Tackling Nitric Oxide Emissions from Dominant Diesel Vehicle Models Using On-road Remote Sensing Technology

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Abstract

Remote sensing provides a rapid detection of vehicle emissions under real driving condition~~, and is emerging as an attractive emission control technology~~. Remote sensing studies showed that diesel NO emissions changed little or were even increasing in recent years despite the tightened emission standards. To more accurately and fairly evaluate the emission trends, it is hypothesized that analysis should be detailed for individual vehicle models as each model adopted different emissions control technologies and retrofitted the engine/vehicle at different time. Therefore, this study was aimed to investigate the recent nitric oxide (NO) emission trends of the dominant diesel vehicle models using a large remote sensing dataset collected in Hong Kong. The results showed that the diesel vehicle fleet was dominated by only seven models, accounting for 78% of the total remote sensing records. Although each model had different emission levels and trends, generally all the ~~seven~~ dominant models showed a steady decrease or stable level in the fuel based NO emission factors (g/kg fuel) over the period studied~~,~~ except for BaM1 and BdM2. A significant increase was observed for the BaM1 2.49 L and early 2.98 L models during 2005-2011, which we attribute to the change in the diesel fuel injection technology. However, the overall mean NO emission factor of all the vehicles was stable during 1991-2006 and then decreased steadily during 2006-2016, in which the emission trends of individual models were averaged out and thus masked. Nevertheless, the latest small, medium and heavy diesel vehicles achieved similar NO emission factors due to the converging of operation windows of the engine and emission control devices. The findings suggested that the increasingly stringent European emission standards were not very effective in reducing the NO emissions of some diesel vehicle models in the real world~~, and remote sensing provides a highly effective tool for detecting high-emitters~~.

Keywords: Nitric oxide; Emission factor; Diesel vehicles; Remote sensing; Real-driving emissions

Capsule

The European emission regulations were not very effective in reducing the NO emissions from some diesel vehicles in the real world.

1. Introduction

Nitrogen oxides (NO_x) emissions, which refer to the combination of nitric oxide (NO) and nitrogen dioxide (NO_2), are one of the major pollutants in the ambient air. NO_x emissions are usually produced from the combustion of fossil fuels via the thermal NO (or Zeldovich) mechanisms under high-temperature rich-oxygen conditions (Huang *et al.*, 2015). Motor vehicles, especially diesel vehicles, are the main source of NO_x emissions (Anenberg *et al.*, 2017; Font and Fuller, 2016; Suarez-Bertoa and Astorga, 2018). The majority of NO_x emissions (~ 90%) from uncontrolled diesel engines are emitted as NO which will later be oxidized into secondary NO_2 (Gentner and Xiong, 2017). Exposure to NO_x emissions has serious adverse health effects on human respiratory systems, including increased morbidity and mortality (Amster *et al.*, 2014). Therefore, NO_x emissions are strictly regulated in both air quality and automotive emission standards.

In Hong Kong, the Air Quality Objectives (AQO) define a maximum number of 18 exceedance for 1-h average NO_2 of 200 $\mu g/m^3$ per year and a maximum annual average NO_2 of 40 $\mu g/m^3$. However, like many other megacities around the world, Hong Kong has faced serious air pollution problem for many years in both street and regional levels (HKEPD, accessed 02.03.2018). Hong Kong has not fully achieved its AQO. In 2017, air quality data from roadside monitoring stations showed that the number of exceedance of the 1-h average NO_2 was 272 and the annual average NO_2 was 97 $\mu g/m^3$ in Causeway Bay, which were 15.1 and 2.4 times the AQO values, respectively (HKEPD, accessed 09.07.2018). Air pollution is a major challenge in Hong Kong and costs the city significantly. The Hedley Environmental Index estimated that air pollution had caused 1863 premature deaths, 2.71 million additional doctor visits and 22.4 billion HKD economic loss in 2017 (Hedley Environmental Index, accessed 29.03.2018).

One effective and economic tool for use in automotive emissions control is on-road remote sensing technology (Beaton *et al.*, 1995; Huang *et al.*, 2018b). Remote sensing is a non-intrusive technology that can measure a large number of vehicles at a relatively low cost (Burgard *et al.*, 2006). It measures the emissions of a vehicle in a half second when it passes by a measurement site. The instantaneous emissions of a vehicle under real-driving conditions are highly variable. As a result, such a snapshot measurement cannot fully represent the emission level of the passed vehicle. However, if the remote sensing readings exceed some conservative cutpoints concurrently in two sets of remote sensing equipment arranged in tandem, then the chance of this vehicle being a high-emitter is relatively high. Therefore, the emissions data can be used to determine if the passing vehicle is dirty or not, 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 gasoline and liquefied petroleum gas (LPG) vehicles for enforcement purposes since 1 September 2014 (Borken-Kleefeld and Dallmann, 2018; HKEPD, accessed 06.04.2018). The program has been proved to be effective in tackling the excessive emission problems of gasoline and LPG vehicles (Huang *et al.*, 2018b). However, the current remote sensing technology will likely produce significant false detections of diesel high-emitters. The underlying reasons include low pollutant concentrations and large variations in CO_2 (not stoichiometric or rich combustion) in the exhaust plume of diesel vehicles. Further research is being conducted to make the technology effective for the enforcement of diesel vehicles (Huang *et al.*, 2018b). Firstly, a new generation of remote sensing device with higher accuracy is under development. Secondly, the cutpoints for diesel high-emitters should be defined in concentration ratios (Q_P) or emission factors (g/kg fuel), rather than absolute concentrations (ppm or %) which are used in the current program.

Remote sensing is also a very useful tool to monitor and evaluate the effectiveness of various emissions control programs and technologies under real-driving conditions (Bishop and Haugen, 2018). Remote sensing data is widely used to analyze the trends of emission factors as a function of manufacture year. With a large remote sensing database, it can generate accurate results on the emission average and trends within a vehicle fleet (Ko and Cho, 2006). One unexpected and concerning finding from recent remote sensing studies was that NO emissions of diesel vehicles changed little or were even increasing in recent years in spite of the greatly tightened emission standards. Carslaw *et al.* (2011); Carslaw and Rhys-Tyler (2013) reported that there was little evidence of NO_x emissions (NO_x/CO_2) reduction from all types of diesel vehicles in UK over the past 15-20 years. Lau *et al.* (2012) observed an increase in the NO emissions (g/km) of light-duty diesel vehicles in Hong Kong during model years of 2002-2006. Bishop *et al.* (2013) found that the NO_x emissions (g/kg fuel) of heavy-duty diesel vehicles in California increased in 1990-1995. Bishop and Stedman (2015) reported that the NO_x emissions (g/kg fuel) of Los Angeles diesel truck increased in 1994-2004 and diesel passenger cars generally increased in 2002-2010. Chen and Borken-Kleefeld (2014) reported that the NO_x emissions (g/kg fuel) of diesel cars and light commercial vehicles in Zurich increased during model years of 1992-2003. Pujadas *et al.* (2017) reported that NO/CO_2 of the diesel cars in Spain increased from pre-Euro to Euro 2 and from Euro 4 to 5, and was unchanged from Euro 2 to 3. Huang *et al.* (2018a) found that the diesel NO emissions (g/kg fuel) in Hong Kong showed an unexpected increase for small vehicles (engine size ≤ 3000 cc) during 1999-2006, medium vehicles (3001-6000 cc) during 1997-2002, and large vehicles (≥ 6001 cc) during 1998-2004.

