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Emission Characteristics of Heavy-Duty Vehicle Diesel Engines at High Altitudes

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ABSTRACT

The aim of this study was to accurately quantify the emission characteristics of pollutants at different altitudes. We used an intake and exhaust altitude simulation system that could simulate the intake and exhaust pressures of a national sixth vehicle diesel engine at different altitudes. Experimental research was conducted on the World Harmonized Transient Cycle (WHTC) and World Harmonized Steady State Cycle (WHSC) of the diesel engine. The results showed that carbon monoxide (CO) emissions increased with the altitude at full load, but their rates were significantly reduced at low speed (800 rpm), increasing by 0.0084 – 0.665 ppm/m. Hydrocarbon (HC) emissions showed an initial decreasing and then increasing trend, with a rise of up to 30%. Nitrogen oxides (NOx) showed a linear decreasing trend, especially at low speed. With the increase in altitude, the cycle work of the diesel engine decreased in a non-linear manner, and the decrease became more pronounced above 3000 m. The raw emission results of the WHTC and WHSC tests also revealed that CO increased exponentially, NOx decreased slightly and then increased rapidly, HC increased linearly, and the emissions of all pollutants deteriorated significantly above 3000 m. The exhaust emission results of the WHTC and WHSC tests showed that the CO emission showed an initial decreasing and then increasing trend with the elevation of the altitude, approximately 15 ± 5 mg/kWh. HC emissions showed an increasing trend, with HC emissions of 3 – 6 mg/kWh for the WHTC and 1 – 2 mg/kWh for the WHSC. NOx emissions did not follow any obvious rule, while the particulate matter (PM) tended to increase and then decrease with the elevation of the altitude. In relation to the current emission standards, the limit value margin for CO and HC exhaust emissions is greater than 95% and the limit value margin for PM emissions is greater than 88% at an altitude of 4000 m. The NOx emission limit is greater than 87% (within 3000 m), but there is a risk of exceeding the limit above 3000 m.The second sampling data from the WHTC and WHSC showed that the raw emissions of the engine were higher in the high-altitude area than in the low-altitude area, but the change law of the exhaust emissions was not obvious, and the levels of both emissions were low.

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1. INTRODUCTION

With the progress of science and technology, human exploitation of natural resources is increasing (Sayed et al., 2021; Zhang et al., 2022), especially the development and use of fossil energy, which releases a large number of pollutants and carbon dioxide (CO_2) into the atmosphere (Chen et al., 2019; Li et al., 2022). This increased fossil energy consumption leads to a rise in the average global temperature (Duan et al., 2017), which contributes to sea level elevation, greater desertification, and more frequent extreme natural disasters (Greene & Façanha 2019). Diesel engines are widely used in transport, shipping, aerospace, and other sectors due to their excellent fuel economy, reliability, and adaptability (Agarwal et al., 2022; Ye & Peng 2023). However, whith the rapid growth of vehicle diesel engines, energy consumption (Sun et al., 2017; Snow et al., 2023) and pollutant emissions have increased. Vehicle exhaust is also a major source of environmental pollution, especially diesel emissions, whose pollutants include carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NOx), methane (CH_4), particulate matter, etc. Vehicle emissions not only pollute the environment, causing adverse environmental events such as acid rain and photochemical smog (Liu et al., 2023), but also have a profound effect on human physical and mental health (Fenger 2009; Kelly & Fussell, 2012). For example, metals in the exhaust particles can induce cellular oxidative stress by generating reactive oxygen species, leading to lung injury and cardiovascular disease (Gallagher et al., 2019). To reduce the harmful effects of vehicle exhaust pollutants on human health and the natural environment, binding restrictive legislation and regulations have been proposed worldwide to encourage technological innovation in automotive products and reduce pollutant emissions. In addition, CO_2 as a greenhouse gas will also be included in the next-stage emission regulations to promote the achievement of the global zero carbon target (Benjumea et al., 2009). It is therefore necessary to analyse and optimise the effect of altitude on engine performance.

Vehicle diesel engines are widely used in road freight transport, but their energy efficiency is low, especially at high altitudes (Chaffin & Ullman 1994). It has been shown that with increasing altitude, diesel engine performance and fuel consumption decrease (Zhu et al., 2015; Yang et al., 2018), combustion deteriorates, and soot emissions increase (Liu, J. et al. 2017; Liu, R. et al. 2017). This is because most vehicle engines are not designed for high-altitude applications, and their performance has not been adapted for high-altitude operation. However, the world's plateaus are widely distributed, and vehicle engines often operate at high fuel consumption and low efficiency, leading to increased carbon emissions. In China, for example, land situated at an altitude above 1000 m accounts for 58% of the country's total area, and land above 2000 m accounts for 33% (Serrano et al., 2019). In Europe, about 19.1% of the population lives at an altitude above 1000 m (Giraldo & Huertas 2019), and in Latin America, most cities are above 2000 m (Shannak & Alhasan, 2002). The decrease in the atmospheric pressure at high altitudes leads to a decrease in engine intake mass flow, a decrease in ignition temperature and pressure in the cylinder, a delay in ignition and a deterioration in combustion, resulting in a decrease in engine power and an increase in fuel consumption and generated emissions (Wang et al. 2013). In addition, the spray characteristics of diesel fuel are also affected by altitude, particularly the spray penetration distance. In low density and low pressure media, the spray penetration distance increases (Shi et al., 2019). Wang et al. (2022) and Bo et al. (2021) investigated the effect of air density and temperature on diesel spray atomization. The results showed that the high altitude and cold environment deteriorated the spray and ignition quality, leading to ignition failure. In addition, Liu & Liu (2021) and Motahari & Chitsaz (2019) investigated the effect of different altitude and intake temperature on the combustion and emission characteristics of engine cylinders for supercharged engines. The results show that the supercharging is beneficial in restoring engine performance at high altitude, but with increasing altitude, the engine ignition delay increases significantly, the oil - gas mixing quality deteriorates significantly, and the combustion deterioration and power loss become more obvious. Therefore, diesel engine combustion deteriorates at high altitudes due to improper air-fuel matching.

The implementation of the China VI emission regulation has increased the attention of engine and automobile enterprises to the emissions of plateau vehicle engines. The actual road emission detection range of vehicles has been extended to 2400 m (China VI b), reflecting the urgency of controlling pollutant emissions from plateau vehicles, which is a key link to achieving the "dual carbon" goal. In recent years, most studies have focused on issues such as engine dynamic recovery and optimization at high altitudes, emission control, and post-processing development (Kim et al., 2012; Rounce et al., 2012; Hamedi et al., 2014). However, most current studies lack quantitative information on the pollutant emissions from diesel engines, and qualitative judgements may weaken concerns about their hazards. Fang et al. (2022) used environmental chamber and numerical simulation methods to analyse the cold start combustion characteristics of diesel engines at high altitudes and low temperatures. The results showed that the ignition delay is longer, and the atomisation is more severe at high altitudes and low temperatures, resulting in a longer time from an idle to a steady state. Wang et al. (2020) analyzed the data from visualization experiments of diesel injection and combustion at different altitudes. The results showed that at high altitudes, the injection penetration increased, and the injection angle decreased, resulting in more diesel droplets adhering to the cylinder wall, which worsened combustion. Liu et al. (2022) selected field altitudes of 41m, 1890 m and 3650 m to conduct real-life on-road emission test (PEMS). The results show that the higher the altitude, the worse the fuel injection parameters, the higher the risk of fuel hitting the wall, the worse the combustion environment in the cylinder and the lower the engine power. Jiao et al. (2019) carried out tests on the combustion and emission characteristics of diesel hybrid fuel engines at different altitudes. These scientists found that the hybrid fuel improved the performance and particulate matter (PM) emission of the diesel engine at high altitudes, but the NOx emission was slightly higher. Additionally, Nie et al. (2022) investigated the influence of exhaust thermal management control strategies at different altitudes on engine performance and after-treatment catalytic conversion efficiency. Their results showed that thermal management techniques increased the exhaust temperature, improved the operating temperature of the aftertreatment system and thus promoted the removal rate of exhaust pollutants. However, some of the control strategies increased fuel consumption. The results of the above studies show that engine combustion deteriorates, power decreases and emissions increase at high altitudes, but more detailed quantitative information is lacking.

In summary, low pressure, low oxygen, and low temperature intake conditions affect the fuel-air matching properties and injection atomisation effects of diesel engines. Due to the inadequate combustion caused by more fuel and less air, and the reduction in catalytic conversion efficiency of the after-treatment system at high altitude, vehicle emissions increase. Moreover, previous studies have done little to quantify the amount of emissions at different altitudes in detail. Therefore, in this research, we systematically analyzed the plateau emission characteristics and differences of heavy-duty diesel engines

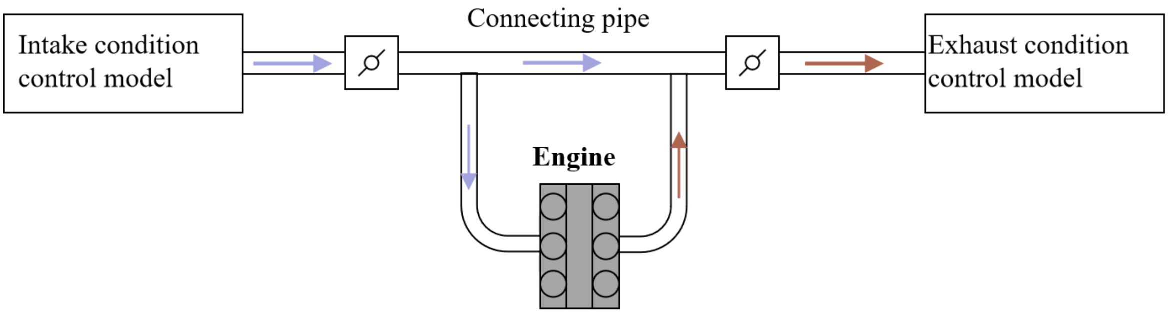


Fig. 1 Working diagram of the altitude simulation system

Table 1 Main parameters of the test engine

Project	**Parameter**
Engine type	6, DI, CI
Intake type	Supercharged
Bore/Stroke	116/ 150 mm
Compression ratio	17.5 ± 0.5:1
Rated power/speed	294 kW/ 1900 r/min
Maximum torque/speed	1900 Nm 1200–1300 r/min

under different operating conditions and test cycles. The change rule and emission trend of each pollutant at different altitudes are analysed and the risk of exceedance for each pollutant is explained. The results can provide data to support the development of high-altitude emission test methods and limits for heavy-duty diesel engines.

