Characterisation of diesel vehicle emissions and determination of remote sensing cutpoints for diesel high-emitters

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Abstract

Diesel vehicles are a major source of air pollutants in cities and have caused significant health risks to the public globally. This study used both on-road remote sensing and transient chassis dynamometer to characterise emissions of diesel light goods vehicles. A large sample size of 183 diesel vans were tested on a transient chassis dynamometer to evaluate the emission levels of in-service diesel vehicles and to determine a set of remote sensing cutpoints for diesel high-emitters. The results showed that 79% and 19% of the Euro 4 and Euro 5 diesel vehicles failed the transient cycle test, respectively. Most of the high-emitters failed the NO limits, while no vehicle failed the HC limits and only a few vehicles failed the CO limits. Vehicles that failed NO limits occurred in both old and new vehicles. NO/CO_2 ratios of 57.30 and 22.85 ppm/% were chosen as the remote sensing cutpoints for Euro 4 and Euro 5 high-emitters, respectively. The cutpoints could capture a Euro 4 and Euro 5 high-emitter at a probability of 27% and 57% with one snapshot remote sensing measurement, while only producing 1% of false high-emitter detections. The probability of high-emitting events was generally evenly distributed over the test cycle, indicating that no particular driving condition produced a higher probability of high-emitting events. Analysis on the effect of cutpoints on real-driving diesel fleet was carried out using a three-year remote sensing program. Results showed that 36% of Euro 4 and 47% of Euro 5 remote sensing measurements would be detected as high-emitting using the proposed cutpoints.

Keywords: Emission factors; Transient chassis dynamometer; Real driving emissions; High-emitters identification

1. Introduction

Ambient air pollution is a major health hazard to the public globally. The World Health Organization (WHO, 2019) data showed that 91% of the world population was living in places where the air quality did not meet the WHO guideline levels, causing 4.2 million premature deaths worldwide in 2016. Motor vehicles, especially diesel vehicles, are the main source of air pollution in our cities (Anenberg *et al.*, 2017; HKEPD, 2019b). Air pollution at street level poses direct adverse health impact on local residents and road-users (e.g. pedestrians, drivers and bicycle riders), and is linked to many diseases (Chen *et al.*, 2018; Oldenkamp *et al.*, 2016; Zhong *et al.*, 2016). It was estimated that ~110000 global premature deaths were caused by the emissions of on-road diesel vehicles in 2015 (Anenberg *et al.*, 2017).

To control vehicle emissions, three main legislative elements are needed, including type approval, conformity of production and in-service conformity (Vlachos *et al.*, 2014). Type approval is to ensure that a single engine or vehicle can meet the regulatory requirements in the design stage. Conformity of production is to ensure that all manufactured engines or vehicles can meet the type approval specifications. In-service conformity is to ensure that vehicles can comply with standards when running on roads. The first two elements are only the responsibility of the manufacturers, which are the current focus of regulations. In-service conformity involves both manufactures (e.g. durability requirements of engines/vehicles) and users (e.g. proper services, maintenance and repairs of engines/vehicles). A recent study showed that potential engine malfunctions due to wear-and-tear and improper maintenance could increase tailpipe pollutant emissions by up to 16 times (Huang *et al.*, 2019). In-service conformity is an essential element to achieve the air quality targets but is not well covered by current regulations.

On-road remote sensing technology is an effective, economic and rapid method to monitor and control the emissions from in-service vehicles (Beaton *et al.*, 1995; Burgard *et al.*, 2006; Huang *et al.*, 2018c). Remote sensing does not interfere with driving and can measure a large number of vehicles (typically thousands of vehicles per day) at a relatively low cost (Burgard *et al.*, 2006), as only a half second is needed for a measurement when a vehicle passes by a measurement site. Remote sensors are placed at the vehicle tailpipe height at roadside and the emissions are measured by the attenuation of infrared (IR) and ultraviolet (UV) beams through the exhaust plume of the passing vehicle (Huang *et al.*, 2018c; Huang *et al.*, 2018d). The emissions data can be used to determine if the passing vehicle complies with or exceeds the emission standard, and thus implement targeted emissions control programs such as inspection and maintenance (I/M). The Hong Kong Environmental Protection Department (HKEPD) pioneered using on-road remote sensing as a legislative tool to detect high-emitting vehicles for enforcement purposes from 1 September 2014 (HKEPD, 2018). If a vehicle is detected as a high-emitter by remote sensing, an Emission Testing Notice will be issued to the owner to require the vehicle be serviced/repaired and tested at an authorised Emission Testing Centre within 12 working days. The vehicle is required to pass a short transient chassis dynamometer emission test. If a vehicle failed the test, the licence would be cancelled and the vehicle would be removed from the road. The program has been proven to be very effective in tackling the excessive emission problems of gasoline and liquefied petroleum gas (LPG) vehicles (Huang *et al.*, 2018c), and has caught the attention of other cities worldwide (Borken-Kleefeld and Dallmann, 2018; HKEPD Symposium, 2018). However, diesel vehicles, which are a major source of NO_x and particulate matter (PM) emissions and have caused serious air pollution problem, are not included in the current enforcement program. This is because a significant number of diesel high-emitters detected by a snapshot on-road remote sensing measurement would pass the following laboratory test (i.e. false high-emitter detections). It was inferred that the different combustion mechanisms between gasoline (stoichiometric premixed combustion) and diesel (lean non-premixed combustion) engines were the main reason (Huang *et al.*, 2018c).

