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Assessment of Heavy-Duty Diesel Vehicle NOx and CO_2 Emissions Based on OBD Data

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Abstract: Controlling NOx and CO_2 emissions from heavy-duty diesel vehicles (HDDVs) is receiving increasing attention. Accurate measurement of HDDV NOx and CO_2 emissions is the prerequisite for HDDV emission control. Vehicle emission regulations srecommend the measurement of NOx and CO_2 emissions from vehicles using an emission analyzer, which is expensive and unsuitable to measure a large number of vehicles in a short time. The on-board diagnostics (OBD) data stream of HDDVs provides great convenience for calculating vehicle NOx and CO_2 emissions by providing the engine fuel flow rate, NOx sensor output, and air mass flow. The calculated vehicle NOx and CO_2 emissions based on the OBD data were validated by testing a heavy-duty truck's emissions on the chassis dynamometer over the CHTC-HT driving cycle, showing that the calculated NOx and CO_2 emissions based on the OBD data are consistent with the measured results by the emission analyzer. The calculated vehicle fuel consumptions based on the OBD data were close to the calculated results based on the carbon balance method and the measured results by the fuel flowmeter. The experimental results show that accessing vehicle NOx and CO_2 emissions based on the OBD data is a convenient and applicable method.

Keywords: heavy-duty diesel vehicle; NOx; CO_2; on-board diagnostics; on-board emission testing

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1. Introduction

Vehicle exhaust contains hundreds of different compounds, becoming the main source of atmospheric pollution. Vehicle exhaust emissions are mostly concentrated at a low level about 1 m from the ground, which is near the human respiratory belt and is extremely harmful to human health, mainly reflected in the damage to human cells, decreased immunity, and susceptibility to respiratory and cardiovascular diseases [1–3]. The main pollutants controlled by vehicle emission standards are hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM), among which the NOx and PM emissions of diesel vehicles account for 80% and 90% of the total vehicle emissions of NOx and PM, respectively [4]. In addition, NOx and PM are the main cause of haze and ozone formation in the atmosphere, which has a serious impact on human health, crop production, and climate [5]. In addition, the CO_2 emitted by vehicles will cause the greenhouse effect, which will lead to an increase in the atmospheric temperature on the earth's surface and cause a serious impact on the earth's environment. Therefore, with the increase in vehicle ownership, the world automobile industry is facing great pressure to reduce greenhouse gas emissions and toxic pollutant emissions. Accordingly, vehicle emission regulations and fuel economy regulations are also being tightened in order to effectively reduce vehicle emissions and fuel consumption [4,6].

Since California established the world's first vehicle emission regulation in 1966, the vehicle emission standards in the United States have been continuously tightened. The

U.S. vehicle emission standard EPA 2010 was issued in 2001 and fully implemented in 2010. California adopted almost identical vehicle emission standards in October 2001 [7]. The European Union (EU) implemented the Euro I emission standard in 1992, and the latest Euro VI standard was implemented in 2013 [8]. China started relatively late in the field of emission regulations. It was only in 2001 that the China I emission standard was implemented nationwide, and stricter regulations were introduced successively. Since 2020, the China VI emission standard has been implemented nationwide [4].

In recent years, vehicle CO_2 emissions have become increasingly concerning. In Europe, the CO_2 emissions of heavy-duty vehicles (HDVs) (i.e., trucks and buses) account for about 25% of the total road transport CO_2 emissions. Reducing CO_2 emissions of HDVs is a critical priority in the European Union policy agenda [9,10]. In 2020, the average CO_2 emissions were 107.8 g/km for passenger cars and 157.7 g/km for light-duty commercial vehicles in Europe. The sales-weighted CO_2 emissions of passenger cars sold in 2025 and 2030 will be reduced by 15% and 37.5%, respectively. The CO_2 emission reduction of light-duty commercial vehicles is about 15% and 31%. Compared with the 2019 CO_2 emissions, the CO_2 emissions of medium- and heavy-duty trucks need to be reduced by 15% and 30%, respectively, by 2025 and 2030 [11]. The targets for 2030 have been revised, with the proposed more ambitious reductions of CO_2 emissions for cars and light trucks by 55% and 50%, respectively. By 2035, these two categories of vehicles need to reach the target of 100% carbon emission reduction.

A similar situation also exists in the United States. HDVs account for a small proportion of the vehicle fleet in use, but they are responsible for 22.8% of the CO_2 emissions from road traffic [12]. The regulations on vehicle fuel economy in the United States were issued with the signing of the Energy Independence and Security Act in 2007. In addition to improving the average fuel economy of light-duty vehicles, the Act also proposed the formulation of fuel economy standards for medium- and heavy-duty vehicles in the United States. Later, the United States successively issued regulations on fuel economy and greenhouse gas emissions of medium- and heavy-duty vehicles and engines. The latest fuel economy regulations require that from 2021 to 2027 the phased-in fuel economy standards reduce CO_2 emissions and fuel consumption by 8 to 16 percent for combined tractors, trailers, occupational vehicles, and trucks based on the average level of the 2017 model year [13].