2. TEST METHODS AND EQUIPMENT

2.1 Test Methods

The tests were carried out in the engine plateau bench test laboratory (altitude of 1900 m) of China Automotive Research & Development Automotive Inspection Center (Kunming) Co., LTD. which is equipped with an intake and exhaust altitude simulation system. The full load and emission test cycle of the China VI engine was tested and studied under different altitude conditions. Altitudes of 0, 1000, 1900, 2400, 3000, and 4000 m were simulated, corresponding to the simulated atmospheric pressure of 101, 90, 81, 75.6, 70, and 60 kPa (laboratory ambient pressure of 80.3 kPa). The engine intake temperature was controlled and maintained at 25 ± 2°C, and the intake relative humidity was maintained at 50 ± 10%. Data were recorded during the test, and the effects of the different altitudes on the exhaust emission characteristics of the diesel engine at full load and during the emission test cycle were analyzed. The engine under test is a supercharged, medium-cooled National Six heavy-duty diesel engine with high-pressure common rail and in-cylinder direct injection. The main engine parameters are shown in Table 1.

The intake and exhaust altitude simulation system consisted of HORIBA's STARS test control system and AVL's Intake Air Conditioning ("ACS") and Exhaust Emission Control Unit ("EEU"). The working diagram of the high altitude simulation system is shown in Fig. 1. The intake air conditioner controls the humidity, pressure, and temperature of the intake air. After passing through the intake vacuum control valve, part of the air enters the engine, and the other part enters the side duct. The engine exhaust air meets the by-pass air and flows into the exhaust back-pressure control valve, which then flows into the heat exchanger for cooling and finally into the exhaust system. The altitude simulation system can achieve 0-5000 m altitude simulation, 540-1050 mbar pressure simulation, 10-70°C temperature simulation, and 8–20 g H2O/dry air humidity simulation.

2.2 Equipment

In addition to the intake and exhaust height simulation system, the test equipment includes an electric dynamometer, an emission analyzer, a fuel consumption meter, an intake flow meter, etc. HORIBA's MEXA-ONE-D2 emission analyser samples and analyses CO, CO2, NO, NO2, NOx, H2O, NH3, CH4, HC. Among them, HC can be measured in 9 ranges (0-50 /100/ 500/ 1000/ 2000/ 5000/ 10000/ 20000/ 60000 ppm), NOx can be measured in 9 ranges (0-10/ 20/ 50/ 100/ 200/ 500/ 1000/ 2000/ 10000 ppm), CO can be measured in 4 ranges (0-50/ 100/ 1000/ 5000 ppm). The sampling frequency is 10 HZ. The parameters of the test equipment are listed in Table 2. Conventional detection methods cannot directly measure the emission of pollutants, and thus the addition of another chemical agent is necessary to react with it and measure the consumption of this agent to determine the amount of pollutants emitted. The most commonly utilized agents for these purposes are O2 and H2.

Table 2 Test equipment

Name	**Parameter**
Electric dynamometer (HORIBA HT460)	Torque: 2680 Nm Power: 460 kW
Emission analyzer (MEXA-ONE-D2)	CO, CO_2, NO, NO_2, NOx, H_2O, NH_3, CH_4, HC
Fuel consumption meter (HORIBA FQ-3200)	0–250 kg/h ≤ ± 0.01% F.S
Intake flowmeter (ABB)	0–2400 kg/h ≤ ± 2% R.S

Fig. 2 Engine test bench equipped with an altitude simulation system

2.3 Altitude Simulation Test Verification

In this paper, the experimental results of the altitude simulation system and the actual environment at the altitude of 1900 m were compared, and the applicability and feasibility of the altitude simulation system were analyzed. Figure 2 showed the engine test bed with the intake and exhaust altitude simulation system installed.

The intake and exhaust altitude simulation system was used to simulate the engine's intake and exhaust pressures at an altitude of 1900 m. The altitude simulation (AS) and local ambient (LA) test data were compared to verify the accuracy of the intake and exhaust altitude simulation system. Altitude changes directly affect the engine's intake and exhaust boundaries, leading to a deterioration of the engine's in-cylinder combustion and low energy utilization, and ultimately to a reduction in engine power and an increase in fuel consumption and emissions. The full-load test of the engine was used to record the performance of the engine at different speeds, and the difference between the test results of the altitude simulation system and the field test was analysed to show whether the altitude simulation system could meet the test requirements. The validation results are shown in Fig. 3 and Fig. 4.

In this paper, the intake and exhaust boundary conditions of the engine were determined and confirmed, including the post-cooling pressure (P_pc), post-cooling temperature (T_pc), intake mass flow rate (MF R_in), intake relative humidity (RH_in), exhaust mass flow rate (MF R_exh), exhaust temperature (T_exh), exhaust pressure (P_exh), exhaust pressure drop (PD_exh), peak in-cylinder pressure (P_max), torque, effective fuel consumption rate (BSFC), and CO_2, CO, O_2, and NOx emission levels. Of these, CO_2, CO, O_2 and NOx are the original emissions from the engine. The comparison of the engine's intake and exhaust boundaries revealed that the altitude simulation system was able to accurately simulate the actual engine's intake and exhaust environment. The difference in in-cylinder combustion and emission can reflect the influence of the simulated environment and the actual test environment on engine performance and emissions. The experimental results obtained from the intake and exhaust altitude simulation system under the local environmental conditions showed that the engine's intake and exhaust boundaries, torque, fuel consumption, peak pressure, and emissions were consistent, with deviations within 5%.

3. EMISSION ANALYSIS OF THE FULL LOAD AT DIFFERENT ALTITUDES

Diffuse combustion is the predominant operating process in diesel engines, where the inhomogeneity of fuel and air mixing in the cylinder has a major impact on the combustion process. In addition, intake pressure, temperature, and oxygen content directly affect the ignition time in the cylinder. With increasing in altitude, atmospheric pressure, temperature, humidity and oxygen content of the air decrease, and atmospheric pressure and oxygen content are particularly important for complete combustion of the fuel in the cylinder. A decrease in

