Pollutant emission and CO2 emission at various vehicle loading for a heavy-duty commercial vehicle by EIL methodology

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Abstract: Pollutants and carbon dioxide (CO2) under different vehicle loading were investigated on a dump truck with a maximum designed total mass of 18000 kg. An engine-in-the-loop (EIL) methodology was applied to achieve the test consistency because EIL can use the same road, driver and vehicle model. The results show that the total CO2 emission increases while the brake specific CO2 emission decrease as the vehicle loading increases. Both the total and specific emissions of PN increase when vehicle loading increases. The effect regularity of increasing vehicle loading on NOx, THC and CO is not significant. It is necessary to comprehensively consider the changes in the raw exhaust due to the engine operation points changes and in the SCR catalytic efficiency derived from the SCR inlet temperature variation. The DPF generation is also need to be concerned because the CO2, PN and NOx emissions will rapidly increase during this period.

Key words: Heavy-duty commercial vehicle, Pollutant emission, CO2 emission, Engine-in-the-loop, Vehicle loading

1. Introduction

Commercial vehicles are a major contributor to pollutant emissions and carbon emissions in the transportation sector. According to the "China Mobile Source Environmental Management Annual Report (2021)" released by the Ministry of Ecology and Environment [1], carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM) emissions from commercial vehicles were 2.073 million tons, 460,000 tons, 5.178 million tons and 58,000 tons respectively in 2020, accounting for 29.8%, 26.6%, 84.3% and 90.9% respectively of the total vehicle emissions. According to the calculations of Huang et al[2], the carbon dioxide (CO2) emissions of commercial vehicles accounted for 61.5% of the total vehicle CO2 emissions in 2019. Therefore, controlling the emissions from commercial vehicles is the top priority in order to reduce pollutant emissions and carbon emissions in the transportation sector.

Commercial vehicles have a wide load range between unloaded and fully loaded. And vehicle load has a huge impact on pollutant emissions and carbon emissions. Therefore, it is vital to study the pollutant emission and carbon emission characteristics of commercial vehicles under different loads. Yao et al. [3] tested the actual driving emissions of a 16-ton commercial vehicle under unload, half-load, and full-load conditions using a portable emission measurement system (PEMS). The results show that the NOx and PM emission of commercial vehicles are 43% and 59% higher at half-load and 62% and 44% higher at full-load respectively than those at unload. Frey et al. [4] also measured the real driving emissions of a 29-ton commercial vehicle through the PEMS method, and found that the difference percentages of CO2, NOx, PM, HC and CO under the fully loaded and unloaded conditions of the commercial vehicle were 44%, 78%, 23%, 30% and 22%. Song et al. [5] studied the real driving emissions of two 25-ton commercial vehicles, and the results showed that the NOx, CO, and HC emissions under half-load and full-load conditions were higher than unloaded conditions. However, real driving emission tests are greatly affected by factors such as traffic conditions, environmental conditions, and driving behaviors. It is difficult to ensure the repeatability and consistency of the tests so as not to suitable for the study of the impact of a single variable such as load on emissions. Some researchers use the vehicle specific power (VSP) method to further characterize the relationship between traffic conditions and vehicle emissions. For example, Zhang et al. [6] proposed the VSP method to study the emission characteristics of a 15.5-ton commercial vehicle under fully loaded and unloaded. However, the current commercial vehicles are all equipped with selective catalytic reducers (SCR) whose catalytic efficiency is strongly related to the inlet temperature of SCR. The variation in the load will lead to an change in the NOx raw

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emission of the commercial vehicle. Simultaneously, the exhaust temperature will also change resulting in variety in catalytic efficiency. Therefore, the impact of load changes on emissions needs to be further studied [7].

Engine-In-the-Loop (EIL) is a good method to study the influence of single parameters on emissions [8-11]. EIL is a special hardware-in-the-loop method which regard the engine as the actual physical hardware, and takes the vehicle, the driver and the road as virtual subsystems.So the EIL can put vehicle performance test on the engine bench. Due to the good control accuracy of the laboratory environment, the same driving road model and driver model, it can eliminate the interference from driving, traffic conditions, and environmental conditions. Therefore, EIL is especially suitable for studying the impact of load changes on emissions under real driving conditions.