In China, the first, second, and third phases of the fuel economy limit for heavy-duty commercial vehicles were implemented in 2012, 2014, and 2019 respectively, which played an essential role in reducing the fuel consumption of heavy-duty commercial vehicles, effectively promoted the introduction, application, and development of advanced energy-saving technologies, and significantly improved the fuel economy of heavy-duty commercial vehicles and reduced their carbon emissions. In 2025, the fuel consumption limits of China's commercial vehicles in the fourth phase will be tightened by 12% to 16% based on the standard limit in the third phase of 2018 [14]. At the same time, the vehicle test cycle is also built based on the actual road driving conditions of Chinese vehicles. To coordinate the future vehicle fuel economy and emission standards, the measurement and calculation methods of fuel consumption and CO_2 emissions are added [15,16].

As the main freight vehicle, diesel vehicles account for a high proportion of the total fuel consumption and pollution emissions of vehicles and have received more attention. Because the CO and HC emissions of diesel vehicles are very low, the main concern is the NOx and PM emissions of diesel vehicles. At present, a diesel particulate filter (DPF) can effectively reduce the PM emissions of diesel vehicles [17], while the diesel SCR after-treatment system is often affected by the operation conditions and deterioration status, the risk of vehicle NOx emission exceeding the standard is high, and the NOx emissions during actual road driving are very easy to exceed the emission standard [18,19]. Therefore, NOx emission is the main concern for diesel vehicle emission control. Therefore, the NOx sensor is used to detect the concentration of NOx and uses the electrochemical principle to measure the NOx content in the vehicle exhaust gas by measuring the current. The output signal of the NOx sensor is sent to the CAN bus through the NOx sensor control unit and will be used for the closed-loop control of the vehicle's NOx emissions by controlling the amount of urea injected into the exhaust system. Many environmental factors may affect the detection accuracy of the NOx sensor. Not only does the concentration of NOx in the exhaust change, but the parameters such as exhaust pressure, humidity, and temperature also change with the engine's working conditions. Therefore, the detection accuracy and stability of the NOx sensor have a significant impact on the effectiveness of NOx emission monitoring and control.

The vehicle emission control system has no CO_2 sensor. Based on the combustion mechanism of diesel engines, the equivalent emission of CO_2 can be calculated according to vehicle fuel consumption. The fuel flow data provided by the vehicle engine OBD data stream is an important reference parameter for the prediction of engine torque output, vehicle fuel consumption, and vehicle CO_2 emission. The calculation accuracy of fuel flow is also affected by many factors. At present, the electronically controlled fuel injection system is widely used in diesel vehicle engines. The electronic control unit (ECU) controls the fuel injection quantity of the engine by controlling the switching time of the fuel injector according to engine operating conditions. Ideally, knowing the fuel injection quantity per cylinder controlled by ECU, the vehicle's fuel flow rate can be calculated by relating the engine speed and other data. However, due to the complex hydraulic process of the fuel injection system, injection pressure fluctuation, nozzle orifice throttling characteristics, electrical and mechanical inertia delay of the solenoid valve (the needle valve of the injector has a nozzle opening delay and a nozzle closure delay), and other factors [20,21], the actual fuel injection quantity is usually inconsistent with the target injection quantity. In particular, in order to reduce PM and NOx emissions, the diesel engine ECU optimizes the fuel injection control strategy and improves the diesel engine combustion process through flexible adjustment of fuel injection rate and multiple injection capability [22,23]; all of these measures further increase the difficulty of precise control of fuel injection quantity. In many cases, researchers cannot access the fuel injection quantity data from the engine ECU without special scanning tools. Therefore, researchers usually use test or model simulation methods to evaluate vehicle fuel consumption, CO_2 emissions, and other pollutant emissions.

At present, the standard method for testing vehicle NOx and CO_2 emissions is to use the emission analyzer to test the vehicle through a chassis dynamometer or through an on-road driving emission test [21,24,25]. However, the cost of emission test equipment is high, the test operation is complex and time-consuming, and it is unsuitable to measure a large number of vehicles in a short time. Meanwhile, on-board diagnostics (OBD) emerged with the development of vehicle electronic control technology and can monitor vehicle emissions with good economic benefits and cost advantages [26,27]. For heavy-duty diesel vehicles in China, remote OBD is required to monitor vehicle emissions during real-road driving. The vehicle OBD system monitors vehicle parameters and sends the required data related to engine emissions through the data stream, including vehicle speed, engine speed, engine output torque (for example, calculated based on the amount of fuel injected), engine fuel flow rate, NOx sensor output, air mass flow, and other data. Based on the OBD data, the diesel vehicle NOx and CO_2 emissions can be estimated and used to evaluate the vehicle emission level. Zhang et al. used vehicle engine OBD parameters and emission sensor data to study the on-board monitoring (OBM) system for emissions monitoring of heavy-duty diesel vehicles (HDDVs) in China [28]. They also tested eight HDDVs equipped with OBM on the road using a portable emission measurement system (PEMS). Most of the experimental results showed good consistency between OBM and PEMS results. This early assessment suggests that the OBM method may play a core role in China's HDDV emission monitoring. Regulatory agencies should focus on the data integrity and reliability of NOx sensors by developing effective verification procedures.

