Effects of road slope on emission characteristics for a heavy-duty diesel vehicle based on engine-in-the-loop methodology

Su Li [1], Xiaowei Wang[1], Tao Gao[1], Yongzhan Huo[1], Yang Lu[2], Mingda Wang[3,*]

[1] CATARC Automotive Test Center (Tianjin) Co., Ltd., Tianjin 300300, China.
[2] Beijing Municipal Ecological and Environmental Monitoring Center, Beijing, 100012, China 3- Chinese Research Academy of Environmental Sciences, Beijing, 100012, China

Abstract: A dump truck with a maximum designed total mass of 24500 kg was selected to measure the emission characteristics of pollutants and carbon dioxide (CO2) under fully-loaded and unloaded conditions at the same simulated road with different road slope, same driver and vehicle model by using the engine-in-the-loop methodology. The results show that driving at gradient road will result in an increase in power and total emissions. The brake specific emissions of gaseous pollutant and CO2 are lower at gradient road, while the brake emission of particle number are higher at gradient road. Road slope affects exhaust temperature so as to affect nitrogen oxide (NOx) emissions. Under unloaded conditions, long-slope conditions are more likely to cause an increase in NOx emissions.

Key words: Heavy-duty diesel vehicle, Pollutant emission, CO2 emission, Engine-in-the-loop, Road slope

1. Introduction

In 2020, carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), particulate matter (PM) emissions from commercial vehicles accounts for 29.8%, 26.6%, 84.3% and 90.9% respectively of the total vehicle emissions in China[1]. Meanwhile, the carbon dioxide (CO2) emissions of commercial vehicles accounted for 61.5% of the total vehicle CO2 emissions in 2019 [2]. Therefore, It is urgent to control the pollutant emissions and carbon emissions from commercial vehicles. The Chinese government issued the “Limits and measurement methods for emissions from diesel fueled heavy-duty vehicle (Chinese Ⅵ)” in 2018 which significantly tightened various pollutant emission limits [3]. The future fuel consumption standard of heavy-duty commercial vehicles will also significantly tighten the fuel consumption limits [4].

Many factors will affect pollutant emissions and CO2 emissions [5-6], including driving behavior, traffic flow conditions, road conditions, environmental conditions, vehicle loads, etc. But among them, the influence of road gradient is easier to ignore. This is mainly because the current fuel consumption and emission standards in China do not take into account the influence of road gradients. However, in the calculation of carbon emissions based on Vehicle Energy Consumption Calculation Tool (VECTO) in Europe, the road slope is taken into account [7]. Moreover, the current traditional vehicle energy consumption model is mainly based on the vehicle specific power (VSP) method, which also considers the influence of the road slope. Changes in road slope will affect the road resistance, resulting in changes in power and CO2 emissions. However, the impact of road slope on emissions is more complex. ZHANG et al. [8] studied the relationship between road slope less than 4% and heavy vehicle emissions and found that CO emission is the most sensitive to road slope. Prati et al. [9] conducted an actual road test on a light-duty diesel vehicle and found that uphill slopes lead to an 85% and 33% increase in CO2 and NOx emissions, while downhill slopes lead to a 45% and 60% reduction in CO2 and NOx emissions respectively. Xu et al. [10] studied the actual road emissions of a light-duty vehicle and a heavy-duty vehicle and found that the CO2 and NOx emissions of both vehicles increased with the increase of the road slope. However, these studies are based on actual road tests which 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, and it is not suitable to conduct research on the impact of a single variable such as road slope on emissions. Moreover, these studies only considered the emission of gaseous pollutants, but did not consider the emission of particulate matter. Because the slope resistance is closely related to the vehicle loading, the effect of vehicle loading on emissions under different road slope still need to be studied.

In this context, this paper selected a dump truck with a maximum designed total mass of 24500 kg to study the emission characteristics of pollutants and CO2 under different loading and road slope based on an engine-in-the-loop (EIL) methodology.

