Fuel Consumption and Emissions at China Automotive Test Cycle for A Heavy Duty Vehicle based on Engine-in-the-loop Methodology

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Abstract. In this paper, the engine-in-the-loop (EIL) method was used to study the fuel consumption and emission characteristics of heavy-duty trucks at China Automotive Test Cycle (CHTC-HT) and world transient vehicle cycle (C-WTVC) on an engine test bed. The result of the vehicle speed followability shows that the difference between the actual vehicle speed and the target vehicle speed is within ±2 km/h, indicating that the vehicle cycle can be well reproduced on the engine test bed by EIL method. The consistency results of fuel consumption and emissions indicate that the fuel consumption error is 0.89%, the NOx error is 1.02%, and the particle number (PN) error is 5.04%. For this vehicle, the fuel consumption per 100 kilometers at CHTC-HT is 21.33L, which is 2% higher than that of C-WTVC; while NOx emissions of CHTC-HT are 59.2% higher than that of C-WTVC. It is more difficult for enterprises to meet the fuel consumption and NOx emission standards under China Automotive Test Cycle.

1. Introduction
The fast-growing Chinese automobile industry has become one of the pillars of China's economy. However, with the rapid increase in car ownership, the environmental problems have also attracted more and more attention. The exhaust pollution of diesel vehicles, especially heavy-duty diesel vehicles, is even more serious. In the "China Motor Vehicle Environmental Management Annual Report (2018)", diesel trucks only accounts for 7.8% of automotive ownership, emitting 57.3% of nitrogen oxides and 77.8% of particulate matter. The government issued the "Limits and Measurement Methods for Pollutant Emissions from Heavy Duty Diesel Vehicles (China's Sixth Phase)" [2]. 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. Therefore, how to ensure that all types of vehicles meet the follow-up supervision of production consistency and compliance requirements is a huge challenge for heavy-duty trucks/heavy-duty engine enterprises.

The fuel consumption of commercial vehicles is another focus. According the requirement of "Heavy Commercial Vehicle Fuel Consumption Test Method", the fuel consumption test method should be C-WTVC, which foundation is the world transient vehicle cycle (WTVC), and cannot completely represent the actual working conditions of China [3]. In this context, China Automotive Technology and Research...
Center Co., Ltd. has developed the China heavy-duty test cycle (CHTC) and submitted for approval and will be used in the fuel consumption test of heavy commercial vehicles in the near future.

In this paper, we investigate the emissions and fuel consumption under CHTC in a heavy-duty vehicle by an advanced engine-in-the-loop (EIL) method, explores the application of EIL methodology on development of fuel consumption and emission, and evaluates the difference in emissions and fuel consumption under CHTC and C-WTVC.

2. Experimental Setup

2.1. Engine-in-the-loop Methodology

Hardware-in-the-loop (HIL) refers to "simulating the system by embedding the actual physical hardware of some subsystems into the remaining virtual subsystems to achieve closed-loop simulation" [4-5]. In the automotive industry, traditional HIL usually means that only the electrical control unit (ECU) is physical hardware, while the engine, powertrain, and vehicle are modeled to interact with the ECU through appropriate interfaces [6-8]. Although HIL has proven to be effective in predicting and optimizing the performance and fuel economy of conventional and hybrid systems, accurately predicting transient emissions (especially soot emissions) in internal combustion engines remains a challenge [9-11]. In this case, as shown in Figure 1, the definition of "hardware" in HIL gradually extends from the ECU to the engine, the powertrain or even the real vehicle, which are called engine-in-the-loop, powertrain-in-the-loop, and vehicle-in-the-loop, respectively. Due to the scarcity of heavy-duty chassis dynamometer and powertrain benches, engine-in-the-loop development methods are more advantageous because it can finish a part of vehicle development work on the engine test bed so as to greatly shorten the development period.