Vehicle on-board monitoring (OBM) and on-board fuel and energy consumption monitoring (OBFCM) are important technologies for future vehicle fuel consumption and emission monitoring [29]. OBM requires emission sensors to accurately detect vehicle emissions, and the fuel consumption and net output torque of the engine are calculated based on the engine fuel flow rate. The accuracy of emission sensor signals and the fuel flow rate provided by the engine OBD data stream need to be evaluated. This study aims to evaluate the feasibility of using OBD data in future vehicle on-board monitoring (OBM) and vehicle fuel and energy consumption monitoring (OBFCM) data calculations. In the past, the vehicle NOx and CO_2 emissions are usually measured by the emission analyzer. Few works of the literature related to the study of diesel vehicle NOx and CO_2 emissions are based on the OBD data. In this study, the NOx and CO_2 emissions of a heavy-duty truck calculated based on OBD data were validated by testing the vehicle emissions and fuel consumption on the chassis dynamometer over the CHTC-HT driving cycle. The calculated NOx and CO_2 emissions based on OBD data were compared with the results measured by the emission analyzer. Meanwhile, the vehicle fuel consumptions calculated using OBD data were compared with the measured results by the fuel flowmeter and the calculated results based on the carbon balance method. The accuracy and convenience of calculating NOx and CO_2 emissions based on OBD data were verified.

2. Materials and Methods

2.1. Vehicle NOx and CO_2 Emissions Calculation Based on OBD Data

The output of the NOx sensor installed downstream of the SCR catalyst, engine fuel flow rate, and air mass flow in the OBD data stream for heavy-duty diesel vehicles were used to calculate NOx emissions, and the engine fuel flow and air mass flow are used to calculate the engine's instantaneous exhaust flow. Therefore, the mass emission rate of NOx is calculated by the NOx concentration downstream of the SCR catalyst and the instantaneous vehicle exhaust flow rate.

$$\dot{m}_{NOx} = \frac{M_{NOx}}{1000 M_e} \cdot C_{NOx} \cdot \dot{m}_e \quad (1)$$

where $\dot{m}_{NOx}$ is the mass emission rate of NOx, g·s^{-1}; M_{NOx} is the molar mass of NOx, g·mol^{-1}; M_e is the molar mass of the exhaust gas, g·mol^{-1}; C_{NOx} is the instantaneous NOx concentration in the exhaust gas measured by the NOx sensor installed downstream of the SCR catalyst, 10^{-6} (ppm); $\dot{m}_e$ is the instantaneous exhaust mass flow, kg·s^{-1}; and t_0 and t_c are the start and end times of the test cycle.

According to the engine fuel injection control strategy, the engine ECU records the fuel injection quantity of each cylinder and calculates the real-time fuel flow rate, which can be sent to the vehicle CAN bus and can be accessed as the standardized OBD information. The fuel flow rate is defined as

$$\dot{m}_f = q \cdot n \cdot i / (30, \tau) \quad (2)$$

where $\dot{m}_f$ is the fuel flow rate, g·s^{-1}; q is the fuel injection quantity per cylinder per cycle, g; n is the engine speed, r·min^{-1}; i is the number of engine cylinders; and τ is the number of engine strokes per operating cycle.

The mass emission rate of CO_2 can be calculated as

$$m_{\dot{CO2}} = k_{CO2} \cdot \dot{m}_f \quad (3)$$

where k_{CO2} is the mass coefficient of diesel fuel and CO_2 generated; k_{CO2} can be obtained by calculating the ratio of CO_2 emission mass to the total fuel consumption mass over the entire emission test cycle, which is the CHTC-HT driving cycle in this study, and the calculated value of k_{CO2} is 3.186. The CHTC-HT driving cycle includes various vehicle driving conditions, so the calculated coefficient of k_{CO2} is representative and applicable.

According to the emission regulations and engine fuel injection control strategy, the engine fuel flow rate sent by ECU to the CAN bus indicates the calculated amount of fuel consumed only by the engine in grams per 1 s and does not include fuel injected directly into the after-treatment system. Meanwhile, the vehicle fuel flow rate refers to the total amount of fuel consumed by the engine and fuel injected directly into the after-treatment system per unit of time in grams per 1 s. For the test vehicle of this study, there was no fuel injected directly into the after-treatment system. Therefore, the vehicle fuel flow rate equals the engine fuel flow rate, which is calculated as the sum of the fuel consumed over the last 1000 milliseconds. The engine fuel flow rate is usually updated at the rate of 1 s. The engine fuel flow rate and the vehicle fuel flow rate are assigned as zero $g \cdot s^{-1}$ when the engine is not running.

The mass emissions of NOx or CO_2 can be calculated by integrating the instantaneous emission rate over the test cycle.

$$m_{\mathrm{i}} = \int_{t_0}^{t_{\mathrm{c}}} \dot{m}_{\mathrm{I}} \tag{4}$$

where m_{i} is the mass emission of NOx or CO_2 over the test cycle, g; t_0 and t_{c} are the start and end times of the test cycle.

