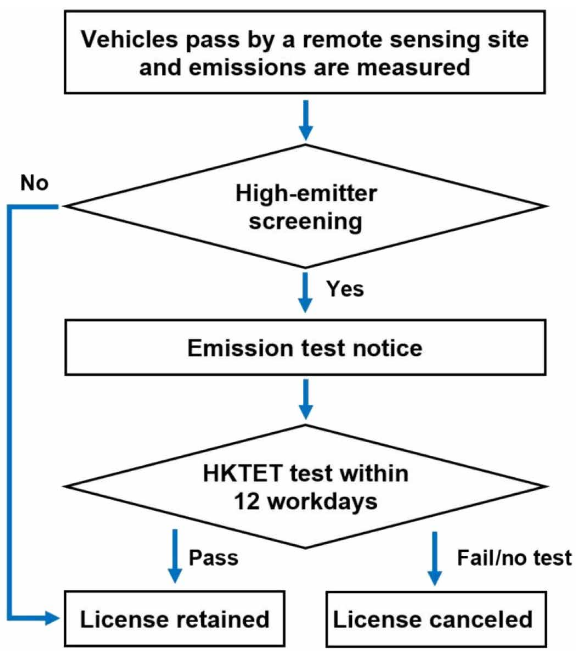

Fig. 3. Procedures of high-emitter screening in the Hong Kong RS enforcement program.

Evaluation of RS enforcement program

The RS enforcement program turned out to be very successful. It effectively solved the excessive emission problems from petrol and LPG vehicles, particularly the taxi and light bus fleets in Hong Kong. The effectiveness of the enforcement program on emission reduction is assessed using data from various sources (Fig. 4), including the HKEPD statistics, RS data, air quality monitoring stations, and air pollutant emission inventory.

Figure 4A shows the statistics of the RS enforcement program during 1 September 2014 to 31 December 2018. About 2.9 million vehicle counts have been measured in the enforcement program in 4 years. In total, 16,365 high-emitting LPG and petrol vehicles were identified by RS, which were issued with ETNs. Among them, 96% of the high emitters were successfully repaired and passed the following HKTETs. Only 1% of vehicles failed the HKTETs, and 2% of vehicles did not take the test, causing license cancelation of 558 vehicles.

The enforcement program greatly cleaned the taxi and light bus fleets. Table S4 gives the percentages of RS measurements that would be detected as high emitters in the survey year of 2016 (i.e., 2 years after the introduction of the enforcement program). Comparing with 2012 (table S3), the overall percentages of high emitters have been substantially reduced to 2%, 9%, and 8% for the private cars, taxis, and light buses, respectively. The reductions are much more obvious for taxis and light buses mainly because of the replacement program, as well as more high emitters being enforced in the following RS program. Figure 4 (B to D) further examines the variations of average emission concentrations of petrol and LPG vehicles measured by on-road RS from 2012 to 2018. The emissions data of the upstream RS system are used to derive the results in Fig. 4 (B to D). This is because the emissions of both the upstream and downstream RS systems converge to the same gamma distribution when sufficient measurements are used (i.e., >200) (*31*, *33*) so that both datasets have the same average emissions and trends for a large dataset (e.g., more than 1 million valid measurements in this study). As shown in Fig. 4 (B to D), petrol vehicles have much lower emission concentrations than LPG vehicles. This is because petrol vehicles are mostly private cars that are less driven and better maintained than LPG vehicles, which are all used for public transport in Hong Kong. The emissions of LPG vehicles reduce obviously from 2012 to 2015, as well as petrol vehicles. Comparing with 2012, the average emissions of LPG vehicles in 2015 are reduced by 38% for CO, 52% for HC, and 63% for NO. For petrol vehicles, the reductions are 48, 30, and 32%, respectively. Since 2015, the emissions generally remain low despite the fact that there are some slight fluctuations, which may be caused by the fast deterioration of oxygen sensors and TWCs of LPG vehicles (with annual mileage over 100,000 km). This clearly demonstrates the effectiveness of the replacement program (August 2013 to April 2014) and the RS enforcement program (since September 2014) in reducing the fleet-wide emissions. The one-off replacement program greatly cleaned the LPG vehicle fleets immediately. The following RS enforcement program further reduced the emissions and prevented the emissions bouncing back by continuously screening out high-emitting vehicles and facilitating fleet renewal.