Therefore further research is needed to investigate the emission characteristics of diesel vehicles, and to establish the potential correlation of measurement data between remote sensing (in-service conformity) and chassis dynamometer (type approval) for both pass and failed diesel vehicles. Chassis dynamometer testing provides the most comprehensive and accurate measurement for vehicle emissions (Huang *et al.*, 2018a) and is widely used for vehicle type-approval, emission certification and research.

Nakashima and Kajii (2017) investigated emission factors of six gasoline passenger cars using a chassis dynamometer. The results showed that nitrous acid (HONO) emissions from a warmed-up catalyst were higher than those of a cold catalyst, while CO, NO_x and HC emissions showed the opposite tendency. However, Louis *et al.* (2016) reported that cold-start urban cycles increased unregulated emissions by a factor of two, but reduced NO_2 by a factor of 1.3-6.0 than hot-start, based on chassis dynamometer tests of six gasoline and diesel passenger cars. Chassis dynamometer testing on two gasoline cars showed that HONO/NO_x ratio was in the range of 0.03%-0.42% with an average of 0.18% (Liu *et al.*, 2017). Huang *et al.* (2017) evaluated emission factors of CO, HC, NO_x and PM of 51 Euro 2-5 light-duty gasoline vehicles on chassis dynamometer and observed high percentages of high-emitters among Euro 2 and Euro 3 fleets. In investigating the PM characteristics of three diesel passenger cars using chassis dynamometer, Jung *et al.* (2017) reported that the total particle number decreased gradually and the size-segregated peak of particle number shifted to smaller particles with the increase of driving speed. Li *et al.* (2013) compared fine particle emissions of one light-duty gasoline vehicle between chassis dynamometer and on-road measurements. Overall, as reviewed above, the number of vehicles tested was generally small. To accurately evaluate the emissions of a fleet, a significantly large sample is needed. Pang *et al.* (2014) investigated the trends of volatile organic compounds from about 300 light-duty gasoline vehicles per surveillance program on chassis dynamometers. They found that although the percentage of malfunctioning vehicles decreased from 10% in 1995 fleet to 5% in 2003 fleet, their contribution to total fleet emissions increased from 16% to 32%. However, the tested vehicle fleets were relatively old, with model years ranging from 1995 to 2003.

This study was therefore conducted to evaluate the emission levels of in-service diesel light goods vehicles (LGVs), and to determine a set of remote sensing cutpoints for diesel high-emitters so that the remote sensing enforcement program could be expanded to all vehicles on roads. A large sample size of 183 Euro 3-5 diesel vans were also tested using a transient chassis dynamometer. The study provides insights into the emission levels of in-service diesel fleet and provides scientific proof to justify the necessity of an enforcement programme for diesel vehicles. Remote sensing cutpoints for diesel high-emitters are proposed based on this analysis. The accuracy and effect of the proposed cutpoints on real-world diesel fleet are also evaluated using both chassis dynamometer and remote sensing data.

2. Methodology

2.1. Transient chassis dynamometer testing

2.1.1. Test vehicles

Being a mega city, Hong Kong is prone to vehicle-derived air pollution, hence a total of 183 diesel LGVs (i.e. diesel vans) were recruited in this study. LGVs are the most popular diesel vehicles in Hong Kong. By April 2017, LGVs alone accounted for 50.4% (69836 out of 138555) of the total licensed diesel vehicles (Transport Department of Hong Kong, 2017). **Table 1** summarises the main characteristics of the test vehicles. The sample fleet consisted of 13 Euro 3, 90 Euro 4 and 80 Euro 5 vehicles. The majority of the test vehicles were the Toyota HiAce (160 vehicles), followed by Hyundai H1 (13 vehicles), Nissan Urvan (9 vehicles) and Ford Transit (1 vehicle). The selection of test vehicles represented the market shares of the current emission standards and vehicle models in Hong Kong. In October 2018, the number of licensed LGVs in Hong Kong was 29977 for Toyota HiAce, 7919 for Hyundai H1, 4267 for Nissan Urvan and 1317 for Ford Transit diesel vans. In addition, the remote sensing program (section 2.2) also showed that Toyota HiAce is the dominant diesel LGV model in daily use, accounting for 61% of the valid LGV emission records. Therefore, Toyota HiAce occupied the majority of the test sample fleet.

2.1.2. Experimental procedures

All the vehicles were tested on a Mustang MD150 all-wheel drive (AWD) chassis dynamometer under the Hong Kong Transient Emission Test (HKTET) cycle conditions (Commissioner for Transport, 2012). HKTET is a 200-second transient chassis dynamometer testing cycle. **Fig. 1** shows the speed profile of the HKTET cycle for vehicles with raw weight up to 2750 kg. The total cycle distance is 1969 m and the maximum speed is 90 km/h. The speed tolerance is ±2 km/h (a larger tolerance of ±2.5 km/h is allowed during phase change) and the time tolerance is ±1 second. HKTET is a highly simplified cycle, comparing with real-world driving (e.g. portable emission measurement system (PEMS) test) and type approval test cycles (e.g. worldwide harmonized light vehicle test procedure (WLTP)). However, HKTET, which correlates to New European Driving Cycle (NEDC), provides a fast and cost-effective method to determine if in-use vehicles comply with their respective emission standards such as those Euro 3 to 5 vehicles certified under NEDC. For such purpose, a large number of test vehicles are expected, which prohibits the use of PEMS or WLTP. HKTET is currently being used by the HKEPD for emission compliance check of in-use vehicles that emit excessively.