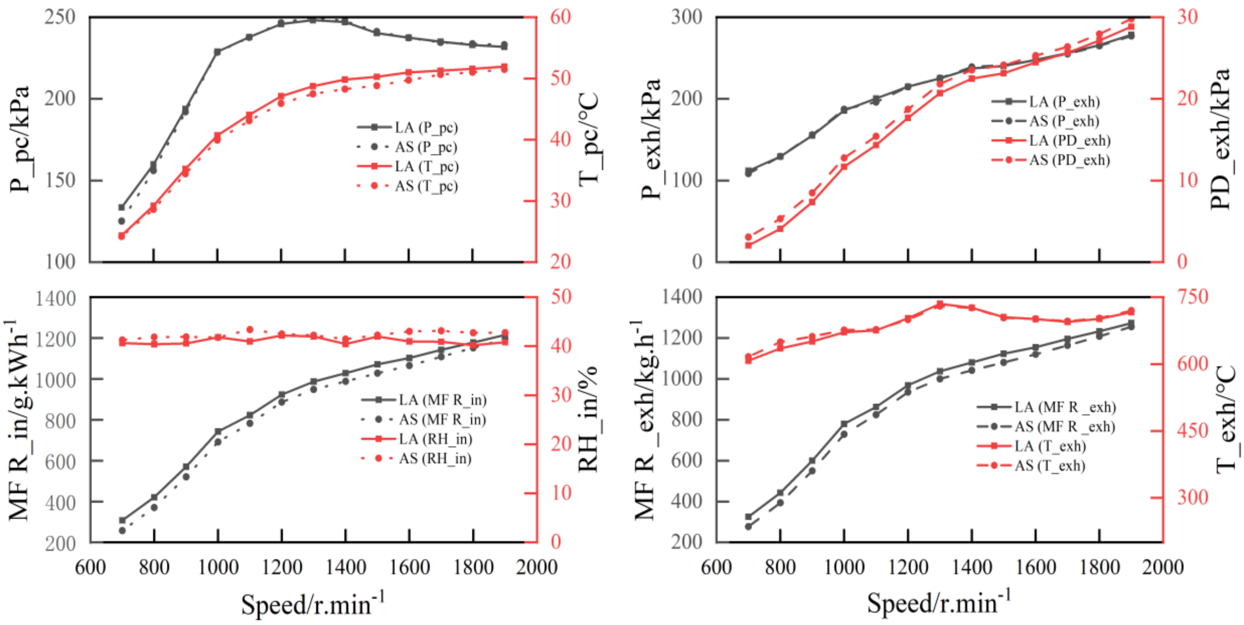


Fig. 3 Comparison of the engine intake and exhaust boundaries

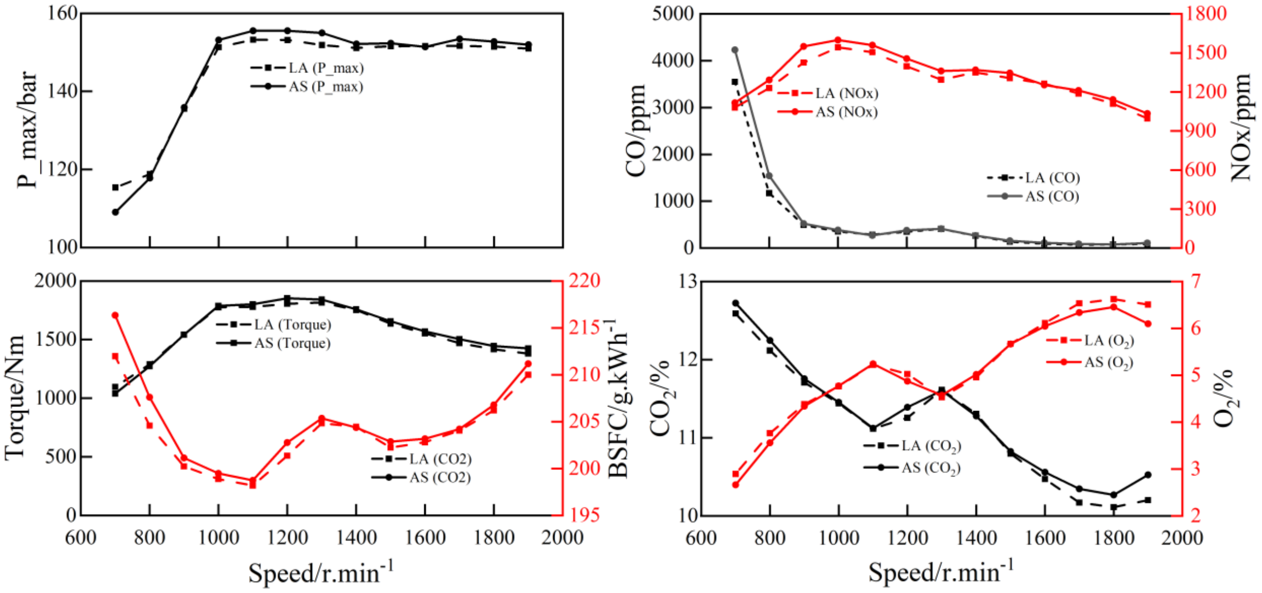


Fig. 4 Comparison of the engine performance and emissions

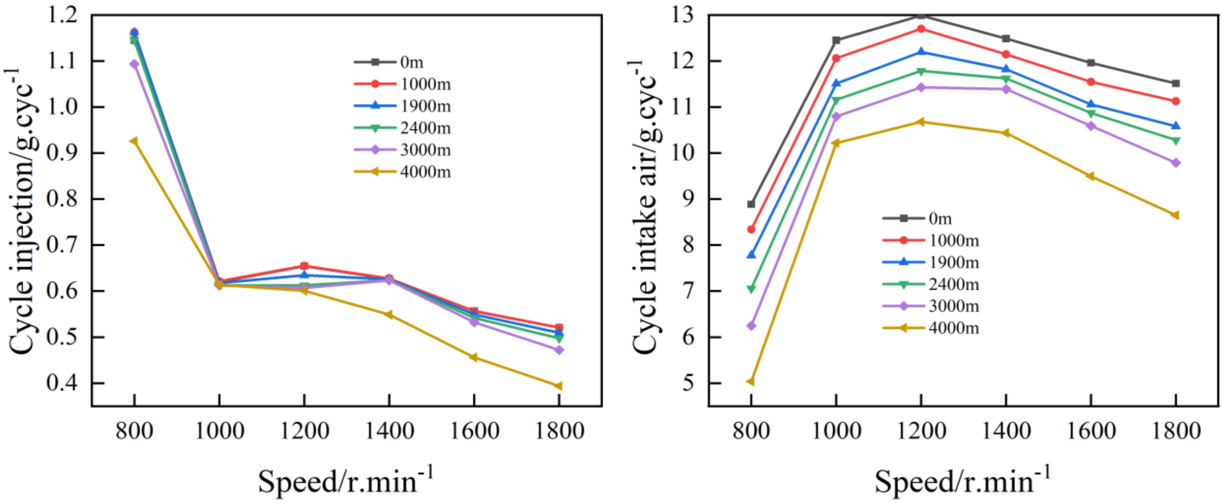


Fig. 5 Cycle injection volume, cycle intake air

atmospheric pressure causes an insufficient intake of air flow into the engine cylinder, resulting in a decrease in pressure and temperature at the compression TDC, followed by a delay in ignition. The decrease in atmospheric oxygen leads to insufficient diffuse combustion in the cylinder, resulting in increased PM and CO emissions. To analyze the in-cylinder combustion of a high altitude diesel engine, it is necessary to know whether the fuel is completely burned. Based on the actual effective fuel consumption rate of the diesel engine at different altitudes, the amount of fuel injected at each speed, i.e., the amount of circulating fuel supply, is calculated as shown in Fig. 4.

The formulas for calculating the actual circular injection volume and circular intake volume are as follows:

$$B = Be*Pe \tag{1}$$

$$B1 = B/(60*n) \tag{2}$$

Where, B is the hourly fuel consumption, g/h; Be is the effective fuel consumption rate, g/kWh; Pe is the power, kWh; B1 is the circulating fuel supply, g/cyc; and n is the engine speed, r/min. Similarly, the actual cyclic intake of a diesel engine can be calculated, as depicted in Fig. 5. At the same altitude, intake initially increases and then decreases with increasing RPM, with the greatest intake in the mid RPM range. At the same RPM, intake decreases with altitude and this decrease is more pronounced at higher altitudes.

Under the influence of the turbocharger, except at 800 rpm (the turbocharger does not work, the combustion is concentrated in the cylinder), the rest of the actually circulating intake air can reach the theoretical condition of full combustion of the fuel in the cylinder, and its excess air coefficient is between 1.2 and 1.45. At the same altitude, the excess air coefficient increases with increasing speed. At the same speed, the excess air coefficient decreases with altitude elevation. The excess air coefficient decreases less due to the supercharger effect.

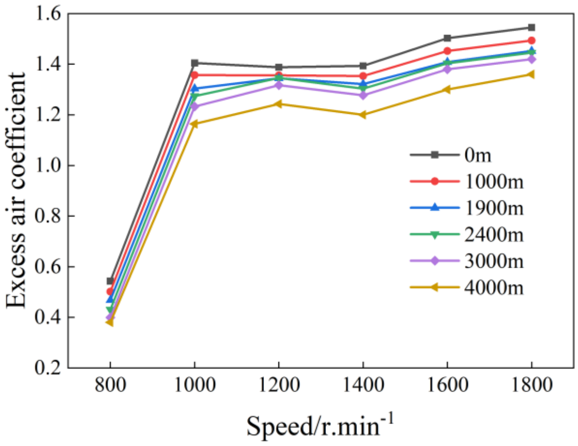


Fig. 6 Excess air coefficient

CO emission is caused by insufficient combustion of carbonaceous fuel and is mainly related to the oxygen content in the engine cylinder. CO emissions decrease as engine speed increases, but increase with altitude. At 800 rpm and altitudes above 1000 m, CO emissions rise sharply to a maximum of 2300 ppm. At 1000 rpm and altitudes above 2400 m, CO emissions increase rapidly to a maximum of 1500 ppm, an increase of 0.665 ppm/m. Between 1200 rpm and 1800 rpm the CO emission is lower than at other speeds, with CO emission values varying between 0.0084 and 0.087 ppm/m. The increase in CO emission is about 0.0084-0.087 ppm/m. CO is produced by incomplete combustion of fuel in the cylinder, which is greatly affected by the amount of engine intake air. As shown in Fig.6, at different altitudes, the excess air coefficient is less than 0.6 at a speed of 800 r/min, which is significantly lower than the excess air coefficient of the diesel engine in normal combustion (> 1). Therefore, the local hypoxia in the cylinder increases and the proportion of incomplete combustion increases, resulting in significantly higher CO emissions than at other speeds. The relationship between CO emission and altitude change is illustrated in Fig. 7.

HC is mainly composed of unburned fuel, which depends on the intake air charge, cylinder temperature and spray atomisation quality. The results of the full-load test show that as the altitude increases, the emission of HC first decreases and then increases. From 0 to 1900 m, the HC emissions decreased by more than 40% with altitude elevation. Above 1900 m, the HC emission rose with altitude elevation, with a maximum increase of 30%. At high and low engine speeds, HC emissions are higher than at medium engine speeds, mainly due to concentrated combustion in the cylinder, resulting in an increase in unburned diesel quantities. In addition, the density of the air decreases with altitude elevation, resulting in a lower density of the working fluid at the top of the compression stroke and an increase in the spray penetration distance. If the spray penetration distance is too long, the "wet wall" phenomenon of the combustion chamber increases, leading to combustion degradation. As a result, HC emission first decreases and then increases with altitude, as seen in Fig. 8.