Independent monitoring data from Air Quality Monitoring Networks in Hong Kong are used to assess the impact of the RS enforcement program on air quality. Improvement of roadside and ambient air quality could be attributed to various local vehicle

A

	Vehicle classes	Number of ETNs	Percentage
Emission test notices	Light goods vehicles	26	0.2%
	Private cars	4510	27.6%
	Light buses	940	5.7%
	Taxis	10,889	66.5%
	Total	16,365	100.0%
HKTET test results	Repaired and passed HKTET	14,529	96.3%
	License canceled because of failing HKTET	204	1.4%
	License canceled because of not taking HKTET	354	2.3%
	Total	15,087	100.0%

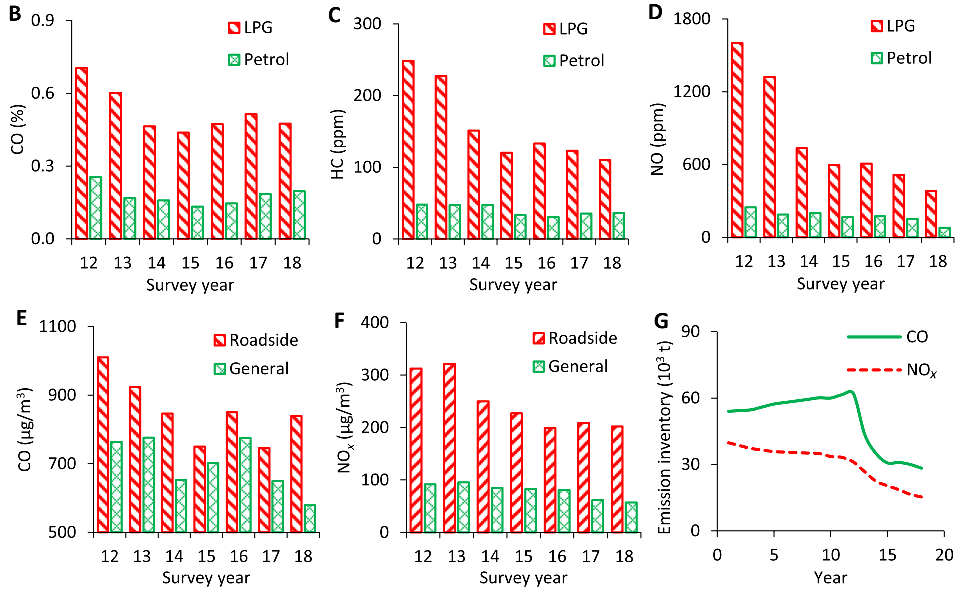

Fig. 4. Effectiveness of the Hong Kong RS high-emitter enforcement program. (**A**) Statistics on the enforcement program from 1 September 2014 to 31 December 2018. (**B** to **D**) Average CO, HC, and NO concentrations of petrol and LPG vehicles measured by RS from 2012 to 2018. (**E** and **F**) Average CO and NO_x concentrations measured by roadside and general air quality monitoring stations from 2012 to 2018. (**G**) Air pollutant emission inventories of CO and NO_x by road transport sector from 2001 to 2018.