The vehicle's total travel distance over the test cycle can be calculated by

$$S = \int_{t_0}^{t_{\mathrm{c}}} v dt \cdot 10^{-3} \tag{5}$$

where S is the vehicle's total travel distance, km; v is the vehicle speed, $m \cdot s^{-1}$.

The diesel vehicle NOx or CO_2 mass emissions per kilometer over the whole test cycle can be calculated by

$$F_i = \frac{m_i}{S} \tag{6}$$

where F_{i} is the mass emission per kilometer during the whole test cycle, g/km; m_{i} represents the total emission of NOx or CO_2 over the whole test cycle.

2.2. Validation of the Vehicle Emission Calculation Method Based on OBD Data

In order to verify the accuracy of vehicle NOx and CO_2 emissions calculated based on OBD data, a heavy-duty diesel truck was tested on a chassis dynamometer, and the vehicle emissions and fuel consumption test was conducted at the same time as the OBD data was collected so as to compare the NOx and CO_2 emissions calculated based on OBD data with the measured results.

2.2.1. Test Facilities and Procedures

Using a chassis dynamometer to test vehicle emissions and fuel consumption has the advantages of high accuracy and good repeatability. It is a widely accepted method for vehicle emission inspection and approval. In this study, a heavy-duty diesel truck was tested on the chassis dynamometer, the exhaust emissions of the heavy-duty truck were measured by the emission analyzer over the CHTC-HT driving cycle, and a fuel flow meter was connected to the fuel line to measure the fuel flow. Test equipment parameters are shown in Table 1. The schematic of the vehicle fuel consumption and emission test system is depicted in Figure 1.

The specifications of the heavy-duty diesel truck are shown in Table 2. The NOx sensor used for engine exhaust emission detection is a smart NOx sensor produced by Continental AG, with a measurement range of NOx concentration from 0 ppm to 1500 ppm and O_2 concentration from −12% to 21%. The NOx sensor is calibrated under various conditions, combined with filtering and correction strategies of the engine electronic control system, to ensure that the NOx sensor can accurately measure the NOx emission concentration.

Table 1. List of test equipment.

Item	Type	Measuring Range	Manufacturer
Heavy-duty vehicle chassis dynamometer	9248	Vehicle Weight: 3500 kg to 450,000 kg	Burke E. Porter Machinery Company
Data acquisition tool	INCA	ECU data	ETAS
Fuel flow meter	FP-2140H	0~120 $L \cdot h^{-1}$	ONOSOKKI
CVS system	CVS i60	0~150 $m^3 \cdot min^{-1}$	AVL
Emission analysis system	AMAi60	NOx: 0~10,000 × 10^{-1} (ppm) CO: 0~10% THC: 0~20,000 × 10^{-1} (ppm) C3 CO_2: 0~20%	AVL

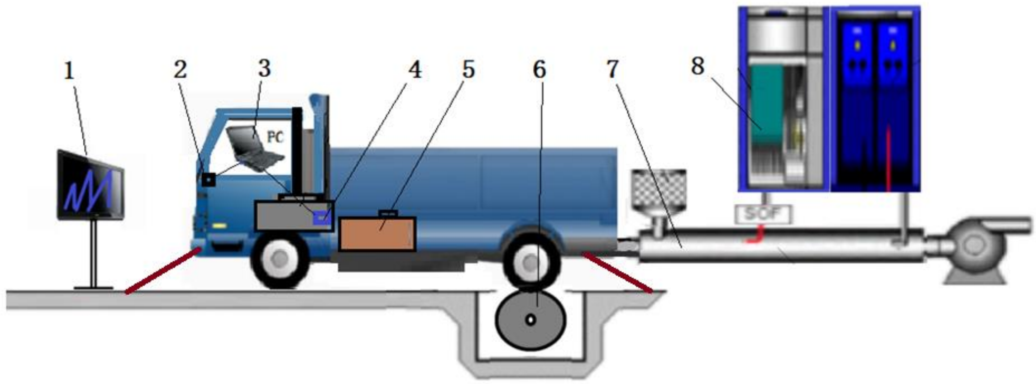


Figure 1. The schematic of vehicle fuel consumption and emission test system. 1: Driver's aid; 2: OBD; 3: computer; 4: fuel flow meter; 5: fuel tank; 6: chassis dynamometer; 7: CVS sampling system; 8: emission analyzer.

Table 2. Technical specifications of the test vehicle.

Item	Content
Vehicle type	N3 *
Emission standard	China-VI
Curb weight (kg)	8800
Total mass (kg)	25,000
Drive form	4 × 2 rear drive
Engine type/fuel	CI/Diesel
Engine form	Inline 6-cylinder water-cooled
Engine capacity (L)	10.5
Intake mode	Turbocharged inter-cooled
Exhaust after-treatment	DOC + DPF + SCR + ASC
Idle speed ($r \cdot min^{-1}$)	650
Rated power/speed ($kW/(r \cdot min^{-1})$)	300/1900
Maximum torque/speed ($N \cdot m/(r \cdot min^{-1})$)	2100/1300

* N3: Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 12 tons.

