Real-World PM, PN and NOx Emission Differences among DOC+CDPF Retrofit Diesel-, Diesel- and Natural Gas-Fueled Buses

Zhiwen Yang, Jingyuan Li, Zhenkai Xie, Jian Ling, Jiguang Wang, Mengliang Li

***Abstract*—**To reflect the influence of after-treatment system retrofit and natural gas-fueled vehicle replace on exhaust emissions emitted by urban buses, a portable emission measurement system (PEMS) was employed herein to conduct real driving emission measurements. This study investigated the differences in particle number (PN), particle mass (PM), and nitrogen oxides (NOx) emissions from a China IV diesel bus retrofitted by catalyzed diesel particulate filter (CDPF), a China IV diesel bus, and a China V natural gas bus. The results show that both tested diesel buses possess markedly advantages in NOx emission control when compared to the lean-burn natural gas bus equipped without any NOx after-treatment system. As to PN and PM, only the DOC+CDPF retrofitting diesel bus exhibits enormous benefits on emission control related to the natural gas bus, especially the normal diesel bus. Meanwhile, the differences in PM and PN emissions between retrofitted and normal diesel buses generally increase with the increase in vehicle specific power (VSP). Furthermore, the differences in PM emissions, especially those in the higher VSP ranges, are more significant than those in PN. In addition, the maximum peak PN particle size (32 nm) of the retrofitted diesel bus was significantly lower than that of the normal diesel bus (100 nm). These phenomena indicate that the CDPF retrofitting can effectively reduce diesel bus exhaust particle emissions, especially those with large particle sizes.

***Keywords*—**CDPF, diesel, natural gas, real-world emissions

I. Introduction

THE particulate matter (PM) and ozone (O_3) pollution control is still not optimistic for urban areas in China, especially with the rapid increase in the population of vehicles that can emit pollutants contributing to the increase of these pollutants. As an important precursor of PM and O_3, NO_x emitted by vehicles are urgently needed to be controlled. Compared to other types of vehicles, heavy-duty diesel vehicles can produce much larger amounts of PM and NOx, thus requiring more prevention to control.

To control the exhaust emissions of heavy-duty diesel vehicles, heavy-duty diesel trucks have been prohibited to drive in urban areas, which in turn makes the diesel bus gradually become an increasingly prominent emission contributor. A large number of new types of buses, equipped with natural gas, gas/oil-electric hybrid, and even pure electric engines, have been gradually put into use so as to alleviate air pollution caused by those exhaust pollutants. However, the exhaust emission control against traditional diesel buses is still becoming increasingly important due to the relatively high population proportion of these vehicles and the aging of those old models. Adhering to the principle of maximizing the use of existing resources, the transformation of the exhaust gas after-treatment system has grown to be an important way to reduce vehicle exhaust emissions.

Nowadays, a large number of researches have been conducted against the impact of the CDPF retrofitting on heavy-duty diesel vehicle particle emissions. For example, Wang et al. [1] conducted a chassis dynamometer test on a China 3 heavy-duty diesel vehicle installed with a CDPF, the result of which indicates that 71.1% of PN emissions can be reduced, and a larger reduction effect can be obtained on agglomerated mode particles (84.5%) related to nuclear mode particles (28.7%). By conducting real-world PEMS measurements on heavy-duty diesel vehicles, Lou et al. [2] investigated that the retrofitted CDPF can reduce 85~90% mass of aggregated particles and 90% of accumulated and nuclear mode PN, and nuclear mode PM. In addition, the emission difference between natural gas-fueled and diesel-fueled heavy-duty vehicles has also been explored widely. Compared to diesel vehicles, natural gas vehicles generally exhibited lower carbon dioxide (CO_2) but higher hydrocarbon (HC) emissions [3]. The PN emissions of natural gas vehicles were higher than those of diesel vehicles under high engine load conditions but lower under low load conditions [4]. However, rarely studies are focused on heavy-duty buses, which is not conducive to the treatment of urban air pollution.

To investigate the effects of different control strategies on vehicle PM, PN, and NOx emissions, urban real-world driving emission measurements were conducted on a natural gas bus, a diesel bus, and a diesel bus retrofitted with a DOC+CDPF after-treatment system in this study. Furthermore, the emission differences in different speed-bin and VSP-bin ranges, as well as the difference in the particle number size distribution (PSD) of different emission control strategies were elaborately analyzed and explored, which is expected to provide a basis for urban bus emission control.