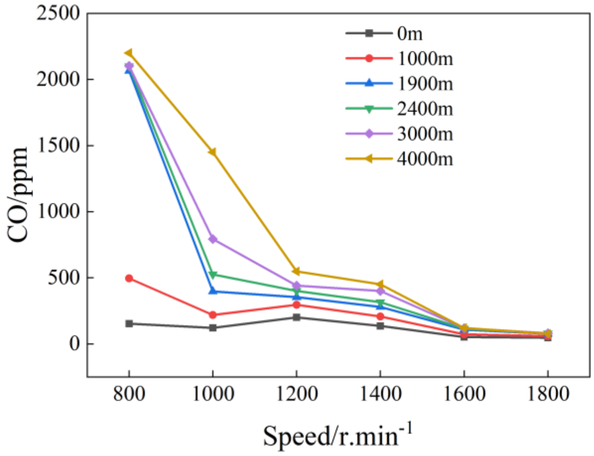


Fig. 7 CO emission changes with speed increase

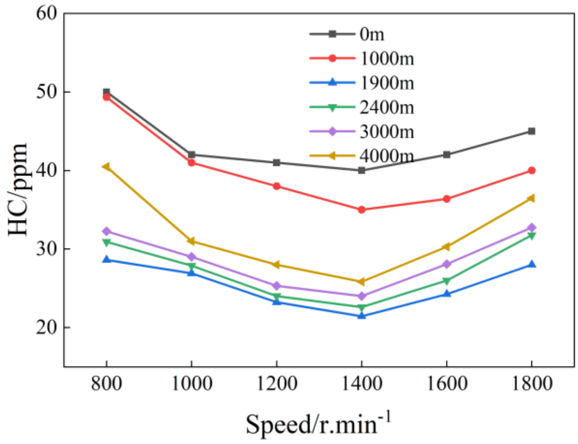


Fig. 8 HC emissions

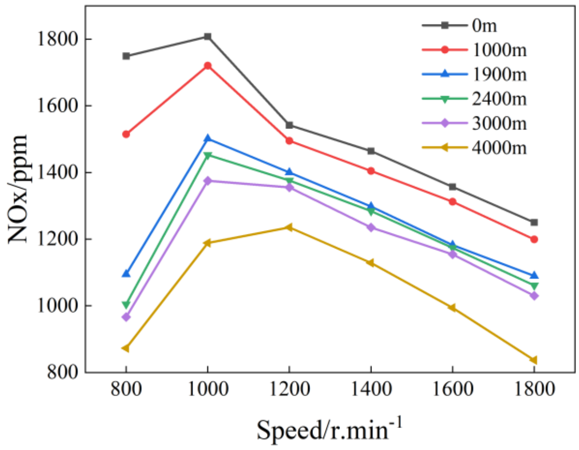


Fig. 9 NOx emissions

NOx is one of the main pollutants emitted by diesel engines and its formation is mainly related to the oxygen content in the cylinder, the temperature in the cylinder, and combustion duration. As the engine speed increased, NOx emissions tended to increase initially, but then decreased. At low rpm, it was influenced mainly by the low oxygen content and temperature in the cylinder. At high rpm, the duration of combustion was the main influencing factor. As the altitude increased, NOx emissions decreased by up to 50 %, mainly due to the reduced air intake at higher altitudes, leading to a decrease in the pressure and temperature in the cylinder, as visible in Fig. 9.

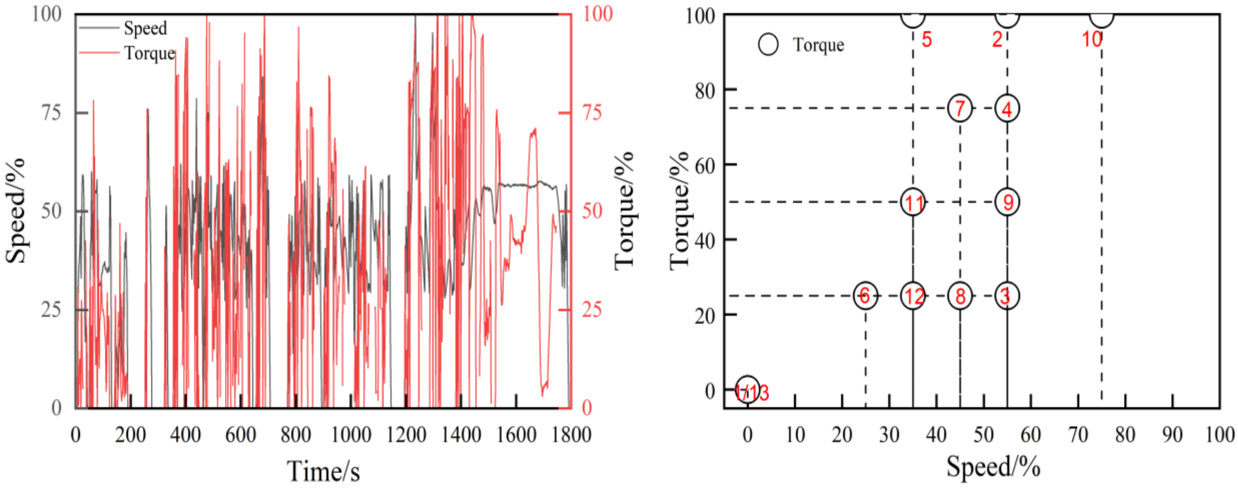


Fig. 10 WHTC and WHSC data

4. EXPERIMENTAL INVESTIGATION OF TRANSIENT AND STEADY-STATE EMISSION.

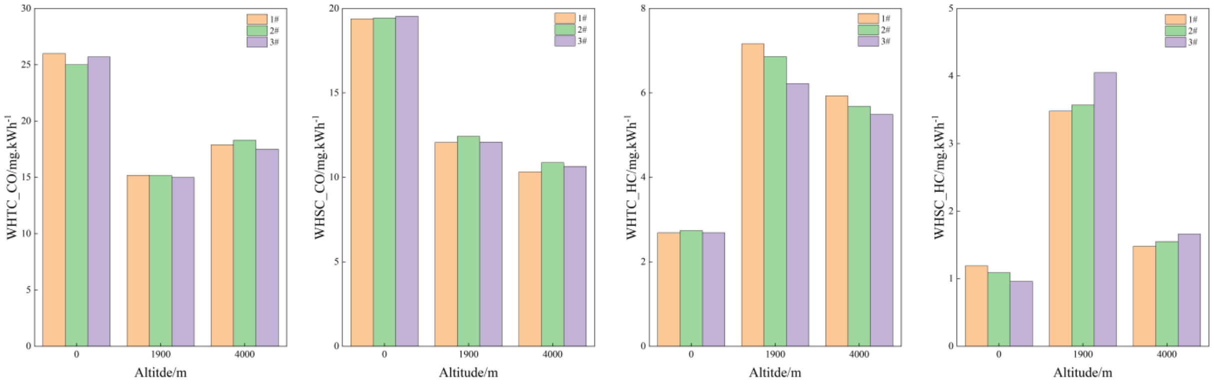
GB 17691-2018 provides the pollutant test methods and limits of China VI heavy vehicle engines. The World Harmonized Transient Cycle (WHTC) and the World Harmonized Steady State Cycle (WHSC) have been adopted to realize the type testing and certification of China VI engines. The WHTC is a transient test period varying by 1800 s, whereas the WHSC is a steady state test period consisting of 13 operating points. During the WHTC test cycle, urban conditions account for 49.6%, suburban conditions for 26%, and high-speed conditions for 24.3%. In six operating conditions, the WHTC test cycle torque is ⩽25%; additionally, there are two idle conditions and four 25% torque conditions corresponding to speeds of 25%, 35%, 45%, and 55%. Atmospheric factors of 0.93 to 1.07 are to be met for engine-type certification tests. The test methods and limits for exhaust emissions are specified. However, real-world emissions testing of vehicles has been extended to an altitude of 2400 m. At altitudes above 3000 m, engine exhaust pollutants increase. In addition, the lower engine exhaust temperature causes the aftertreatment system to fail to reach a proper operating temperature, resulting in lower catalytic conversion efficiency and increased exhaust emissions. Therefore, in this paper, we analyzed the raw and exhaust emissions of WHTC and WHSC engines at different altitudes. The WHTC and WHSC test conditions are presented in Fig. 10.

Both WHTC and WHSC repeated the test three times at different altitudes to determine the accuracy and error of the test results. The results of three tests at 0 m, 1900 m and 4000 m were selected for error analysis. The results reveal that the maximum errors for CO and HC were less than 1 mg/kWh^{-1}. Similarly, the maximum errors for circulating power were less than 0.05 kWh, and for NOx, the maximum errors were less than 2 mg/kWh^{-1} at 0 m and 1900 m. The error in the test results grows with the increase of measured values. As an illustration, in three WHTC tests conducted at an altitude of 4000 m, the average NOx value was 1207 mg.kWh^{-1} with an error of 17 mg.kWh^{-1} (a relative error of merely 1.4%). From an overall analysis, the measurement errors of the three tests are within acceptable limits. The detailed results of the three tests carried out at different altitudes are shown in Fig. 11 and in Table 3 below.

Cycle work is an important parameter for characterizing the power output of an engine. The actual cycle power of the test cycle is obtained by calculating the instantaneous power and integrating it based on the speed and torque values from the engine feedback, unit is kWh. Higher cycle work reflects higher performance. The cycle work of the WHTC and WHSC showed the same trend at different altitudes. However, as the altitude increased, the engine cycle work had a non-linear decrease. At higher altitudes, a greater reduction in cyclic work was observed than on the plain, and at an altitude of 4000 m, this reduction was more than 15%, as can be seen in Fig. 12.