The above remote sensing all reported that the diesel NO emissions increased during specific periods. However, previous remote sensing studies usually averaged the emission factors of all the vehicles in the same manufacture year, regardless of the vehicle models. Although this provided a global picture of the whole fleet or a specific vehicle class, the real trends of individual vehicle models might have been masked and skewed as each model might have adopted different emissions control technologies and retrofitted the engine/vehicle at different time. This study shows that there are always a few dominant diesel vehicle models in each class and each model has very different emission levels and trends. The increase of NO emissions during a certain period is a model specific problem and is mainly caused by the different engine combustion and after-treatment technologies adopted. Therefore, analysis is needed to be detailed for individual vehicle models so as to fairly and accurately assess the emission trends and effectiveness of various emission standards and control technologies.

This study aims to evaluate the recent NO emission trends of diesel vehicles in Hong Kong using on-road remote sensing technology. A large remote sensing dataset containing 679454 records was collected in a three-year measurement program from April 2014 to April 2017. Analysis was performed to identify the dominant diesel vehicle models in each vehicle class and to investigate the trends of NO emission factors for each dominant model.

2. Data collection and treatment

In this study, 14 sets of ETC-S420 remote sensing systems were used to collect the vehicle emissions data. ETC-S420 is assembled in Hong Kong by the Environmental Technology Ltd. Co. according to the technical requirement of HKEPD. Some specific requirements of HKEPD on remote sensing measurement are 1) dual remote sensing set-up, 2) customized data filtering mechanism, 3) customized data filtering in automatic license plate recognition system, and 4) data structure integrated with HKEPD’s data validation system. These are vital to uphold the quality of HKEPD’s enforcement program to achieve zero error of commission. The hardware and operation mechanisms of ETC-S420 are very similar to that of most of the other remote sensing systems, such as AccuScan RSD5000 (RSD5000, 2017) and FEAT (Burgard *et al.*, 2006). ETS-S420 has been used by the HKEPD to detect gasoline and LPG high-emitting vehicles for enforcement since 1 Sep 2014 (HKEPD, accessed 06.04.2018).

Fig. 1 shows the setup of the remote sensing system at one measurement site. The system consists of infrared (IR) and ultraviolet (UV) beam sources and detectors, speed and acceleration sensors, a retroreflector and a vehicle plate camera. A measurement is triggered by the beam being blocked by a passing vehicle. ETC-S420 measures carbon monoxide (CO), carbon dioxide (CO_2) and hydrocarbon (HC) emissions in the IR region and NO emissions in the UV region. CO and HC are products of incomplete combustion. CO is toxic and HC is a major contributor to smog. Although CO_2 is the product of complete combustion and non-toxic, it is the most significant long-lived greenhouse gas in the atmosphere. Therefore, all these emissions are regulated in air quality and automotive emission standards.

Once the remote sensing system is triggered, it records the data at a frequency of 200 Hz and lasts for a half second. The system measures the difference between each pollutant's concentration in the ambient air before the car arrives and that in the exhaust plume ($\Delta P = P_{exhaust} - P_{ambient}$, where P indicates pollutant CO_2, CO, HC or NO). For each vehicle, the remote sensing system records 100 independent ΔP readings for each pollutant. Then, the system plots ΔCO, ΔHC and ΔNO against ΔCO_2. The least square slopes of these lines are the CO/CO_2, HC/CO_2 and NO/CO_2 ratios which are indicated by Q_{CO}, Q_{HC} and Q_{NO}, respectively. These concentration ratios are constant for a given exhaust plume (Bishop *et al.*, 1989; Burgard *et al.*, 2006). As remote sensing is an indirect measurement, it can only determine these relative ratios, but not the absolute concentrations. The measurement uncertainties are about ±15% of the readings. These ratios are very useful parameters for indicating the performance of a combustion system. The fuel based NO emission factors (EF_{NO}) in g/kg fuel can be calculated based on the principle of carbon balance using equation (1) (Bishop, 2014; Huang *et al.*, 2018b), in which 30 is the molecular weight of NO in g/mol and 0.014 is the molecular weight of diesel in kg/mol (assuming CH_2 for diesel). The fuel volume based EFs (g/L fuel) can be calculated if the fuel density is known, e.g. 0.85 kg/L for diesel (Chan and Ning, 2005). The distance based EFs (g/km) can also be calculated if the fuel economy factor (km/L fuel) is known for the vehicle (Lau *et al.*, 2012; Zhou *et al.*, 2014).

$$EF_{NO} = \frac{30}{0.014} * \frac{Q_{NO}}{1+Q_{CO}+6Q_{HC}} [g/\,kg\ fuel] \qquad (1)$$

Meanwhile, the speed, acceleration and license plate number of the passing vehicle were also measured. The vehicle information, including the brand, model, fuel type, manufacture year, engine size, vehicle class and gross weight, was obtained from the registration database of the Transport Department of the Hong Kong Special Administration Region (SAR) Government by using the license plate number. During the measurements, calibration checks were performed every two hours using span gases to ensure the data quality.

The measurements were taken at 158 sites across Hong Kong by the HKEPD from April 2014 to April 2017. The selection of a measurement site is based on the following criteria:

- 5-m width single lane traffic,
- slight uphill gradient,
- away from traffic lights or intersections to avoid hard acceleration/deceleration,
- vehicle speeds in the range of 7-90 km/h, and
- sufficient traffic volume.

The three-year measurement program obtained 679454 records of diesel vehicle emissions with matched licence plate numbers. A measurement was considered valid when the following criteria are met:

- measured CO_2 exhaust plume size was sufficient to determine the emission ratios (Carslaw *et al.*, 2011; Chen and Borken-Kleefeld, 2014, 2016), and
- driving conditions were within speed ~~(~~< 90 km/h~~)~~ and acceleration ~~(~~-5 to 3 km/h/s~~)~~ ~~envelopes~~ of the Hong Kong Transient Emission Testing (HKTET) cycle (Commissioner for Transport, 2012), which is the laboratory testing cycle for emission certificates for in-use vehicles in Hong Kong.

