Real Driving Emissions Evaluation for A Heavy Duty Diesel Vehicle based on Engine-in-the-loop Methodology

Xiaowei Wang [1], Tao Gao [1], Gang Li [2, *], Xiaojun Jing [1], Youyuan Zhang [3]

[1] CATARC Automotive Test Center (Tianjin) Co., Ltd., Tianjin 300300, China.
[2] Chinese Research Academy of Environmental Sciences, Beijing, 100012, China
[3] Dongfeng Liuzhou Motor Co., Ltd., Guangxi 545000, China

Abstract. Real driving emissions of a heavy-duty vehicle with a maximum total mass of 18000 kg were investigated by the engine-in-the-loop (EIL) methodology. Virtual vehicle model, driver model and real road model was established, then to combined with the actual engine and emission test equipment to fulfill the vehicle emission evaluation on engine test bed. The results indicate the road driving can be well reproduced on engine laboratory with good vehicle speed followability, engine speed and torque consistence. However, the emission results show a larger difference with a 3.6 gap for CO2, a 72.3% gap for NOx and a 40% gap for PN., respectively. Analysis shows that the intercooler temperature, the exhaust temperature and equipment difference has a combined effect on the emission accuracy.

1. Introduction

The government issued the "Limits and Measurement Methods for Pollutant Emissions from Heavy Duty Diesel Vehicles (China VI)" [1]. This regulation require to conduct certification of the engine and the vehicle separately. And the emissions and fuel consumption of heavy duty vehicle need to be measured at the same test. Due to the characteristics of “one diesel engine with multiple vehicle type”, it is possible that one engine matches multiple vehicle types such as bus, dump truck, and cargo, leading to a steady increase in the powertrain complexity [2-3]. Ensure all types of vehicles to meet the legislation requirements such as production consistency and in-use compliance is a huge challenge for heavy-duty vehicle enterprises.

For certification and supervision of heavy duty vehicle, the test method required by legislation is the PEMS (Portable Emission Measurement System) test to evaluate the real driving emissions. However,the additional validation of the PEMS as part of the homologation process in an increasing number of vehicle sales markets, lead to a drastic increase in the scope of tests to verify the real driving emission behavior of new vehicles and vehicle concepts due to the stochastic nature of PEMS test drives, which are highly non-reproducible due to the impact of a variety of environmental factors such as weather, traffic situations, road conditions and driving styles[5-7].

In this context, we developed a new methods to meet the challenges resulting from the PEMS test requirements and the related calibration tasks to maintain or improve the product quality.An advanced engine-in-the-loop (EIL) methodology was used in this paper to explores the application of EIL methodology on evaluation the real driving emissions[8-12]. The differences in emissions under EIL and actual driving conditions are compared. The reasons for the differences are analyzed, and suggestions are made for the next improvement of the EIL methodology.

2. Experimental Setup

2.1 Engine-in-the-loop platform setup

The EIL test platform constructed is shown in Figure 1. The details of this EIL platform can be seen in References[13-14].

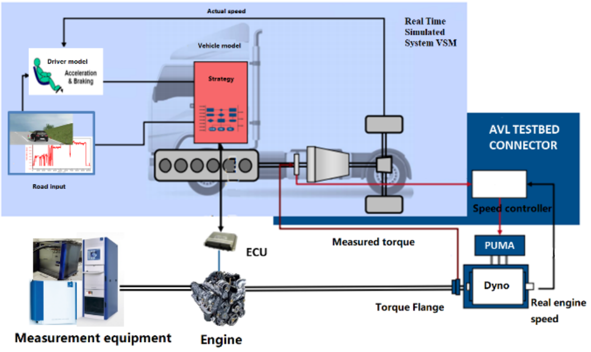

Figure 1 Engine-In-the-Loop test platform

The main equipment used in this paper is shown in Table 1.

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[*] Corresponding author: ligang@vecc.org.cn

Table 1 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 number (PN) measurement	AVL 489
Fuel consumption measurement	AVL 753C/735S
Vehicle model system	AVL VSM™
Real time system	AVL Testbed CONNECT™ (RT)
PEMS test equipment	AVL PEMS

2.2 Vehicle and engine specifications

The engine used in this paper is a heavy-duty diesel engine with a displacement of 7.7 liter and a rated power of 234 kW which meets the China VI emission legislation. The engine are equipped on a heavy-duty truck with a curb weight of 6800 kg and a 9-speed manual transmission. The specifications of the vehicle and engine are shown in Table 2.

