Effect of diesel particulate filter regeneration on fuel consumption and emissions performance under real-driving conditions

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Abstract

Diesel particulate filters (DPF) are widely adopted in diesel vehicles to meet the increasingly stringent emission regulations, which require continuous passive regenerations or/and periodic active regenerations to burn off the accumulated particulate matter (PM). In spite of many laboratory studies using DPF benches and engine/chassis dynamometers, there is currently a lack of investigation on DPF regeneration under real-world conditions. Therefore, this study was conducted to investigate the impact of active DPF regenerations on the fuel consumption and gaseous and particulate emissions performance of a diesel light goods vehicle under real-driving conditions by using the state-of-the-art portable emission measurement system. In total, 60 real-driving emission (RDE) tests (~1200 km in total) were performed on the same route during the same periods of a day, to minimise the effect of uncontrollable real-world factors on the performance evaluation. The results showed that real-world active DPF regenerations occurred every 130 km for the studied vehicle. Although they did not occur frequently, DPF regenerations increased the trip-averaged fuel consumption rate by 13% on average. CO and THC emission factors tended to increase with DPF regenerations because the post combustion used to achieve the high exhaust temperature for regeneration of the filter occurred under oxygen-lean conditions. Total NO_x emissions were not affected but NO_2/NO_x ratio was greatly reduced by DPF regeneration due to lower NO oxidation by the diesel oxidation catalyst and higher NO_2 reduction by the DPF. Finally, DPF regenerations sharply increased PM emission factors by 27 times compared with a trip without DPF regeneration, resulting in significant exceedance of the emission limit.

Keywords**:** Diesel particulate filter; Regeneration; Fuel consumption; Gaseous and particulate emissions; Portable emission measurement system

1. Introduction

Diesel vehicles are widely used for commercial road transport worldwide due to their high thermal efficiency and durability. However, a major challenge of diesel engines is that their diffusion combustion mode is prone to produce high particulate matter (PM) and nitrogen oxides (NO_x) emissions [1, 2], and the latter are also key precursors for the formation of secondary air pollutants of PM and ozone (O_3) [3, 4]. Despite representing a small proportion (<5%) of the total fleet, heavy-duty diesel vehicles account for 40-60% of global on-road NO_x and PM emissions [5-8], as well as a significant share (> 40%) of global on-road energy consumption [9]. These pollutants have caused significant health and economic damages. It was estimated that 385,000 premature deaths and US$1 trillion health losses were associated with global transport emissions (including on-road vehicles, non-road mobile sources, and international shipping) in 2015 [10]. Among various emission sources, on-road diesel vehicles were the biggest contributor to these health burdens, which alone were responsible for approximately 110,000 premature deaths in 2015 [5, 11].

Increasingly stringent regulations have been enforced to limit the pollutant emissions from diesel vehicles. For example, the PM emission limits for light-duty diesel vehicles were significantly reduced from 0.025 g/km in Euro 4 to 0.0045 g/km in Euro 5 and 6 standards [12, 13]. Although the limits remained the same after Euro 5, the emission testing methods became stricter in Euro 6 which introduced a more dynamic Worldwide harmonized Light vehicles Test Procedure (WLTP) to replace the outdated New European Driving Cycle (NEDC) for laboratory testing using a chassis dynamometer [14, 15] and a Real Driving Emissions (RDE) test procedure for real-world testing using a portable emission measurement system (PEMS) [16, 17]. The new test procedures aimed to reduce the discrepancies between laboratory and real-world fuel consumption and pollutant emissions [18, 19], which received great research attention after the discovery of the Volkswagen dieselgate in 2015 [20, 21].

Various technologies including in-cylinder combustion optimization and exhaust after-treatment have been adopted to meet the stringent emission regulations. For PM emission control, the most effective method involves using a diesel particulate filter (DPF) which has become a mandatory emission control device after Euro 5 [9, 22, 23]. A DPF traps PM when exhaust gas flows through the porous substrate walls by two filtration mechanisms, i.e. deep bed and surface filtration [24]. The deep bed filtration dominates if the pore size of filter media is larger than that of PM. However, surface filtration becomes important as the filter pores are filled. The materials used for manufacturing DPFs include cordierite, silicon carbide, acicular mullite, aluminum titanate, metal foams and fibers, with the first two materials being the most widely used [24-27]. Modern DPFs are highly efficient in reducing PM emissions, which could achieve a high filtration efficiency of over 99% [22, 28]. However, back pressure builds up across DPF as PM accumulates, which may deteriorate engine combustion and consequently worsen fuel consumption and emissions performance. Therefore, continuous or periodic DPF regenerations are needed to remove the accumulated PM in order to restore its filtration capacity.

DPF regenerations oxidize PM to carbon dioxide (CO_2) using either oxygen (O_2) or nitrogen dioxide (NO_2). The former is abundant in diesel exhaust gas due to the lean combustion mode, while the latter is produced by diesel oxidation catalyst (DOC) via the oxidation of nitric oxide (NO) which is the dominant species in raw diesel NO_x emissions [29]. Since NO_2 is a much stronger oxidizer than O_2, NO_2-based regenerations can occur at a lower temperature (260-300 °C) than O_2-based regenerations (~600 °C) [22]. NO_2-based regenerations (usually referred as passive regenerations) occur continuously during normal engine operation. The main advantages of passive regenerations are no fuel consumption penalty and low thermal stress on DPF, while the disadvantage is that regeneration efficiency is limited by a number of factors including NO_x/PM ratio, engine conditions (i.e. exhaust temperature) and fuel sulfur content (i.e. catalyst poisoning) [30, 31]. O_2-based regenerations (usually referred as active regenerations) periodically realize a high exhaust temperature via extra efforts such as in-cylinder post-injection, in-exhaust fuel injection before the DOC and electric heating. Active regenerations are more independent of engine conditions and more effective than passive regenerations, while the main drawbacks are increased fuel consumption and higher thermal stress. Pure passive regenerations may be insufficient to remove the accumulated PM under all engine conditions, and thus modern diesel vehicles mostly adopt active or hybrid regenerations [22].