By applying the above criteria, 198690 records were invalid due to insufficient exhaust plume size and 166608 records were invalid due to speed or acceleration (some records were invalid for both criteria). Finally, 363287 (53%) valid records for 75450 unique vehicles were retained, which still represented a large sample of the on-road diesel fleet. The total number of licensed diesel vehicles in Hong Kong was 138555 by April 2017 (Transport Department of Hong Kong, 2017).

3. Results and discussion

3.1. Fleet characteristics

Table 1 shows the characteristics of the most measured diesel vehicle models in the three-year remote sensing program, ranked by the number of records. Hong Kong vehicles are certified to Euro standards. Unlike private petrol cars, there are always a few dominant diesel vehicle models in each class.

As shown in Table 1, for light commercial diesel vehicles, the dominant models are BaM1[†], BcM1 and BeM1, with 108559, 21573 and 12290 records, respectively. Their engine sizes are usually smaller than 3 L and the gross weight is within 3.5 t. These models are mostly used as light goods vehicles (LGV) in Hong Kong.

For medium commercial vehicles, the dominant models are BaM2 and BdM1, with 77727 and 20433 records, respectively. Their engine sizes are generally in the range of 4-6 L and the gross weight is from 4 to 10 t. These models are widely seen as public/private light buses (LB) and light/medium goods vehicles (LGV/MGV).

For heavy commercial vehicles, the dominant models are BbM1 and BdM2, with 38331 and 4408 records, respectively. Their engine sizes are larger than 7 L and the gross weight is over 15 t. These models are mostly used as public buses (PB) and MGV in Hong Kong.

These seven dominant vehicle models alone have contributed to 283321 valid remote sensing records, accounting for 78% of the total records. One vehicle model may have different engine sizes due to the retrofit of engine/vehicle. However, mostly, there is only one engine size for each dominant vehicle model in one year, as shown in Table 2. In the following section, the effect of manufacture year on the NO emission factors is investigated for the dominant diesel vehicle models identified in this section.

3.2. Emission trends

Fig. 2 shows the trends of the mean NO emission factors of the dominant light commercial vehicles, namely BaM1 (a), BcM1 (b) and BeM1 (c). Each data point contains at least 100 valid remote sensing measurements to ensure the statistical validity (Chen and Borken-Kleefeld, 2016; Huang *et al.*, 2018a). The NO emission factors reported in this study are in grams of NO per kg of fuel consumed (g/kg fuel). It should be noted that the emission factors of remote sensing (g/kg fuel, left y-axis in Fig 2a) and Euro standards (g/km, right y-axis in Fig. 2a) are different and thus cannot be compared quantitatively.

BaM1 is the most popular diesel vehicle model running on Hong Kong roads and entered the market since the late 1980s. As shown in Fig. 2a, the NO emission factor of 2.78 L model was stable during 1990-1996 and then decreased by 21% from 10.52 g/kg fuel in 1996 to 8.26 g/kg fuel in 1998. After 1998, the 2.99 L model entered the market and replaced the 2.78 L model, which further reduced the NO emission factors by 24% from 7.81 g/kg fuel in 1998 to 5.93 g/kg fuel 2004. In 2005, the 2.49 L model was introduced into the market. It exhibited a notably higher NO emission factor by 95% than the 2.99 L model in 2004 and increased from 2005 to 2006 although the NO_x limit was reduced significantly by 50% from Euro 3 (0.78 g/km) to Euro 4 (0.39 g/km). Its succeeding 2.98 L model had comparable emission levels to that of 2.49 L model, but decreased slowly by 8% from 2006 (12.40 g/kg fuel) to 2011 (11.37 g/kg fuel). However, the 2.98 L model showed a significant drop of 52% in NO emission factor between 2011 and 2012 (5.49 g/kg fuel), so that its emission factor became comparable to that of 2.99 L model. The NO emissions of 2.98 L model reduced further by 29% from 2012 to 2016. This significant drop could be explained by the introduction of a new Euro 5 BaM1 model in 2012 to replace the old Euro 4 model with an upgraded engine management system (the two engines were mechanically identical but with different injectors). In addition, the remote sensing system used in this study could only measure the NO. No account of NO_2 was made and one could not rule out any in cylinder formation of NO_2 or post combustion oxidation of NO although the Euro 4 and Euro 5 models are equipped with DOC and DOC+DPF respectively (Bishop *et al.*, 2010).

The ~~unusual~~ increasing trends of BaM1 2.49 L and early 2.98 L models would be caused by the different engine combustion and exhaust after-treatment technologies adopted in different generations. Table ~~2~~ 3 shows the specifications of all the BaM1 models running on Hong Kong roads. For manufacturing years between 1989 and 2004, the Euro 1-3 BaM1 models are installed with the EM1a[†], EM1b and EM1c engines, respectively. These EM1 series diesel engines adopted the indirect injection (IDI) technology. An IDI engine features a pre-chamber where the diesel is injected for initial ignition. The pre-chamber is connected to the main combustion chamber above the piston through a narrow passage. The compression ratio of an IDI engine has to be much higher than that of a direct ignition (DI) engine to achieve the desired air temperature for triggering ignition. The typical compression ratio of IDI and DI engines are 20~24:1 (e.g. EM1a, EM1b and EM1c) and 15~18:1 (e.g. EM2a and EM2b), respectively. The extra heat loss due to larger surface area-volume ratio in an IDI engine not only decreases the engine efficiency but also typically requires a glow plug for a cold start. The direct effect of lower efficiency is the lower torque of IDI engines. IDI technology was widely adopted for small diesel engines because of its good performance at high engine speeds. DI technology is a better choice for larger diesel engines that do not require high speed operation. The introduction of common-rail injection system allows small diesel engines to use DI technology. It is because the electronically controlled injection provides higher flexibility in controlling the diesel injection timing and duration, as well as a much higher and more precise fuel pressure to allow a much smaller nozzle size to improve fuel atomization.

Table ~~2~~ 3 shows that the more advanced DI engines with common-rail system (EM2a and EM2b) obviously offer a much better engine torque performance than the earlier IDI engines (EM1a, EM1b and EM1c). However, remote sensing data (Fig. 2a) shows that the EM2a and EM2b engines emit at least 80% higher NO than their predecessor (EM1c) in the real world. This is mainly caused by the different diesel fuel injection technologies adopted by the engines. EM2a and EM2b engines used the common-rail DI technology, while EM1c engine used the IDI technology. The common-rail system allows a flexibility in manipulating the engine map, and hence their torque curves can achieve a plateau over a range of engine speed to improve drivability. When making a use of this flexibility, one of the possibilities for the higher NO from the EM2a and EM2b engines than their predecessor EM1c is a tradeoff between torque and fuel economy performance and pollutant emissions of NO, CO, HC and PM for IDI and DI engines. The PM emissions may be a more significant concern when there is additional loading to the exhaust filtration devices. Huang *et al.* (2011) experimentally investigated the performance of two diesel engines of the same model except one was equipped with IDI technology and the other was equipped with DI technology. The results show that the NO_x and smoke emissions of the IDI engine were significantly lower than those of the DI engine. On the other hand, the DI engine showed better performance in terms of fuel consumption and thermal efficiency than the IDI engine did.