Table 2 Main parameters of tested vehicle and engine

Parameter	Value
Vehicle type	N3
Vehicle curb weight	6800 kg
Maximum total mass	18000 kg
Maximum design speed	110 km/h
Transmission system	9-speed manual
Tire specifications	12R22.5
Engine capacity	7.7 L
Bore×Stroke	110 mm×135 mm
Rated power/speed	243 kw/2200 rpm
Emission Control Technology Route	EGR+DOC+DPF+SCR+ASC
Emission Standards	China VI

2.3 PEMS test information and road spectrum transformation

A PEMS test with a payload of 10% was carried out on the actual road according to the China VI emission legislation requirements.The total mileage of this test is 136.5 km with an average speed of 56.5 km/h, consisting of 19.5% of urban driving, 25.3% of rural driving, and 55.2% of motorway driving. The total test lasts 9239 seconds. The average environmental temperature and humidity are 10.5 centigrade and 49%, respectively. The vehicle velocity profile of this PEMS test is shown in Figure 2.

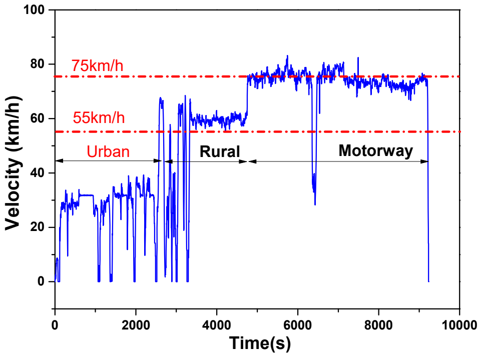

Figure 2 Vehicle velocity profile of PEMS test

The GPS information of this PEMS test is converted into road spectrum information with road curvature and gradient through Google Earth and AVL VSM software. The real road curvature and gradient are shown in Figure 3. It can be seen from this figure that changes in road curvature mainly occur in urban driving condition, while changes in gradient mainly occur in rural and highway driving conditions.

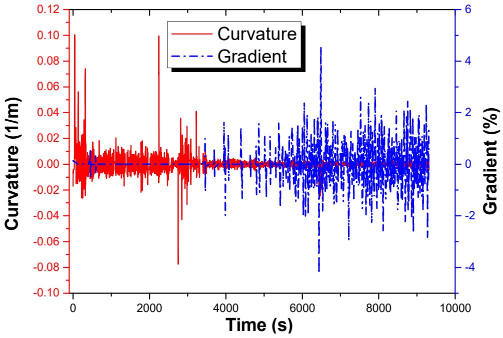

Figure 3 Real road curvature and gradient

The vehicle model and the driver model was constructed by AVL VSM software. In this paper, the gears during EIL test are completely set to same the actual gears which are recorded by INCA during the PEMS test. Driving resistance coefficient is derived from the actual vehicle sliding test with a payload of 10%.

3. Results and Discussions

3.1 PEMS velocity followability of EIL methodology

PEMS test was performed on the engine test bed by the EIL methodology. The EIL followed the PEMS target velocity by optimize the PID controller in the driver model. The obtained vehicle velocity followability is shown in Figure 4. From the results, the actual speed can basically follow the target speed. In most cases, the difference between the actual vehicle speed and the target vehicle speed is within ± 1 km/h. In some acceleration and deceleration cases, the speed difference exceeds ± 1 km/h, but both are lower than ± 2 km/h. This shows that the EIL methodology can better reproduce the driving cycles.

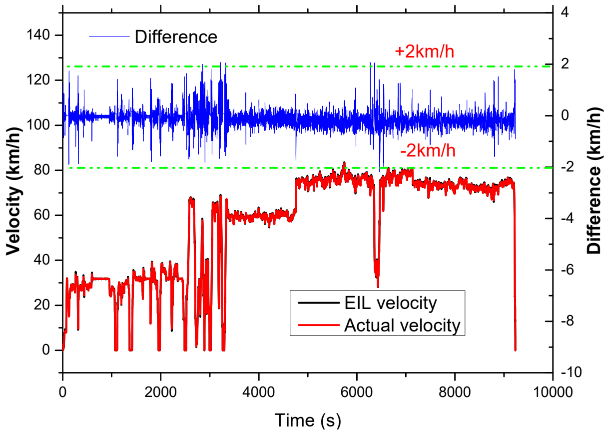

Figure 4 Vehicle speed followability of EIL method

3.2 Correlation analysis of engine speed and torque

The correlation of engine speed and torque between EIL and real PEMS test are shown in Figure 5. It shows good linearity for both engine speed and torque between EIL and real PEMS test. Moreover, it can be seen from the figure that the correlation coefficient of engine speed between EIL and real PEMS test is 0.8674, while the correlation coefficient of engine torque between EIL and real PEMS test is 0.8748.