The equipment used for exhaust emissions testing was a Sensors Inc. SEMTECH EFM-HS for exhaust flow rate measurement, an EMS 5002/3 five-gas analyser for emission concentration measurement and a National Instruments data acquisition system for data recording. During each test, the second-by-second exhaust flow rate (kg/h) and emission concentrations of CO_2 (%), CO (%), HC (ppm) and NO (ppm) were measured. CO_2, CO and HC were measured by non-dispersive infrared (NDIR) with a solid state sensor; and NO and O_2 were measured by an electro-chemical cell. The accuracy specifications were 0.1% for O_2, 0.3% for CO_2, 0.06% for CO, 4 ppm for HC and 25 ppm for NO. The accuracy specifications of an EMS 5002/3 five-gas analyser are much lower than those of chemi-luminescence detector (CLD), non-dispersive ultra violet (NDUV) and flame ionization detector (FID) sensors. This equipment complies with BAR97 specifications defined by the California Bureau of Automotive Repair which is generally applied for I/M programs worldwide including Hong Kong. Therefore, using the equipment meets the study aim which is to determine if in-service vehicles comply or exceed their respective emission standards. For such high-emitting vehicles, the emission concentrations are relatively high and the accuracy of an EMS 5002/3 five-gas analyser is sensitive enough to measure their emissions. The measured NO data shows marked variation at different driving conditions and is considered suitable for pass/fail evaluation. The emission factors in g/km were calculated using the method defined in the Regulation No 83 of the Economic Commission for Europe of the United Nations (UNECE, 2015).

2.2. On-road remote sensing

A three-year remote sensing program from April 2014 to April 2017 was carried out in Hong Kong to obtain a large dataset of on-road diesel vehicle emissions (Huang *et al.*, 2018d). The program obtained 679454 records of diesel vehicle emissions with matched licence plate number, of which 350891 were LGVs.

A record was considered valid when the following two criteria were met. Firstly, the measured CO_2 exhaust plume size was sufficient to determine the emission ratios. Secondly, the driving condition was in the speed (≤ 90 km/h) and acceleration (-5 to 3 km/h/s) ranges of the HKTET cycle. This was because on-road remote sensing usually covered much wider driving conditions than the laboratory dynamometer test cycle. Therefore, remote sensing and dynamometer testing would have different average emission factors (Lee and Frey, 2012). To avoid off-cycle driving conditions and thus to reduce false high-emitter detections, only the remote sensing emission records with driving conditions within the HKTET ranges were used for analysis. The deceleration conditions were also included in this study, while previous studies usually excluded them when analysing remote sensing data (Carslaw *et al.*, 2011; Chen and Borken-Kleefeld, 2014, 2016). This is because the results in this study show that there is equal probability of being high-emitting whether decelerating or accelerating. Excluding deceleration conditions would omit a significant proportion of remote sensing data and thus reduce the number of high-emitters to be detected. The current remote sensing enforcement program for gasoline and LPG vehicles (HKEPD, 2018) also used data under both acceleration and deceleration conditions.

In total, 178792 valid records of diesel LGV emissions were remained. This database includes 49938 unique vehicles, which covers 72% of the LGVs registered in Hong Kong. On average, each LGV was measured for 3.6 times.

3. Results and Discussion

3.1. Overall emission characteristics

Fig. 2 shows the emission factors of the 183 test vehicles as a function of manufacture year. Each data point represents the cycle average emission factor of one test vehicle. The red lines represent the criteria of failed vehicles, which are defined as two times the respective European automotive emission limits by the HKEPD. This is reasonable as experimental data showed that the emission rates increased by about 100% with normal deterioration for vehicles up to 16 years old (Pang *et al.*, 2014). It should be noted here that the introduction of each emission standard in Hong Kong was about 2-3 years later than that in the European Union (Huang *et al.*, 2018b). Therefore, Euro 3, 4 and 5 standards here cover the manufacture years of 2003-2006, 2007-2011 and 2012-2016, respectively.

As shown in **Fig. 2(a)**, HC emission factors of all the test vehicles are well below the high-emitting criteria, even including the Euro 3 vehicles manufactured in 2005 and 2006. No obvious increase of emission factors is observed with the increase of vehicle age. Compared with HC, CO emission factors are closer to the red line, as shown in **Fig. 2(b)**. A few vehicles exceed the high-emitting criteria and most of them are 2007-2010 (Euro 4) vehicles, indicating a deterioration of the engine combustion and after-treatment systems with vehicle age. The generally low HC and CO emission factors of diesel vehicles are mainly attributed to the lean combustion mechanism (non-premixed/diffusion flames) of diesel engines.

However, NO emission factors show a clear increase with the increase of vehicle age, as shown in **Fig. 2(c)**. Moreover, a significant number of vehicles exceed the high-emitting criteria, including even the newest vehicles. This indicates the necessity of an I/M program for both old and new vehicles, as Hong Kong is facing serious air pollution of NO and O_3 emissions (HKEPD, 2019a; Huang *et al.*, 2018d). Unexpectedly, **Fig. 2(c)** shows an increase of NO emission factor from 2004 to 2008, in spite of the tightened emission standards and less deterioration/aging of 2007-2008 vehicles. This tendency agrees well with the observations in previous remote sensing studies, which reported an increase of diesel NO emissions during a certain period of manufacture years (Bishop *et al.*, 2013; Carslaw *et al.*, 2011; Chen and Borken-Kleefeld, 2014; Huang *et al.*, 2018b; Huang *et al.*, 2018d; Lau *et al.*, 2012; Pujadas *et al.*, 2017). It was reported that NO emissions of diesel LGVs increased significantly from Euro 3 to 4 standard due to the change from in-direct injection (IDI) to direct injection (DI) technology in the fuel injection system, which improved the engine torque and fuel economy performance but the trade-off was an significant increase in NO emissions (Huang *et al.*, 2018d).