* Corresponding author: wangmingda@vecc.org.cn

2. Experimental setup

2.1 Methodology and test equipment

EIL is a special hardware-in-the-loop method which regards the engine as the actual physical hardware, while the vehicle, the driver and the road is defined by virtual model [11-13]. The EIL can then finish the vehicle tests on the engine test bed with good repeatability and consistency due to the accurate control on the laboratory environment. EIL is the most suitable method for studying the impact of single variable such as road slope on emissions. The engine-in-the-loop test platform can be seen in Figure 1.

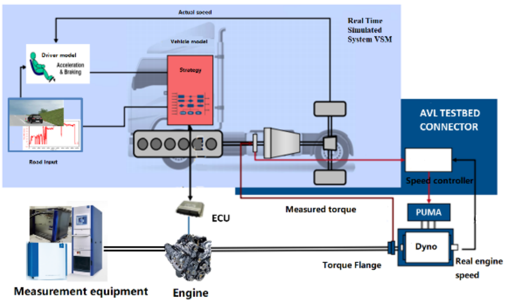

Figure 1 Engine-In-the-Loop test platform

The vehicle and driver models were constructed through the AVL VSM™ real-time system. And the road model considered the road slope. Boundary conditions such as environmental temperature and humidity were well controlled to ensure a consistent environment for each test. Pollutant emissions and CO2 emissions are obtained through the AVL AMA i60 and AVL 489 particle counter. Details of the test equipment and software are listed in Table 1.

Table 1 Test equipment and software

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 vehicle is an N3 non-city dump truck, with a curb weight of 9000 kg, a maximum total mass of 24500 kg and a manual transmission with 10 forward gears. The rated power and the maximum torque of the equipped engine is 180kW and 1140Nm, respectively. Exhaust gas re-circulation (EGR), diesel oxidation catalyst (DOC), diesel particulate filter (DPF), selective catalytic reducer (SCR) and ammonia catalyst (ASC) make up the emission control system to meet the China VI emission standard. The road resistance coefficients under fully-loaded and unloaded are measured in the test field following the procedures of GB27840-2011 [12]. Table 2 listed the parameters of vehicle and engine used in this paper.

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	9000 kg
Drive type	6×2
Tire type/number	11.00R22.5/8
Maximum total mass	24500 kg
Transmission system	10-speed manual
Final drive ratio	5.286

2.3 Test scenarios

The selected road is a PEMS test route of the corresponding N3 non-urban vehicle, located in Jianshui County, Yunnan Province, as shown in Figure 2. The total distance of the PEMS route is about 120 kilometers, which ran back and forth four times along a section of about 30 kilometers trip. The maximum altitude change for this section of the trip was more than 200 meters which brings a large slope change.

Figure 2 Schematic of the actual road at Jianshui County, Yunnan Province

The variation of vehicle speed, altitude and road slope with running distance is shown in Figure 3. The total

https://doi.org/10.1051/e3sconf/202235801006

running distance is 31.58 km, the average speed is 33.36 km/h, and the maximum speed is 75.53 km/h.

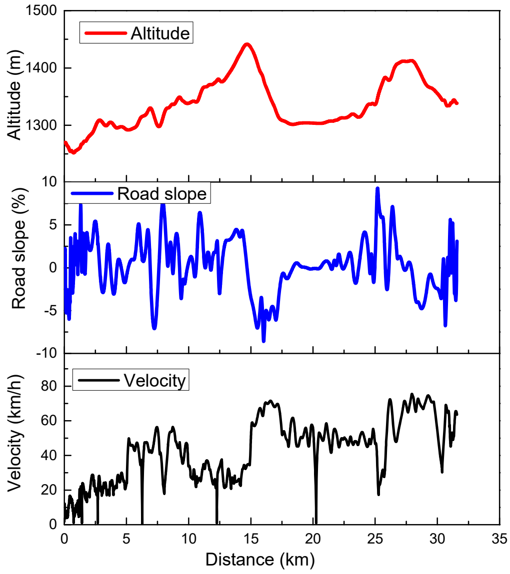

Figure 3 The variation of vehicle speed, altitude and road slope with running distance

The road slope is calculated using the road modeling software of AVL VSM™, which constructed a terrain surface model based on GPS data to correct altitude data. The model construction schematic diagram is shown in Figure 4. The parameter selection for road modeling is based on the AVL recommendation without modification.