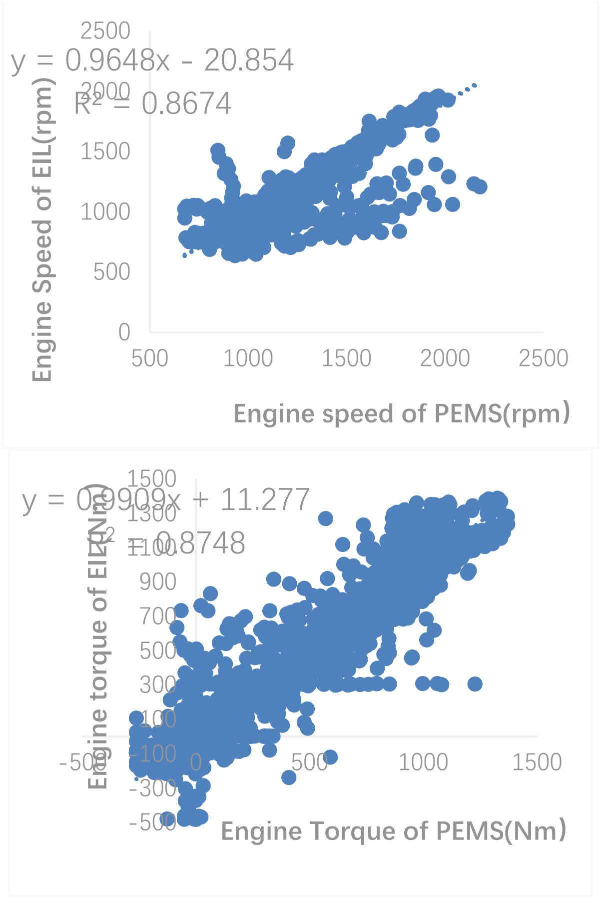

Figure 5. Correlation analysis left: engine speed, right:engine torque

3.3 Emissions difference between EIL and real PEMS test

The previous two sections shows the EIL methodology can follow the actual vehicle velocity very well, and exhibit a good correlation for both engine speed and torque, indicating the EIL methodology can well reproduce the run conditions of PEMS on engine test bed. In this section, we continue to explore the emission difference between EIL and real driving for a PEMS test cycle.

Figure 6 shows the cumulative emissions difference between EIL and actual road test under PEMS conditions.The cumulative CO2 emission of EIL is about 3.6% lower than that of PEMS. While the cumulative NOx emission of EIL is about 72.3% lower than that of PEMS, and the cumulative PN emission of EIL is about 40% lower than that of PEMS. It seems that except the CO2 emission difference is a acceptable value, but NOx and PN emissions of EIL test exists a hug gap compared with the real PEMS test. Considering the engine operating points for both tests have little difference from Figure 5, What caused such a huge difference?

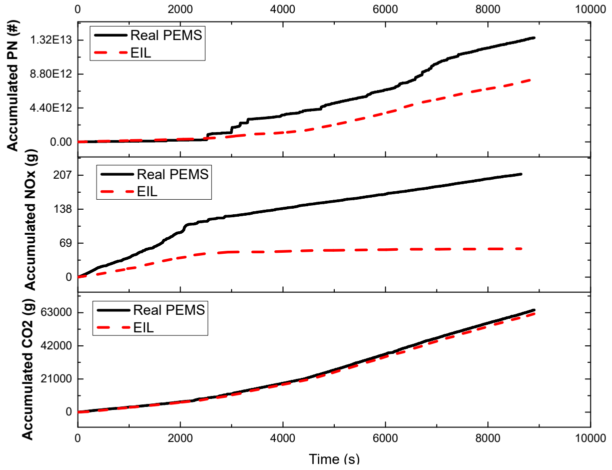

Figure 6 Cumulative emissions of NOx, PN and CO2 between EIL and actual road test under PEMS cycle

There are different for real vehicle measurement and engine test bed measurement. The first is the difference caused by the test equipment. The PEMS test uses a portable emission test equipment which has a lower accuracy, while the EIL test uses a gas analyzer and particle counter on the engine test bed. Especially for the PN measurement, the AVL PN PEMS uses a Faraday cage potentiometer to measure the number of particles in the exhaust gas with the principle of diffusion charging, while the AVL 489 on engine test bed count the particle number with a principle of light scattering. For determining this difference, 3 WHTC (World harmonized Transient-State Cycle) tests were carried out with the PEMS equipment sampling probe installing a position very close to the original sampling position of the equipment of test bed to eliminate the influence of pipeline deposition on emissions. The average emission results of NOx, PN and CO2 for two set of equipment are shown in Figure 7. The transient emission trend of NOx and CO2 for these two set of equipment are similar. However, the transient emission trend of PN for these two set of equipment exhibit a little bit variation especially in the high vehicle speed phase, which mostly due to the difference of PN measurement principle for these two set of equipment.