Table 2 shows the number of failed vehicles for different emissions. Using two times the respective standard limits as the criteria, one Euro 3, 71 Euro 4 and 15 Euro 5 vehicles have failed the HKTET test. They account for 8%, 79% and 19% of the Euro 3, 4 and 5 diesel vehicle fleets, respectively. The percentage of high-emitters increases significantly from Euro 5 to 4. However, the percentage of Euro 3 high-emitters is lower than that of Euro 4 high-emitters. This is mainly because the NO emission limit has been tightened greatly from Euro 3 to 4 standards, as shown in **Fig. 2(c)**. 85% of Euro 3 vehicles would fail if applying the same NO high-emitting limit as Euro 4.

Table 2 also shows that the majority of high-emitting vehicles (75) fail the NO limits. No vehicle fails the HC limits and only six vehicles fail the CO limits. In addition, there is little correlation of diesel high-emitters between CO, HC and NO emissions. Only six vehicles fail both the CO and NO limits, while no vehicle fails other emission limit combinations (i.e. CO & HC, HC & NO, and CO & HC & NO). This is due to the different/conflicting emission formation mechanisms where HC and CO are results of unburnt and incomplete combustion respectively (mainly rich fuel combustion) while NO is formed in high-temperature rich-oxygen condition (slightly lean fuel combustion) (Huang *et al.*, 2015).

3.2. Remote sensing cutpoints for diesel high-emitters

Remote sensing technology uses a snapshot measurement to determine if a passing vehicle is clean or high-emitting. However, the transient emissions of vehicles are highly variable. It is important to recognize that a vehicle with high instantaneous emissions does not necessarily mean that it is a permanent high-emitter. Clean vehicles may have high emissions occasionally, such as during load change conditions. To ensure the confidence of high-emitters determination by remote sensing, a key procedure is that the cutpoints should be safely above the emission levels of clean vehicles while still capture as many high-emitting vehicles as possible. Therefore, the remote sensing cutpoints are defined as the highest instantaneous emission levels of vehicles that could still pass the HKTET test. In practical implementation of remote sensing enforcement program, other procedures to ensure the confidence of high-emitters determination include: 1) using remote sensing readings only within the speed and acceleration ranges of the HKTET cycle to avoid off-cycle emissions; and 2) using two units of remote sensing systems with one second distance in between, and both measurements must above the cutpoints.

Only NO remote sensing cutpoints are investigated in this study due to the following reasons. Firstly, as shown section 3.1, most high-emitting vehicles fail the NO limits, while no vehicle fails HC and only a few vehicles fail CO. Secondly, CO and HC concentrations of both pass and failed diesel vehicles are relatively low, which are under the measurement uncertainty of the remote sensing device (Huang *et al.*, 2018c). Thirdly, HC and CO concentrations of failed vehicles are not significantly different to those of pass vehicles (Huang *et al.*, 2018c), and thus determining whether a vehicle is clean or dirty becomes difficult/impossible with one snapshot remote sensing measurement. Finally and most importantly, NO emissions are the most significant concern for their role in the formation of harmful ozone, smog and acid rain which are the main air pollution problems in Hong Kong (HKEPD, 2019a; Huang *et al.*, 2018d), as well as many other megacities worldwide (Grange *et al.*, 2017).

Finally, cutpoints are expressed in relative concentration ratio of NO/CO_2 (ppm/%) which is the only measured parameter in a remote sensing system (Burgard *et al.*, 2006). Absolute NO concentration can be calculated based a key assumption that the engine is running under stoichiometric or rich conditions with no excess oxygen in the exhaust. This is true for the gasoline and LPG (or spark ignition) engines, but not for diesel (or compression ignition) engines. This is believed to be a main reason leading to the issue of frequent false detection of diesel high-emitters (Huang *et al.*, 2018c).

Fig. 3 shows the NO/CO_2 percentiles of pass and failed vehicles. Euro 3 vehicles are not investigated as the sample size is small (13 vehicles) and they will be phased out by the local government soon (HKEPD, 2019c). As shown in **Fig. 3**, NO/CO_2 of failed vehicles is higher than that of pass vehicles at each percentile. The difference between failed and pass vehicles is much more significant for Euro 5 vehicles than Euro 4 vehicles. For Euro 4 vehicles, the 99th NO/CO_2 percentile of pass vehicles is 57.30 ppm/% which corresponds to the 73rd percentile of failed vehicles. However, for Euro 5 vehicles, the 99th NO/CO_2 percentile of pass vehicles is 22.85 ppm/% which corresponds to the 43rd percentile of failed vehicles. Using the definition discussed above, NO/CO_2 ratios of 57.30 and 22.85 ppm/% are chosen as the remote sensing cutpoints for Euro 4 and Euro 5 vehicles, respectively.