Effective and reliable DPF regenerations are of great importance for maintaining the desired fuel consumption and emissions performance of modern diesel vehicles. Many studies have been carried out to investigate the performance of DPF regenerations. Rossomando *et al.* [32] measured the particle size distributions of a Euro 5 light-duty diesel engine during both DPF accumulation and regeneration phases using an engine dynamometer. The results showed that the regeneration phase increased the particle number concentration by up to two orders of magnitude than the accumulation phase. Meng *et al.* [33] explored the formation mechanisms and influencing factors of PM emissions during DPF regenerations using both DPF and engine test benches. They found that 10 nm nucleation mode particles were emitted by high temperature inlet flows during the DPF heating-up stage, leading to 2-3 orders of magnitude increase in particle number concentration. These particles were mainly from the penetration of exhaust particles, as well as the blow-out of the deposited soot layer. Using a longer DPF inlet transition section could improve the particle deposition and regeneration performance [34]. Beatrice *et al.* [35] measured the PM characteristics of a Euro 5 diesel engine under real regeneration strategies using an engine dynamometer. The results showed that a large number of small particles were produced by DPF regenerations controlled by multiple in-cylinder post-injections. Engine dynamometer experiments on a diesel-methanol dual fuel engine [36] showed that the dual fuel mode had better active and passive regeneration performance than pure diesel mode, in terms of regeneration rates, fuel penalty, and PM and NO_2 emissions. This was mostly likely due to the oxygen in the methanol. Yoon *et al.* [37] measured the PM emissions of parked active DPF regenerations from two heavy-duty diesel trucks using an ambient air dilution tunnel. They found that PM number was highly dominated by nucleation mode particles (i.e. < 50 nm) for both trucks, while accumulation mode particles (i.e. 50-500 nm) contributed significant percentages (varied from 7%-28% to 78%-96%) of PM mass. Pechout *et al.* [38] compared the effects of traditional biodiesel and hydro-treated vegetable oil (HVO) on a Euro 6 diesel car using a chassis dynamometer. It was reported that, during DPF regeneration, HVO had comparable/lower particle loading while traditional biodiesel had considerably lower particle loading than diesel fuel. Fuel oxygen content has consistently been found to reduce particle mass. Smith *et al.* [39] analyzed the real-time PM emissions of active and passive DPF regenerations of two heavy-duty diesel vehicles under steady-state driving conditions using a chassis dynamometer. The results showed that regeneration PM emissions were dominated by particles < 100 nm, and passive regenerations had lower PM emissions than active regenerations. All these experiments have well revealed that fuel consumption and emissions could be significantly increased during active DPF regenerations. To address this issue, various solutions have been studied, such as more accurate air-fraction and soot loading modelling [40, 41], microwave [42], hydrocarbon injection [43], and non-thermal plasma technology [44].

The above studies all adopted laboratory testing methods such as DPF test benches, parked testing and engine/chassis dynamometers. Although laboratory experiments are highly accurate and repeatable, they may not fully replicate the real-world conditions which are far more varied and thus could produce very different fuel consumption and emissions performance than laboratory results. So far, very few studies have investigated DPF regenerations under real driving conditions. Ruehl *et al.* [45] investigated the emission performance of two heavy-duty diesel vehicles during parked active, driving active and passive regenerations using PEMS. They found that 0.2-16.3 g of PM was emitted after each regeneration, under the frequency of one real-world active regeneration every 28.0 h or 599 miles. Ko *et al.* [46] evaluated the on-road NO_x emissions from a 2.2 L diesel vehicle using NO_x sensors and an exhaust flow meter (not PEMS). They found that NO_x emissions were 30% higher under DPF regeneration than normal conditions. Papadopoulos *et al.* [47] measured the emission factors of 14 Euro IV-VI diesel medium goods trucks under real-world conditions using PEMS. It was found that DPF regenerations could significantly increase total hydrocarbons (THC) and PM emissions by eight and 34 times, respectively than normal vehicle operation.

As reviewed above, there is a lack of investigation on DPF regeneration performance under real driving conditions. Although DPF regenerations do not occur frequently or last long, they may significantly affect the vehicle performance for a given trip. Therefore, this study was carried out to comprehensively evaluate the effects of DPF regeneration on fuel consumption and gaseous and particulate emissions under RDE conditions using a state-of-the-art PEMS. A total of 60 RDE trips, which incurred nine active DPF regeneration trips, were performed using the same diesel vehicle on the same route during the same periods of a day, which minimised the effect of uncontrollable real-world factors on performance evaluation of the test vehicle. The results reveal the impact of a DPF regeneration event on a typical RDE trip and provide valuable information for developing more effective DPF technologies.

2. Experimental methods

2.1. Test vehicle and emission sensors

Fig. S1 shows the test vehicle installed with a set of on-board emission test equipment. The experiments were performed on a Toyota HiAce diesel light goods vehicle (LGV), which is the most common diesel vehicle model in Hong Kong [48]. The test vehicle was powered by a 2.98 L turbocharged diesel engine and a four-speed automatic transmission. The model year was 2014 and it was certified to Euro 5 standard which was achieved by the widely adopted exhaust after-treatment systems of diesel oxidation catalyst (DOC), a DPF that actively regenerated and exhaust gas recirculation (EGR).

