Emission characteristics analysis under California low load cycle for a China Ⅵ heavy-duty diesel engine

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Abstract: A 6.2 L diesel engine that meets China VI emission standard was selected to run world harmonized transient cycle (WHTC) and California Low Load Cycle (LLC) to measure the pollutants. The brake specific emission under the two cycles were compared, and nitrogen oxides (NOx) emission were analyzed carefully. The results show that the NOx emission of the LLC of this engine is about 15 times than that of the hot WHTC, and 4.7 times than that of the limitation of current China VI emission standard. The low inlet temperature of selective catalytic reduction (SCR) is the predominant reason for the high NOx emission in the LLC. The SCR inlet temperature of lower than 200°C in LLC accounts for 52% of the total time with an average inlet temperature of only 190°C. While the inlet temperature of lower than 200°C of the hot WHTC only accounts for 7% with the average inlet temperature of 275°C. The average SCR catalytic efficiency calculated by NOx sensor amounted on the upstream and downstream of LLC is only 75%, while the efficiency is 98% for hot WHTC. It is necessary to focus on thermal management of the aftertreatment system and the SCR catalytic performance at low temperature.

1. Introduction

The China Mobile Source Environmental Management Annual Report (2021) shows that the emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx) and particulate matter (PM) from mobile source were 7.697 million tons, 1.902 million tons, 6.263 million tons and 68,000 tons respectively. Vehicles are a major contributor, accounting for more than 90% of CO, HC, NOx and PM. The NOx emission of diesel vehicles exceeds 80% of the total vehicle emission. Therefore, further reduction of NOx emissions from heavy-duty vehicles has a positive effect on improving air quality.

China has made a lot of efforts to control pollution emissions. In 2018, the Limits and Measurement Methods for Emissions from Heavy Duty Diesel Vehicles (China VI) has been issued, in which the NOx emission limit was reduced by 77% compared with the China V emission standard, and the PEMS (Portable Emission Measurement System) test was added to evaluate the real driving emissions. The PEMS test can more effectively reflect the actual road emissions, however, the power-based window calculation method cannot evaluate emissions with small average power under low-load running. The road emissions data showed that the low-speed and low-load operating account for a high proportion accompanied by high NOx emissions. Research by the International Committee on Clean Transportation showed that the emission of urban driving is about 7 times the emission limit, while the emission of suburban driving is about 3 times the emission limit [3]. Jiang et al. also found that NOx emissions in most cases of urban areas exceeded the limit requirements [4]. China is also facing the same situation.

At present, neither the engine test bed test nor the PEMS test have fully considered the emission under low load conditions. Therefore, the California Air Resources Board commissioned the Southwest Research Institute to develop a new supplementary test procedure for heavy-duty engines and vehicles, named Low Load Cycle (LLC) [5-7]. In China, it is also necessary to study and develop low-load cycle in order to meet the requirements of further emission reduction in the next stage of heavy-duty vehicle emission standard. In this context, this paper selected a 6.2L diesel engine that meets the China VI emission standard to carry out the emission test at the world harmonized transient cycle (WHTC) and LLC cycle, and then compared and analyzed the pollutant emission characteristics of the two cycles.

2. Experimental Introduction

2.1 Engine specifications

The test prototype studied in this paper is a 6.2 L heavy-duty diesel engine that meets the China VI emission standard, with a rated power of 195 kW and a maximum torque of 1035 Nm. The specific parameters of the engine are shown in Table 1. The emision control technology route is exhaust gas recirculation (EGR) + diesel

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oxidation catalyst (DOC) + diesel particulate filter (DPF) + selective catalytic reduction (SCR) + ammonia slip catalyst (ASC).

Table 1 Main parameters of tested engine

Parameter	Value
Engine capacity	6.2 L
Compression ratio	17.2
Cylinder number	6
Rated power/speed	195 kw/2300 rpm
Maximum torque/speed	1035 Nm/1200~1700 rpm
Emission Control Technology Route	EGR+DOC+DPF+SCR+ASC
Emission Standards	China VI

2.2 Test equipment

The test was carried out in engine test bed. The engine was connected to an AC dynamometer to measure the speed and torque. The pollutants from the exhaust pipe located downstream of aftertreatment system were sampled and measured by equipment.Schematic diagram of the test system can be seen in Figure 1.