Fig. 4 shows the correlation of NO (ppm) with CO_2 (%) for both pass and failed Euro 4 and 5 vehicles. Each data point represents one-second measurement in the HKTET cycle test. The dashed lines indicate the remote sensing cutpoints derived from **Fig. 3**, which separate the data points into high-emitting (red points) and non-high-emitting (blue points) events. As shown in **Fig. 4(a)**, a few high-emitting events are observed under low CO_2 concentration (0-4%) conditions for Euro 4 pass vehicles, which are considered as false high-emitter detections (red points) because these vehicles will still be able to pass the HKTET test although high instantaneous NO/CO_2 ratios are detected. However, probability of such false detections is relatively low, which is only 1% (45 out of 4439 seconds total HKTET time). On the other hand, the high-emitting events of Euro 4 failed vehicles are observed in the CO_2 range of 0-10%, as shown in **Fig. 4(b)**. The change of high-emitter detection is 27% (3750 out of 13719 seconds) for Euro 4 failed vehicles.

For Euro 5 pass vehicles (**Fig. 4(c)**), false high-emitter detections (red points) occur under both low and high CO_2 conditions, and the probability of false detection is 1% (138 out of 13722 seconds). For Euro 5 failed vehicles, high-emitting events are concentrated in a smaller CO_2 range of 0-9% although a few high-emitting events are observed in the CO_2 range of 11-12%, as shown in **Fig. 4(d)**. The probability of high-emitter detection is 57% (1384 out of 2421 seconds) for Euro 5 failed vehicles.

Fig. 5 shows the probability of being high-emitting over the HKTET cycle. The probability is calculated by the number high-emitting events at each HKTET second over the total number of high-emitting events. Since each HKTET second corresponds to a specific driving condition (i.e. speed and acceleration, as indicated by the blue dotted line), **Fig. 5** gives information on the possibility of high-emitting events under different driving conditions. Unexpectedly, **Fig. 5** shows that the probability of being high-emitting is generally evenly distributed over the whole HKTET cycle from 0 to 200 s. This implies that no particular driving condition produces higher probability of high-emitting events, either accelerating, decelerating or idling. It should be noted here that **Fig. 5** shows the chance of instantaneous very high-emitting events (higher than the 99th percentile emission level of a clean vehicle) in one second, rather than the mean emission level over a longer test time under one driving condition. Although some driving conditions (e.g. acceleration and high driving speed) are believed to be more likely to have higher mean emissions, their probability of having instantaneous very high-emitting events is not higher than other conditions (e.g. deceleration, cruising and idling).

3.3. Impact of remote sensing cutpoints on real-world diesel fleet

Remote sensing can measure a large number of vehicles quickly and thus can have a large coverage of real-world vehicles. Therefore, remote sensing data is used here to evaluate the effect of the proposed remote sensing cutpoints on the real-world diesel fleet. **Fig. 6** shows the percentages of Euro 4 (2007-2011) and Euro 5 (2012-2015) high-emitters in the remote sensing records. By applying the cutpoints of 57.30 (Euro 4) and 22.85 (Euro 5) proposed in Section 3.2, 36% of Euro 4 and 47% of Euro 5 remote sensing measurements will be considered as high-emitting. Higher percentage of Euro 5 vehicles being detected as high-emitting is due to the fact that the difference of emission levels between pass and failed vehicles is more significant for Euro 5 than for Euro 4 vehicles, as shown in **Fig. 3**. Consequently, the proposed remote sensing cutpoints are able to screen out more Euro 5 high-emitters. **Fig. 6** also shows that the percentage of high-emitting records decreases for newer vehicles due to less deterioration/aging within each emission standard. It should be noted here that two units of remote sensing systems will be used in a practical enforcement program, and both readings must be over the cutpoints for high-emitters determination to increase the accuracy. Therefore, a much lower percentage of real-world vehicles would be identified as high-emitters.

4. Conclusions

This study evaluated the emission levels of in-service diesel LGVs and determined a set of remote sensing cutpoints for diesel high-emitters. A transient chassis dynamometer was used to test a large sample size of 183 diesel vans under the HKTET cycle conditions. The accuracy and effect of the proposed cutpoints were evaluated using both chassis dynamometer and remote sensing data. The major findings of this study are summarised as follows:

1) Using two times the standard limits as high-emitting criteria, 8%, 79% and 19% of the Euro 3, 4 and 5 diesel fleets would fail the HKTET test, respectively. Most of the high-emitting vehicles failed the NO limits, while no vehicle failed the HC limits and only a few vehicles failed the CO limits. Vehicles that failed NO limits occurred in both old and new vehicles, indicating that new vehicles should not be exempted from I/M programs. In addition, there was little correlation of diesel high-emitters between CO, HC and NO emissions.
2) The remote sensing cutpoints were defined as the highest instantaneous emission levels of vehicles that could still pass the HKTET test. Based on this definition, NO/CO_2 ratios of 57.30 and 22.85 ppm/% were chosen as the cutpoints for Euro 4 and 5 high-emitters, respectively. The cutpoints would capture a Euro 4 and Euro 5 high-emitter with a probability of 27% and 57% with one remote sensing measurement, respectively, while only producing 1% of false high-emitter detections.
3) The probability of high-emitting events was generally evenly distributed over the HKTET cycle from 0 to 200 s, indicating that no particular driving condition produced higher probability of instantaneous high-emitting events, whether idling, cruising, accelerating or decelerating.
4) Analysis on the effect of cutpoints on real-world diesel LGV fleet was carried out using a three-year remote sensing program. Results showed that 36% of Euro 4 and 47% of

Euro 5 remote sensing measurements would be detected as high-emitting using the proposed cutpoints.