The real-driving fuel consumption and emissions performance were measured by a state-of-the-art PEMS which consisted of an AVL M.O.V.E Gas PEMS 493, an AVL M.O.V.E PM PEMS 494, a 2.5-inch EFM-2 flow meter, a weather station, a Peiseler MT wheel speed sensor and a Garmin global positioning system (GPS). The Gas PEMS unit measured CO and CO_2 concentrations by a non-dispersive infra-red (NDIR) analyzer, NO and NO_2 concentrations by a non-dispersive ultra-violet (NDUV) analyzer, and THC concentrations by a heated flame ionization detector (FID). The

PM PEMS unit measured time-resolved PM mass by a photo-acoustic measurement unit and a gravimetric filter module. The EFM-2 flow meter was installed in the tailpipe exit to measure the flow rate and temperature of the exhaust gas. The weather station and GPS were installed on the vehicle roof to measure the ambient (i.e. temperature, relative humidity and atmospheric pressure) and route (i.e. elevation and ground speed) conditions, respectively. In addition to GPS, the wheel speed sensor also measured the vehicle driving speed to provide a quality control check on the vehicle speed data provided by the GPS and on-board diagnostics (OBD). The PEMS system was mounted in the cabin of the test vehicle and was supplied by a Honda EU 30IS generator and three lead acid batteries, so that no additional load was put on the vehicle engine. In this study, all the above measurements were taken at a sampling frequency of 10 Hz.

2.2. Experimental conditions and procedures

Previous experiments were usually conducted using simulated PM loading and regenerations. In this study, real-world DPF regenerations were studied. Since DPF regenerations do not occur frequently and depend on a number of factors such as engine load and exhaust temperature, significant RDE tests were carried out: i.e. 60 RDE trips which were completed by 30 drivers (two trips per driver) and accounted for ~1200 km in total. To minimise the impact of uncontrollable real-world conditions on performance evaluation (e.g. traffic and road conditions), all drivers used the same test vehicle to drive on the same route during the same periods of a day (i.e. 11.00-12.00 and 14.00-15.00). In addition, all drivers did not receive any training or use any driver assistance device during the tests, so that they followed their normal driving style. The RDE test route (**Fig. S2**) was representative of daily driving in Hong Kong. It was a round trip between Tsing Yi and Sham Tseng in New Territories of Hong Kong. The total distance was 19 km, which consisted of 5, 6 and 8 km of urban, rural and highway driving, respectively. It took approximately 25-30 minutes to complete one trip. All RDE tests were carried out under hot start conditions when the engine coolant temperature was over 80 °C in the OBD system. To assure data quality, the PEMS was zeroed using pure nitrogen gas before each RDE test and was calibrated using standard EPA protocol standard gas before each test day. In addition, the system was purged before each test day and a leak check was performed before each test according to the RDE test procedure.

2.3. Data treatment and identification of DPF regenerations

In this study, both the instantaneous emission concentrations (% or ppm) and trip-averaged distance specific emission factors (EFs, g/km) were analysed to evaluate the effect of DPF regeneration on RDE performance. The instantaneous emission concentrations were the raw RDE data measured by PEMS at a frequency of 10 Hz. The distance-specific EFs were calculated from the instantaneous emission concentrations, exhaust flow rates and driving speeds for each RDE trip according to the Euro 6 RDE standard [49]. The fuel consumption rates (L/100 km) were calculated from the EFs of CO_2, CO and THC by applying the principle of carbon balance [50, 51].

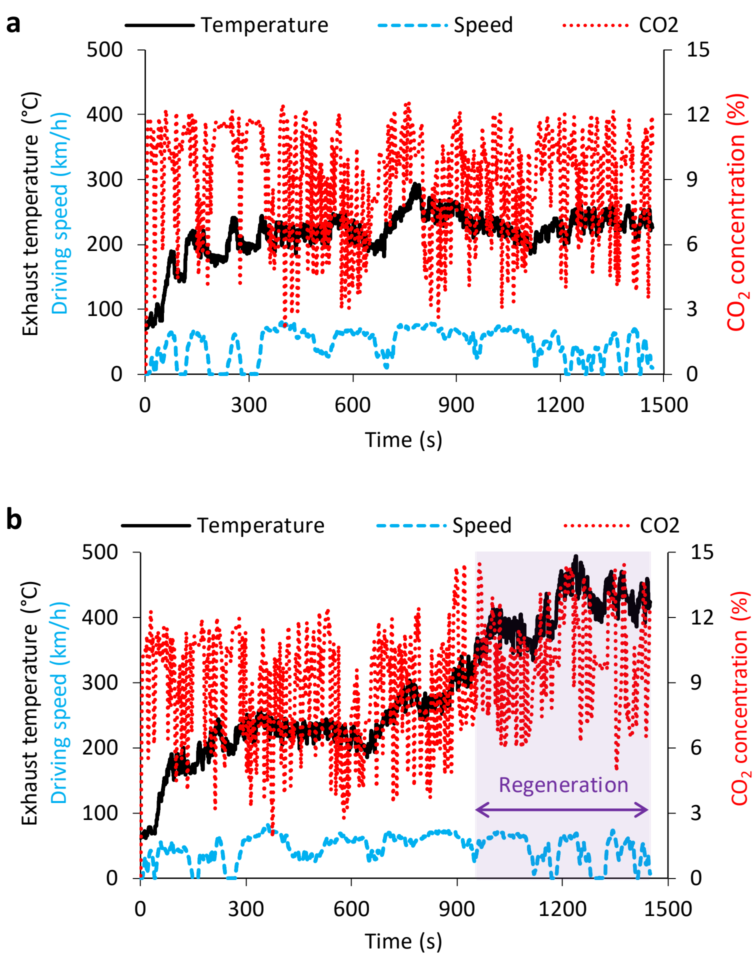

Fig. 1. Instantaneous driving speed, exhaust temperature and CO_2 concentration of one pair of RDE tests completed by Driver 1: **a**) morning test without DPF regeneration, **b**) afternoon test with DPF regeneration. The regeneration window is identified in shadow band.