emission control programs (e.g., phasing out pre–Euro IV diesel commercial vehicles, retrofitting Euro II and III franchised buses with selective catalytic reduction devices, and emission reduction from many pollution sources in the Great Bay Area) in addition to the RS enforcement program. The current study focuses on the potential benefit of CO and NO_x reduction from LPG and petrol vehicles. From engine combustion principles, CO mostly comes from petrol and LPG vehicles, while NO_x could come from all fuel types including diesel, petrol, and LPG. Figure 4 (E and F) shows the annual average concentrations of CO and NO_x measured by roadside and general air quality monitoring stations. The general stations measure the ambient air quality that may be influenced by multiple emission sources including vehicle emissions (*34*). In contrast, the roadside stations measure roadside air quality that is dominated by vehicle emissions. Therefore, air quality monitoring stations, especially the roadside ones, provide useful emissions data to access the effectiveness of vehicle emission control programs. As shown in Fig. 4 (E and F), the concentrations of both pollutants are obviously higher at roadside stations than at general stations because of their close proximity to motor vehicles. In general, the air quality variation trends in Fig. 4 (B to D) agree well with the vehicle emission trends observed in Fig. 4 (E and F), particularly for roadside air pollutant concentrations, which reduce quickly from 2012 to 2015 and then fluctuate slightly after 2015. For roadside air quality, CO and NO_x concentrations reduce by 26 and 27%, respectively, from 2012 to 2015. For ambient air quality, the corresponding reductions are 8 and 10%, respectively. These results demonstrate that the RS enforcement program is very effective in mitigating the roadside air pollution problem.

Last, the latest Hong Kong Air Pollutant Emission Inventory (Fig. 4G) reported that CO and NO_x emissions from the road transport sector reduced much more quickly by 50 and 34%, respectively, in only 3 years during 2012–2015 than the previous one decade of 2001–2011 during which CO increased by 3% and NO_x reduced by only 14%, although the vehicle kilometers traveled are increasing year by year (*35*).

Challenges and future perspectives

The current RS enforcement program has effectively addressed the excessive emission problems from petrol and LPG vehicles, particularly for the high-mileage fleets such as taxis and light buses. However, there are some challenges and limitations in further improving the emission performance of on-road vehicles.

First, as discussed in Fig. 2D, the cut points are relatively high, which are to achieve zero false positive and are mainly limited by the accuracy of the current RS systems. Newer vehicles, especially after Euro 5, are much cleaner and more reliable than older vehicles. As a result, the conservatively high cut points can only detect very few of the worst high emitters for enforcement, which significantly constrains the effectiveness of the enforcement program in controlling emissions from newer vehicles. To tighten the cut points for newer vehicles, a new-generation RS system with lower detection limits will be needed, which is under development.

Second, current RS systems adopt a horizontal optical configuration, which limits their application to single-lane roads. This ensures that the measured emissions are well resolved for each passing vehicle and avoids the effect of interlane interference due to vehicle- and wind (especially side wind)–induced turbulence on the measurements. However, such a horizontal configuration limits site selection and measurement efficiency, with the most suitable sites at highway on-ramps, which are usually single-lane roads with slight uphill grades and large traffic flows. A highway on-ramp only captures a small proportion of all vehicles running on the highway. To achieve a large/full fleet coverage, RS systems need to be deployed at many sites across a city. In the case of the HKEPD enforcement program, more than 150 candidate RS sites have been identified and two to three sites are used for measurements per day. Choosing many sites simultaneously in 1 day would be too costly because RS systems require constant human supervision on-site (e.g., calibration every 2 hours). One promising solution to greatly improve the measurement efficiency is to use a vertical optical configuration, which enables measurements on multilane roads. In particular, setting up vertical RS systems at a strategic location can achieve a much larger fleet coverage, which substitutes the regular rotation of the deployment of a horizontal RS system over different locations. Ropkins *et al.* (*36*) investigated the performance of a vertical RS system and reported that the vertical system demonstrated high sensitivity and linearity under various vehicle speed conditions.