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Table 1. Characteristics of the test vehicles.

	Euro 3	Euro 4	Euro 5
Number of vehicles	13	90	80
Mean odometer	305601 km	262996 km	115341 km
Manufacture year	2005 (7), 2006 (6)	2007 (14), 2008 (23), 2009 (14), 2010 (19), 2011 (20)	2012 (20), 2013 (25), 2014 (17), 2015 (17), 2016 (1)
Transmission	Automatic (9) Manual (4)	Automatic (63) Manual (27)	Automatic (71) Manual (9)
Vehicle model	Toyota HiAce (13)	Toyota HiAce (78) Hyundai H1 (5) Nissan Urvan (7)	Toyota HiAce (69) Hyundai H1 (8) Nissan Urvan (2) Ford Transit (1)

Note: Number in parenthesis indicates the number of test vehicles for that group.

Table 2. Number of failed vehicles for different emission criteria.

	Euro 3	Euro 4	Euro 5
Fail HC limit only	0	0	0
Fail CO limit only	0	3	3
Fail NO limit only	1	62	12
Fail CO & NO	0	6	0
Fail CO & HC	0	0	0
Fail CO & HC & NO	0	0	0
Total number of high-emitters	1	71	15
Percentage of high-emitters	8%	79%	19%

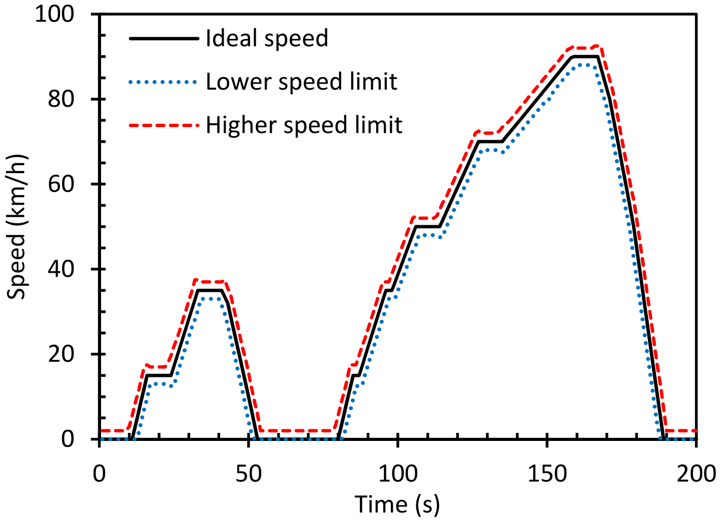

Fig. 1. The HKTET driving cycle for vehicles up to 2750 kg raw weight.