Active DPF regenerations can only occur under relatively high exhaust temperatures that are usually realized by extra fuel combustion such as post in-cylinder or in-exhaust injections. Thus, exhaust temperature and CO_2 concentration are useful indicators of active DPF regenerations. **Fig. 1** shows the variations of instantaneous driving speed, exhaust temperature and CO_2 concentration of one pair of RDE tests that were completed by Driver 1. The morning test (**Fig. 1a**) was a normal trip with no DPF regeneration occurring. Although the driving conditions (i.e. speed and acceleration) are highly variable during a RDE trip, the exhaust temperature and CO_2 concentration remained in the ranges of 150-300 ºC and 3-12%, respectively during the whole test. Then, a DPF regeneration event occurred in the afternoon test (**Fig. 1b**). Comparing with a normal trip (**Fig. 1a**), the exhaust temperature (350-500 ºC) and CO_2 concentration (6%-15%) increased significantly when DPF regeneration occurred during 1000-1500 s (**Fig. 1b**), although the driving conditions were similar to those in the morning test.

Table 1. Characteristics of identified real-driving DPF regenerations.

Driver No.	**RDE test session**	**DPF regeneration duration (length), s**	**Exhaust temperature range (average), °C**	**CO_2 concentration range (average), %**
1	Afternoon	953-1450* (497)	330-494 (412)	4.9-14.5 (10.0)
4	Afternoon	232-963 (731)	318-522 (426)	1.6-14.1 (9.5)
6	Morning	901-1526* (625)	329-495 (421)	3.9-14.0 (9.0)
9	Morning	1434-1544* (110)	333-407 (367)	6.6-14.0 (10.1)
12	Afternoon	913-1518* (605)	342-507 (413)	3.3-14.3 (9.3)
16	Morning	703-1261* (558)	332-508 (427)	3.7-13.5 (9.4)
22	Afternoon	198-776 (578)	319-498 (404)	1.5-14.1 (9.4)
26	Morning	788-1429 (641)	338-462 (396)	4.6-13.7 (9.5)
29	Afternoon	597-1132 (535)	334-487 (420)	3.1-13.9 (9.5)

*Notes: * indicates that DPF regeneration was still ongoing when the RDE trip was finished (i.e. incomplete DPF regeneration).*

Therefore, this study defined that an active DPF regeneration occurred if exhaust temperature continuously exceeded 350 ºC and CO_2 concentration frequently exceeded 13%. Compared with CO_2 concentration, exhaust temperature was a clearer and more reliable indicator and thus was used as the primary parameter for determining the occurrence of DPF regenerations. In addition, the colour of the PEMS PM filter changed from white to grey after a RDE test if a DPF regeneration occurred. Using the above criteria, nine out of 60 RDE trips were found to have DPF regenerations in this study. On average, real-world active DPF regenerations occurred every 130 km for the studied diesel LGV. **Table 1** shows the characteristics of the identified DPF regenerations. Their instantaneous exhaust temperature profiles and the identification of DPF regenerations are presented in **Fig. S3**. Among the nine DPF regenerations, four occurred in the middle of RDE tests and were completed before the trips were finished. The other five occurred at the end of RDE tests and were still ongoing when the trips finished, and thus were considered as incomplete DPF regenerations. Nevertheless, four of these five incomplete regenerations lasted for over eight minutes and were almost completed (**Fig. S3**). Specially, the DPF regeneration of Driver 9 occurred at the very end of that RDE test, resulting in a very short regeneration time (~2 minutes) and a much lower average exhaust temperature (367 °C) than others (396-427 °C). As shown in **Table 1**, a complete real-driving DPF regeneration on average took around 10 minutes, with an average exhaust temperature and CO_2 concentration of 412 °C and 9.5%, respectively. The DPF regeneration time of the studied diesel LGV was comparable to that of medium diesel trucks (550 s) [47]. It should be noted that the exhaust temperature measured by the PEMS was at the tailpipe exit and was thus lower than that in the DPF [39].

3. Results and discussion

3.1. Effect of DPF regenerations on fuel consumption

Fig. 2 shows the real-driving fuel consumption performance of trips with and without DPF regenerations. As shown in **Fig. 2a**, although all the tests were performed using the same vehicle on the same route during the same periods of a day, there are noticeable differences in the fuel consumption rates among the 60 RDE trips. Such differences exist among both the individual drivers and the two trips of the same driver. They are mainly caused by the different driving behaviours and traffic conditions of each RDE trip. Each driver adopts different driving styles in response to the dynamic traffic conditions in a RDE trip, which is reflected in the use of the accelerator and brake pedals. Drivers using the accelerator pedal more aggressively generally consume more fuel and produce higher pollutant emissions [50]. In spite of the large differences among individual RDE trips, **Fig. 2a** shows that the fuel consumption rate of a trip with DPF regeneration is significantly higher than that without DPF regeneration by the same driver, except for Driver 9. This is because Driver 9 had a relatively short incomplete DPF regeneration at the end of that RDE test (**Fig. S3**), and thus its impact on the trip-averaged fuel consumption rate is insignificant. Overall, the average and median fuel consumption rates of DPF regeneration trips are 13% and 15% higher than those of normal trips, respectively (statistically significant difference exists, $p = 5.40\times10^{-5}$) (**Fig. 2b**). Active DPF regenerations need to burn extra fuel to achieve the high exhaust temperature for soot oxidation, which results in the increased fuel consumption rates. This study demonstrates that the real-driving fuel consumption could be increased by 13% on average for a short trip of 19 km if a DPF regeneration event occurs.