While testing on the chassis dynamometer, the vehicle driving resistive force was simulated and exerted by the chassis dynamometer. An AVL AMAi60 emission analyzer and an i60 CVS sampling system were utilized to measure vehicle exhaust emissions, including CO, HC, NOx, and CO_2. The AVL AMAi60 emission analyzer uses an infrared detector (IRD) for the measurement of CO and CO_2, a chemiluminescent detector (CLD) for NOx, and a heated flame ionization detector (HFID) for THC. During the test, the INCA calibration device was used to read vehicle engine OBD data, including vehicle speed, engine speed and torque, engine fuel flow, NOx sensor output, air mass flow, and other related data. INCA is a calibration tool for automotive electronic control systems under ETAS; it has comprehensive testing and calibration functions, supports the CAN Calibration Protocol

(CCP), can manage calibration data, and can be used for data acquisition, calibration, ECU flash programming, and other functions. The data sampling rate of the emission analyzer is 1 HZ, while the data sampling rate of INCA is 10 HZ.

The diesel used in the test meets the China VI diesel emission standard, which has been fully implemented in China from 1 January 2019 [30].

After the engine was fully warmed up, the vehicle emissions and fuel consumption were conducted over the CHTC-HT driving cycle [16]. The CHTC-HT driving cycle is shown in Figure 2. It contains three stages that characterize typical urban, suburban, and highway driving conditions and is used to test the fuel consumption of heavy-duty trucks. The total driving cycle lasts 1800 s, of which the driving time ratios for urban, suburban, and highway are 19.0%, 54.9%, and 26.1%, respectively. The total mileage of the CHTC-HT driving cycle is 17.32 km, with an average speed of 34.7 km·h^{-1} and a maximum speed of 88.5 km·h^{-1} [15].

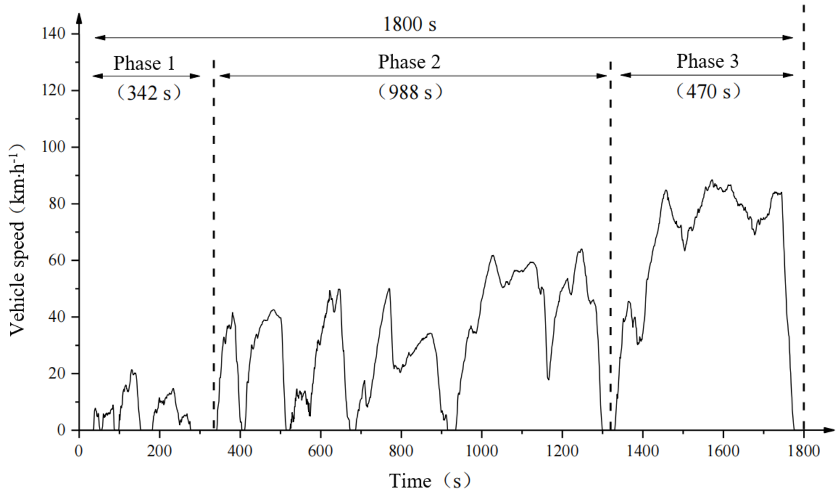


Figure 2. The CHTC-HT driving cycle.

2.2.2. Vehicle NOx and CO_2 Emission Test

During the vehicle test, the emission analyzer AMAi60 was used to measure the concentrations of exhaust components. The CVS i60 was utilized to measure the total volume flow of diluted exhaust gas. The hydrocarbons in diesel engine exhaust are primarily high molecular hydrocarbons, which are easy to condense, so the sampling bag cannot be used for sampling HC in diesel engine exhaust. The heated sampling tube was used to keep the temperature at about 190 °C, and a heated hydrogen flame ionization detector (HFID) was used to measure HC continuously.

The mass emission rate of component i during the test cycle is calculated by

$$\dot{m}_{\mathrm{i}} = k \cdot C_{\mathrm{i}} \cdot \dot{V}_{\mathrm{mix}} \cdot \rho_{\mathrm{i}} \tag{7}$$

where $\dot{m}_{\mathrm{i}}$ is the mass emission rate of component i during the test cycle, g·s^{-1}; i refers to CO, HC, NOx, and CO_2; k is the coefficient; $\dot{V}_{\mathrm{mix}}$ is the volume flow rate of the diluted exhaust gas, m^3·min^{-1}; ρ_{i} is the density of component i, g·L^{-1}.; and C_i is the sampled real-time concentration of component i in the diluted exhaust gas, % or 10^{-6} (ppm).

Therefore, the emission factor of each emission component i over the test cycle can be calculated by

$$F_{\mathrm{i}} = \int_{t_0}^{t_{\mathrm{c}}} \dot{m}_{\mathrm{i}} \cdot dt / S \tag{8}$$

where t_0 and t_{c} are the start and end times of the test cycle and S is the vehicle's total travel distance, km.