Irrespective of any reason, the significantly higher NO emission factors from Euro 4 BaM1 than its Euro 1-3 models shows ~~depicts~~ that the increasingly strengthened emission standards and its type approval mechanism under the European emission regulations were not very effective in reducing the NO emissions from diesel vehicles in the real world. Nevertheless, the Euro 5 BaM1 model emits less than half of NO when compared to its Euro 4 predecessor. Although the late Euro 4 and Euro 5 BaM1 model shared the same EM2b engine, the two engines are not identical in terms of engine management and exhaust after-treatment device. The improvement in NO emission from Euro 1 to 5 illustrated the continuous technology improvements, as shown in Fig. 2a.

The second most popular diesel light commercial vehicle model in Hong Kong is the BcM1 which started in the market in 2008. As shown in Fig. 2b, the NO emission factor of BcM1 decreased by 32% from 11.31 g/kg fuel in 2008 to 7.72 g/kg fuel in 2016 (the large error bars for manufacture year of 2016 are mainly due to the small number of measurements for those new vehicles). The emission level of BcM1 was comparable to that of early BaM1 2.98 L model during 2008-2011, but a significant decrease was not observed for BcM1 after 2011. As a result, the emission level of BcM1 was significantly higher than that of BaM1 2.98 L model after 2012.

BeM1 is the third most popular diesel light commercial vehicle model, which was introduced into Hong Kong in 2001. There were two sub-models for BeM1, namely 2.95 L

(2001-2011) and 2.49 L (2012-2016). As shown in Fig. 2c, the NO emission factor of the 2.95 L model decreased by 17% from 2001 (14.83 g/kg fuel) to 2006 (12.29 g/kg fuel), and then decreased significantly by 52% between 2006 and 2008 (5.96 g/kg fuel) before becoming stable during 2008-2011. The significant drop of 2.95 L model made its NO emission level comparable to that of the late BaM1 2.98 L model after 2008. Same as the BaM1 2.98 L model, this could also be explained by the introduction of new fuel injection and exhaust after-treatment technologies. The 2.49 L model replaced the 2.95 L model in 2012 and its emission level was kept stable during 2012-2016. Although the level is stable, the newest BeM1 model emit higher emission than BaM1 with the same model year. It should be noted that the emission factors of BeM1 were almost unchanged during 2008-2016 although the emission limit had been reduced by 28% form Euro 4 (0.39 g/km) to Euro 5 (0.28 g/km) during the same period. This again demonstrates that the increasingly stringent European emission standards were not very effective in reducing the NO emissions of some vehicle models during specific stages.

Table ~~3~~ 4 compares the specifications and emissions of the latest dominant Euro 5 diesel vans in Hong Kong. As shown in Table ~~3~~4, the real-world NO emission factors from Euro 5 diesel vans vary significantly among different brands. Table ~~3~~ 4 and Fig. 2 show that BcM1 and BeM1 emit noticeably more NO than BaM1 does although they are equivalent vehicles of the same age, identical Euro 5 emission standard, and similar body type and vehicle weight. The remote sensing data also shows an emission deterioration from 3.9 to 5.5 g/kg fuel for BaM1 vehicles from 1 to 5 years old (Fig. 2a), from 7.7 to 11.5 g/kg fuel for BcM1 vehicles (Fig. 2b), and from 5.2 to 5.9 for BeM1 vehicles (Fig. 2c). In comparison, the emissions control system of BcM1 deteriorates more quickly than those of BaM1 and BeM1.

Fig. 3 shows the NO emission factor trends of the two dominant diesel medium commercial vehicle models, namely BaM2 (Fig. 3a) and BdM1 (Fig. 3b). Compared with light commercial vehicles in Fig. 2, Fig. 3 shows that medium commercial vehicles generally have higher NO emission factors. For both BaM2 and BdM1 models, the NO emission factors did not show obvious increasing or decreasing trends before 2006, except for an obvious drop of 19% between 2001 (14.24 g/kg fuel) and 2002 (11.51 g/kg fuel) for BaM2 4.10 L model. However, after 2006, both BaM2 and BdM1 models showed a steady decrease in NO emission factors.

Fig. 4 shows the NO emission factor trends of the two dominant diesel heavy commercial vehicle models, namely BbM1 (Fig. 4a) and BdM2 (Fig. 4b). Generally, heavy commercial vehicles showed higher NO emission factors than those of light commercial vehicles. However, unlike medium commercial vehicles, the two heavy diesel models showed very different emission trends. For BbM1, the NO emission factor of 10.82 L model was generally fluctuating around 9 g/kg fuel during manufacture years of 1998-2006. Then, a decrease of 31% was observed for 8.90 L model manufactured between 2007 (8.40 g/kg/fuel) and 2009 (5.78 g/kg fuel). Finally, the emission factor became stable again for the 8.85 L model during 2009-2016, except for a spike in 2011. The spike was mainly caused by a higher percentage (3.1%) of NO high-emitters in 2011 than the average BbM1 8.85L fleet (2.0%), using a NO high-emitting cutpoint of 29.11 g/kg fuel (Huang *et al.*, 2018a). For BdM2, as shown in Fig. 4b, the NO emission factor increased by 26% from 15.30 g/kg fuel in 2002 to 19.34 g/kg fuel in 2005, and then decreased continuously until it became stable around 7 g/kg fuel after 2011.