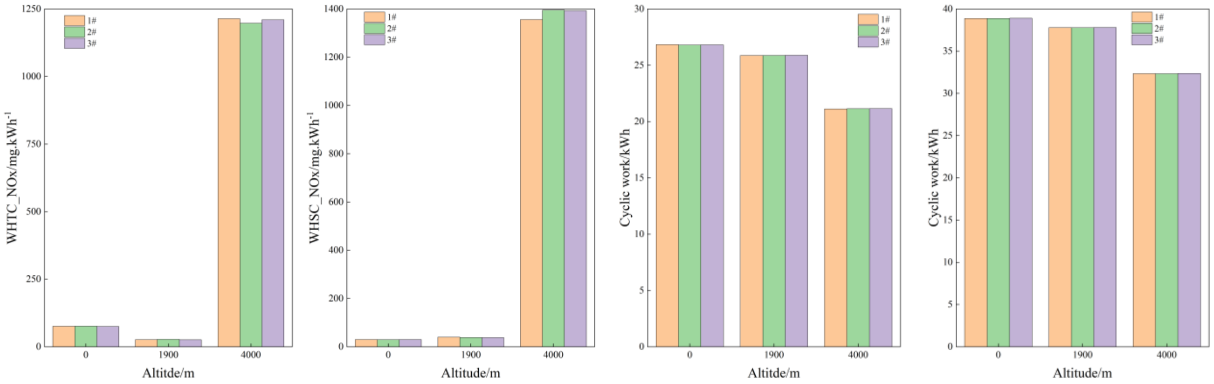
Table 3 Error analysis of three trials at different altitudes

Project		**CO/mg.kWh^{-1}**		**HC/mg.kWh^{-1}**		**NOx/mg.kWh^{-1}**		**Cyclic work/kWh**	
		Average	**Max error**	**Average**	**Max error**	**Average**	**Max error**	**Average**	**Max error**
WHTC	0	25.68	0.67	2.71	0.05	75.63	1.50	26.82	0.03
	1900	15.12	0.19	6.75	0.94	26.38	1.97	25.87	0.02
	4000	17.90	0.80	5.70	0.44	1,207.00	17.00	21.14	0.03
WHSC	0	19.45	0.16	1.08	0.23	29.73	0.50	38.88	0.03
	1900	12.20	0.36	3.70	0.57	38.68	1.88	37.79	0.02
	4000	10.61	0.55	1.56	0.18	1,381.00	39.00	32.35	0.04



a. CO

a. CO



c. NOx

d. Cyclic work

Fig. 11 Test results at different altitudes

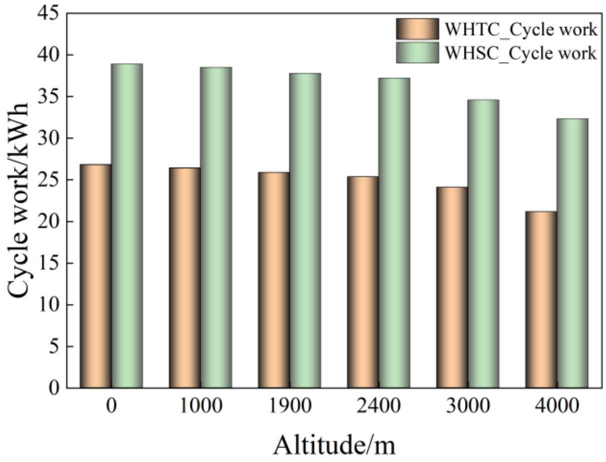


Fig. 12 Cyclic work

4.1 Raw Emission at Different Altitudes

The normal operation of a diesel engine is dominated by diffusive combustion, all of which have an excess air factor greater than 1. However, the diffusion rate of the fuel and the air-fuel mixture directly determine the efficiency of the combustion process. An uneven distribution of fuel and air contributes to the formation of local 'oxygen-rich' or 'fuel-rich' zones, resulting in increased pollutant emissions. The main exhaust pollutants from diesel engines are CO, HC, NOx, and PM, which are formed by different mechanisms. CO formation is mainly influenced by excess air in the cylinder. There are two predominant mechanisms for excessive CO formation in diesel engines. The first is the inhomogeneous mixing of fuel and air, which creates localized hypoxia resulting in incomplete fuel oxidation. The second is that CO_2 and H_2O undergo pyrolysis reactions to form CO at high temperatures. HC is primarily an unburned and incompletely burned fuel, the level of which is strongly influenced by combustion instabilities in the cylinder. At an over-low temperature in the cylinder, the flame is extinguished. The quenching effect of the cylinder walls leads to an increase in HC emissions. For example, at high altitudes, the spray penetration distance increases, and fuel droplets adhere to the cylinder or combustion chamber walls, resulting in unburned fuel and incomplete combustion. In addition, the flame could not propagate through the clearance of the valve seat, cylinder block, cylinder head, etc., so the mixture did not burn in time and was carried away with the exhaust.

Figure 13 illustrates the comparison of raw CO emissions at different altitudes. With increasing altitude, the raw CO emission of the WHTC and WHSC test showed an increasing trend, but the CO of the WHTC was more than twice that of the WHSC, which is related to the WHSC emission without transition condition. In addition, CO increased rapidly at altitudes above 3000 m but was within the limit values. With increasing altitude, the raw HC emission of the engine increased slightly. At different altitudes, the HC was around 160 ± 30 mg/kWh, but above 3000 m, the limit was exceeded by more than 10%. As the altitude increased, the raw NOx emission from the engine showed an initial trend of a small decrease, followed by an increase, with a rapid rise at an altitude above 2400 m. In addition, the raw NOx emission exceeded the upper limit at all altitudes. As the altitude

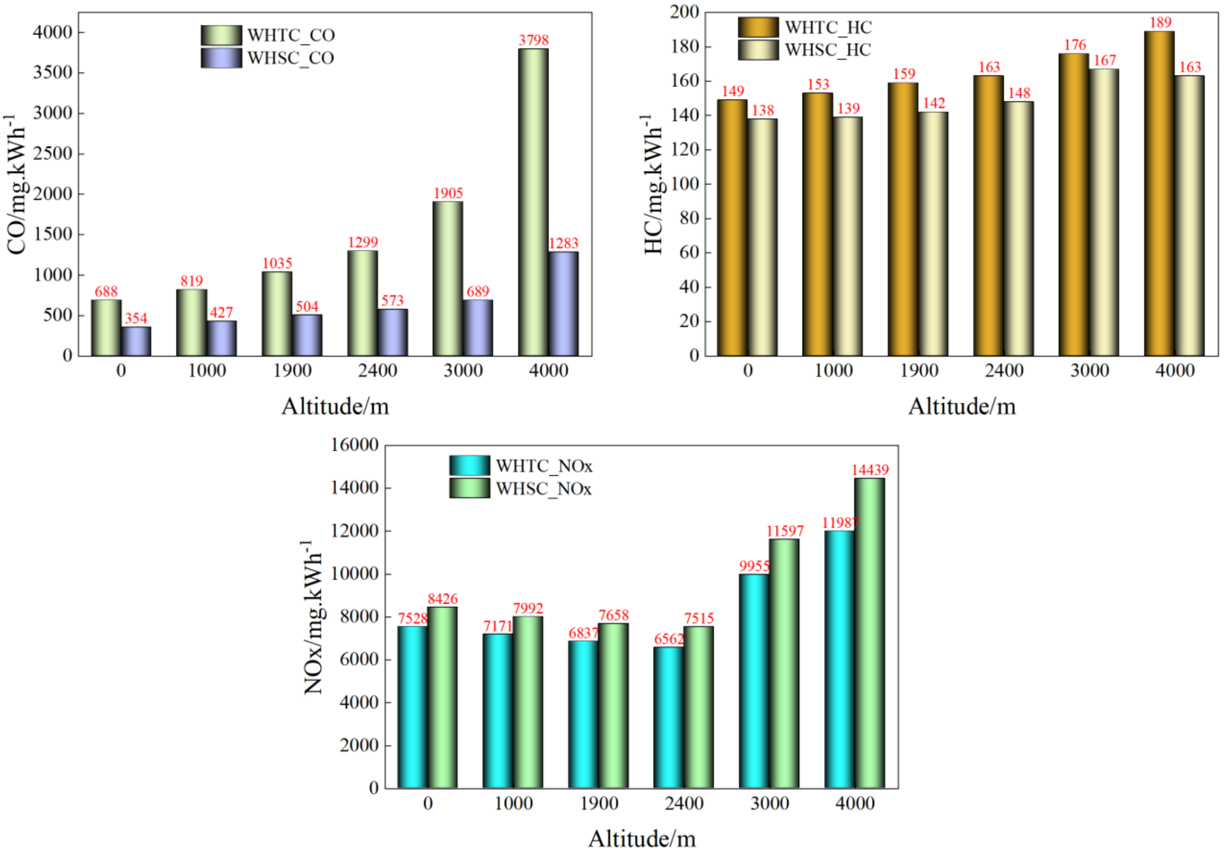


Fig. 13 Comparison of the raw emissions of CO, HC, and NOx at different altitudes

increased, the engine intake temperature and pressure decreased, resulting in a slight decrease in NOx emissions from 0 m to 2400 m. At high altitudes (3000 m and above), to restore the performance of the diesel engine, the injection advance angle was increased in the engine calibration process, but the proportion of premixed combustion increased accordingly, resulting in a rise in the temperature and NOx formation rate.