Furthermore, the current HKEPD enforcement program does not include diesel vehicles, which are a major contributor of NO_x and particulate matter (PM) emissions, although they only account for a small proportion of the total vehicles (*1*, *37*, *38*). The current enforcement method may generate many false detections of diesel high emitters due to several factors. First, current high-emitter identification method uses cut points in concentrations (Fig. 2D), which are available for petrol and LPG vehicles in RS data but not for diesel vehicles. This is because diesel engines operate in a lean combustion mode (i.e., nonpremixed compression ignition flames), which is very different from the stoichiometric combustion mode of petrol and LPG engines (i.e., premixed spark ignition flames). For petrol and LPG engines, it is valid to assume that there is no excess oxygen in the exhaust and the CO_2 concentration is usually around 15% so that the absolute CO, HC, and NO concentrations can be calculated from the emission ratios measured in RS (*39*). On the other hand, the CO_2 concentrations of diesel engines can vary in a large range from 2% at idle to 10 to 12% at full power. Thus, using the same calculation method for petrol engines may significantly overestimate the absolute pollutant concentrations for diesel engines, resulting in false high-emitter detections. To solve this problem, the diesel high-emitter cut points should be defined by a different method that does not rely on the assumption of no excess oxygen in exhaust gas, such as using emission ratios or fuel mass-based emission factors. A previous study showed that the NO/CO_2 ratios of high-emitting and clean diesel vehicles demonstrated clear differences (*40*), indicating that defining cut points in emission ratios is feasible to screen out diesel high emitters. There is also a practical issue with diesel NO/CO_2 ratio during high-speed high-load deceleration. Since NO formation relates to the abundance of oxygen at high temperature, fuel cut-off during rapid deceleration will produce extremely high NO/CO_2 ratios due to much reduced CO_2 while the combustion chamber is still at high temperature. Future diesel RS must be capable of quantifying CO_2 in the exhaust to filter out such erroneous high ratios. NO/CO_2 ratios for clean diesel vehicles also tend to be much higher under light load conditions. Such false positives could be avoided by not using RS measurements when vehicle speed and acceleration are lower than specific values or when vehicle is under deceleration at high speed.

The second challenge is that pollutant concentrations are very low even for the highest diesel emitters, posing a great challenge for reliable RS measurements. As shown in Fig. 2 (A to C), the 99% emission percentiles of LPG high emitters are about 8% for CO, 800 ppm for HC, and 3400 ppm for NO, which can be readily measured by current RS systems. In comparison, the 99% emission percentiles of diesel high emitters were only about 0.3% for CO, 15 ppm for HC, and 600 ppm for NO (*22*). Such low concentrations are very close to the detection limits of current RS systems, which are 0.15% for CO, 150 ppm for HC, and 225 ppm for NO (or ±15% of the readings, whichever is larger) (*41*). This implies that future RS enforcement program on diesel vehicles should only target NO emissions, which are more detectable for RS, as well as the major concern of urban air pollution.

Other challenges of detecting diesel high emitters include diverse tailpipe arrangements and hot exhaust gases of heavy-duty diesel vehicles. Petrol and LPG vehicles are mainly light-duty vehicles and usually install their tailpipes at the rear bottom, whose emissions can be well captured by horizontal RS system placing at an average tailpipe height. However, the tailpipes of many heavy-duty diesel vehicles are positioned vertically upward, whose emissions cannot be captured by horizontal RS systems. A promising solution would be vertical RS systems that can measure both bottom- and top-arranged tailpipes. Besides, heavy-duty diesel vehicles produce large amounts of hot exhaust gases, which can significantly heat up the air after tailpipe exit. This heating effect may have a significant effect on the absorption of infrared and ultraviolet beams in RS measurements, producing high emission readings from clean vehicles. This temperature effect requires further research to determine the optimal measurement region for RS.

MATERIALS AND METHODS

Chassis dynamometer testing

Chassis dynamometer tests were conducted under the HKTET cycle (fig. S1). HKTET is a 200-s transient chassis dynamometer test, which is the emission test for in-use vehicles in Hong Kong, i.e., vehicles screened out as high emitters by RS are required to be repaired and pass this test to prove compliance. HKTET provides a fast, reliable, and cost-effective method to measure the emissions of in-use vehicles, which aligns with the common practices of inspection and maintenance programs worldwide. The detailed HKTET testing method and its suitability are described in text S1.

