Re-evaluating effectiveness of vehicle emission control programs targeting high-emitters

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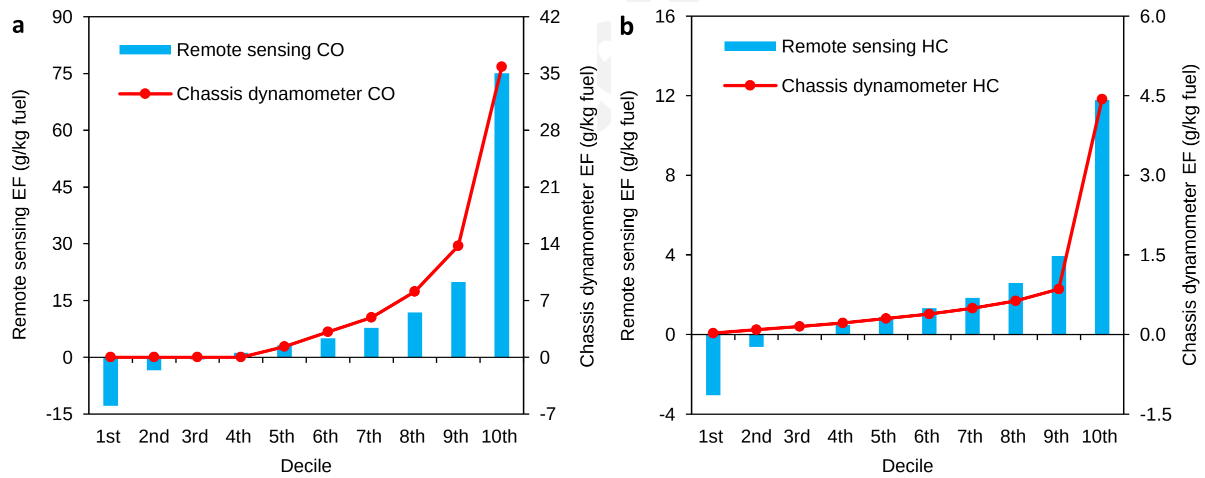
Estimating emission distribution within a vehicle fleet is critical for air pollution control. Previous studies reported that more than half of total fleet emissions were produced by only the highest 10% emitters, making repairing or deregistering a small percentage of high-emitters the most cost-effective measure to control vehicle emissions. With diesel emissions data from chassis dynamometer testing and on-road remote sensing, we show that such a strategy may be oversimplified.

Roadside pollutant concentrations are exceeding air quality standards in many cities worldwide[1,2]. Motor vehicles, especially diesel vehicles, are the major source of air pollution in urban areas. It was estimated that on-road diesel vehicles contributed 55% of global surface transport NO_x emissions and were linked to ~110000 global premature deaths in 2015[3]. Other major gaseous pollutants from motor vehicles include CO and HC emissions. Various emission control technologies and programs are being adopted to address the air pollution issue caused by road transport[4]. To effectively control vehicle emissions, estimating the emission distribution within a vehicle fleet is of great importance for setting air quality policies and standards.

It has been suggested that the most cost-effective emission control measure was to repair or deregister a small percentage of the highest-emitting vehicles[5]. This conclusion was drawn from on-road remote sensing studies that the emission distribution within a fleet was highly skewed; namely that the dirtiest 10% vehicles contributed more than half of the total fleet emissions, while the cleanest 50% vehicles contributed less than 10% of total fleet emissions, regardless of vehicle age[5,6]. Following from this, many remote sensing studies have reported similar conclusions which were predominately for gasoline vehicles[7-13]. Only a few studies distinguished the distribution by fuel type and showed that diesel vehicles would be more skewed in CO and HC but less skewed in NO[11-13]. However, on-road remote sensing only measures a snapshot of emissions from a vehicle in less than one second and cannot fully represent the overall emission level of a vehicle exhibiting high variability in its instantaneous emissions[14,15]. The overall emission level of a vehicle can be measured accurately over a transient chassis dynamometer cycle test which includes different driving conditions. Therefore, the contribution of the dirtiest 10% vehicles to the total fleet emissions should be carefully re-evaluated. The aim of this study is to re-assess the remote sensing conclusion of emission distribution of Euro 3-5 diesel light goods vehicles (< 3.5 t), by comparing with data from independent transient chassis dynamometer testing. The remote sensing and chassis dynamometer testing programs measured 31348 and 183 unique Euro 3-5 diesel light goods vehicles, respectively.