Figure 4 Schematic diagram of slope calculation and correction based on AVL VSMTM

Four test scenarios were selected, namely, fully-loaded with slope (Test 1), fully-loaded without slope (Test 2), unloaded with slope (Test 3), and unloaded without slope (Test 4). Where no slope means directly replacing the slope value with 0 in the road model. For each test scenario, the same vehicle model (but different vehicle weight and road resistance coefficients) and the same driving strategy were used for testing. Calculation methods of pollutant emissions and CO2 emissions followed the requirements of GB17691-2018 [3].

3. Results and Discussions

3.1 Pollutant and CO2 emissions

Figure 5 shows the power, brake specific emissions of CO2 and pollutant of the whole trip for the four test scenarios. Under fully-loaded conditions (corresponding to Test 1 and Test 2), the power produced by running the same trip with and without slope is 47.85 and 29.82 kW, respectively. Running at gradient road increases power by 60% compared to running without road slope, while total CO2 emissions only increase by 50%. Therefore, the CO2 brake specific emission of running with slope is 6% lower than that of no gradient. The CO, THC and NOx brake specific emissions of running with gradient are 80%, 63% and 73% lower than those of running without gradient, respectively. While the PN ratio is 63% higher for running with slope than running without slope.
Under unloaded conditions (corresponding to Test 3 and Test 4), the tendency is similar to fully-loaded conditions. Running at gradient road increases power by 39% compared to running at road without slope, while total CO2 emissions increased by only 21%. Therefore, the CO2 brake specific emission of running with gradient is 13% lower than that of no gradient. The CO, THC and NOx brake specific emissions of running with slope are 88%, 67% and 79% lower than those of running without slope, respectively. While the PN brake specific emission is 65% higher for running with slope than running without slope. The above results show that the increase in gaseous pollutant emissions caused by the slope is not as great as the increase in power, so that the gaseous pollutant brake specific emissions of running with a slope are lower. The effect of slope on particulate emissions is greater than the effect on power.
In addition, under the condition with slope (corresponding to Test 1 and Test 3), the power, brake specific emissions of CO and PN at full load are 107%, 41% and 68% higher than those at unloaded conditions, respectively, and the specific emissions of CO2, THC and NOx at full load are 16%, 82% and 65% lower than at unloaded conditions, respectively. Similar tendency exist for the conditions without slope (corresponding to Test2 and Test 4). The power, brake specific emissions of CO and PN at full load are 80%, 25% and 71% higher than those at no load, respectively. And the brake specific emissions of CO2, THC and NOx at full load are 22%, 89% and 72% lower than those at no load, respectively.