In this context, this paper selected a dump truck with a maximum designed total mass of 18 tons to study the emission characteristics of pollutants and CO2 under different load conditions based on the EIL method.

2. Experimental setup

2.1 Experimental methodology and equipment

The engine-in-the-loop test platform constructed in this paper is shown in Figure 1. The vehicle and driver models are constructed through the AVL VSM™ real-time system. The real-time system calculates the speed and torque required by the engine through the input road model, combined with the vehicle model and the driver model, and sends them to the test bed. Simultaneously, the sensor of the engine test bed collects the engine parameters and transmits them back to the real-time system to form the closed-loop control of the engine speed and torque.

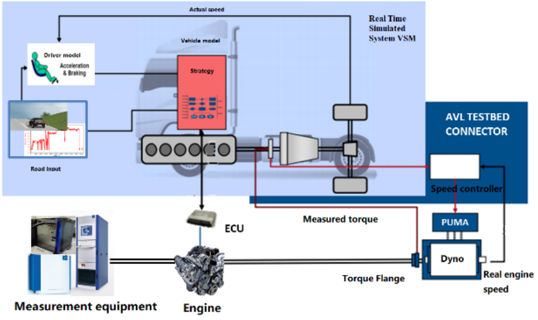

Figure 1 Engine-In-the-Loop test platform

Boundary conditions were controlled by equipment such as intake air conditioning and ambient air conditioning to ensure a consistent environment for each test. Pollutant emissions and carbon emissions for each test are obtained through the emissions analyzer. Details of the test equipment and software are shown in Table 1.

Table 1 Test equipment

Equipment name	Equipment Type and Manufacturer	Accuracy
AC Dynamometer	AVL INDY P44	Torque: ±0.3%F.S. Speed: ±1rpm
Intake air temperature conditioning	AVL Air Conditioning System 2400	Pressure: ±1mbar Temperature: ±0.5℃ Humidity: ±3[%RH]
Gaseous emission measurement	AVL Emission Bench AMA i60	±2%
Particle number (PN) measurement	AVL 489	±10%
Fuel consumption measurement	AVL 753C/735S	±0.12%
Vehicle model system	AVL VSM™	
Real time system	AVL Testbed CONNECT™ (RT)	
Coastdown evaluation software	AVL Coastdown manager	

2.2 Vehicle and engine specifications

The test prototype selected in this paper is a 6L diesel engine that meets the China VI emission standard, with a rated power of 180kW and a maximum torque of 1140Nm. The emission control technology route is exhaust gas recirculation (EGR) + diesel oxidation catalyst (DOC) + diesel particulate filter (DPF) + Selective Catalytic Reducer (SCR) + Ammonia Catalyst (ASC). The corresponding vehicle model is an N3 non-city dump truck, with a curb weight of 7815 kg, a maximum total mass of 18000 kg and a manual transmission with 10 forward gears. Since the PEMS test loading required by China VI b is 10%-100%, five load percentages of 10%, 25%, 50%, 75% and 100% were selected, and the corresponding vehicle weights were 8833.5 kg., 10361.25 kg, 12907.5 kg, 15453.75 kg and 18000 kg, respectively. The coastdown coefficients under different loading are obtained from the test results on the road in the test field according to the requirements of GB27840-2011 [12]. The obtained coastdown coefficient is then evaluated and adjusted by AVL's Coastdown

Manager software. The detailed parameters of engine and vehicle modeling are shown in Table 2.

Table 2 Main parameters of tested vehicle and engine

Engine capacity	6.234L
Cylinder number	6
Compression ratio	17.2
Rated power/speed	180 kW/2300 rpm
Maximum torque/speed	1140 Nm/1100 - 1800rpm
Idle speed	650 rpm
Emission Control Technology Route	EGR+DOC+DPF+SCR+ASC
Emission Standards	China 6
Curb mass	7815 kg
Drive type	4×2
Tire type/number	11.00R20/6
Maximum total mass	18000 kg
Transmission system	10-speed manual
Final drive ratio	5.262

2.3 Simulation cycles

The selected road is the PEMS test route of the corresponding N3 non-urban vehicle, as shown in Figure 2.