To survey the baseline emission levels of in-use vehicles, 340 Euro 0 to 4 petrol cars and 121 Euro 2 to 4 LPG taxis were recruited for the HKTETs during 2007–2009. Another 563 LPG taxis were recruited for a pilot repair demonstration program from October to December 2011, of which the effectiveness was evaluated by HKTETs as well. The sampling size followed the Euro standard composition of the taxi fleet. LPG taxis are targeted because they are the most heavily used vehicles, which may accumulate an annual mileage of over 100,000 km so that their emission control systems deteriorate quickly (*42*, *43*). Consequently, LPG taxis are considered a key contributor to the urban air pollution problem, although they only account for a small percentage of the total fleet. In addition, these LPG taxis share the same engine type (i.e., spark ignition engines) and emission control systems (i.e., EGR, oxygen sensors, and TWCs) with petrol vehicles.

In particular, one LPG taxi was further tested to investigate the effect of various engine faults on the emissions, fuel consumption, and drivability performance. The studied faults included those commonly seen in the air intake, fuel supply, ignition, and exhaust systems of an LPG vehicle (table S1). The tests aimed to identify the engine faults that had the highest impact on emissions. This provided essential knowledge to the vehicle owners and automotive repair industry when dealing with emission-related problems, which did not receive much attention previously. A fault was simulated by either mechanically disabling/disconnecting the component, replacing with a faulty component, or feeding an artificial false electric signal. The vehicle was first tested under the HKTET cycle with all engine systems functioning correctly (achieved by a thorough maintenance), which served as the baseline for comparison. Then, the engine faults were tested one at a time to isolate the effect of each fault. More details on engine fault testing can be found in (*38*, *44*).

On-road RS

Vehicle emissions under real-world driving are highly dynamic (*14*, *45*, *46*). To enhance the accuracy of high-emitter identification, a unique dual RS method is developed (fig. S2A). The emissions (i.e., CO_2, CO, HC, and NO), driving conditions (i.e., speed and acceleration), and license plate number (for obtaining vehicle registration information) are measured twice when a vehicle passes by an RS site. The detailed dual RS measurement method is described in text S2.

HKEPD started continuously monitoring vehicle emissions using on-road RS technology since 2012. More than 2.6 million petrol and LPG vehicles had been measured with matched license plate numbers in a 7-year continuous measurement program from 2012 to 2018. Table S2 shows the characteristics of the sampled vehicle fleets. A pair of emission records is considered valid if the following two criteria are satisfied. First, sufficient CO_2 exhaust gases are measured by both RS systems. Second, the vehicle driving conditions when passing by both RS systems are matched with the HKTET cycle conditions (i.e., speed within 7 to 90 km $hour^{-1}$ and acceleration within −5 to 3 km $hour^{-1}$ s^{-1}). This is to eliminate high emissions due to off-cycle driving conditions and thus to increase the accuracy of high-emitter identification. After applying these two criteria, 1,057,913 pairs of valid emission records are obtained from the whole dataset, including 661,003 petrol and 396,910 LPG vehicles.

Air quality monitoring

HKEPD is currently deploying an air quality monitoring network to continuously measure the concentrations of criteria pollutants hourly, including CO, NO_x, O_3, SO_2, PM_{10}, and $PM_{2.5}$. The air quality monitoring network consists of three roadside and 15 general air quality monitoring stations, which monitor the roadside and ambient air quality, respectively. Pollutants relevant to this study are CO and NO_x, for which on-road vehicle emissions are a major contributor. NO_x emissions are measured by the chemiluminescence method using commercial instruments of T-API 200A, T-API T200, or TECO 42i. CO emissions are measured by the nondispersive infrared method using T-API 300, T-API T300, or TECO 48C. More details about the air quality monitoring network can be found in (*34*, *47*), including the monitoring locations, accuracy performance, and instrument calibration.

SUPPLEMENTARY MATERIALS

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