Fig. 5 shows the overall mean NO emission trends of all the diesel vehicles, including both the dominant and less popular models. The overall NO emission factor increased during 1989-1991~~,~~ but became stable during 1991-2006. Finally, it decreased steadily from 2006 to 2016. It is obvious that the emission trends of individual vehicle models were averaged out. Consequently, emission trends of individual vehicle models were skewed by the other dominant models that had different trends. For example, NO emission factor of BaM1 was significantly higher than its previous and succeeding models during 2005-2011 (Fig. 2a), while this unexpected trend was not shown in the overall emission trend in Fig. 5 at all. Although

BaM1 was the most popular model, its absolute number was still small compared to all the remaining models. In this study, the total number of remote sensing records obtained during 2005-2011 was 131632 for the whole fleet and 47962 (36% of the total records) for BaM1. Therefore, when averaged together, the rest 64% vehicles that showed different emission levels and trends were still able to average out and thus mask the unexpected emission trends of BaM1 during that period. Comparing the results shown in Figs. 2-5, it is clear that the latest small, medium and heavy diesel vehicles can achieve similar NO emission factors (around 5 g/kg fuel). This could be due to the converging of operation windows of the engine and emission control devices. However, it should be noted that the emission limits and start years of Euro standards are different for different types of diesel vehicles. The emission limits are distance based (i.e. g/km) for light duty vehicles and engine work based (i.e. g/kW-h) for heavy duty vehicles (Williams and Minjares, 2016). In addition, even for light duty vehicles, the limits and start years are also different for passenger cars and light commercial vehicles with different reference mass (European Commission, 2012).

4. Conclusions

This study has evaluated the NO emission factors of diesel vehicles in Hong Kong using a large remote sensing database collected in a three-year measurement program from April 2014 to April 2017. The dominant diesel vehicle models were identified and analysis was performed to investigate the variation of NO emission factors as a function of manufacture year for each dominant vehicle model. The main results are summarized as follows~~.~~:

1. The Hong Kong diesel vehicle fleet was dominated by only seven models, namely BaM1, BcM1 and BeM1 for the light commercial vehicle class, BaM2 and BdM1 for the medium commercial vehicle class, and BbM1 and BdM2 for the heavy commercial vehicle class.

These seven dominant vehicle models alone accounted for 78% of the total remote sensing records.

2. Each dominant diesel vehicle model showed distinctive trajectories in NO emission factors over the period studied. However, generally NO emission factors of all the seven dominant models were decreasing steadily or were stable for most of the time, except for BaM1 and BdM2. BaM1 experienced a significant increase for the 2.49 L and early 2.98 L models during 2005-2011. This would be caused by the change from IDI to DI in the fuel injection system, which improved the engine torque and fuel economy performance but the trade-off was an increase in NO emissions.
3. The overall mean NO emission factor of all the vehicles was generally stable during 1991-2006 and then decreased steadily during 2006-2016, in which the emission trends of individual models were averaged out and thus masked. Except for individual models, the latest small, medium and heavy diesel vehicles can achieve similar NO emission factors. This could be due to the converging of operation windows of the engine and emission control devices.
4. Each dominant vehicle model showed unchanged or even increased NO emissions in specific periods. This implied that the increasingly stringent emission standards and its type approval mechanism under the European emission regulations were not very effective in reducing the NO emissions from some diesel vehicles in the real world, in particular for BaM1 from Euro 3 to 4 standards.

~~5. Remote sensing offers a rapid and highly effective detection of most-polluting diesel vehicles under real driving, therefore playing a crucial role in controlling vehicle emissions.~~

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~~6.~~ References

E.D. Amster, M. Haim, J. Dubnov, *et al.*, 2014. Contribution of nitrogen oxide and sulfur dioxide exposure from power plant emissions on respiratory symptom and disease prevalence. *Environ. Pollut.* 186, 20-28.

S.C. Anenberg, J. Miller, R. Minjares, *et al.*, 2017. Impacts and mitigation of excess diesel-related NOx emissions in 11 major vehicle markets. *Nature* 545, 467-471.

S.P. Beaton, G.A. Bishop, Y. Zhang, *et al.*, 1995. On-Road Vehicle Emissions: Regulations, Costs, and Benefits. *Science* 268, 991-993.

G.A. Bishop, 2014, FEAT Equations for CO, HC and NO, *University of Denver*.

G.A. Bishop, M.J. Haugen, 2018. The Story of Ever Diminishing Vehicle Tailpipe Emissions as Observed in the Chicago, Illinois Area. *Environ. Sci. Technol.* 52, 7587-7593.

G.A. Bishop, A.M. Peddle, D.H. Stedman, *et al.*, 2010. On-Road Emission Measurements of Reactive Nitrogen Compounds from Three California Cities. *Environ. Sci. Technol.* 44, 3616-3620.

G.A. Bishop, B.G. Schuchmann, D.H. Stedman, 2013. Heavy-Duty Truck Emissions in the South Coast Air Basin of California. *Environ. Sci. Technol.* 47, 9523-9529.

G.A. Bishop, J.R. Starkey, A. Ihlenfeldt, *et al.*, 1989. IR Long-Path Photometry: A Remote Sensing Tool for Automobile Emissions. *Anal. Chem.* 61, 671A-677A.

G.A. Bishop, D.H. Stedman, 2015. Reactive Nitrogen Species Emission Trends in Three Light-/Medium-Duty United States Fleets. *Environ. Sci. Technol.* 49, 11234-11240.

J. Borken-Kleefeld, T. Dallmann, 2018, Remote Sensing of Motor Vehicle Exhaust Emissions, *The International Council on Clean Transportation*.

D.A. Burgard, G.A. Bishop, R.S. Stadtmuller, *et al.*, 2006. Spectroscopy Applied to On-Road Mobile Source Emissions. *Appl. Spectrosc.* 60, 135A-148A.

D.C. Carslaw, S.D. Beevers, J.E. Tate, *et al.*, 2011. Recent evidence concerning higher NOx emissions from passenger cars and light duty vehicles. *Atmos. Environ.* 45, 7053-7063.

D.C. Carslaw, G. Rhys-Tyler, 2013. New insights from comprehensive on-road measurements of NOx, NO2 and NH3 from vehicle emission remote sensing in London, UK. *Atmos. Environ.* 81, 339-347.

T.L. Chan, Z. Ning, 2005. On-road remote sensing of diesel vehicle emissions measurement and emission factors estimation in Hong Kong. *Atmos. Environ.* 39, 6843-6856.

Y. Chen, J. Borken-Kleefeld, 2014. Real-driving emissions from cars and light commercial vehicles - Results from 13 years remote sensing at Zurich/CH. *Atmos. Environ.* 88, 157-164.

Y. Chen, J. Borken-Kleefeld, 2016. NOx Emissions from Diesel Passenger Cars Worsen with Age. *Environ. Sci. Technol.* 50, 3327-3332.

Commissioner for Transport, 2012, Code of Practice for Designated Vehicle Emission Testing Centres (volume 3),

European Commission, 2012. COMMISSION REGULATION (EU) No 459/2012 of 29 May 2012 amending Regulation (EC) No 715/2007 of the European Parliament and of the Council and Commission Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles (Euro 6). *Official Journal of the European Union* 142, 16-24.

A. Font, G.W. Fuller, 2016. Did policies to abate atmospheric emissions from traffic have a positive effect in London? *Environ. Pollut.* 218, 463-474.