4.2 Exhaust Emissions at Different Altitudes

Raw emissions reflect the potential for internal engine cleaning, but do not predict the level of exhaust emissions from the vehicle. The National VI regulations have added new limits to the actual on-road emissions of vehicles, and the National VI Stage B test altitude has been extended to 2400 m, indicating an important need for emission control of high-altitude vehicles. In practice, the performance of a vehicle engine is affected by the geographical and atmospheric environment. As altitude increases, the vehicle's operating environment tends to become more complex, and the transient conditions become more convoluted. Frequent high and low load switching of the engine causes significant mechanical damage to the engine and results in poor combustion stability and increased pollutant emissions. In addition, the drop in atmospheric pressure and temperature at high altitudes leads to difficulties in cold starting the engine or an increase in idling emissions at low exhaust temperatures, resulting in a period of low conversion efficiency of diesel oxidation catalysts and an increase in idling pollutant emissions. At high altitudes, engine raw CO_2 emissions increase, diesel particulate filter (DPF) carbon accumulation time is shortened, and frequent regeneration is required, reducing DPF performance and lifetime.

Figure 14 depicts the exhaust emissions of the engine at different heights. There is little difference between the results for the WHTC and WHSC test cycles. As the altitude increases, the CO emission tends to decrease and then increase, with an emission of about 15 ± 5 mg/kWh. HC follows an increasing trend, with THC emissions in the range of 3-6 mg/kWh for the transient test cycle and 1-2 mg/kWh for the steady state test cycle.

In Fig. 15, NOx and PM emissions from the exhaust at different altitudes are displayed. With increasing altitude, NOx emissions did not show a significant change trend. At an altitude of 4000 m, the NOx emission was 1200 mg/kWh. After post-treatment purification, the gaseous pollutant emissions are within the limit values. PM decreases with increasing altitude, which is related to the increase in raw PM and the increase in DPF collection efficiency. The PM exhaust emissions were kept at a low level (1 mg/kWh) at different altitudes, but the PM emissions were slightly higher for WHTC than WHSC, mainly due to the effect exerted by the transitional operating conditions. Because of the engine's reduced intake at high altitude, engineers reduce the amount of fuel injected during engine calibration, which also reduces CO and soot production. In addition, excessive raw PM emissions can increase the amount of carbon deposited in the DPF and increase the DPF's collection efficiency.