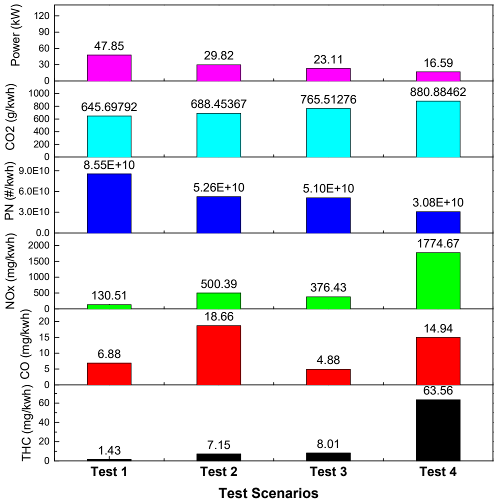

Figure 5 Power and brake specific emissions in four scenarios

3.2 Pollutant and CO_2 transient emissions

Due to the low emissions of THC and CO from diesel engines, these two emissions are no longer analyzed, and only transient emissions of NOx, PN and CO2 are analyzed. The cumulative emissions of NOx, PN and CO2 under full load conditions are shown in Figure 6. Compared with Test 2 without slope, the PN and CO2 emissions have a consistent tendency. For example, in the circled areas A, B and C in the figure, PN and CO2 emissions have increased significantly. The common feature is that these three positions are located in the acceleration phase which increase the fuel injection to meet the requirements of increased load. The corresponding circle areas D, E, and F increase significantly in NOx. The common features of D and E areas are lower vehicle speed and lower exhaust temperature. The F zone is for vehicle acceleration and hill climbing. From the characteristics of transient emissions, the effect of road slope is not as great as that of vehicle acceleration. The main reason may be that the vehicle is fully loaded at this time, and more power is required to accelerate the vehicle, so more fuel needs to be injected to achieve vehicle acceleration, resulting in an increase in PN and CO2. In addition, the influence of slope on the change of exhaust temperature is greater. In the case of no slope, the exhaust temperature is relatively stable. Only when the vehicle decelerates and idling, the exhaust temperature decreases, and when the vehicle accelerates, the exhaust temperature increases. Under the condition with slope, the change of slope will cause the change of exhaust temperature, especially under the condition of long down slope. The decrease of exhaust temperature may affect the conversion efficiency of SCR. Under full load conditions, due to the high exhaust temperature itself, the effect of this decrease in exhaust temperature on the conversion efficiency is not very significant.

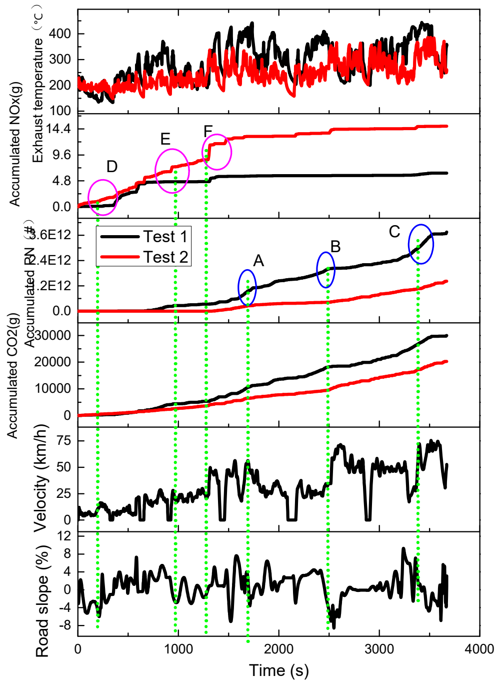

Figure 6 Cumulative emissions and exhaust temperature at full load

The cumulative emissions of NOx, PN and CO2 under no-load conditions are shown in Figure 7. Compared to the no-slope scenario, it can be seen that the areas with more obvious PN and CO2 emission growth rates are still consistent with the full load conditions, such as the circle areas A, B and C. In addition to the increase in NOx emissions in areas with lower exhaust temperatures, there is also a more significant feature that when the slope decreases but the vehicle speed increases. The exhaust temperature decreases and NOx emissions increase, as shown in the circled area F in the figure.