D.R. Gentner, F. Xiong, 2017. Tracking pollutant emissions. *Nat. Geosci.* 10, 883-884.

Hedley Environmental Index, accessed 29.03.2018, Historical Data, School of Public Health of The University of Hong Kong, http://hedleyindex.hku.hk/historical?lang=en#.

HKEPD, accessed 02.03.2018, An Overview on Air Quality and Air Pollution Control in Hong Kong, http://www.epd.gov.hk/epd/english/environmentinhk/air/air_maincontent.html.

HKEPD, accessed 06.04.2018, Strengthened Emissions Control for Petrol and LPG Vehicles, http://www.epd.gov.hk/epd/english/environmentinhk/air/guide_ref/remote_sensing_Petrol_n_LPG.htm.

HKEPD, accessed 09.07.2018, Air Quality Statistics in 2017, https://www.epd.gov.hk/epd/english/environmentinhk/air/data/aq_stat.html.

J. Huang, L. Lin, Y. Wang, *et al.*, 2011. Experimental study of the performance and emission characteristics of diesel engine using direct and indirect injection systems and different fuels. *Fuel Process. Technol.* 92, 1380-1386.

Y. Huang, G. Hong, R. Huang, 2015. Numerical investigation to the dual-fuel spray combustion process in an ethanol direct injection plus gasoline port injection (EDI + GPI) engine. *Energy Convers. Manage.* 92, 275-286.

Y. Huang, B. Organ, J.L. Zhou, *et al.*, 2018a. Emission measurement of diesel vehicles in Hong Kong through on-road remote sensing: Performance review and identification of high-emitters. *Environ. Pollut.* 237, 133-142.

Y. Huang, B. Organ, J.L. Zhou, *et al.*, 2018b. Remote sensing of on-road vehicle emissions: Mechanism, applications and a case study from Hong Kong. *Atmos. Environ.* 182, 58-74.

Y.-W. Ko, C.-H. Cho, 2006. Characterization of large fleets of vehicle exhaust emissions in middle Taiwan by remote sensing. *Sci. Total Environ.* 354, 75-82.

J. Lau, W.T. Hung, C.S. Cheung, 2012. Observation of increases in emission from modern vehicles over time in Hong Kong using remote sensing. *Environ. Pollut.* 163, 14-23.

M. Pujadas, A. Domínguez-Sáez, J. De la Fuente, 2017. Real-driving emissions of circulating Spanish car fleet in 2015 using RSD Technology. *Sci. Total Environ.* 576, 193-209.

RSD5000, 2017, AccuScan RSD5000 Remote Sensing Device, On-Road Motor Vehicle Emissions Monitoring and Enforcement,

R. Suarez-Bertoa, C. Astorga, 2018. Impact of cold temperature on Euro 6 passenger car emissions. *Environ. Pollut.* 234, 318-329.

Transport Department of Hong Kong, 2017, Table 4.4: Registration and Licensing of Vehicles by Fuel Type (April 2017), http://www.td.gov.hk/filemanager/en/content_4855/table44.pdf.

M. Williams, R. Minjares, 2016, A technical summary of Euro 6/VI vehicle emission standards, *The International Council on Clean Transportation*.

Y. Zhou, Y. Wu, S. Zhang, *et al.*, 2014. Evaluating the emission status of light-duty gasoline vehicles and motorcycles in Macao with real-world remote sensing measurement. *J. Environ. Sci.* 26, 2240-2248.

Table 1. The most measured vehicle models by on-road remote sensing in Hong Kong.

No.	Vehicle model †	Engine size (L)	No. of records	% of total records	Manufacture year	European standards	Vehicle class ‡
1	BaM1	2.98	69545	19.1%	2006-2016	3, 4, 5	LGV
		2.99	19415	5.3%	1998-2004	2, 3	LGV
		2.49	13715	3.8%	2004-2006	3	LGV
		2.78	5884	1.6%	1989-1998	Pre-Euro, 1, 2	LGV
2	BaM2	4.10	43801	12.1%	1997-2006	1, 2, 3, 4	LB, PB
		4.01	30072	8.3%	2000-2016	2, 3, 4, 5	LB, PB
		3.66	3854	1.1%	1993-1998	Pre-Euro, 1, 2	LB
3	BbM1	8.85	26613	7.3%	2009-2016	IV, V, VI	PB
		10.82	8678	2.4%	1997-2007	II, III, IV	PB
		8.90	3040	0.8%	2005-2009	III, IV	PB
4	BcM1	2.50	21573	5.9%	2007-2016	4, 5	LGV
5	BdM1	5.19	13933	3.8%	2006-2016	4, 5	LGV, MGV
		4.75	6500	1.8%	1998-2006	2, 3, 4	LGV, MGV
6	BdM2	7.79	4408	1.2%	2001-2016	III, IV, V	MGV, PB
7	BeM1	2.95	8227	2.3%	2001-2012	2, 3, 4, 5	LGV
		2.49	4063	1.1%	2012-2016	5	LGV

†: B'x'M'y' refers to vehicle Brand x Model y. The real brand and model names are masked out due to privacy concerns. This study does not point to or discriminate any specific vehicle models.

‡: Abbreviations: LB, light bus; LGV, light goods vehicle; MGV, medium goods vehicle; PB, public bus.

Table 2. Number of valid records per manufacture year per vehicle model. Blank cell indicates that no vehicle~~s~~ was measured for that manufacture year.

Manu. year	BaM1				BaM2			BbM1			BcM1	BdM1		BdM2	BeM1		Total fleet
	2.78 L	2.99 L	2.49 L	2.98 L	3.66 L	4.10 L	4.01 L	10.82 L	8.90 L	8.85 L	2.50 L	4.75 L	5.19 L	7.79 L	2.95 L	2.49 L	
≤1988																	146
1989	69																155
1990	103																224
1991	203																470
1992	228																546
1993	283				102												785
1994	437				263												1249
1995	525				1437												2498
1996	882				466												2422
1997	2091				1253	101											4911
1998	1063	715			333	1260		13				5					6745
1999		2567				3015		2248				308					10759
2000		2955				6260	15	3524				793					13100
2001		3050				7668		680				672		7	219		13411
2002		2878				1233	6	415				717		141			9772
2003		3099				10601		262				745		249	307		17086
2004		4151	1			9035		819				1153		217	876		17885
2005			6672			3350		352	16			946		229	913		14808
2006			7042	1282		1278	269	199				1161	32	320	1104		19468
2007				9177			2859	166	358		1		1138	275	397		17557
2008				8572			5235		1790		827		1170	533	1384		22923
2009				2774			1571		876	985	654		644	210	349		11047
2010				5557			3645			3172	1913		1624	336	1258		23334
2011				6886			1905			1181	3675		1734	353	1284		22495
2012				6372			4381			2766	4172		1482	463	136	563	26294
2013				10483			1975			7992	4351		1886	387		929	35282
2014				11537			4941			4460	4493		2800	474		1737	40858
2015				5397			2275			5254	1292		1205	187		723	21938
2016				1508			995			803	195		218	27		111	5119
Sum	5884	19415	13715	69545	3854	43801	30072	8678	3040	26613	21573	6500	13933	4408	8227	4063	363287

Table ~~2~~3. Specifications of Euro 1-5 BaM1 models in Hong Kong.