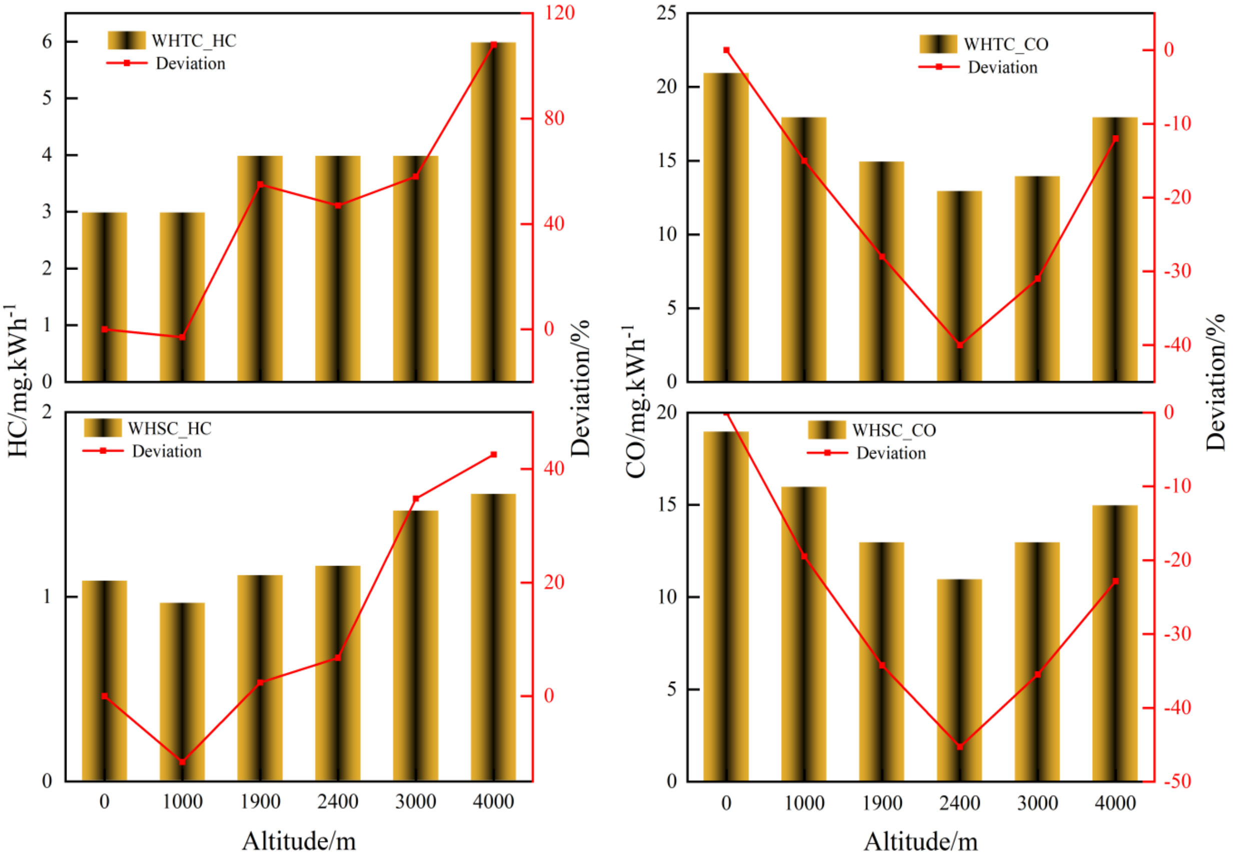


Fig. 14 Comparison of the exhaust emission CO and HC at different altitudes

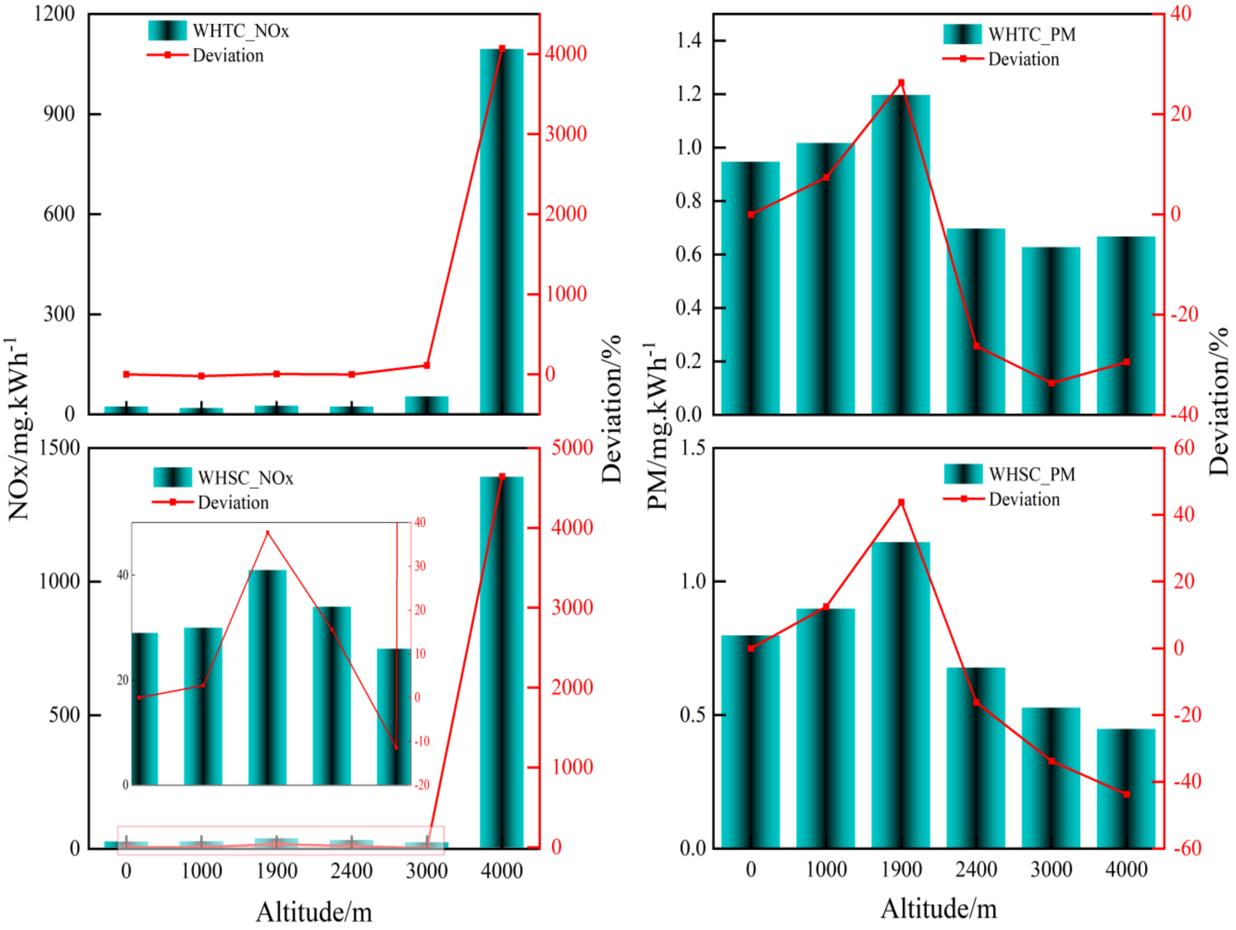


Fig. 15 Comparison of NOx and PM exhaust emission at different altitudes

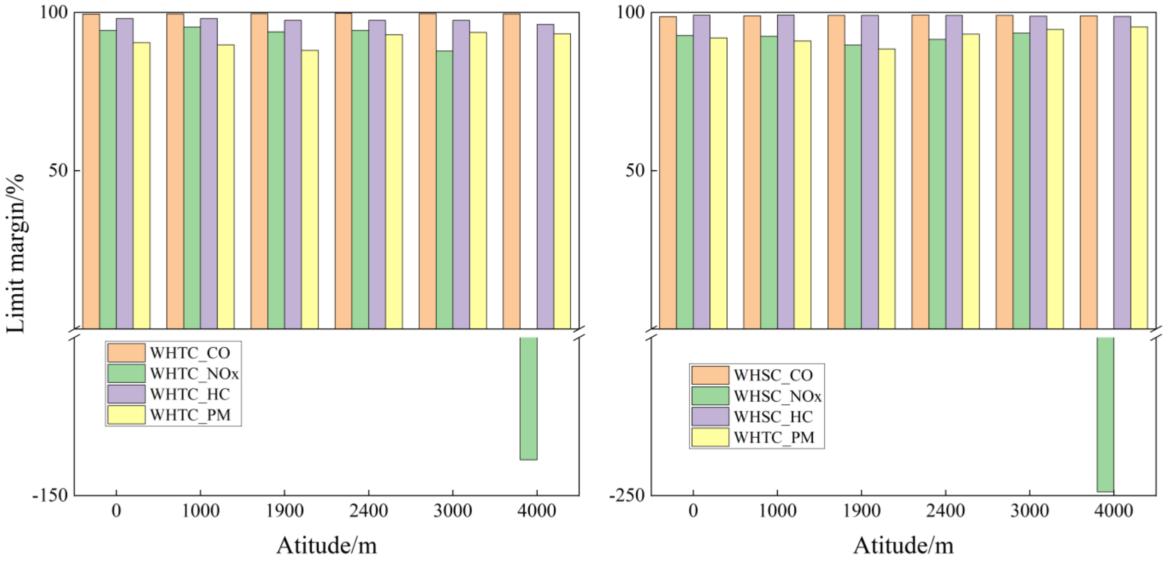


Fig. 16 Residual limit values for each exhaust pollutant at different altitudes

Table 4 Engine standard cycle emission limits

Tests	CO mg/kWh	HC mg/kWh	NOx mg/kWh	PM mg/kWh
WHTC	4000	160	460	10
WHSC	1500	130	400	10

However, frequent carbon build-up and regeneration of DPF in high-altitude environments can exacerbate DPF damage and reduce engine performance and lifetime.

Fig. 16 shows the margin of limit values for exhaust pollutants at different altitudes. The differences between pollutant emissions and standard limits at different altitudes are compared according to the latest current emission standards. The results show that the minimum limit margins for CO, HC and NOx emissions are 98%, 96% and 87%(within 3000 m) respectively, and NOx emissions exceed 130% of the limit value at an altitude of 4000 m. The limit margin for PM emissions is greater than 88%. Therefore, compared to the current standard limits, the engine's CO, HC, NOx and PM emissions can meet the requirements, but only at altitudes above 4000 m is there a risk of exceeding the limits. Table 4 shows the pollutant emission limits for the engine's emission cycle.

4.3 Comparison of Data Collected in Seconds

The statistical results for the emission cycle do not reflect the emission of each pollutant for each engine operating condition. The deterioration in emissions is more pronounced in the transition from one stable condition to another. This section therefore focuses on the emissions at each operating point of the WHTC. The WHTC test results at 0, 2000, and 4000 m were selected for further analysis. The WHTC included 49.6% urban road conditions, 26% suburban road conditions, and 24.3% high speed road conditions, i.e., the first 890 s were urban road conditions, the middle 460 s were suburban road conditions, and the last 440 s were high speed road conditions.

Figure 17 depicts a comparison of the instantaneous CO_2 emissions for the WHTC cycle at 0, 1900, and 4000 m altitudes. At the same altitude, CO_2 emissions also varied considerably due to different engine operating conditions. Of these, suburban and urban road conditions produced almost the same level of CO_2 emissions, with high-speed road conditions generating 1.5% more CO_2 than other conditions, mainly due to the increased engine load. CO_2 emissions increased with altitude elevation. At 4000 m, the CO_2 emissions were approximately 30% higher than those at 0 m. In summary, CO_2 emissions are related mainly to the fuel consumption of diesel engines at different altitudes. An increase in CO_2 emissions indicates a rise in fuel consumption, and a decrease in engine power at high altitudes reveals a decrease in the effective fuel efficiency of an engine.

A comparison of the engine's instantaneous raw and exhaust CO emissions at different altitudes is shown in Fig. 18. As can be seen in the Fig., at an altitude of 0 m, the CO emission is predominantly distributed in the range of 0-1000 ppm. At 1900 m, the CO emission is in the range of 0-1500 ppm. At 4000 m, the CO emission is mainly in the range of 0-5000 ppm. Therefore, the raw

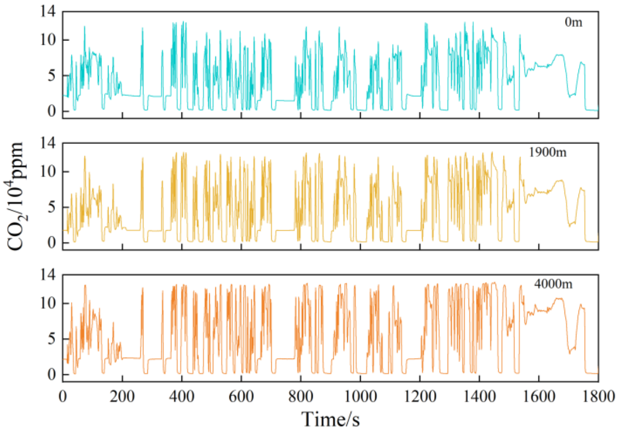


Fig. 17 Comparison of instantaneous CO_2 emissions at different altitudes

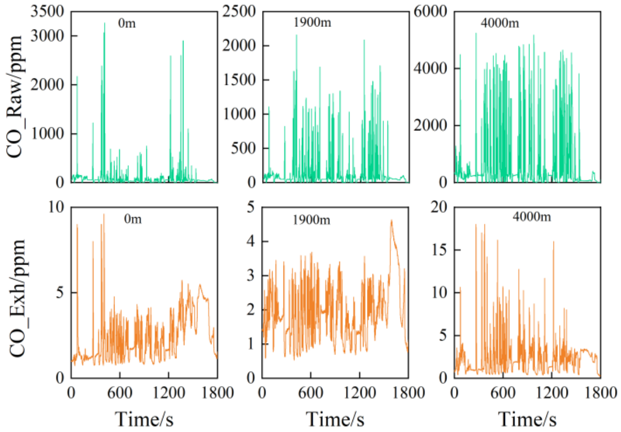


Fig. 18 Comparison of CO raw emission (raw) and exhaust emission (Exh)

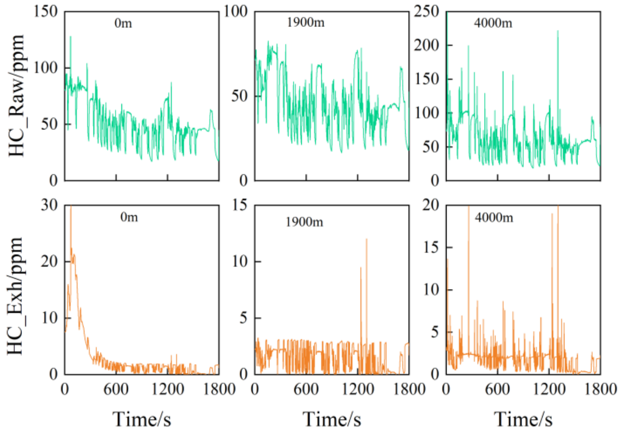


Fig. 19 Comparison of HC raw emission (raw) and exhaust emission (Exh)

exhaust CO from the engine increases with altitude elevation. Meanwhile, the differences in engine exhaust CO emissions were analyzed in the present investigation. At 0 and 1900 m, the CO emission was concentrated between 0 and 5 ppm. At some operating points of the WHTC cycle at 0 m, the exhaust CO emission increases with the raw emission and approaches 10 ppm. At 4000 m, the exhaust CO emission is distributed mainly in the range of 0-20 ppm and concentrated in the range of 0-10 ppm, which is caused chiefly by the excessively high raw exhaust CO emission of the engine. Therefore, changes in altitude affect the engine's exhaust CO emissions. Due to the use of proven aftertreatment technology, there is no significant difference in exhaust CO emissions at different altitudes, which are all within a certain range. However, the limitations of critical equipment and technical operating conditions are more pronounced at higher altitudes. The untreated CO emission increased significantly beyond the purification limit of the aftertreatment system, so that the vehicle exhaust CO emission was higher at high altitudes than at low altitudes.