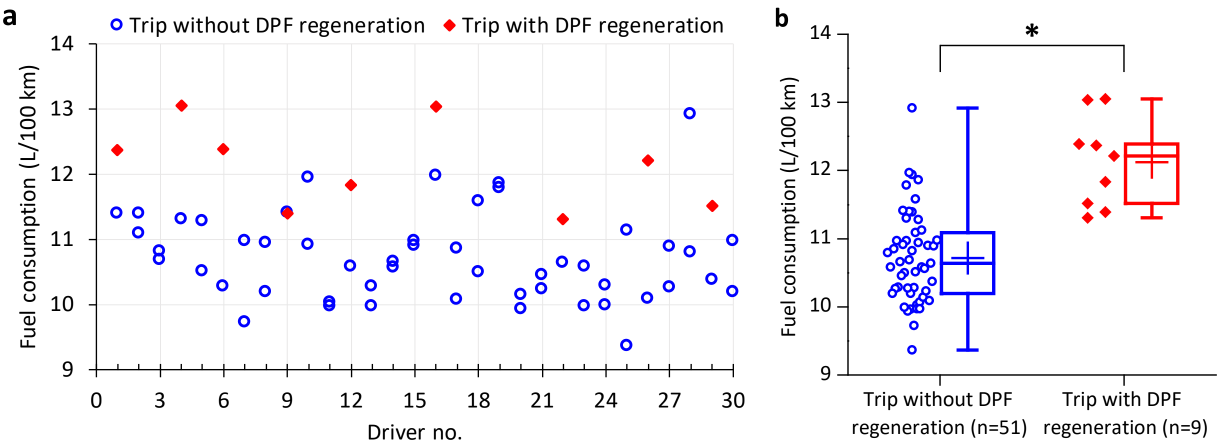

Fig. 2. Comparison of real-driving fuel consumption performance between trips with and without DPF regenerations: **a**) individual drivers, **b**) overall statistics (boxplot: 25th and 75th percentiles, box; median, centre line; mean, plus; minimum and maximum, whiskers). * $p = 5.40 \times 10^{-5}$ by unpaired one-tailed t-tests.

3.2. *Effect of DPF regenerations on gaseous and particulate emissions*

Figs. 3 and **4** compare the real-driving emission factors of CO and THC between trips with and without DPF regenerations, respectively. Generally, CO and THC emissions of diesel vehicles are extremely low due to the lean combustion mechanism of a diesel engine's diffusion flame. During RDE tests, the measured instantaneous CO and THC concentrations were mostly below the detection limits of the PEMS gas analysers. As shown in **Figs. 3a** and **4a**, the CO and THC emission factors are mostly around zero. In addition, no obvious trends can be observed between normal and DPF regeneration trips for the same driver. Among the nine drivers experiencing DPF regenerations during their trips (**Fig. 3a**), five drivers (i.e. Drivers 1, 4, 6, 22 and 29) produced higher CO emission factors while the remaining four drivers (i.e. Drivers 9, 12, 16 and 26) had lower CO emission factors in DPF regeneration trips than normal trips. Regarding THC emissions (**Fig. 4a**), six drivers (i.e. Drivers 1, 4, 9, 16, 22 and 29) had higher emission factors during DPF regeneration trips than normal trips, while the remaining three drivers (i.e. Drivers 6, 12 and 26) experienced slightly lower emission factors. The overall statistics (**Figs. 3b** and **4b**) show that DPF regeneration trips have higher CO and THC emission factors than the normal trips, by 241%/298% and 82%/47% for the mean/median CO and THC emissions, respectively (statistically significant difference exists for THC ($p = 4.63 \times 10^{-2}$) but not for CO ($p = 1.11 \times 10^{-1}$)). The emission factor of CO is affected by a large scattering, thus a statistically significant difference does not exist between normal and DPF regeneration trips. This can be explained by the fact that the post-combustion used to achieve high exhaust temperature for active DPF regeneration takes place in the burnt gas from the main combustion event, which contains a lower oxygen concentration and thus tends to produce more CO and THC emissions. Nevertheless, such increases are not a concern for the studied vehicle, as even their maximum values are still much lower than the Euro 5 emission limits of 0.74 g/km for CO and 0.07 g/km for THC.