The highly skewed distribution of vehicle emissions is usually expressed by the decile bar charts in remote sensing studies (Fig. 1). It shows that the emission factors of the 10% highest-emitting vehicles are significantly higher than the remaining 90% of less emitting vehicles, especially for CO and HC emissions. The emission factors measured by remote sensing have larger ranges than those by chassis dynamometer due to its larger instrumental noise. However, statistical analysis found insignificant bias of instrumental noise on the emission distribution[9]. When using the method from [5] to quantify the skewness of emission distribution, Fig. 1 suggests that the 10% highest-emitting vehicles account for 70%, 61% and 32% of the total CO, HC and NO emissions, respectively. These values are similar to previous reports but are over-estimated due to the facts that (1) each remote sensing record is a snapshot of highly variable instantaneous emissions and hence cannot represent the overall vehicle emission level, (2) high-emitting vehicles may emit at low levels hence being included in the 1st-9th deciles, and (3) vice versa low-emitting vehicles could emit at high levels hence being included in the 10th decile. The instantaneous emissions of a vehicle can be highly variable, even under similar driving speed and acceleration conditions[14,16,17]. This high variability is not due to the testing methods but due to the vehicle itself. Studies were carried out to compare remote sensing with chassis dynamometers[18-20] and portable emission measurement systems[21,22], and showed good or reasonable agreements between different measurement techniques. Huang et al.[15] reported that the instantaneous emissions of a high-emitter actually remained relatively low for most of the driving duration, while a clean vehicle showed high instantaneous emissions occasionally. As a result, the highest 10% remote sensing measurements (10^{th} decile, Fig. 1) are not necessarily all from the true high-emitting vehicles (i.e. *false positive*), while the rest 90% measurements (1^{st}-9^{th} deciles) could include a large number of high-emitting vehicles (i.e. *false negative*). There is a major uncertainty if a passing vehicle is high-emitting or not based on remote sensing, but which can be easily established in chassis dynamometer testing (as the standard method). Further breakdowns of chassis dynamometer data show that the 10^{th} decile only includes about 50% of measurements from the dirtiest 10% vehicles, with approximately 50% of measurements arising from the relatively cleaner vehicles. Therefore, the skewed distribution of remote sensing data can be regarded as the high variability of instantaneous vehicle emissions, but not representing the distribution of overall vehicle emission levels within a fleet. This is evidenced by the results (Fig. 1) that both remote sensing and chassis dynamometer testing demonstrate similar skewness of distribution of instantaneous vehicle emissions. Since each measurement is independent, remote sensing measurements could cover the various driving conditions of an emission test cycle (Supplementary Figure 3). Consequently, when there are a sufficient number of measurements from either remote sensing or chassis dynamometer testing, the two datasets will have a similar distribution profile of instantaneous emissions for a particular vehicle fleet.



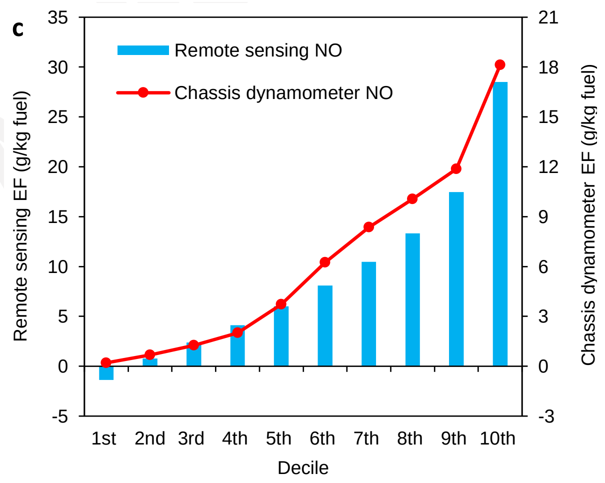


Fig. 1. Distributions of instantaneous CO (a), HC (b) and NO (c) emissions measured by remote sensing and chassis dynamometer. Both datasets were instantaneous emissions measured within one second. In addition, the driving conditions (i.e. vehicle specific power) and sample vehicle characteristics (i.e. vehicle model and emission standard) were matched for the two measurement programs. The remote sensing and chassis dynamometer testing programs measured 31348 and 183 unique Euro 3-5 diesel light goods vehicles with gross weight under 3.5 t, respectively. The average manufacture years of the sampled fleets were 2010.8 in the remote sensing program and 2010.3 in the chassis dynamometer testing program.