Figure 19 illustrates a comparison of the instantaneous HC emissions at different altitudes. With increasing altitude, the raw HC emission and the exhaust HC emission were characterized by an increasing trend. However, the increases were small and mainly related to the engine injection parameters. HC is primarily an intermediate product of fuel combustion and is subject to fuel spray characteristics. For example, the 'wet wall' phenomenon is caused by the increase in fuel penetration distance, so optimizing the fuel injection characteristics of diesel engines at high altitudes can improve combustion and reduce emissions. At an altitude of 0 m, the dominant HC emission was distributed around 1 ppm, which is close to zero emission. At an altitude of 1900 m, the exhaust HC was predominantly distributed between 0 and 3 ppm. At an altitude of 4000 m, the exhaust HC was between 0 and 7 ppm. At the same altitude, At the same altitude, both the exhaust HC and the raw HC emission had a good follow-up rate, indicating that the exhaust emission was strongly influenced by the raw emission.

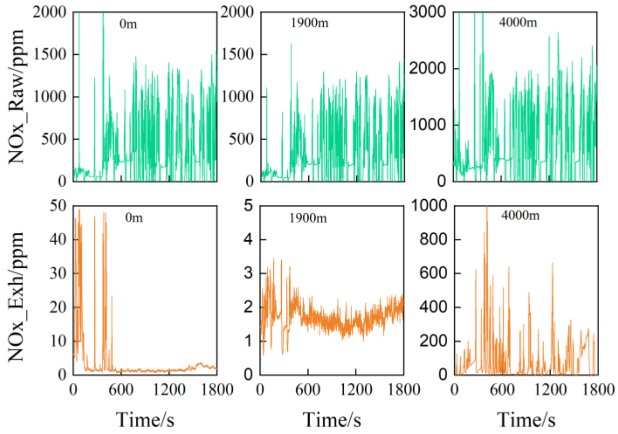


Fig. 20 Comparison of NOx raw emissions (raw) and exhaust emissions (Exh)

Figure 20 depicts a comparison of the instantaneous NOx emissions at different altitudes. As the altitude increased, NOx initially decreased but then increased, which is consistent with the statistical results for the engine's WHTC emission cycle. The key conditions for NOx formation are high temperature, oxygen enrichment and long combustion duration. In general, at high altitudes atmospheric pressure and temperature decrease, resulting in a decrease in pressure and temperature in the engine cylinder and a decrease in the rate of NOx formation. However, the duration of combustion increases as the injection front angle increases, while fuel diffusion is insufficient, resulting in a subsequent increase in NOx emissions. In an after-treatment SCR system, the NOx is catalyzed and reduced to produce N_2 for emission into the air, but the catalytic conversion efficiency of the SCR is affected by the amount of urea injected and the amount of raw NOx emitted. At 4000 m, the exhaust NOx emission was mainly in the range of 0-1000 ppm, which is an increase of about a factor of 1000 as compared to other altitudes.

Figure 21 compares the instantaneous emissions of soot at different altitudes. Particulate matter is a carbonaceous complex consisting mainly of dry smoke, soluble organic components, sulphates, ash, and water. The aftertreatment significantly reduced the emission of soot from the exhaust. However, at high altitudes, the oxygen content decreases, resulting in a soot formation

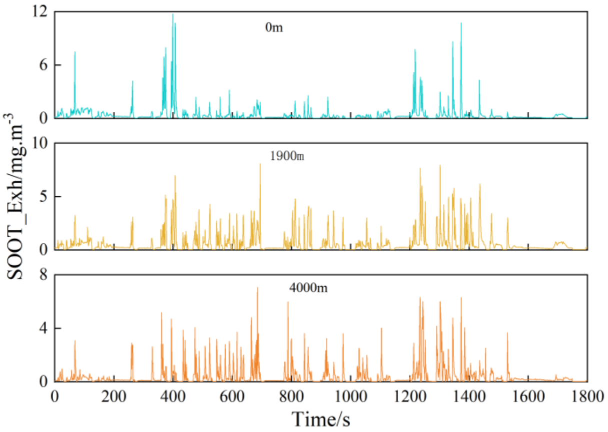


Fig. 21 Comparison of soot exhaust emissions (Exh) at different altitudes

rate greater than the oxidation rate, and an increase in the raw soot emission, leading to after-treatment failure or even damage. With increasing altitude, the exhaust gas soot emission gradually decreased, which was mainly influenced by the air-fuel ratio in the cylinder and the raw soot emission. Under high load operating conditions, the engine's cycle injection was increased, and the rate of soot production was greater than the rate of oxidation, resulting in a significant increase in emissions.

Figure 22 displays a comparison of the instantaneous CH_2O exhaust emissions at different altitudes. CH_2O is one of the unconventional pollutants in engines and is mainly an intermediate product of the engine combustion process. The formation process is extremely complex, and it is difficult to achieve a detailed description of the process in the test process. Therefore, many scholars have applied a numerical simulation to explain the formation mechanism. CH_2O is a major aldehyde pollutant in engine exhaust, which is irritating to the eyes and respiratory tract and toxic to the blood. Formaldehyde (HCHO) has been classified as a Class 1 carcinogen. In addition, with increasing altitude, engine combustion deteriorates and the levels of conventional pollutants (CO, HC, NOx, and PM) increase, as do levels of non-conventional pollutants. Tests at 0, 1900, and 4000 m revealed a slight decrease in HCHO emissions with altitude elevation.

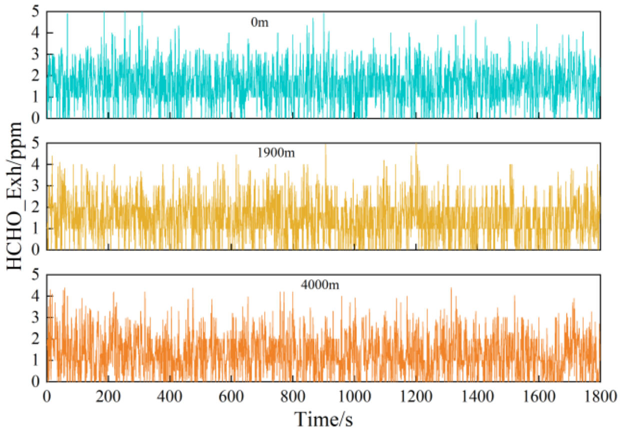


Fig. 22 Comparison of the CH2O exhaust emissions (Exh) at different altitudes

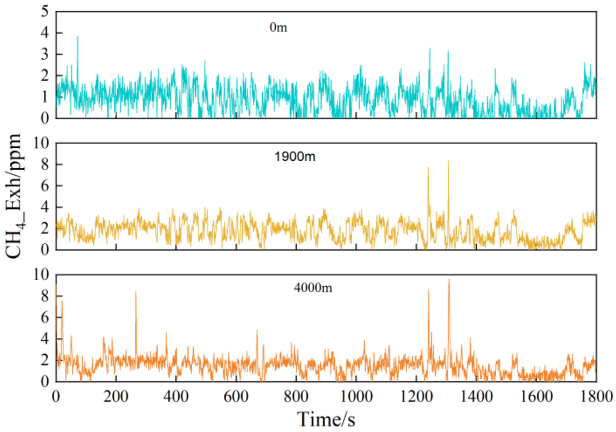


Fig. 23 Comparison of the CH4 exhaust emissions (Exh) at different altitudes

Figure 23 displays a comparison of the instantaneous CH_4 emissions at different altitudes. The CH_4 emission from the engine exhaust increases with altitude elevation. The increase in CH_4 at 1900 m is about 1 ppm compared to the increase at 0 m, but no significant difference was observed between the values at 1900 m and 4000 m.

5. CONCLUSION

Based on the inlet and exhaust altitude simulation system, this paper carries out experimental research on diesel engine emission characteristics under different altitude conditions for a heavy-duty National VI diesel engine, and systematically analyzes the change trend of pollutant emission of heavy-duty diesel engine under different altitude.

(1) At high altitudes, except for the low-speed operation of the engine, the excess air coefficient at the full-load point of a supercharged diesel engine is small, and the remaining excess air coefficient is approximately 1.45. The intake air has reached the theoretical state of complete combustion of the fuel in the cylinder.

(2) With increasing altitude, the emission at the full-load point of the diesel engine changed obviously. The CO emission increased with the increase in altitude, and this rise was more obvious at low and medium speeds, with an increase of 0.0084–0.665 ppm/m. The HC emission initially decreased (by 40%) but then increased (by 30%). The NOx emission showed a decreasing trend of up to 50%.

(3) With increasing altitude, he cycle work of the WHTC\WHSC test decreases non-linearly, the raw CO increases exponentially, the raw NOx decreases slightly and then increases rapidly, and the raw THC increases slightly linearly.

(4) with increasing the altitude, the results of the WHTC and WHSC test cycle showed that the exhaust CO emissions had a decreasing and then increasing trend, HC and NOx showed a non-linear increase, and PM showed a decreasing trend. Compared with the current emission standards, the limit margin of exhaust CO and HC

emissions is more than 95%, and the limit margin of PM emissions is more than 88%.

(5) The second sampling data from WHTC and WHSC revealed that the raw exhaust pollutants of the high-altitude engines were higher than those of the low-altitude engines. After after-treatment purification, the engine exhaust emissions reached a lower level, and the effect of altitude on the exhaust emissions was not obvious.

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CONFLICT OF INTEREST

The authors have no competing interests or conflicts to disclose.

AUTHORS CONTRIBUTION

Y. M. Zheng and L. B. Xie: Conceptualization; methodology; formal analysis; writing – original draft; D. Y. Liu: Formal analysis; Validation; J. L. Ji: writing – review &editing; S. F. Li: Resources; L. L. Zhao: Visualization; X. H. Zen: Project administration. All authors have read and agreed to the published version of the manuscript.

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