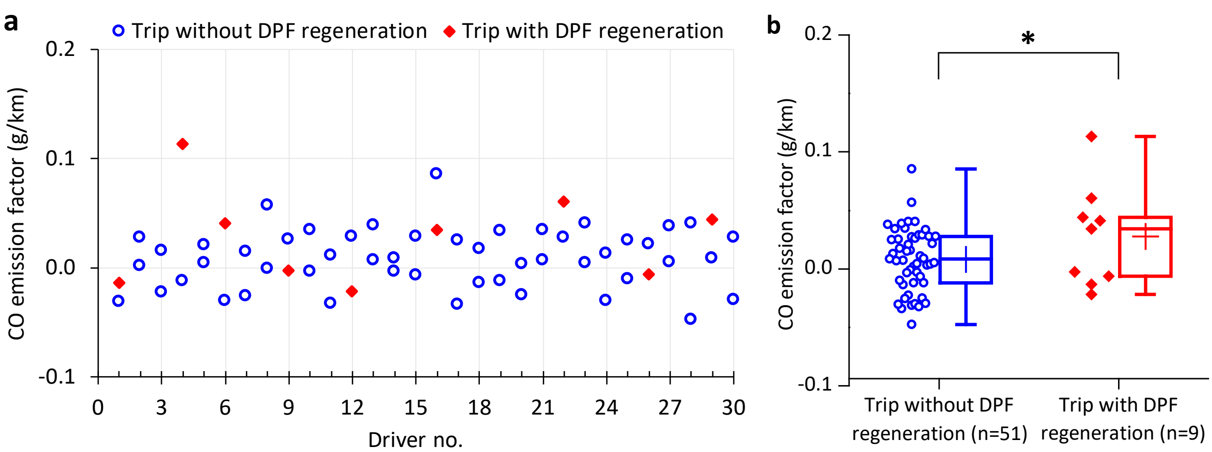

Fig. 3. Comparison of real-driving CO emission factors between trips with and without DPF regenerations: **a**) individual drivers, **b**) overall statistics (boxplot: 25th and 75th percentiles, box; median, centre line; mean, plus; minimum and maximum, whiskers). * $p = 1.11 \times 10^{-1}$ by unpaired one-tailed t-tests.

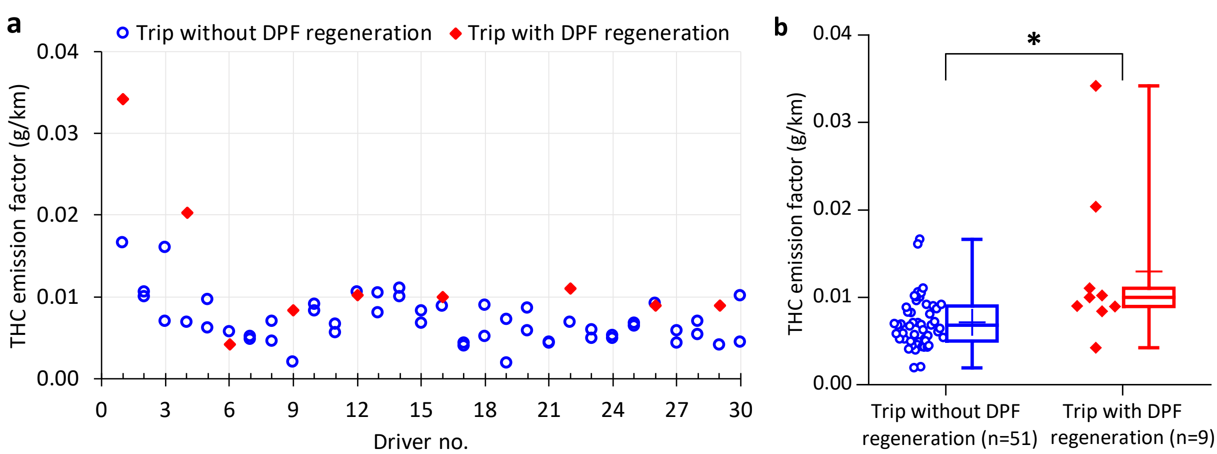

Fig. 4. Comparison of real-driving THC emission factors between trips with and without DPF regenerations: **a**) individual drivers, **b**) overall statistics (boxplot: 25th and 75th percentiles, box; median, centre line; mean, plus; minimum and maximum, whiskers). * $p = 4.63\times10^{-2}$ by unpaired one-tailed t-tests.

Diesel vehicles are the dominant sources of NO_x emissions although they only account for a small proportion of the total fleet [5, 6, 11]. In particular, the Volkswagen scandal in 2015 revealed that real-driving diesel NO_x emissions significantly exceeded the laboratory type-approval limits [20, 21]. Following this, increasing studies have reported higher real-driving diesel NO_x emissions than their respective emission limits, which were not limited to Volkswagen diesel vehicles [52-55]. **Fig. 5** shows the real-driving NO_x emission performance of trips with and without DPF regenerations. As shown in **Fig. 5a**, real-driving NO_x emission factors of the studied diesel vehicle vary greatly from 0.31 to 2.37 g/km, which are constantly higher than its NO_x limit of 0.28 g/km. DPF regenerations generally have insignificant influences on NO_x emission factors. For the nine drivers who experienced DPF regenerations (**Fig. 5a**), three drivers (i.e. Drivers 4, 9 and 29) have noticeably lower NO_x, one driver (i.e. Driver 26) has noticeably higher NO_x, and the rest five drivers (Drivers 1, 6, 12, 16 and 22) have very similar NO_x from DPF regeneration trips than those from normal trips. As a result, no statistically significant difference exists ($p = 4.70\times10^{-1}$) between the mean NO_x emission factors of trips with and without DPF regenerations (**Fig. 5b**).

It should be noted that NO_x emissions collectively refer to both NO and NO_2. The latter is a major air pollutant and also a much stronger oxidizer than O_2 for burning the PM captured in a DPF. While automotive standards set limits for total NO_x emissions, air quality standards only regulate NO_2 concentrations which are closely linked to a range of respiratory diseases. This may result in a counter-intuitive situation that roadside NO_2 concentrations do not decrease accordingly with the reduction of total NO_x emissions [23]. Therefore, the ratio of NO_2/NO_x is of great importance for air quality management, as well as for DPF regenerations. **Fig. 6** compares the instantaneous NO_2/NO_x ratios of trips with and without DPF regeneration. The raw NO_x emissions generated in diesel combustion are mostly (~90%) in the form of NO if without any after-treatment systems [56]. Since NO_2-based regeneration is more energy efficient and can occur under a lower temperature than O_2-based regeneration, diesel vehicles usually use a DOC to promote the conversion of NO to NO_2 for continuous passive DPF regenerations. As a result, the NO_2/NO_x ratio could be relatively high when exhaust temperature is low during normal engine conditions, as shown in **Fig. 6a**. However, as the exhaust temperature increases for active DPF regenerations, the NO_2/NO_x ratio is sharply reduced to below 10% (**Fig. 6b**). This could be mainly caused by two reasons. Firstly, DOC starts NO oxidation at around 150-200 °C. The NO-to-NO_2 conversion efficiency peaks at around 300 °C and reduces rapidly with a further increase of exhaust temperature [57, 58]. Secondly, NO_2 is quickly consumed by PM oxidation before O_2 during DPF regeneration, because NO_2 is a much stronger oxidiser than O_2. Such processes do not affect the total NO_x, but only reduce the NO_2/NO_x ratio via lesser NO oxidation by the DOC ($NO + ½ O_2 \rightarrow NO_2$) and higher NO_2 reduction by the DPF ($NO_2 + ½ C \rightarrow ½ CO_2 + NO$). The results (**Figs. 5** and **6)** suggest that DPF regenerations have little influence on the total NO_x emissions, but can significantly lower the NO_2/NO_x ratios.