II. Materials and Methods

A. Tested Vehicles and Routes

According to the major bus types in Tangshan city, China, three different technical types of buses were selected (Table I),

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including a China V natural gas bus, a normal China IV diesel bus, and a China IV diesel bus retrofitted with a DOC+CDPF after-treatment system. A circular test route (25 km) within 42 bus stations in the urban area was selected to conduct PEMS tests in July 2019. To reflect the real-world driving characteristics of buses, each bus was tested for three trips. During the test, the average values of the atmospheric ambient temperature and the relative humidity were 32.0 ± 1.5 °C and 46.0 ± 5.6%, respectively. In addition, a local driver was selected to drive all the test vehicles so as to avoid the impact of different driving habits of different drivers on the test results.

TABLE I
DETAILED PARAMETERS OF THE TESTED BUSES

Parameters	NGB No. 1	DSB No. 2	DSB No. 3
Vehicle model	FEIYI	SHENWO	SHENWO
Fuel type	natural gas	diesel	diesel
Gross weight (t)	18.0	16.5	16.0
Engine + after-treatment	lean-burn +OC	Diffusion combustion + SCR + DOC + CDPF*	Diffusion combustion + SCR
Emission standard	China V	China IV	China IV
Model year	2015	2012	2015
Odometer (km)	201,150	404,570	210,366

*The after-treatment system is retrofitted with a DOC+CDPF system.

The statistical results of the real-world driving parameters of the test vehicle are demonstrated in Table II. The driving characteristics of the test vehicles are relatively consistent. Meanwhile, the average speed was relatively low (17.1 ± 1.5 ~ 18.5 ± 0.2 km/h), and the density of stop was rather high (1.78 ± 0.06 ~ 2.94 ± 0.03 #/km). In addition, the proportions of different driving conditions exhibited an obvious downward trend from acceleration, idling, deceleration to constant driving conditions. Since the tested buses are required to stop at each bus station, they possess frequent acceleration and deceleration, long idle time, and low driving speed.

TABLE II
REAL-WORLD DRIVING PARAMETERS OF THE TESTED BUSES

Parameters		NGB No. 1	DSB No. 2	DSB No. 3
Vehicle speed (km/h)		18.4 ± 0.1	17.1 ± 1.5	18.5 ± 0.2
Stops (#/km)		2.94 ± 0.03	2.82 ± 0.03	1.78 ± 0.06
Driving proportion (%)	Acceleration	30.2 ± 1.9	27.9 ± 4.4	31.5 ± 2.3
	Cruise	15.7 ± 1.1	22.5 ± 4.3	19.4 ± 3.5
	Deceleration	25.1 ± 1.8	21.8 ± 2.5	23.9 ± 0.5
	Idle	29.0 ± 2.5	27.8 ± 2.6	25.2 ± 0.7

B. Measurement System and Quality Control

The real-world instantaneous and cumulative exhaust emissions of NOx (nitrogen monoxide (NO) and nitrogen dioxide (NO_2)) and particle were collected by a PEMS consisting of a SEMTECH-DS Gas unit and a renewed electrical low-pressure impactor (ELPI+). The SEMTECH-DS, developed by Sensors Inc., adopts a non-dispersive ultraviolet sensor (NDUV) to acquire concentrations of NOx. Besides, several other units fixed around the vehicle body were also included, such as a SEMTECH High-Speed Exhaust Flow Meter (SEMTECH EFM-HS) to continuously and directly monitor the vehicle exhaust flow, a temperature probe to monitor the exhaust temperature near the exit of the tailpipe, a GPS to acquire vehicle speed and location information (i.e., altitude, latitude, and longitude), and a weather probe for the ambient temperature and relative humidity. To prevent the generation of condensates and high molecular weight hydrocarbons during the test periods, the sampling tube between the EFM and SEMTECH-DS analyzer was heated and maintained at 190 °C. For the PM, PN, and PSD over a diameter range of 0.006 μm to 10 μm, the ELPI+, introduced by Dekati Ltd, was utilized to classify particles based on their aerodynamic diameter. A vacuum pump was used to sample particles with a flow of 10 L/min through the instrument. However, the particles in this study were directly collected by the ELPI+, without a dilution system but equipped with a specialized external heating device, which allowed direct measurement of up to 180 °C aerosol samples from the exhaust pipe. Additionally, a 1.5 m heated sampling line was connected between the heating devices and the sampling tube near the exit of the EFM to prevent the condensation of volatile organic compounds.