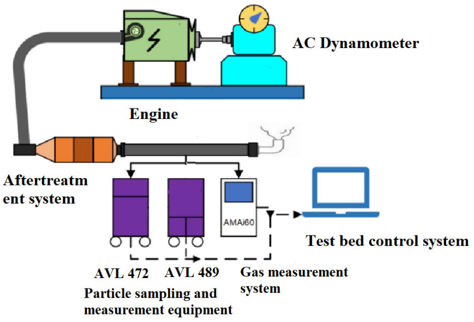

Figure 1 Schematic diagram of the test system

The equipment includes electric dynamometer, gas emission analyzer, particle counter, etc. The main test equipment is shown in Table 2.

Table 2 Test equipment

Equipment name	Equipment Type and Manufacturer
AC Dynamometer	AVL INDY P44
Test bed control system	AVL PUMA Open V1.5.3
Intake air temperature conditioning	AVL Air Conditioning System 2400
Gaseous emission measurement	AVL Emission Bench AMA i60
Particle sampling equipment	AVL SPC 472
Particle number (PN) measurement	AVL 489
Fuel consumption measurement	AVL 753C/735S

2.3 Low load cycle

The LLC includes an engine cycle and a vehicle cycle with duration of 5505 seconds developed by the California Air Resources Board, as shown in Figure 1. During the development of the LLC, various scenarios such as the continuous low load, high load to low load, low load to high load, long idle, middle-speed cruise were considered in order to verify the NOx conversion capability of SCR system under these scenarios. Only the engine LLC were applied in the type certification.

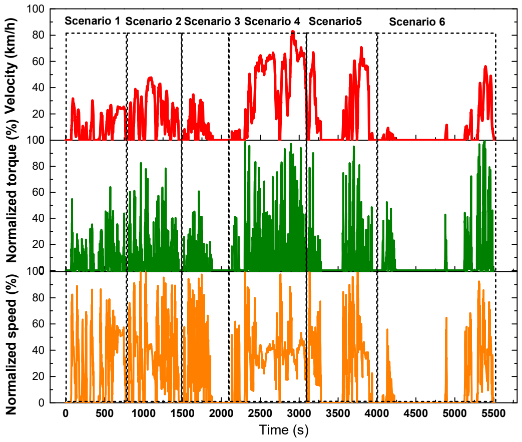

Figure 2 Time-speed-torque-velocity data points of LLC

2.4 Experimental arrangement

LLC engine cycle was run to measure the gaseous pollutants and particle number (PN) emissions. As a contrast, the hot WHTC is also running at the same engine test bed. Additionally, two LLC cycles were done with different soaking conditions to investigate the effect of soaking on test results. One soaking is to immediately run LLC after fully warming the engine, and another soaking is to run LLC at soaking 20-minute after hot WHTC.

3. Results and Discussions

3.1 Pollutant brake specific emission of different cycles

Table 3 lists the brake specific emissions of each pollutant under the hot WHTC and LLC cycles. Compared with WHTC, LLC has lower gaseous pollutant emissions and higher PN emission. The CO emissions of the two LLC cycles are 2.8 and 3 times that of the WHTC, respectively. The THC emissions of two LLC cycles are 15.6 and 14.2 times that of the WHTC, respectively. The NOx emissions of two LLC cycles are two LLC cycles 15.1 and 15.3 times that of the WHTC, respectively. And the PN emissions of two LLC cycles are 0.76 and 0.66 times that of the WHTC, respectively. The NOx emission of the LLC cycle is 4.7 times the limitation of China VI emission regulations. Compared with LLC without soaking (LLC-01), the NOx emission after 20 minutes of soaking increased slightly. The results of NOx are similar to those obtained by Gao Dongzhi et al. They found that the measured NOx brake specific emission of the LLC vehicle cycle were 15 times higher than those of the C-WTVC cycle [8].