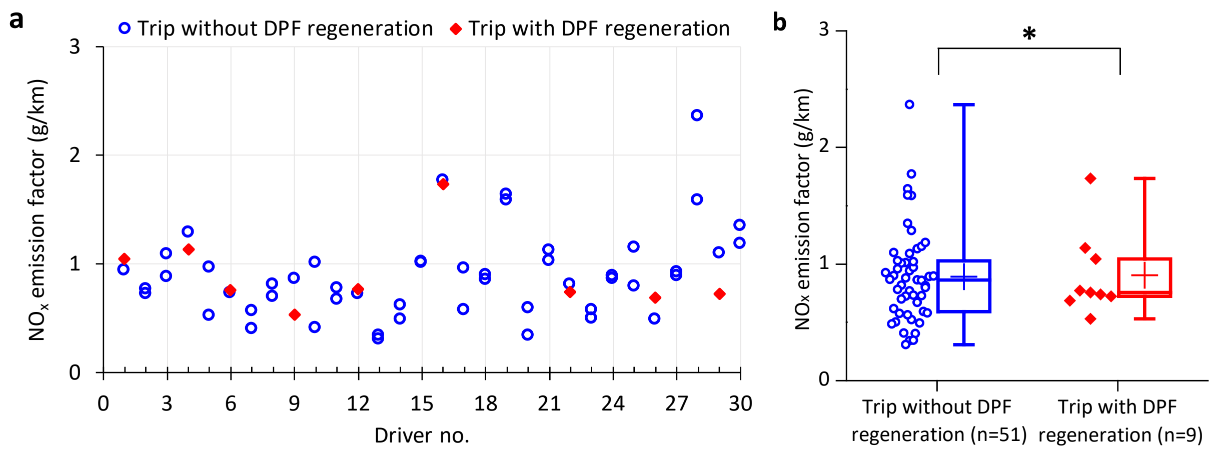

Fig. 5. Comparison of real-driving NO_x emission factors between trips with and without DPF regenerations: **a**) individual drivers, **b**) overall statistics (boxplot: 25th and 75th percentiles, box; median, centre line; mean, plus; minimum and maximum, whiskers). * $p = 4.70 \times 10^{-1}$ by unpaired one-tailed t-tests.

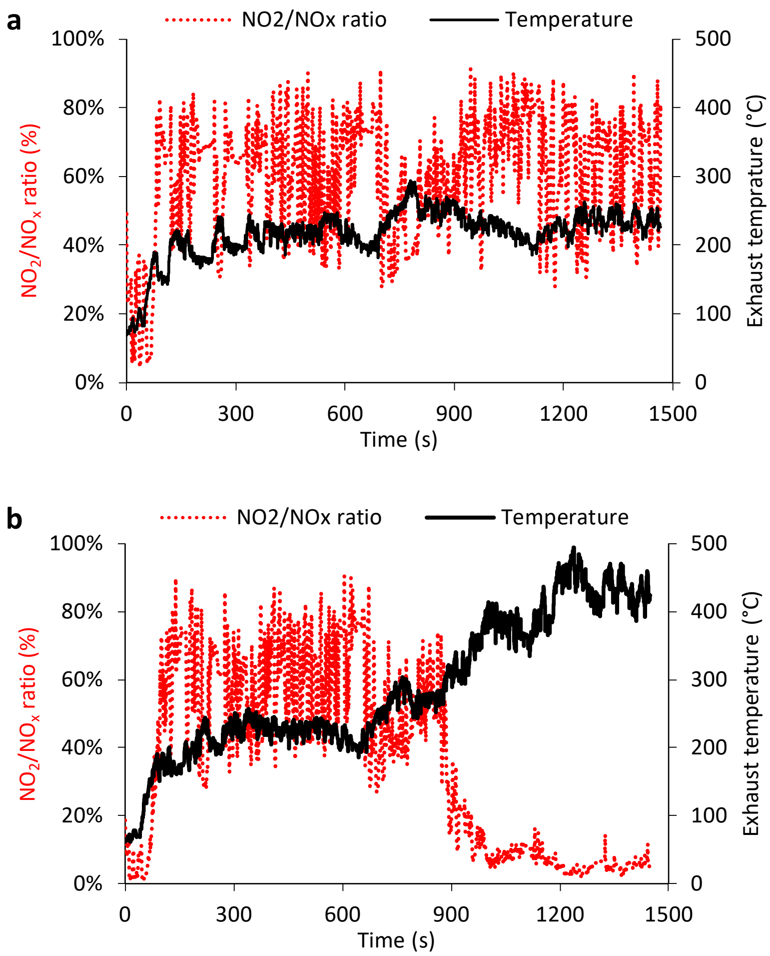

Fig. 6. Variations of instantaneous NO_2/NO_x ratio and exhaust temperature with time of Driver 1: **a**) morning test without DPF regeneration, **b**) afternoon test with DPF regeneration.