To be more accurate, the overall emission level of a vehicle should be an integrated parameter that combines various driving conditions as used in the Hong Kong Transient Emission Test (HKTET) cycle on a chassis dynamometer. Therefore, HKTET cycle-integrated emission factors (Fig. 2 and Supplementary Table 1) are calculated to more accurately evaluate the emission contribution by high-emitting vehicles. Chassis dynamometer data show that the dirtiest 10% vehicles only accounted for 37%, 29% and 27% of the total CO, HC and NO emissions, respectively, which are much smaller than those from remote sensing, in particular for CO and HC. The smaller percentages of NO in both datasets indicate that NO emissions are more uniformly distributed in both the overall vehicle emission levels within a fleet and instantaneous vehicle emissions. The inaccurate estimation of emission contribution by remote sensing applies to both compression ignition and spark ignition engine-powered vehicles (see case study of emission distribution of LPG taxis, Supplementary Discussion).

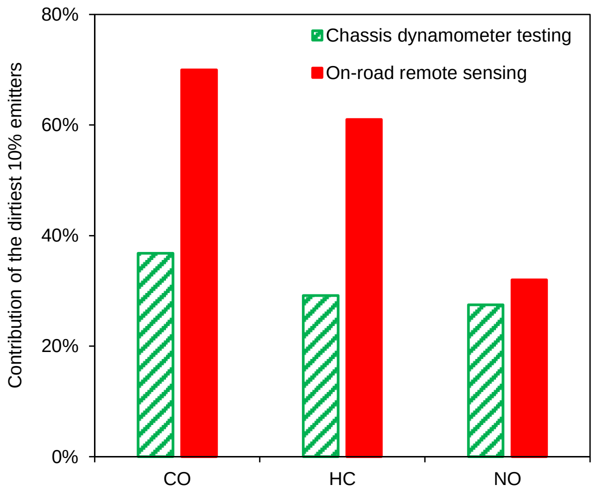


Fig. 2. Emission contribution by the dirtiest 10% emitters of Euro 3-5 diesel light goods vehicles (< 3.5 t). For chassis dynamometer testing, the emission level of a vehicle is represented by the integrated emission factor in g/km over the HKTET cycle. For on-road remote sensing, the emission level of a vehicle is represented by the instantaneous emission measured within one second.

The above findings may have important implications for emission control programs. Previous remote sensing studies have reported that the 10% highest-emitting vehicles produced more than half of the total fleet emissions, making repairing or deregistering a small percentage of high-emitting vehicles potentially the most cost-effective emission control measure[5]. However, this study shows that this interpretation of the highly skewed distribution of remote sensing data may be not fully justified. Each remote sensing is a snapshot emission measurement under one driving condition. With a large number of remote sensing measurements, the averaged emissions represent roadside emissions and their contribution to urban air pollution. The skewed emission distribution from remote sensing could be considered as a reproduction of the second-by-second laboratory chassis dynamometer testing data running on a representative cycle, but could not be regarded as the distribution of overall vehicle emission levels within a fleet. This study demonstrates that the dirtiest 10% vehicles of the sampled fleet only accounted for 20%-40% of the total emissions, using transient chassis dynamometer testing as the standard method. Such estimated contribution from the dirtiest 10% vehicles is substantially less than previously claimed by remote sensing. As a result, emission control programs targeting a small percentage of the highest-emitting vehicles may not be able to achieve the previously estimated high emission reduction[5].