Table 3 Brake specific emissions of different pollutants for different cycles

Cycles	**CO**	**THC**	**NOx**	**PN**
Unit	g.(kw.h)$^{-1}$	g.(kw.h)$^{-1}$	g.(kw.h)$^{-1}$	#.(kw.h)$^{-1}$
WHTC	0.0312	0.0094	0.1418	2.9×10^{10}
LLC-01	0.0882	0.1467	2.1478	2.2×10^{10}
LLC-02	0.0921	0.1339	2.1638	1.9×10^{10}
Limitation of China VI	**4**	**0.16**	**0.46**	$\mathbf{6\times10^{11}}$

3.2 NOx transient emission of different cycles

Since the LLC is targeted to NOx emissions, this section focuses on the transient emission characteristics of NOx under different cycles. For the LLC cycle, as shown in Figure 3, the NOx emission mostly emitted in four regions. The first region (0~1100s) is the sustained low load phase, corresponding to scenarios 1 and 2, where NOx emissions firmly increases with 23.8% proportion. The second region (2280~2500s), third region (3600~3820s), and fourth region (5200~5505s) corresponds to scenarios 4, 5, and 6 with proportions of 18%, 14.2% and 27.8%, respectively. The common feature of these three NOx peaks is that a clipping increase in engine speed and torque after a period of idling. In Scenario 3, although the load is very low, there is no very obvious NOx emission.

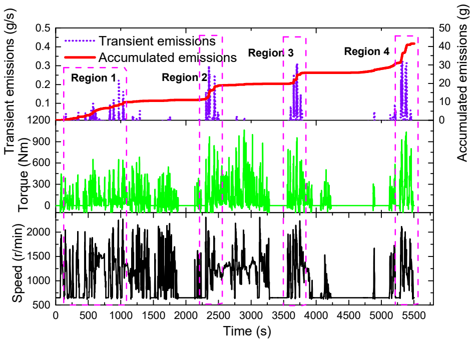

Figure 3 NOx transient emission characteristics of LLC

For the WHTC cycle, as shown in Figure 4, the peak of its transient NOx emission is only 0.038 g/s, while that of the LLC cycle is 0.326 g/s. The NOx emission peak of the WHTC cycle mainly occurs in the rapid acceleration stage after idling, similar to LLC, but the idling duration is much lower than that of LLC.

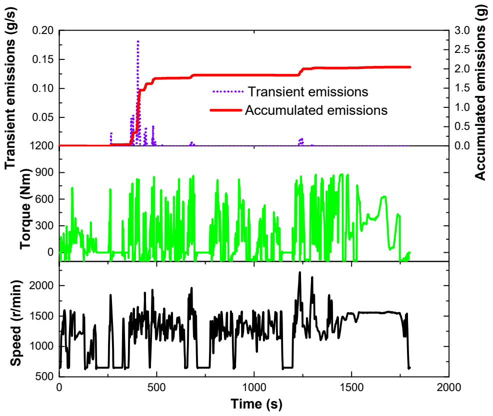

Figure 4 NOx transient emission characteristics of hot WHTC

3.3 SCR catalytic efficiency analysis

Emitted NOx are consolidated results of generating and elimination. Factors affecting the final NOx emissions includes the engine raw NOx emission and catalytic efficiency of SCR, in which the catalytic efficiency of SCR directly depends on exhaust temperatures [9-11]. Parameters such as upstream and downstream NOx sensor data as well as upstream temperature data of of SCR were obtained by OBD diagnostics equipment in order to analyze the high NOx emissions of LLC.

Figure 5 shows a comparison of the NOx sensor transient concentration and the NOx transient concentration obtained by the test bed measurement equipment during the LLC. The NOx sensor exhit a high accuracy with a better trend conformity.

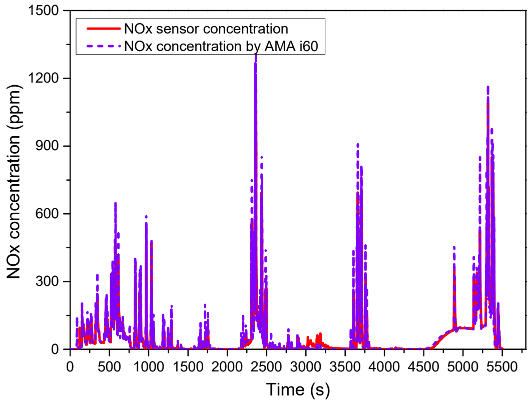

Figure 5 NOx concentration comparison between NOx sensor and AMA i60 measurement

The SCR catalytic efficiency was then calculated by the upstream and downstream NOx sensor data as the Formula (1).

