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Tackling nitric oxide emissions from dominant diesel vehicle models using on-road remote sensing technology☆

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A B S T R A C T

Remote sensing provides a rapid detection of vehicle emissions under real driving condition. Remote sensing studies showed that diesel nitrogen oxides 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 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.

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 oxygen-rich 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 per year for the 1-h average NO_2 of 200 μg/m^3 and a maximum annual average NO_2 of 40 μg/m^3. However, like many other megacities around the world, Hong Kong has faced serious air pollution problem for many years at both street and regional levels (HKEPD, accessed 02.03.2018). Hong Kong

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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 guideline 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 (accessed 29.03.2018) estimated that air pollution had caused 1863 premature deaths, 2.71 million additional doctor visits and 22.4 billion HKD economic loss in 2017.

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 passing 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; similarly 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) observed that the diesel NO emissions (g/kg fuel) in Hong Kong showed an unexpected increase for small vehicles (engine size $\leq$ 3000 cc) during 1999–2006, medium vehicles (3001–6000 cc) during 1997–2002, and large vehicles ($\geq$6001 cc) during 1998–2004.

The above remote sensing studies 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 should 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 (2017) and FEAT (Burgard et al., 2006). ETC-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.