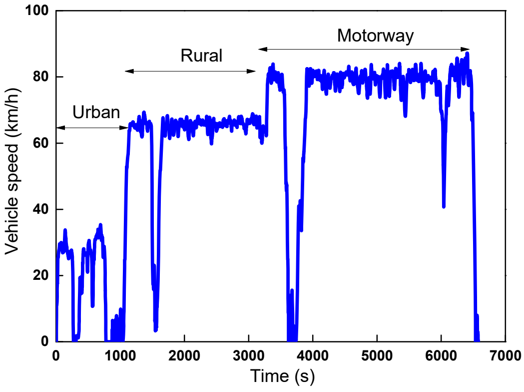

Figure 2 Vehicle speed profile of PEMS test

This PEMS test has a total time of 6570 seconds and a total driving mileage of 109.8 kilometers. The proportion in urban, rural and motorway is 19.2%, 29.1% and 51.7%, respectively. The average vehicle speeds in the urban, rural and motorway are 18.2, 62.9 and 72.5 km/h, respectively. The time proportions of acceleration, deceleration, constant speed and idle speed of the total PEMS are 13.2%, 12.7%, 69.1% and 5.1%, respectively. For each loading, the same full vehicle model (but with varying vehicle weights and coastdown coefficient) and the same driving strategy were used. In addition to using emission equipment to measure pollutants and carbon emissions, OBD data was also collected to obtain aftertreatment temperatures and raw NOx concentrations. The calculation methods of pollutant emissions and CO2 emission can be referred in GB17691-2018 [13].

3. Results and Discussions

3.1 Pollutant and CO2 emissions of PEMS at different vehicle loading

Figure 3 shows the power, pollutant and CO2 emissions of the PEMS under different vehicle loading. Both the power and CO2 emissions increase linearly as the vehicle loading increases. However, the pollutant emissions show a different pattern. When the load percentage was gradually increased from 25% to 100%, the total PN and CO emissions increased linearly. As the load capacity increases, the torque of the engine increases, and more heavy load conditions lead to an increase in incomplete combustion, which leads to an increase in CO and particulate matter. NOx emissions are minimal at fully loaded and highest at unloaded. While the maximum and minimum THC appear at 75%-loaded and 25%-loaded, respectively.

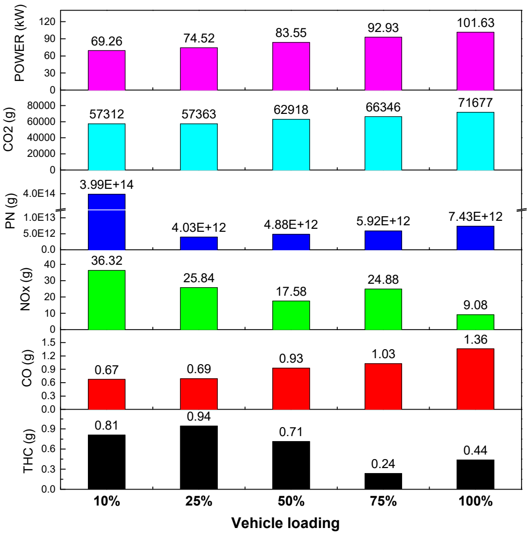

Figure 3 Power, pollutant and CO2 emissions of the PEMS under different vehicle loading

In order to exclude the influence of power, the emission characteristics of the PEMS test are characterized by the brake specific emission method, as shown in Figure 4. Although the total carbon emission increases with the increase of load, the specific emission of CO2 decreases gradually. The maximum CO2 brake specific emission of 827.53 g/kwh and the minimum CO2 brake specific emission of 705.27 g/kwh appears at unloaded and fully loaded, respectively. Except for 10% load, the brake specific emission of PN increases with increasing load. The lowest NOx brake specific emission of 89.33 mg/kwh appears at fully loaded condition. While the highest NOx brake specific emission appears at 10%-loaded, reaching 524.38 mg/kwh, which is close to the limit of 690 mg/kwh required by China VI regulations. The brake specific emission of NOx has no obvious regularity with the change of vehicle loading. This is mainly because the increase of the vehicle loading will change the original exhaust NOx emission and catalytic efficiency of SCR. There is also no obvious regularity between CO and THC, mainly because the CO and THC emissions of diesel engines are inherently low.