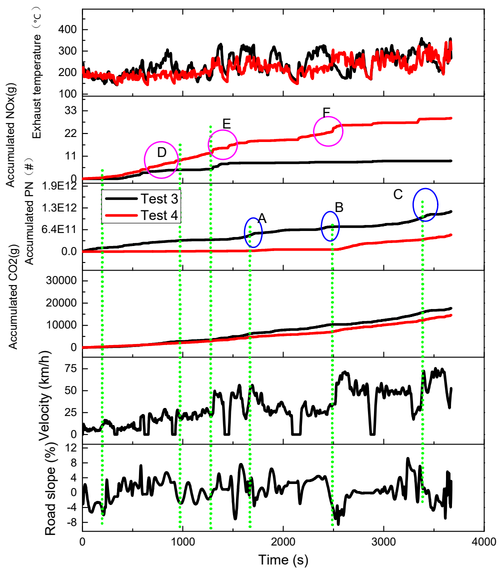

Figure 7 Cumulative emissions and exhaust temperature at no-load

4. Conclusion

The impact of the road slope on the real driving pollutant emissions and CO2 emissions of heavy-duty vehicles is studied based on EIL methodology. At the same trip, running with a slope will cause an increase in power and total emissions, but the increase in gaseous pollutant emissions is not as great as the increase in power, so the gaseous pollutants in running with slopes are lower than the emissions. PN emission of slope scenario is are higher than the scenario without slope. Slope changes affect exhaust temperature, which in turn affects NOx emissions. Under no-load conditions, long-slope driving conditions will result in increased NOx emissions.

Acknowledgments

This work was supported by Beijing Municipal Commission of Science and Technology under Grant Z191100009119014.

References

1. China mobile source environmental management annual report in 2021-Part 1: the situation of vehicle emission [J]. Ministry of Ecology and Environment of the People's Republic of China, 2021.
2. HUANG Z H, JI L, YIN J, et al. Peak Pathway of China's Road Traffic Carbon Emissions[J]. Research of Environmental Sciences, 2022, 35(02):385-393.
3. GB17691-2018 Limits and measurement methods for emissions from diesel fueled heavy-duty vehicle (Chinese Ⅵ) [S]. Ministry of Ecology and Environment of the People's Republic of China, 2018.
4. GB/T 27840-2011, Fuel consumption test methods for heavy-duty commercial vehicles[S]. China Standardization Administration, 2011.
5. WANG X W, YAN Y, JING X J, et al. Effect of Driving Pattern on RDE of Vehicle Equipped with a Port Fuel Injection Gasoline Engine[J]. Automotive Engineering, 2018 ,40(10):1146-1150.
6. SUNIL K, VINEET S, YOGRAJ S, et al. Real world vehicle emissions: Their correlation with driving parameters [J]. Transportation Research Part D 2016 (44): 157–176.
7. REGULATION (EU) 2017/2400 of 12 December 2017 implementing Regulation (EC) No 595/2009 of the European Parliament and of the Council as regards the determination of the CO2 emissions and fuel consumption of heavy-duty vehicles and amending Directive 2007/46/EC of the European Parliament and of the Council and Commission Regulation (EU) No 582/2011[S], European Commission,2017.
8. ZHANG W, LU J, XU P, et al. Moving towards Sustainability: Road Grades and On-Road Emissions of Heavy-Duty Vehicles — A Case Study. Sustainability. 2015; 7(9):12644-12671.
9. PRATI M, MECCARIELLO G, DELLA R et al. Real Driving Emissions of a Light-Duty Vehicle in Naples. Influence of Road Grade, SAE Technical Paper 2015-24-2509, 2015.
10. XU B, XING Y Y, LU J. Study on influence of road slope on exhaust emission of light and heavy vehicles [J]. Journal of Wuhan University of Technology (Transportation Science & Engineering), 2021 ,5(45):834-839.
11. WANG X W FU T Q, WANG C Q, et al. Fuel consumption and emissions at china automotive test cycle for a heavy duty vehicle based on engine-in-the-loop methodology [C]. 2020 J. Phys.: Conf. Ser. 1549 022119.
12. WANG X W, JING X J, GAO T, et al. Study on real driving fine particles emission characteristics for a heavy-duty diesel vehicle based on engine-in-the-loop methodology[J]. Automotive Engineering, 2022,44(1):58-63.
13. WANG X W, LING J, YAN F. Review on engine-in-the-loop simulation: application and development [J]. Small Internal Combustion Engine and Vehicle Technique.2019,48（5）:79-84.