2.2.3. Vehicle Fuel Consumption Test

The CO_2 emissions were calculated based on the vehicle engine fuel flow rate provided by the engine's OBD, so we need to verify the accuracy of the fuel flow data provided by the OBD by comparing it with the measured fuel flow rate. For this reason, the carbon balance method and the fuel flow meter test method were used to detect the vehicle fuel consumption during the vehicle test.

Based on the carbon balance mechanism [31], the diesel vehicle fuel consumption per hundred kilometers in the whole test cycle can be calculated by

$$Q_L = \frac{0.1155}{\rho}\left[\left(0.273 \times F_{CO_2}\right) + \left(0.429 \times F_{CO}\right) + \left(0.866 \times F_{HC}\right)\right] \quad (9)$$

where Q_L is the vehicle fuel consumption in liters per hundred kilometers, F_{CO_2} is the CO_2 emission factor in g·km^{-1}, F_{CO} is the emission factor of CO in g·km^{-1}, F_{HC} is the HC emission factor in g·km^{-1}, and ρ is the density of diesel at 20 °C, g·L^{-1}.

Similarly, the transient fuel consumption rate of the vehicle while driving can also be calculated by the carbon balance method and is calculated as

$$\dot{m}_f = \left(0.273 \times \dot{m}_{CO_2} + 0.429 \times \dot{m}_{CO} + 0.866 \times \dot{m}_{HC}\right)/0.866 \quad (10)$$

where $\dot{m}_f$ is the instantaneous fuel mass consumption rate of the vehicle, g·s^{-1}; $\dot{m}_{CO_2}$; $\dot{m}_{CO}$ and $\dot{m}_{HC}$ are the instantaneous mass emission rates of HC, CO, and CO_2, respectively, g·s^{-1}.

The vehicle fuel consumption can be calculated by integrating the obtained fuel flow rate.

$$m_f = \int_{t_0}^{t_c} \dot{m}_f \mathrm{d}t \quad (11)$$

where m_f is the cumulative fuel consumption of the vehicle over the whole test cycle, g; t_0 and t_c are the start and end times of the test cycle.

Furthermore, the diesel vehicle fuel consumption per hundred kilometers over the whole test cycle can be obtained by

$$Q_L = \frac{100 m_f}{(S \cdot \rho)} \quad (12)$$

where Q_L is the vehicle fuel consumption per hundred kilometers, L·(100 km)$^{-1}$.

During the whole test cycle of the vehicle, the vehicle fuel consumption was also measured by the fuel flowmeter, and the vehicle fuel consumption per hundred kilometers was calculated by

$$Q_L = \frac{\left[Q_V + Q_V \cdot k_V \cdot (T_0 - T_a)\right]}{S} \cdot 100 \quad (13)$$

where Q_V is the total volume fuel consumption of the vehicle over the whole test cycle, L; k_V is the volume expansion coefficient of fuel; T_0 is the reference temperature, 20 °C; T_a is the average fuel temperature during the test; and S is the distance traveled by the vehicle over the test cycle, km.

3. Results and Discussion

3.1. Comparison between the Calculated NOx and CO_2 Emissions Based on OBD Data and the Measured Results

The calculated NOx and CO_2 emissions based on OBD data were compared with the measured NOx and CO_2 emissions during the CHTC-HT test cycle of the heavy-duty diesel truck and are shown in Figure 3. Due to the time delay of different data sampling devices, the sampled data needs to be aligned based on time. The method is to first align the fuel consumption rate data with the engine operating conditions, and then align the emission data with the fuel consumption rate data based on carbon dioxide data. Figure 3 shows that the calculated CO_2 emissions closely follow the transient operating conditions of the vehicle and engine because the CO_2 emissions are closely related to the fuel consumption of the vehicle's engine. Meanwhile, the CO_2 emissions measured by the emission analyzer have fewer transient fluctuations than the OBD data-based CO_2 emissions due to the transportation of exhaust gas in the exhaust pipe and diluted by the air in the CVS system.