PM is another major air pollutant that is dominated by diesel vehicles [6]. **Fig. 7** compares the real-driving PM emission performance of trips with and without DPF regenerations. As shown in **Fig. 7a**, DPF regenerations significantly increased the trip-averaged PM emission factors, except for Driver 9 who experienced a very short and incomplete DPF regeneration event (**Fig. S3**). For trips without DPF regeneration events, PM emission factors are relatively low although only a few trips could meet the Euro 5 PM limit of 0.0045 g/km. However, all nine DPF regeneration trips far exceeded the PM limit, by up to 242 times. Overall, the mean and median PM emission factors of DPF regeneration trips are 27 and 46 times higher than those of normal trips, respectively (statistically significant difference exists, $p = 2.74\times10^{-4}$) (**Fig. 7b**). Such increases are similar to a previous study which observed 34 times increases of real-world PM emissions during PM regeneration for Euro IV-VI medium diesel trucks [47]. Three reasons have contributed to the sharp increases of PM emissions during active DPF regenerations [33]. Firstly, DPF regeneration lowers the filtration efficiency and enhances the penetration of particles through the DPF. Secondly, DPF regeneration changes the structure of the deposited soot layer, which produces new or secondary particles to escape from the DPF. Finally, DPF regeneration can cause the nucleation of semi-volatile particles when gaseous sulphuric acid exits the DPF. It should be noted that the test route is relatively short in this study (19 km, 25-30 min) and the DPF regeneration event accounts for over one third of the test time. In the real-world driving, DPF regenerations do not occur frequently, e.g. every 130 km or 7 trips for the studied vehicle. The impact of DPF regeneration on trip-averaged PM emission factor should be lower for longer test routes. For example, the overall average PM emission factor of all 60 RDE trips (51 normal + 9 regeneration trips) was significantly reduced to be only 4.1 times higher than that of 51 normal trips.

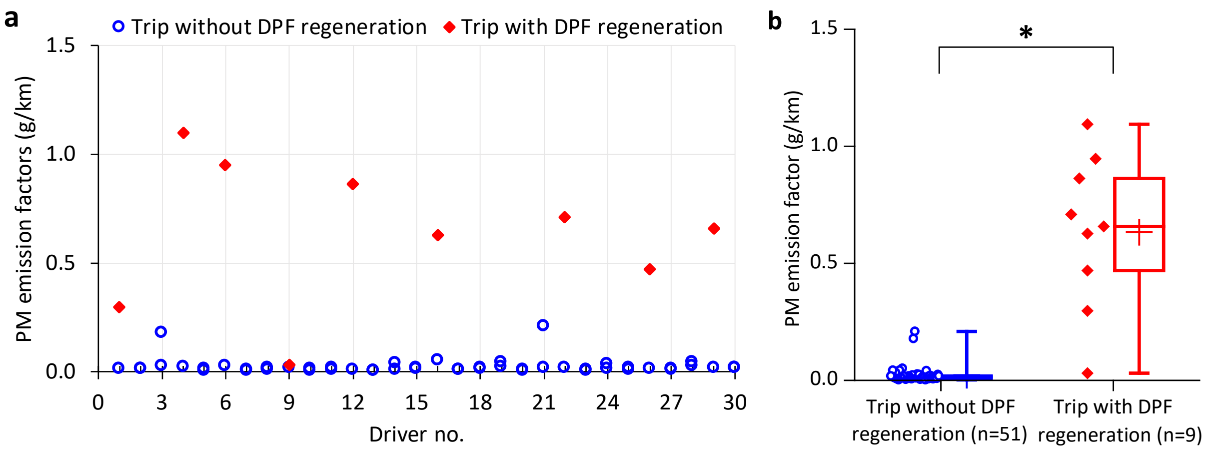

Fig. 7. Comparison of real-driving PM emission factors between trips with and without DPF regenerations: **a**) individual drivers, **b**) overall statistics (boxplot: 25th and 75th percentiles, box; median, centre line; mean, plus; minimum and maximum, whiskers). * $p = 2.74\times10^{-4}$ by unpaired one-tailed t-tests.

4. Conclusions

This study investigated the impact of DPF regenerations on fuel consumption and emissions performance of a diesel LGV under real-driving conditions. A total of 60 RDE trips (~1200 km in total) were performed with the aid of the state-of-the-art PEMS, among which nine real-driving DPF regeneration events were measured. All the RDE trips were driven using the same vehicle on the same route during the same periods of a day, aiming to minimise the effect of environmental and vehicle configuration factors on the analysis. The results showed that, for a 19-km trip, DPF regeneration increased the trip-averaged fuel consumption rate by 13% on average. Regarding pollutant emissions, DPF regenerations tended to increase CO and THC emission as the post combustion was taking place under oxygen-lean conditions. Nevertheless, such impacts were not a concern as CO and THC emission factors were still well below the emission limits even under the impact of DPF regeneration. NO_x emission factors of all RDE trips exceeded the emission limit. DPF regenerations had little influence on the total NO_x emissions, but significantly reduced the NO_2/NO_x ratio due to lower NO oxidation by the DOC and higher NO_2 reduction at DPF. Finally, PM emission factors were relatively low for normal trips but were sharply increased by 27 times on average when DPF regeneration occurred, leading to significant exceedance of emission limit. The findings therefore suggest that a cleaner combustion control that reduces the regeneration frequency and a better DPF design that improves the regeneration quality are needed to reduce the real-driving fuel consumption and PM emissions of diesel vehicles during DPF regenerations.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

Additional information about the test vehicle (**Fig. S1**), RDE test route (**Fig. S2**), and exhaust temperature profiles of DPF regenerations (**Fig. S3**).

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