To conclude, vehicle emissions are highly variable with driving as shown by the highly skewed distribution of instantaneous emissions from remote sensing and chassis dynamometer testing. Clean and most high-emitting vehicles may show high instantaneous emissions for a small proportion of the driving time, but would remain much cleaner for the rest of time. Therefore, the success of the use of remote sensing for detecting high-emitting vehicles would be limited because they could only be identified when passing by a remote sensing measurement site multiple times. In addition, a clean vehicle may also produce high instantaneous emissions although at lower values and less frequently than a high-emitter does. Such constraints require the remote sensing cutpoints for high-emitters to be relatively high in order to avoid potential false detections. Therefore, remote sensing can only identify a small percentage of all high-emitters but the worse ones that exceed the cutpoints more often for enforcement, which has limited effect on the total fleet emission reduction but can still be a useful supplement to other emission control measures[23]. To effectively control emissions from on-road vehicles, a program inclusive of a range of measures is needed, such as high-emitters screening using on-road remote sensing, chassis dynamometer testing, portable emission measurement system, replacement of exhaust after-treatment systems, and government incentives (see case study of the HKEPD remote sensing enforcement program, Supplementary Discussion).

Methods

For our on-road remote sensing program, 14 sets of remote sensing systems were used to collect vehicle emissions data at 163 sites across the Hong Kong city from April 2014 to April 2017 (Supplementary Figure 1). The emission ratios of CO/CO_2, HC/CO_2 and NO/CO_2 were measured in a half second when a vehicle passed by. In addition, the speed, acceleration and licence plate number of the passing vehicle were also measured. More details about the measurement principles can be found in the Supplementary Methods. The three-year remote sensing program obtained 433525 valid emission records of 86917 unique diesel vehicles.

For our chassis dynamometer testing program, 183 in-use diesel vans were recruited for chassis dynamometer testing during October 2016 to February 2017. All the vehicles were tested on a Mustang MD150 all-wheel drive chassis dynamometer under the HKTET cycle conditions (Supplementary Figure 2). HKTET is a 200-second transient chassis dynamometer test for emission certification of in-use vehicles in Hong Kong. During each test, second-by-second exhaust flow rates (kg/h) and emission concentrations of CO_2 (%), CO (%), HC (ppm) and NO (ppm) were measured.

Remote sensing and chassis dynamometer testing programs sampled different vehicles under different driving conditions. To make the comparison in Fig. 1 credible, filters were applied to the vehicle classes and driving conditions measured in the two programs. Firstly, remote sensing measured all the vehicles running on roads while chassis dynamometer testing only sampled 183 in-use Euro 3-5 diesel vans. Therefore, only remote sensing measurements of Euro 3-5 diesel light goods vehicles with gross weight under 3.5 t were selected. Generally, the vehicles sampled in the two programs matched well, including both emission standards and vehicle models (Supplementary Tables 2-5). Secondly, the real-world driving conditions in remote sensing were much wider than the laboratory chassis dynamometer testing (Supplementary Figure 3). Therefore, vehicle specific power (VSP) range of -19 to 16 kW/t was used to filter the data, which were the overlapping engine load conditions covered in the two programs. VSP was calculated using equation (1), where v is the vehicle speed in m/s, a is the vehicle acceleration in m/s^2 and θ is the road grade[24]. Road grade was 0 in chassis dynamometer testing. Remote sensing systems were placed at highway on-ramps with an average road grade of 1.9° (mostly slight uphill). After applying the above filters, 127764 remote sensing records for 31348 unique vehicles and 36910 chassis dynamometer second-by-second records for 183 unique vehicles remained.

$$VSP = v \cdot (1.1 \cdot a + 9.81 \cdot sin\theta + 0.132) + 3.02 \cdot 10^{-4} \cdot v^3 \qquad (1)$$

Remote sensing measured tailpipe emissions as relative ratios of pollutants over CO_2, while chassis dynamometer testing measured absolute emission concentrations. To compare the emissions measured by the two techniques, fuel based emission factors in *g/kg fuel* were calculated using a carbon balance equation (2), where M_P is the molecular weight of pollutant *P* (i.e. CO, HC and NO) in *g/mol* and M_{fuel} is 0.014 *kg/mol*.

$$EF_P = \frac{M_P}{M_{fuel}} \times \frac{P/CO_2}{1+CO/CO_2+6HC/CO_2} \quad (2)$$

In addition, distance based emission factors in *g/km* were calculated for chassis dynamometer cycle tests using the UNECE method[25].

Data availability

The data that support the findings of this study are available from the corresponding authors upon request.

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Author contributions

Y.S.Y. suggested undertaking this study of correcting the skewness of vehicle emission distribution concluded from remote sensing studies. Y.H. completed the analysis and wrote the manuscript. All authors discussed the results and commented on the manuscript.

Competing interests

The authors declare no competing interests.

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