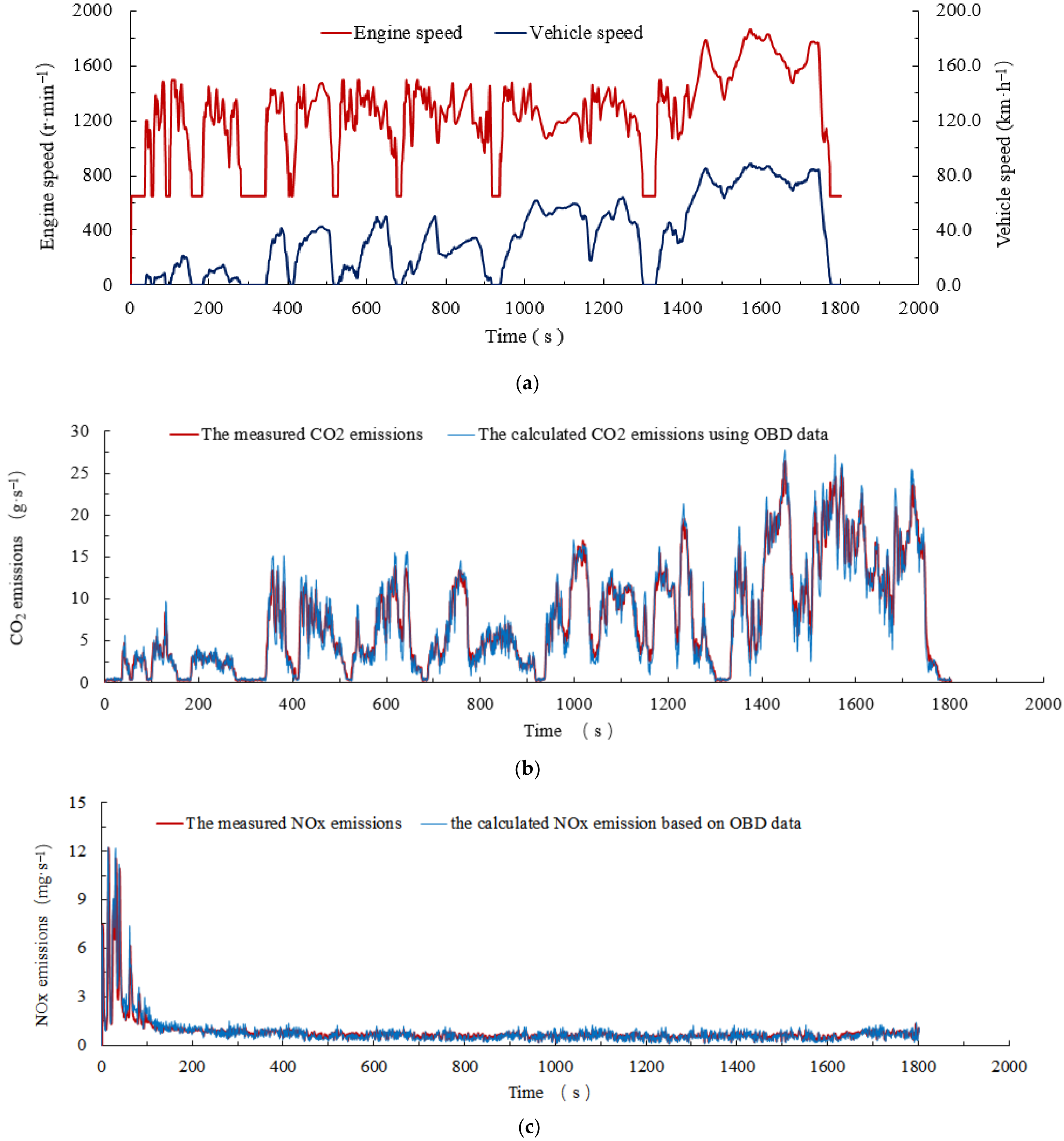


Figure 3. Comparison between the measured CO_2 emission and the calculated CO_2 emission based on OBD data. (**a**) Vehicle speed and engine speed; (**b**) CO_2 emissions; (**c**) NOx emissions.

At the beginning of the test cycle, the peak value and fluctuation of NOx emissions are large, mainly due to the lower temperature of the engine SCR catalyst, resulting in a decrease in NOx purification efficiency. As the vehicle runs, the temperature of the engine SCR catalyst increases, resulting in an increase in NOx purification efficiency and a decrease in NOx emissions. Although NOx emissions vary with the vehicle's engine operating conditions, the fluctuation is significantly reduced. Moreover, since the exhaust gas is diluted with air in the CVS system, the fluctuation of NOx emissions measured by the emission analyzer is also significantly smaller than the calculated NOx emissions based on OBD data.

The comparisons of the OBD data-based NOx and CO_2 emission factors and the measured NOx and CO_2 emission factors over the three CHTC-HT driving cycles are shown in Table 3.

Table 3. Comparison of vehicle NOx and CO_2 emissions over the CHTC-HT driving cycle.