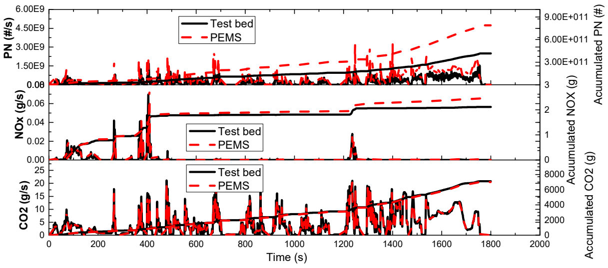

Figure 7 Average emission results of NOx, PN and CO2 for two set of equipment

The cumulative emissions of NOx, PN and CO2 of the average 3 WHTC tests for these two sets of equipment can be seen in the Table 3. The CO2 measured by PEMS equipment is 6988.86 g, while the CO2 measured by test bed equipment is 7105.14 g. The gap of 1.64% shows a good consistency for CO2 measurement. The measurement consistency of NOx is worse than CO2, which exhibit a gap of 16.19%. The measurement consistency of PN is the worst with a hug gap of 41.27%. Compared with the result of Figure 6 that the cumulative PN emission of EIL is about 40% lower than that of PEMS, it can be conclude that the equipment differences are the main reason for PN differences. But there is still other reason for the hug difference of NOx.

Table 3 Cumulative emissions of NOx, PN and CO2

	CO2	NOx	PN
Test bed(g)	7105.14	2.12	4.17E+11
PEMS(g)	6988.86	2.46	5.89E+11
Difference(%)	-1.64	16.19	41.27

The second possible reason is exhaust temperature. It is well known that the exhaust temperature will greatly affect the efficiency of SCR (Selective Catalytic Reduction). The exhaust temperature of real vehicle measurement is different due to the wind, environmental temperature and humidity. Figure 9 shows the difference in temperature before SCR. It can be seen from the figure that the temperature before the SCR in the actual road test is lower than the temperature in the EIL test, resulting in a higher catalytic efficiency of the SCR in the EIL test than in the actual road test. This indicates that the exhaust temperature should be well controlled to similar to vehicle status the real road driving .

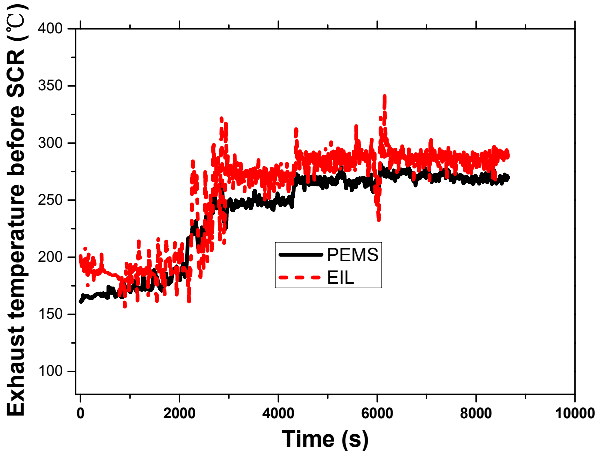

Figure 8 Exhaust temperature before SCR for PEMS and EIL test

The third possible reason is intercooler temperature. Since the intercooling efficiency of the vehicle is lower than the intercooling efficiency of the entine test bed, the intake air temperature will have a certain impact on the combustion efficiency [8]. Unfortunately, in this PEMS test, we did not collect the intercooler temperature data during the real driving cycle. Even so , we still believe that the PEMS test and the emission test results can be well reproduced on engine test bed by EIL methodology once we consider the equipment difference and control the exhaust temperature and intercooler temperature to close to the real vehicle level.

4. Conclusion

The EIL methodology can be applied to evaluate the emissions and fuel consumption of heavy-duty vehicles on the engine test bed. This method can well follow the target vehicle speed and provide good test consistency. The part of development and verification workload for vehicle can be done forward to engine test bed, greatly improving efficiency and reducing development period.

The emissions and fuel consumption of this heavy truck at CHTC-HT and C-WTVC were studied by EIL methodology. The results show that the fuel consumption of this heavy-duty truck has a little effect if the test cycle changed from C-WTVC to CHTC-HT. However, Changing the C-WTVC to CHTC-HT will greatly affect the NOx emission. The difficulty to meet the NOx emission limits will be increased. Enterprises need to re-calibrate the engine based on the CHTC, like improving the exhaust heat management and increasing NOx conversion efficiency under low temperature conditions.

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