The lithium battery was employed to power the PEMS instrument to make sure that the vehicle engine operation will not be affected by the power demand of the device. All data acquired in this study were recorded at a frequency of 1 Hertz. The whole PEMS together with the co-driver, with a total weight being around 450 kg, resulted in around 2.7% of the curb weight of the tested buses. To ensure the accuracy of the PEMS, routine calibrations before and after tests of gaseous and particle pollutants were conducted by controlling for the zero and span drift of the gaseous analyzers, purging and verifying the zero flow of the EFM, and executing flush and zero calibrations for the electrometer in the ELPI+. Moreover, due to the different response times for instruments, time synchronization of data acquired by different devices was performed before data analysis. Besides, a laptop computer, connected to the instrument by the local area network, was employed to monitor the real-time operational status of the device.

C. Data Analysis

To investigate the effects of different technologies on emissions in different speed ranges, the method related to the COPERT model was utilized herein to obtain average speed bin EFs. The average speed bin EFs were obtained firstly by integrating vehicle exhaust emissions from on-road tests over 1 km distance bins and then by splitting in speed bins of 10 km/h.

To further reflect the differences of various technical types in emissions under different driving conditions, VSP defined as the instantaneous power demand per unit of vehicle mass (kW/ton) was used to illustrate the correlation between vehicle operating modes and gaseous emissions. According to the motor vehicle emission simulator (MOVES) of the US Environmental Protection Agency, VSP can be calculated as (1):

$$\mathrm{VSP} = \frac{A}{M} \cdot v + \frac{B}{M} \cdot v^2 + \frac{C}{M} \cdot v^3 + a \cdot v + \mathrm{g} \cdot v \cdot sin\theta \qquad (1)$$

where M is the gross vehicle weight (tons), v is the vehicle speed (m/s), a is the vehicle acceleration (m/s^2), g is the gravitational acceleration (9.81 m/s^2), and θ is the road grade (radians). Besides, A (kW s/m), B (kW s^2/m^2), and C (kW s^3/m^3) represent the coefficients of the rolling resistance, rotational resistance, and aerodynamic drag, respectively. Obtained from the MOVES model, the values of A, B, and C coefficients are 1.12525, 0, and 0.00411, respectively, for the tested buses.

III. Results and Discussion

A. Differences in On-road Driving based Emissions

The distance-based emission factors (EFs) of PM, PN, and NOx (NO+NO_2) are illustrated in Table III. For NOx, a significant difference occurred between the tested diesel buses and the tested natural gas bus (NGB No. 1), while a smaller difference can be found between the retrofitted diesel bus (DSB No. 2) and the tested normal diesel bus (DSB No. 3). The NOx EFs of the tested diesel buses were 62.7 ~ 70.0% lower than that of the tested natural gas bus, proving that diesel vehicles equipped with SCR possess obvious advantages in NOx emission control compared with lean-burn natural gas vehicles equipped without any after-treatment system against NOx [5], [6]. This phenomenon can be explained by the following two aspects: (1) the lean-burn engine used in the natural gas vehicle has a larger air-fuel ratio and thus more sufficient combustion, leading to higher NOx emissions [7]; (2) the SCR of the tested diesel bus can effectively reduce NOx emissions once the exhaust temperature reaches a proper level.