	Euro 1	Euro 2	Euro 3	Euro 3	Euro 4	Euro 5
Manufacture year	1995 - 1998	1998 - 2001	2002 - 2004	2005 - 2006	2006 - 2011	2011 - 2017
Engine model †	EM1a	EM1b	EM1c	EM2a	EM2b	EM2b
Engine displacement (L)	2.78	2.99	2.99	2.49	2.98	2.98
Power output (kW @ rpm)	60 @ 3800	66 @ 4000	66 @ 4000	75 @ 3600	80 @ 3000	100 @ 3400
Peak torque (Nm @ rpm)	174 @ 2400	192 @ 2400	192 @ 2400	260 @ 1600 - 2400	286 @ 1200 - 2400	300 @ 1200 - 3200
Compression ratio	22.2 : 1	22.2 : 1	22.2 : 1	15.6 : 1	15.0 : 1	15.0 : 1
Fuel injection system	IDI, Mechanical diesel injector			DI, Common-rail injection system		
Intake system ‡	No EGR		Un-cooled EGR	Cooled EGR, Turbocharger		
Exhaust after-treatment ‡	Nil	Nil	Nil	Nil	DOC	DPF
Range of NO emission factor in Fig. 2 (g/kg fuel)	9.8 - 8.3	7.8 - 6.6	6.4 - 5.9	11.6 - 12.7	12.4 - 11.4	5.5 - 3.9

†: EM'xy' refers to engine series x model y. The real engine model names are masked out due to privacy concerns. This study does not point to or discriminate any specific engine models.

‡: Abbreviations: EGR, exhaust gas recirculation; DOC, diesel oxidation catalyst; DPF, diesel particulate filter.

Table ~~3~~4. Comparison of popular Euro 5 diesel vans (LGVs ≤ 3.5 t) in Hong Kong.

	BaM1	BcM1	BeM1
Year of first registration	2012 - 2017	2012 - 2017	2012 - 2017
Engine model †	EM2b	EM3	EM4
Engine displacement (L)	2.98	2.50	2.49
Power output (kW @ rpm))	100 @ 3400	85-125 @ 3600-3800	95 @ 3200
Peak torque (Nm @ rpm)	300 @ 1200 - 3200	343/441 @ 1500	356 @ 1400-2000
Compression ratio	15.0 : 1	16.4 : 1	15.0 : 1
Fuel injection system	DI, Common-rail injection system		
Intake system	Cooled EGR, Turbocharger		
Exhaust after-treatment	DPF	DPF, DOC*	DPF, DOC
Range of NO emission factor in Fig. 2 (g/kg fuel)	3.9 - 5.5	7.7 - 11.5	5.2 - 5.9

†: EM'xy' refers to engine series x model y. The real engine model names are masked out due to privacy concerns. This study does not point to or discriminate any specific engine models.

**: Some vehicles are equipped with DOC while some are not.*

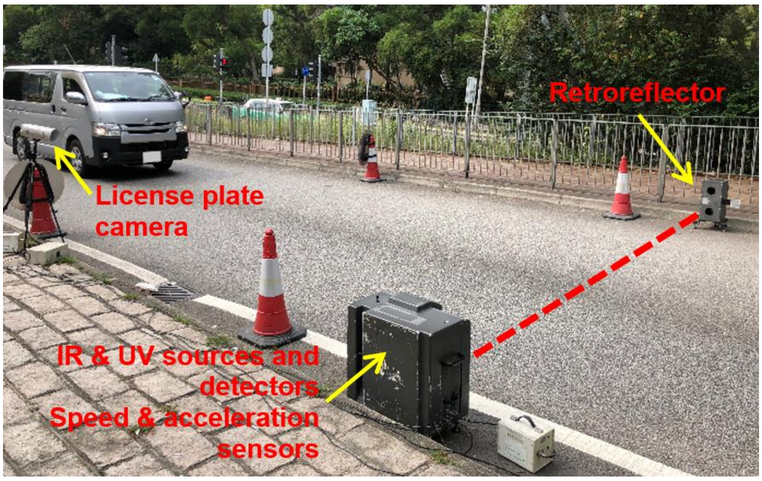

Fig. 1. Setup of a typical remote sensing measurement site in Hong Kong.