The "actual physical hardware" of the EIL is the engine and its controller, while the virtual subsystem is the vehicle, the driver and the environment. In addition, compared to HIL, the EIL method does not need to model the engine because the engine is actual physical hardware, so it can more accurately and realistically evaluate emissions and fuel consumption under engine transient conditions [12, 13]. Guse et al. [14] measured the vehicle's emissions under the World Light-duty Vehicle Test Cycle (WLTC) by EIL methodology and the chassis dynamometer, respectively. It was found that the CO2 emissions and acceleration pedal actions from EIL are highly consistent with the results of the chassis dynamometer test. However, the particulate matter emissions obtained by EIL are higher than that of the chassis dynamometer. Zhang et al. [15] used EIL methodology to optimize the development process of vehicle transmission system. They designed different powertrain system matching scheme to evaluate the effects of powertrain system parameters on vehicle performance and fuel consumption based on the EIL platform respectively. Therefore, the rationality of the powertrain matching can be evaluated in advance. In addition, they also conducted fuel consumption tests on the EIL platform [16]. The test results showed that the fuel consumption from EIL can be very close to that from the real road test.

![Figure 1. X-in-the-Loop application for heavy duty vehicle development and tests](image-url)
2.2. Engine-in-the-loop platform setup

The EIL test platform constructed in this paper is shown in Figure 2.

![Figure 2. Engine-In-the-Loop test platform](image)

The vehicle and driver models are built using the AVL VSM™ real-time system, and the simulation model is connected to the AVL dynamometer control software to ensure a stable interface between the simulation model and the test bench operation. AVL Testbed CONNECT is integrated with the dynamometer system via CAN bus. The real-time system calculates the demand engine speed and torque based on the inputs such as vehicle speed, gear ratio and driving resistance then sends these demands to the dynamometer control system. The dynamometer control system determines the dynamometer speed and the pedal to make the engine take corresponding actions. At the same time, the sensors installed on the engine test bed collect the engine parameters, then transmit back to the real-time system as inputs for calculation in the next step, which forms a closed loop of engine speed and torque. In this process, the fuel consumption and emissions under different test cycles are measured by actual equipment. The main equipment used in this paper is shown in Table 1.

| 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 1600 |
| 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) |

2.3. Test vehicle and engine

The engine used in this paper is a heavy-duty diesel engine with a displacement of 7.7 liter which meets the China VI emission legislation. The engine are equipped on a heavy-duty truck with a curb weight of 6800 kg. The specific parameters 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                     | 42000 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            |
| Idle speed                             | 600 rpm                    |
| Emission Control Technology Route      | EGR+DOC+DPF+SCR+ASC        |
| Emission Standards                     | China VI                   |

2.4. Test cycle

China Heavy duty vehicle Test Cycle includes six cycles, corresponding to city bus, bus, light duty truck, heavy duty truck, dump truck and semi-trailer. In this paper, China Automotive Test Cycle for Heavy-duty truck (CHTC-HT) was used. The CHTC-HT is an 1800 second cycle with a total mileage of 17.33 km. In addition, the C-WTVC specified in the regulations are also used for comparison. The speed curve of CHTC-HT and C-WTVC is shown in Figure 3.

![Speed curve of CHTC-HT and C-WTVC](image)

The detailed of CHTC-HT can be seen in Table 3.

Table 3. Characteristics parameters of CHTC-HT

| Parameter                              | Value                      |
|----------------------------------------|----------------------------|
| Time(s)                                | 1800                       |
| Mileage(km)                            | 17.33                      |
| Maximum speed (km/h)                   | 88.5                       |
| Maximum acceleration (m/s²)            | 1.14                       |
| Maximum deceleration (m/s²)            | -1.21                      |
| Average speed (km/h)                   | 34.65                      |
| Acceleration ratio (%)                 | 24.22                      |
| Deceleration ratio (%)                 | 18.06                      |
| Uniform speed ratio (%)                | 44                         |
| Idle speed ratio (%)                   | 13.72                      |
3. Results and Discussions

3.1. Speed followability of EIL methodology

CHTC-HT and C-WTVC were performed on the engine test bed by the EIL methodology. The obtained vehicle speed 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. Left: CHTC-HT, right: C-WTVC](image)

3.2. Consistency of fuel consumption and emission of EIL methodology

CHTC-HT were repeated four times on the engine test bed by EIL methodology. The fuel consumption and emission were measured during the tests. The fuel consumption was obtained by the carbon balance method referring to the GB / T27840-2011 [3]. The diesel consumption is calculated by the following formula:

$$FC = \frac{0.1155}{\rho_d} \left[ (0.866 \times EF_{HC}) + (0.429 \times EF_{CO}) + (0.273 \times EF_{CO2}) \right]$$

Where FC is Fuel consumption (L per one hundred kilometer), $\rho_d$ is diesel density at 15 ℃ (g/cm³), $EF_{HC}$, $EF_{CO}$ and $EF_{CO2}$ is the emission factor of THC, CO and CO2 emission, respectively.