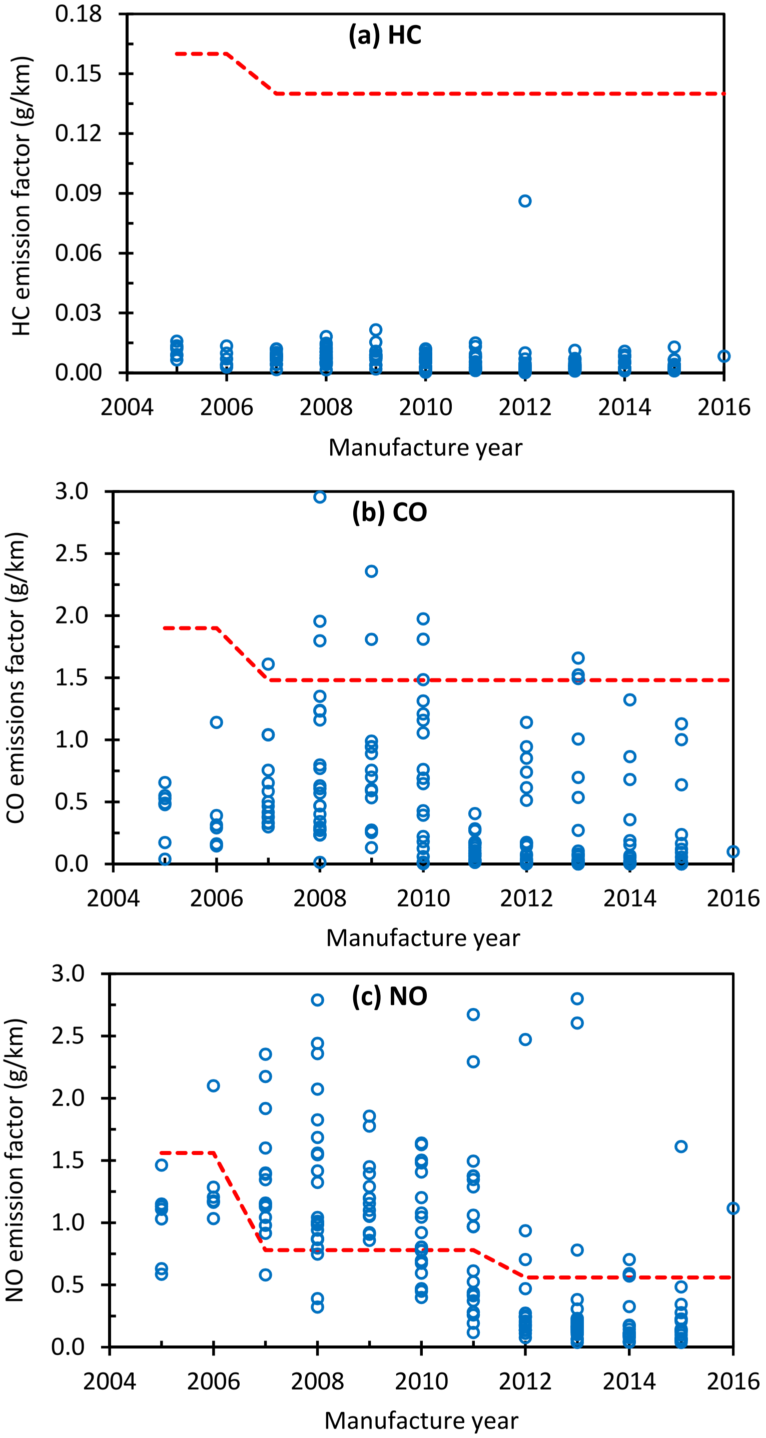

Fig. 2. Emission factors of HC (a), CO (b) and NO (c) as a function of manufacture year. Each data point represents the cycle average emission factor of one test vehicle. The dashed lines represent the criteria for vehicles to pass in Hong Kong, which are two times the respective European automotive emission limits.

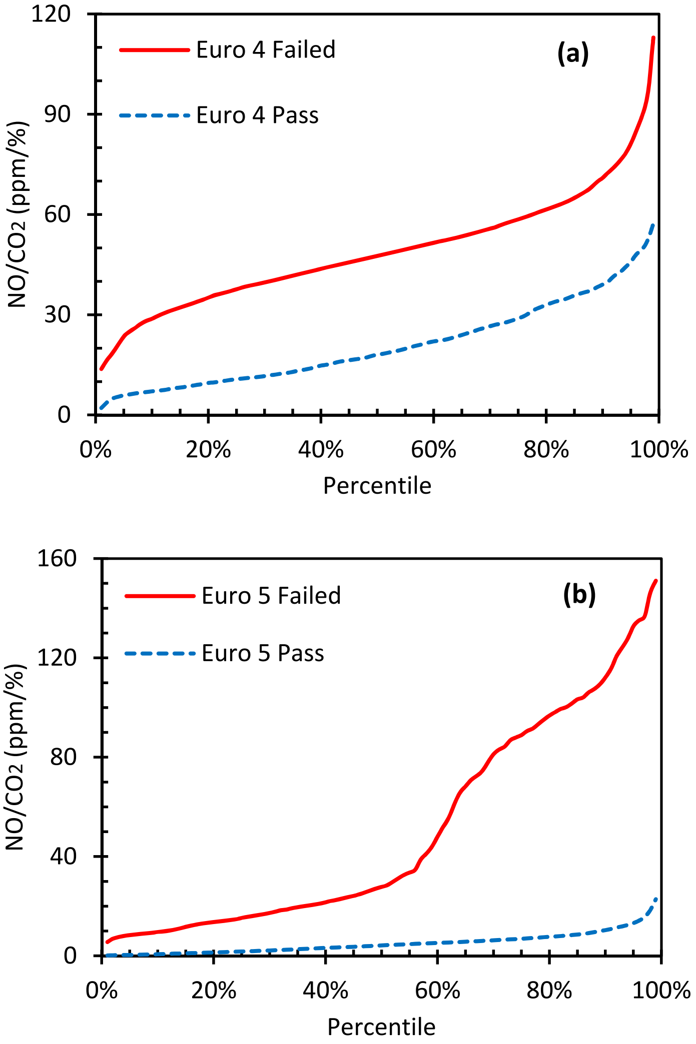

Fig. 3. NO/CO_2 percentiles of pass and failed vehicles in Euro 4 (a) and 5 (b) standards.