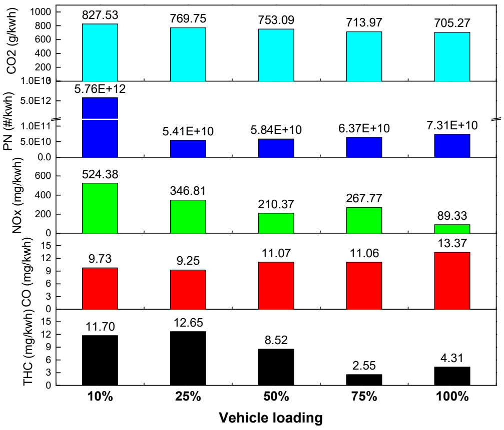

Figure 4 Pollutant and CO2 brake specific emissions of the PEMS under different vehicle loading

Furthermore, it can be seen from Figures 3 and 4 that the emission for the 10%-loaded appears to be anomalous. Especially the PN emission is 2 orders of magnitude higher than other loaded, which is likely due to DPF regeneration. Figure 5 shows the PN and NOx cumulative emissions as well as DOC inlet and SCR inlet temperature changes at 10% load. It can be seen that the exhaust gas temperature starts to rise sharply around 4500 seconds, and the SCR inlet temperature is obviously higher than the DOC inlet temperaute. PN and NOx start to rise rapidly after about 300 seconds. During this period, the vehicle speed stabilized at a high speed. Normal driving will not cause the exhaust temperature to rise, indicating that the DPF regeneration strategy begin to work. More post-injection fuel leads to a rapid increase in engine exhaust temperature, which is why CO2 emissions at 10%-loaded is very close to the 25%-loaded. When the DPF is regenerated, the soot particles deposited on the DPF are oxidized to smaller particles, resulting in an increase in PN. At the same time, the inlet temperature of the SCR is close to 600 ℃, which also deviates from the optimal catalytic efficiency range of the SCR, resulting in a rapid increase in NOx emissions. Based on this, the 10%-loaded test was excluded from the subsequent analysis.

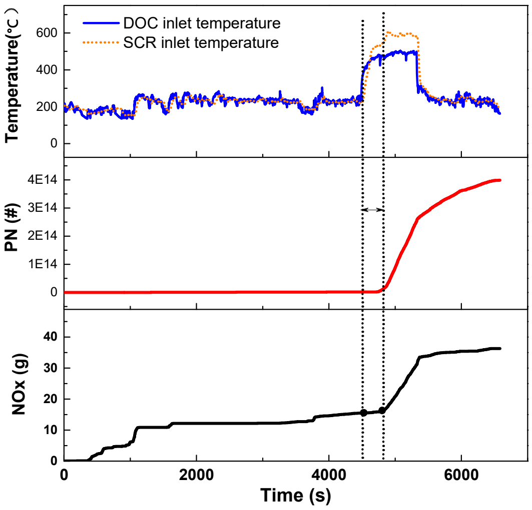

Figure 5 Exhaust temperatures, PN and NOx cumulative emissions at 10%-loaded

3.2 NOx emissions analysis of PEMS at different vehicle loading

From the analysis in the previous section, it can be seen that both CO2 emissions and PN emissions increase linearly with increasing vehicle loading after excluding the 10%-loaded test where regeneration occurred. Since the final NOx emission is a synergistic result raw exhaust NOx emission and SCR catalytic efficiency, the NOx emission is analyzed in details in this section combined with test data from the engine test bed and OBD.