Table 4 shows the fuel consumption and emissions results of the four CHTC-HT tests. Because heavy vehicles are mainly concerned with NOx and PN emissions and the emission factors of CO and THC are very low, so the emission consistency analysis are focus on NOx and PN emissions. The CO and THC emissions are only used for calculating fuel consumption. It can be seen that the error of the mileage for the four tests is only 0.1%, indicating that the speed repeatability of each test is very high. The errors of fuel consumption and NOX emission is 0.89% and 1.02%, respectively. The error of PN emission is higher, reaching 5.04%. The possible reason is the inconsistent carbon load of the DPF during each test, which affects the capture efficiency of the DPF and causes a large deviation in the final measured particle number [18].

| Items          | Fuel consumption (L/100 km) | PN ($1 \times 10^{12}$ #) | Nox (g) | Mileage (km) |
|----------------|----------------------------|---------------------------|---------|--------------|
| 1st            | 21.33                      | 1.1                       | 22.755  | 17.344       |
| 2nd            | 21.16                      | 0.98                      | 24.772  | 17.345       |
| 3rd            | 21.36                      | 1.04                      | 24.273  | 17.348       |
| 4th            | 20.95                      | 1.08                      | 26.797  | 17.348       |
| Standard deviation | 0.19                    | 0.0529                    | 0.25    | 0.002        |
| Average value  | 21.2                       | 1.05                      | 24.65   | 17.35        |
| Error (%)      | 0.89                       | 5.04                      | 1.02    | 0.01         |
3.3. Fuel consumption and emission under CHTC-HT and C-WTVC

The previous two sections shows the EIL methodology can follow the actual vehicle speed very well, and exhibit a very good consistence for emissions and fuel consumption in several times test. Therefore, we can use this EIL platform to evaluate the fuel consumption and emission of heavy duty vehicle at different test cycles.

Figure 5 shows the accumulated CO$_2$ emissions at CHTC-HT and C-WTVC. The cumulative CO$_2$ emission of CHTC-HT is 9939 g, which is lower than that of C-WTVC (11778 g). However, the calculated fuel consumption per 100 kilometer by carbon balance method calculation is 21.33 L per 100 km in CHTC-HT, which is 2% higher than that of C-WTVC (20.91 L). The reason for this is the mileage of C-WTVC (20.5 km) is higher than that of CHTC-HT (17.3 km).

![Figure 5. Accumulated CO2 emissions of CHTC-HT and C-WTVC by using EIL methodology](image)

Figure 6 shows the accumulated NOx and PN emissions at CHTC-HT and C-WTVC. The accumulated PN emission is $8.8 \times 10^{11}$ # for CHTC-HT, while it is $9.7 \times 10^{11}$ # for C-WTVC. The accumulated NOx emission is 24.27 g for CHTC-HT, while it is 15.25 g for C-WTVC. The CHTC-HT and C-WTVC exhibits a similar PN emission. However, The NOx emission of CHTC-HT is 59.2% higher than that of C-WTVC.

![Figure 6. Accumulated NOx and PN emissions of CHTC-HT and C-WTVC by using EIL methodology](image)
For the same engine, the NOx emissions of heavy vehicles mainly depend on the conversion efficiency of the SCR system. The conversion efficiency of the SCR system mainly depends on the exhaust temperature [18]. From the exhaust temperature in both cycles shown in Figure 7, the exhaust temperature of CHTC-HT is significantly lower than that of C-WTVC, which leads to an increase in NOx emissions.

![Exhaust temperature comparison at CHTC-HT and C-WTVC by using EIL methodolog](image)

**Figure 7.** Exhaust temperature comparison at CHTC-HT and C-WTVC by using EIL methodolog

4. Conclusion

1) 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.

2) 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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