$$\text{SCR catalytic efficiency}(\%) = \frac{\text{Total NOx from downstream NOx sensor value}}{\text{Total NOx from upstream NOx sensor value}} \times 100\% \quad (1)$$

The SCR catalytic efficiency of each scenario of LLC and WHTC is shown in Table 4. The average SCR catalytic efficiency of NOx under the two LLC cycles are 75% and 74%, respectively, with little difference. But the SCR catalytic efficiency of hot WHTC is as high as 98%. In addition, compared with the case without soaking, the 20-minute soaking mainly affects the SCR catalytic efficiency of scenario 1. After 20-minute soaking, the SCR catalytic efficiency of scenario 1 is only 36%. The highest catalytic efficiency is scenario 3, which exceeds 96%. while the lowest catalytic efficiency appears at scenario 1 and 6, both are less than 60%.

Table 4 SCR catalytic efficiency

SCR catalytic efficiency (%)	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**	**Total LLC**
LLC-01	54	86	96	82	83	56	75
LLC-02	36	85	98	84	85	56	74
Hot WHTC	98						

The SCR catalytic efficiency mainly depends on the SCR inlet temperature. Figure 6 shows the inlet temperature of different cycles. It can be found that the SCR inlet temperatures in most of time of scenario 1 of LLC are below 200 ° C, corresponding to a low SCR catalytic efficiency, especially for the 20-minute soaking LLC. In addition, in the scenarios 4, 5, 6, the SCR inlet temperature drops below 200 ° C after a long time idle. In this situation, high transient emissions of NOx appears when loading increases rapidly. By contrast, the SCR inlet temperature of hot WHTC is substantially above 200 ° C. Therefore, the overall SCR catalytic efficiency of LLC is much lower than that of WHTC.

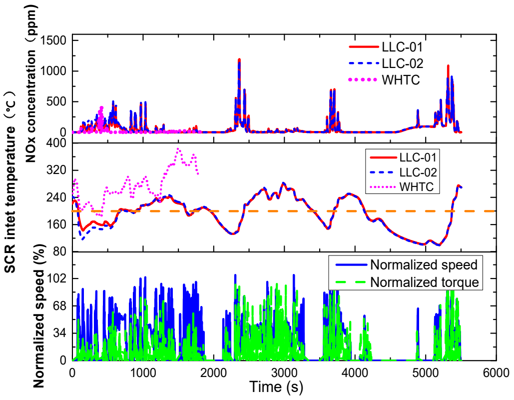

Figure 6 NOx transient emission characteristics of hot WHTC

Figure 7 is the SCR inlet temperature distribution histogram. The SCR inlet temperature of lower than 200°C of the LLC accounts for 52% of the total time, and the average inlet temperature is only 190°C. while inlet temperature of lower than 200°C of the hot WHTC only accounts for 7% and the average inlet temperature is 275°C.

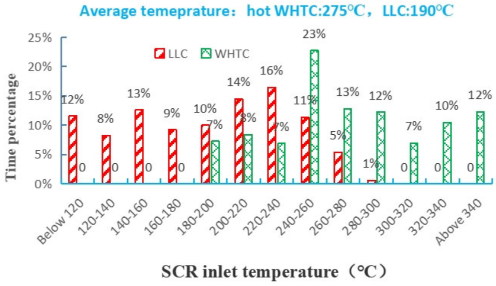

Figure 7 SCR inlet temperature distribution histogram of LLC and WHTC

4. Conclusion

1) For this diesel engine, the LLC cycle NOx emissions is about 15 times than that of the hot WHTC cycle, and 4.7 times than that of the limitation of current China VI emission standard.

2) The SCR inlet temperature is the most important reason for the high LLC cycle NOx emissions. Since the long duration idle causes a decrease in exhaust temperature, the NOx emission peak is extremely easy to appear in the next loading condition. Therefore, it is important to focus on the thermal management of the SCR system.

3) LLC can effectively reflect the actual driving situation such as low load and long idle, while the current WHTC can hardly assess the emission under these scenarios.

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