TABLE III
Real-World EFs of the Tested Buses

Pollutants	NGB No. 1	DSB No. 2	DSB No. 3
NOx (g/km)	23.3 ± 0.1	8.7 ± 0.4	7.0 ± 0.6
NO (g/km)	22.5 ± 0.1	8.7 ± 0.5	6.9 ± 0.6
NO_2 (g/km)	0.82 ± 0.01	0.06 ± 0.06	0.15 ± 0.02
PM (mg/km)	7.5 ± 1.3	0.2 ± 0.0	104 ± 44.9
PN ($\times 10^{13}$#/km)	1.4 ± 0.5	0.014 ± 0.004	2.6 ± 0.9

Compared to the difference in NOx between different vehicles, the difference of NO EFs is nearly consistent, while the difference of NO_2 EFs is markedly different. Compared with the natural gas bus (NGB No. 1), the retrofitted diesel bus (DSB No. 2) and the normal diesel bus (DSB No. 3) exhibited 61.3% and 69.3% lower NO EFs, respectively, and 92.7% and 81.7% lower NO_2 EFs, respectively. A more obvious difference can be found in NO_2 related to NO emissions between different fuel-based buses. Meanwhile, the ratio of NO_2/NOx EFs is significantly higher for the natural gas bus (NGB No. 1:3.5%) when compared to the tested diesel buses (DSB No. 2: 0.7%, DSB No. 3: 2.1%), which may be related to the oxidation of OC on NO emission for the natural gas bus. In addition, compared with the normal diesel bus (DSB No. 3), the retrofitted diesel bus (DSB No. 2) exhibited 60% and 66.7% lower NO_2 EF and NO_2/NOx EF ratio, respectively. This was probably caused by the effect of oxidative consumption on NO_2 that occurred in DPF [8].

For particle emissions, the PM and PN EFs of different buses exhibited a downward trend from the normal diesel bus (DSB No. 3), the natural gas bus (NGB No. 1) to the retrofitted diesel bus (DSB No. 2). The PM and PN EFs of the normal diesel bus (DSB No. 3) are 520 and 189 times that of the retrofitted diesel bus (DSB No. 2), while those of the natural gas are 37.5 and 100 times that of the retrofitted diesel bus (DSB No. 2). Obviously, the installation of DPF can effectively reduce the PN and PM emission levels. However, the reduction effectiveness on PM was more prominent than that on PN for both tested diesel buses, indicating that the filtering effect of DPF on PM is better than that on PN. This is mainly because PM, mainly composed of large-sized particles, is easier to be retained and filtered by DPF. In addition, more prominent differences can be found in PN relate to PM between the natural gas bus (NGB No. 1) and the retrofitted diesel bus (DSB No. 2), which was probably related to the higher proportion of particles in the small particle size for the natural gas bus caused by the more complete combustion in the natural gas engine compared to the diesel engine. On the contrary, less prominent differences can be found in PN related to PM between the natural gas bus (NGB No. 1) and the normal diesel bus (DSB No. 3), which are consistent with previous research results [9].

B. Differences in Speed-Bin Emissions

To explore the differences in speed-bin EFs of NO, NO_2, PN, and PM between different technologies, the variations in the average speed-bin EFs were elaborately studied as shown in Fig. 1. As shown in Figs. 1 (a) and (b), the average speed-bin NO and NO_2 EFs of both the retrofitted diesel bus (DSB No. 2) and the normal diesel bus (DSB No. 3) are significantly lower than those of the natural gas bus (NGB No. 1). Compared with the normal diesel bus (DSB No. 3), the retrofitted diesel bus exhibited relatively higher and lower average speed-bin NO and NO_2 EFs, respectively. This is consistent with the above results against on-road driving-based EFs, which may be related to the oxidative consumption of NO2 by PM in DPF. As illustrated in Figs. 1 (c) and (d), the average speed-bin PN and PM EFs of the retrofitted diesel bus (DSB No. 2) in all speed ranges are significantly lower than that of the natural gas bus (NGB No. 1), especially than that of the normal diesel bus (DSB No. 3). Noticeably, as the speed increases, the average speed-bin PN and PM EFs of both tested diesel buses exhibited a trend of first decreasing and then increasing, while that of the natural gas bus (NGB No. 1) showed both a decreasing trend. It was clear that the PN and PM emissions are more susceptible to high speeds for the diesel buses compared to the natural gas bus.