Figure 6 shows the raw exhaust NOx emission at different vehicle loading. The NOx raw emission at 25%-loaded is the lowest, followed by 100%-loaded. And the highest is at 50%-loaded. The regularity of the influence of vehicle loading variation on the NOx raw emission is not obvious. The generation of NOx is related to in-cylinder temperature, oxygen content and high temperature residence time. The increase in vehicle loading may lead to an increase in in-cylinder temperature, but it also reduces the oxygen content in the cylinder. The engine condition variation during the PEMS tests at different vehicle loading can be seen in Figure 7. The high torque area is obviously reduced as the vehicle loading decreases.

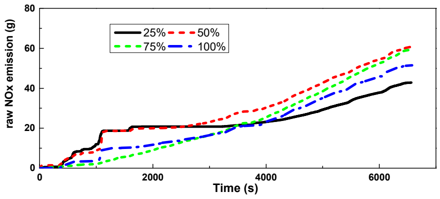

Figure 6 Raw exhaust NOx emission at different vehicle loading.

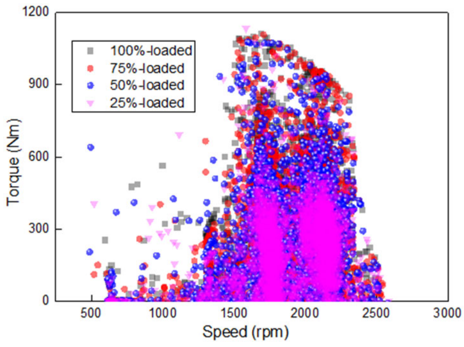

Figure 7 Engine condition variation during the PEMS tests at different vehicle loading

The temperatures at the DOC inlet and the SCR inlet at different vehicle loading are shown in Figure 7. The variation trend of exhaust temperature with time under different vehicle loading is basically the same. And as the loading increases, the SCR inlet temperature increases. The average SCR inlet temperatures are 225.0, 233.4, 244.1 and 257.5 °C at 25%, 50%, 75% and 100% loaded, respectively. The increase of SCR inlet temperature is beneficial to the improvement of SCR catalytic efficiency.

Although the NOx raw emission at 25%-loaded is the lowest, the catalytic efficiency of the SCR is low due to its low SCR inlet temperature, resulting in the highest NOx specific emission at 25%-loaded. At 100%-loaded, the NOx raw emission is not high, but the catalytic efficiency is the highest at this time, so its NOx specific emission is the lowest. Raw emissions at 50% and 75% loaded are high, but because of the higher catalytic efficiency at 75%-loaded, NOx emissions at 75% -loaded are lower than that at 50%-loaded.

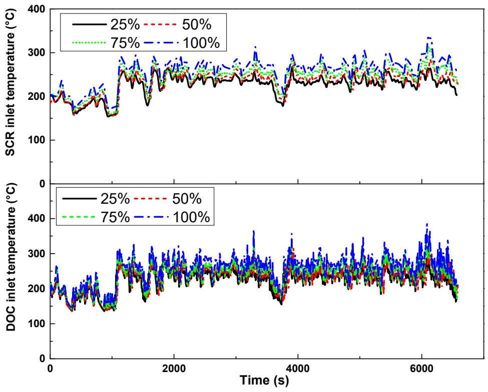

Figure 8 Temperatures at the DOC inlet and the SCR inlet at different vehicle loading

4. Conclusion

The impact of the vehicle loading on the real driving pollutant emissions and CO2 emissions of heavy-duty vehicles is studied based on EIL methodology. As the vehicle loading increases, the total emission of CO2 increases, but the specific emission decreases. Both the total and specific emissions of PN increase when vehicle loading increases. The effect of increasing load on NOx, THC and CO is not significant. It is necessary to comprehensively consider the changes in the raw exhaust due to the engine operation points and in the SCR catalytic efficiency derived from the SCR inlet temperature. The DPF generation is also need to be concerned because the CO2, PN and NOx emissions will rapidly increase during this period.

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