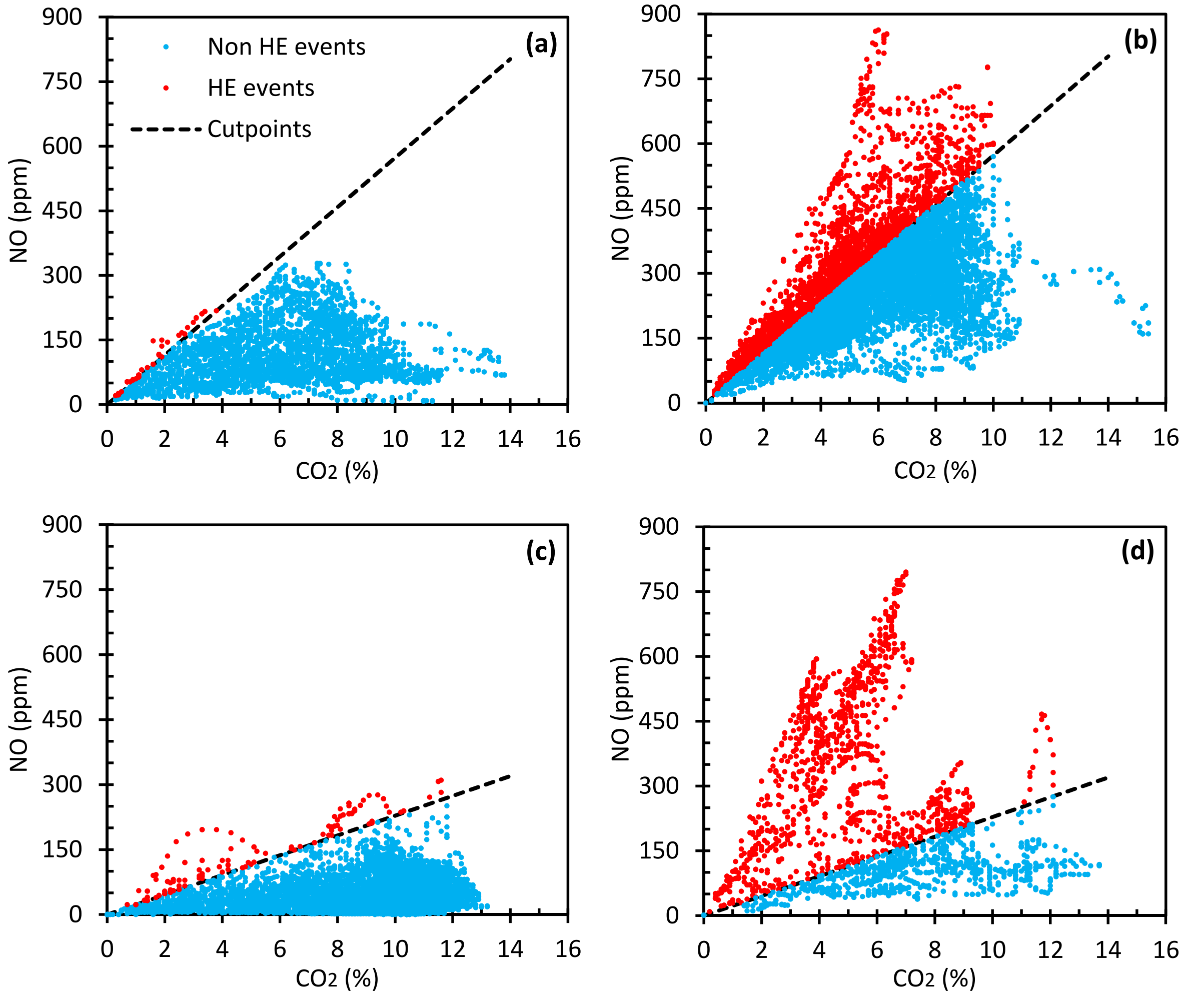

Fig. 4. High-emitting and non-high-emitting events in HKTET test cycle: (a) Euro 4 pass vehicles, (b) Euro 4 failed vehicles, (c) Euro 5 pass vehicles and (d) Euro 5 failed vehicles.

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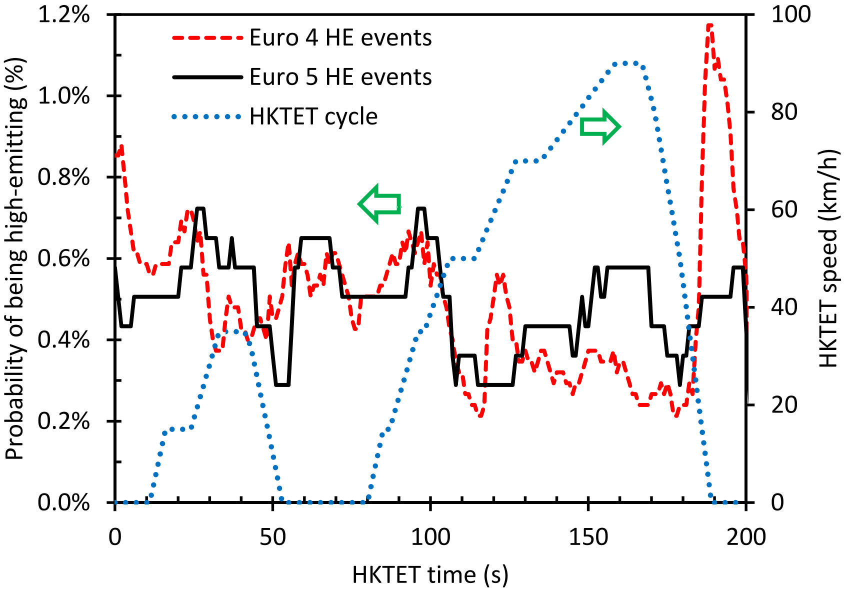

505 **Fig. 5.** Distribution of high-emitting events over the HKTET test cycle.

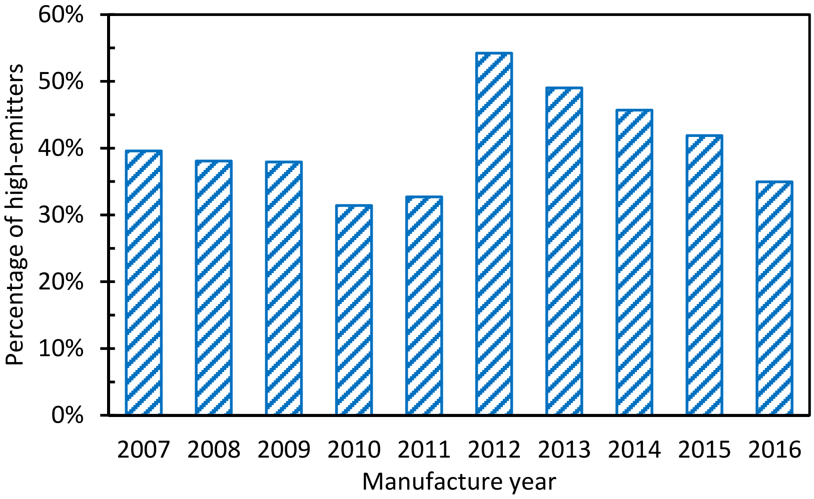

Fig. 6. Percentage of high-emitting remote sensing records as a function of manufacture year.