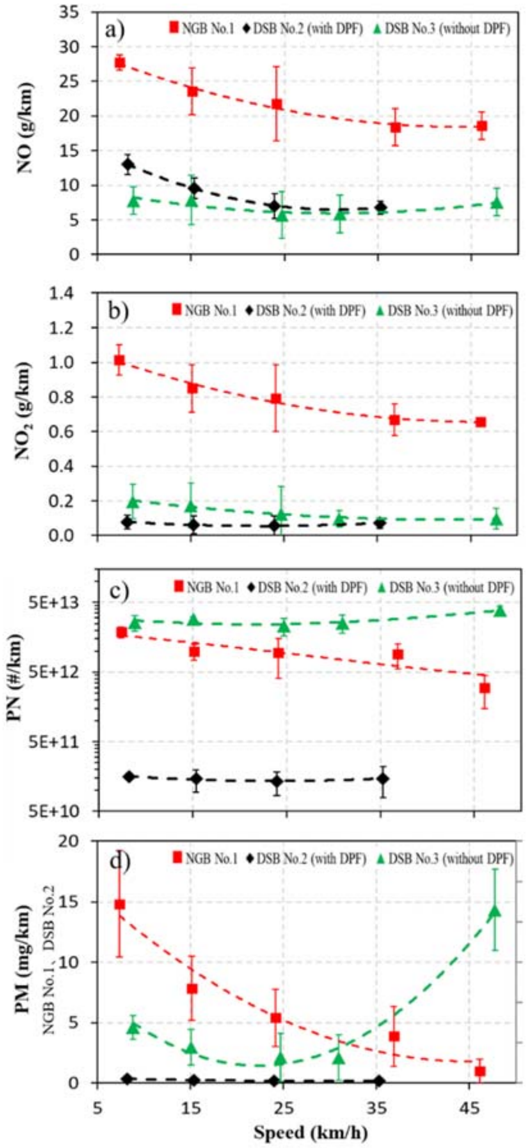

Fig. 1 Variations of the speed-bin EFs for the tested buses

C. Differences in VSP-Bin Emissions

Fig. 2 shows the variations of average VSP-bin emission rates of NO, NO_2, PN, and PM of the tested buses. The average VSP-bin emission rates basically increase with the increase of VSP. As shown in Figs. 2 (a) and (b), the average VSP-bin emission rates of NO and NO_2 for the natural gas bus (NGB No. 1) were significantly higher than that for the tested diesel buses in most VSP bins. Compared to the retrofitted diesel bus (DSB No. 2), the natural gas bus (NGB No. 1) and especially the normal diesel bus (DSB No. 3) exhibited higher average VSP-bin PN and PM emission rates (Figs. 2 (c) and (d)). Moreover, the differences in VSP-bin PN and PM emission rates between the retrofitted diesel bus (DSB No. 2) and the normal diesel bus (DSB No. 3) generally increase with the increase of VSP. And the differences in VSP-bin PM, especially that in the high VSP interval, are more significant than that in VSP-bin PN. Generally, the reduction effect of the DPF on PN and especially on PM demonstrated an increasing trend with the increase in engine load.