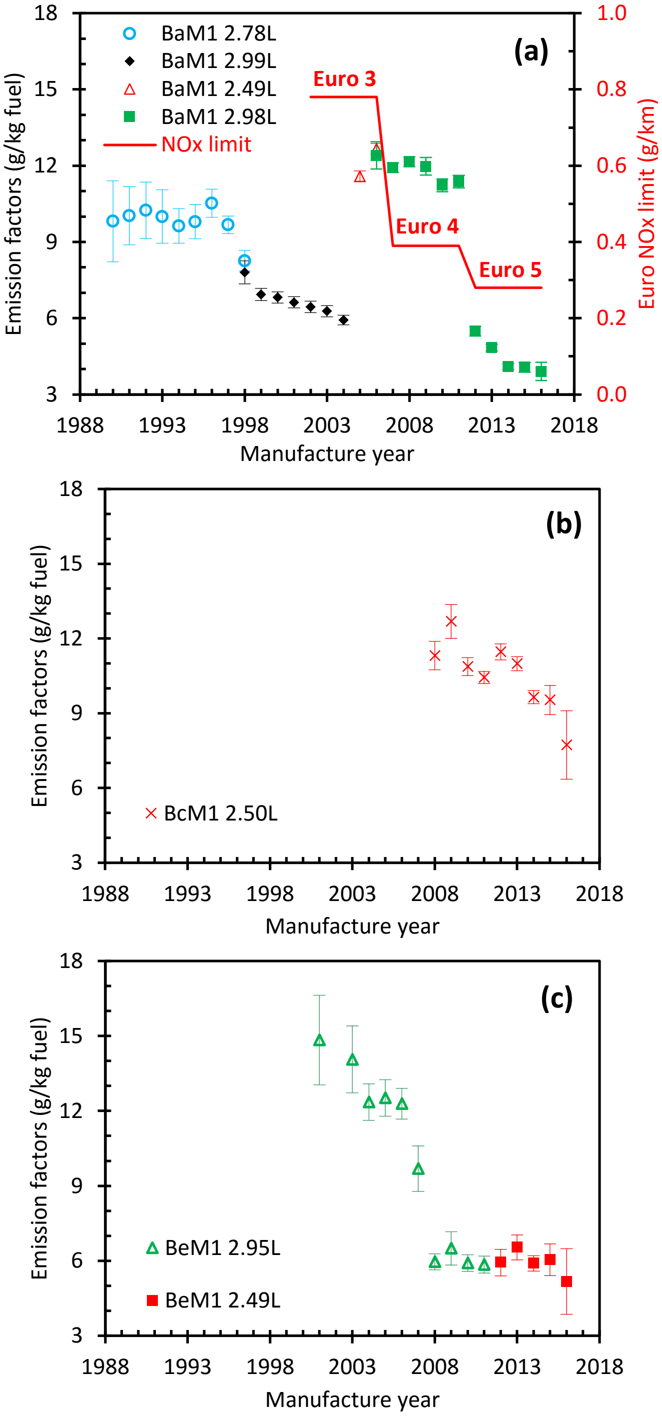

Fig. 2. Mean NO emission factors of dominant light commercial vehicles: (a) BaM1, (b) BcM1 and (c) BeM1. The error bars indicate 95% confidence interval over the mean. The red solid line in Fig. 2a indicates the NO_x limits defined in the European regulations for light commercial vehicles within 1760-3500 kg.

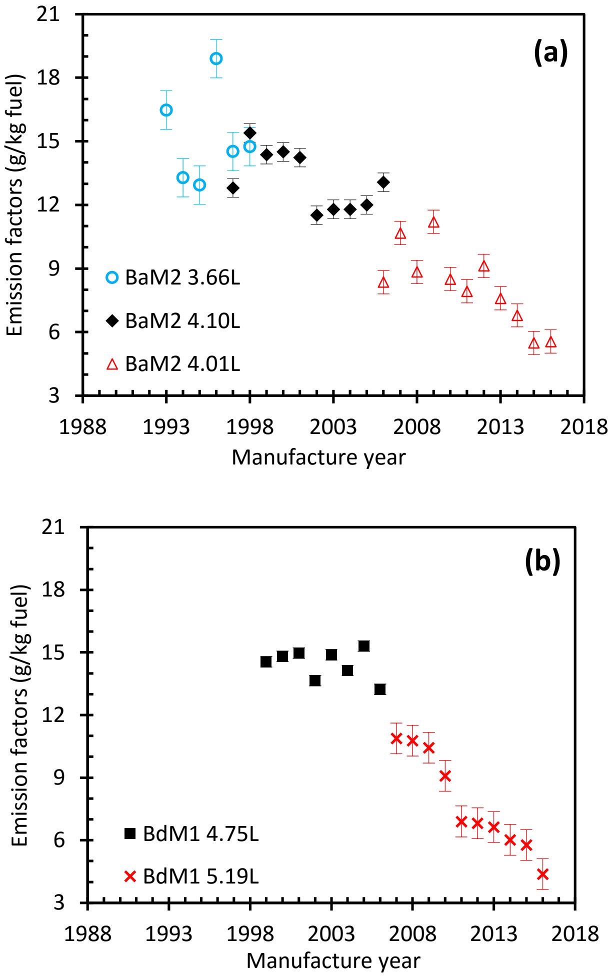

Fig. 3. Mean NO emission factors of dominant medium commercial vehicles: (a) BaM2 and (b) BdM1. The error bars indicate 95% confidence interval over the mean.

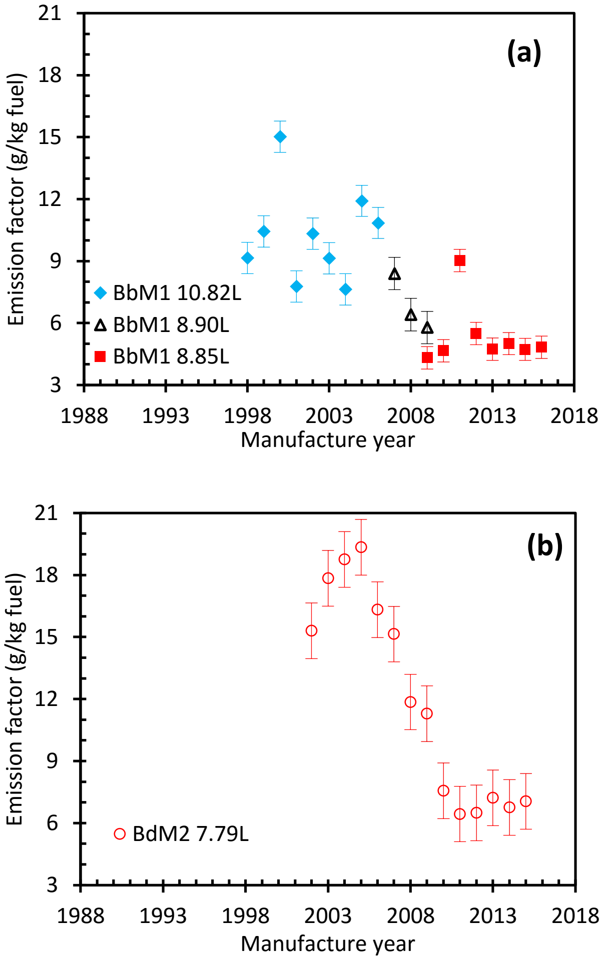

Fig. 4. Mean NO emission factors of dominant heavy commercial vehicles: (a) BbM1 and (b) BdM2. The error bars indicate 95% confidence interval over the mean.

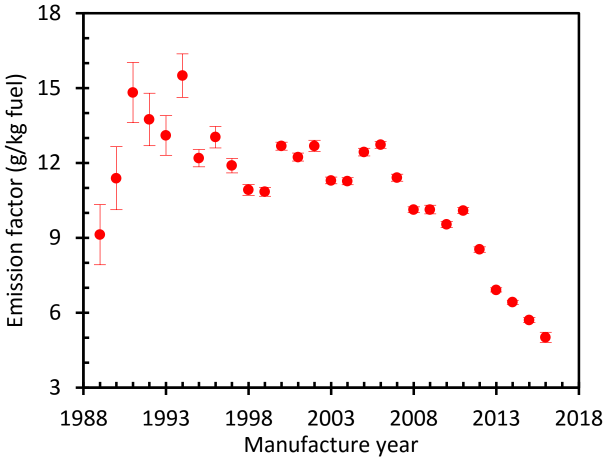

Fig. 5. Mean NO emission factors of the whole diesel vehicle fleet. The error bars indicate 95% confidence interval over the mean.