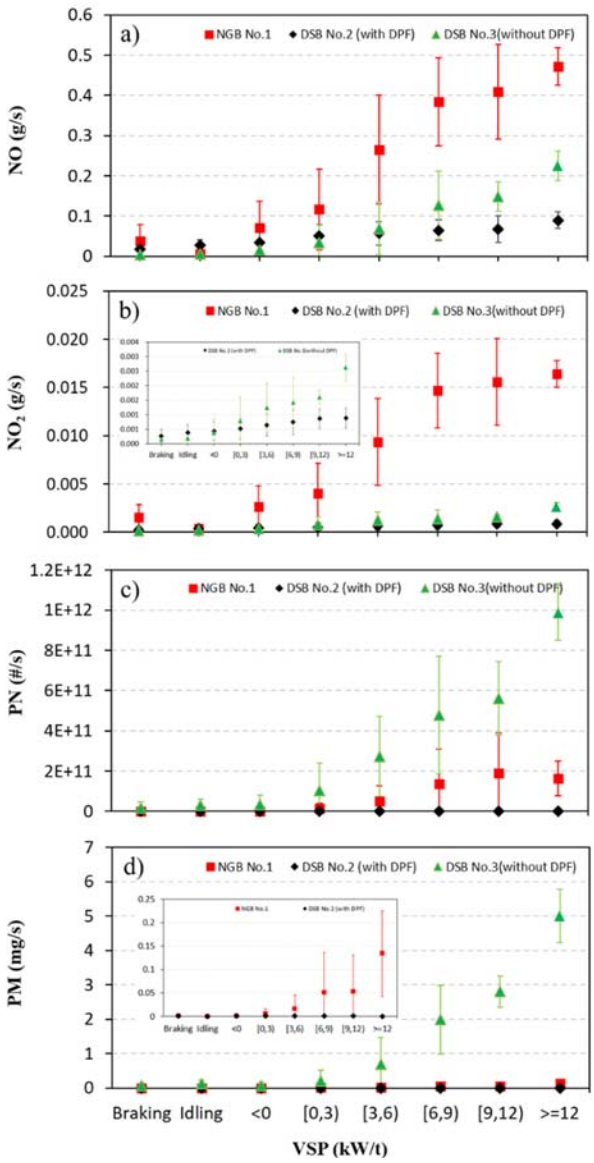

Fig. 2 Variations of the VSP-bin emission rates for the tested buses

D. Differences in PSDs

The variations of PSD for different vehicles are demonstrated in Fig. 3. The PSD of the natural gas bus (NGB No. 1), the normal diesel bus (DSB No. 3), and the retrofitted diesel bus (DSB No. 2) generally exhibited a unimodal (mode size: 9 nm), bimodal (mode size: 9 nm and 100 nm), and trimodal distribution (mode size: 9 nm, 17 nm, and 32 nm), respectively. The particles of the natural gas bus (NGB No. 1) were mainly composed of particles with a particle size of about 10 nm, while the particles of the diesel buses were also composed of particles with relatively larger particle sizes except for those with a particle size of around 10 nm. This may be due to the fact that the combustion in the natural gas engine is more sufficient and thus produces fewer large particles with a particle size above 10 nm, while the diffusion combustion inside the engine for the diesel bus is relatively inadequate and thus leads to the easier generation of particles with larger size [10]. In addition, the maximum peak particle size of the retrofitted diesel bus (DSB No. 2: 32 nm) is apparently smaller than that of the normal diesel bus (DSB No. 3: 100 nm). This is consistent with the above result, namely, the DPF can more effectively remove particles in the large-diameter section, which therefore makes the reduction effect on PM is more obvious than that on PN.

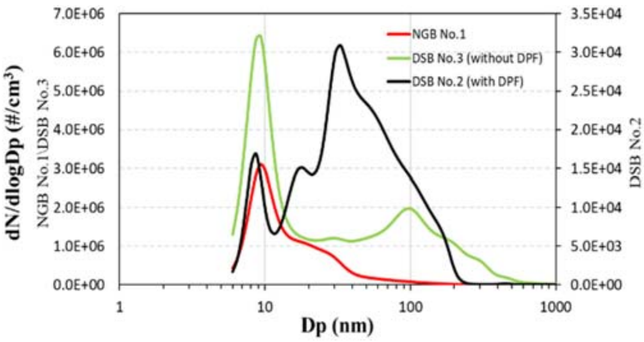

Fig. 3 Changes of PSD under different technical conditions for the tested bus

IV. Conclusions

1. For urban roads, different speed bins, and most VSP-bin intervals, the tested diesel buses exhibited obvious lower NOx (NO, NO_2) emissions when compared with the tested natural gas bus. As to PN and PM, the emissions of the normal diesel bus were higher than that of the natural gas bus, while the emissions of the DPF retrofitting diesel bus were significantly lower than that of the natural gas bus. In addition, the difference in PN and especially that in PM between the normal and DPF retrofitting diesel buses generally increases with VSP increase.
2. Under urban driving conditions, the average speed-bin EFs of PN and PM for the tested diesel buses both demonstrated a trend of first decreasing and then increasing, while that for the natural gas bus exhibited a downward trend. It is clear that the PN and PM of the diesel buses are more susceptible to high speeds than that of the natural bus.
3. For the PSD, the natural gas bus, the normal diesel bus, and the DPF retrofitting bus exhibited obvious unimodal (mode size: 9 nm), bimodal (mode size: 9 nm and 100 nm), and trimodal distributions (mode size: 9 nm, 17 nm, and 32 nm), respectively. Clearly, the maximum peak particle size of the retrofitted diesel bus is smaller than that of the normal diesel bus, proving that the DPF is more conducive to the removal of large particles compared to small particles.

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