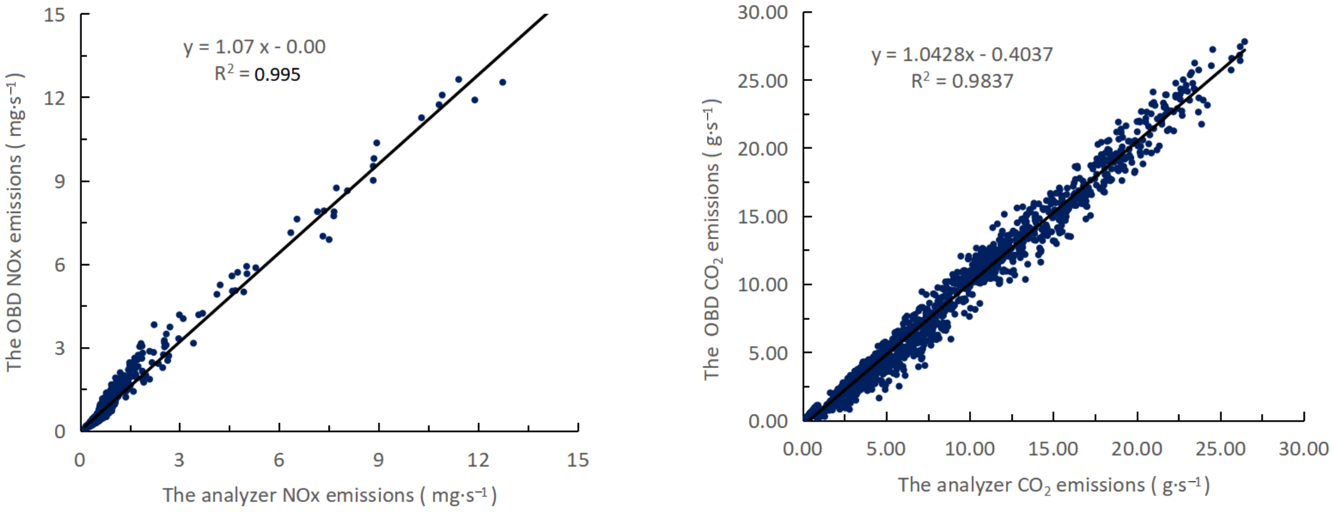
	NOx Emissions			CO_2 Emissions		
Number of Tests	**Calculated Data Based on OBD Data ($g \cdot km^{-1}$)**	**Measured Data by Emission Analyzer ($g \cdot km^{-1}$)**	**Deviation (%)**	**Calculated Data Based on OBD Data ($g \cdot km^{-1}$)**	**Measured Data by Emission Analyzer ($g \cdot km^{-1}$)**	**Deviation (%)**
Test 1	0.812	0.804	0.99	785.52	776.84	1.10
Test 2	0.805	0.813	−0.99	772.76	767.72	0.65
Test 3	0.803	0.785	2.24	768.51	750.80	2.30
Mean value	0.807	0.801	0.74	775.60	765.12	1.35

As shown in Table 3, the calculated NOx emission factors based on OBD data in the three CHTC-HT driving cycles are 0.812, 0.805, and 0.803 $g \cdot km^{-1}$, respectively, while the measured NOx emission factors by emission analyzer are 0.804, 0.813, and 0.785 $g \cdot km^{-1}$, correspondingly. The relative errors between the calculated NOx emission factors based on the OBD data and the measured NOx emission factors are −0.99%, 0.99%, and 2.24%, respectively, with the average error of 0.74%, indicating that the NOx emission data downstream of SCR catalyst and engine fuel flow and air mass flow provided by the OBD data stream for heavy-duty diesel vehicles can be used to calculate vehicle NOx emissions.

The calculated CO_2 emission factors based on OBD data in the three CHTC-HT driving cycles are 785.52, 772.76, and 768.51 $g \cdot km^{-1}$, respectively, while the measured CO_2 emission factors by emission analyzer are 776.84, 767.72, and 750.80 $g \cdot km^{-1}$, correspondingly. The relative errors between the calculated CO_2 emission factors based on the OBD data and the measured CO_2 emission factors are 1.10%, 0.65%, and 2.30%, respectively, with an average error of 1.35%. The main reason is that the OBD-based data is calculated based on the assumption that the diesel fuel is completely combusted. However, the degree of fuel combustion completeness varies under different operating conditions of internal combustion engines, resulting in the actual measured emissions being less than the value calculated based on the fuel flow rate provided by the OBD data stream. The maximum error of the calculated CO_2 emission factors based on the OBD data with the actually measured emission factors is 2.3%, and the average error is 1.35%, indicating that the CO_2 emissions calculated based on OBD fuel flow rate can predict vehicle CO_2 emissions and has great convenience.

3.2. Correlation Analysis of NOx and CO_2 Emission Data

The correlation between the calculated NOx and CO_2 emissions based on the OBD data and the actual measured emission results of NOx and CO_2 is shown in Figure 4.



(**a**) (**b**)

Figure 4. Correlation analysis of vehicle NOx and CO_2 emissions. (**a**) NOx emissions; (**b**) CO_2 emissions.

Figure 4a shows that vehicle NOx emissions calculated based on OBD data are highly correlated with the results measured by the emission analyzer. R^2 equals 0.995, indicating that the vehicle NOx emissions calculated based on OBD data are consistent with the results tested by the emission analyzer. Similarly, Figure 4b shows that vehicle CO_2 emissions calculated based on OBD fuel flow rate are highly correlated with the results measured by the emission analyzer and R^2 is greater than 0.98. That means that the vehicle NOx and CO_2 emissions can be estimated by the vehicle OBD data.

3.3. Comparison between the Fuel Consumption Calculated Based on OBD Data and the Measured Results

The CO_2 emission estimation is based on the vehicle OBD fuel flow data, so it is necessary to further verify the accuracy of the fuel consumption calculated based on the OBD fuel flow data and compare it with the fuel flow calculated using the carbon balance method and the fuel flow meter.

The mass emission rate of various exhaust components during the CHTC-HT cycle test of the vehicle can be calculated by Formula (10). The fuel consumption rate of the vehicle can be calculated according to the carbon balance method. Figure 5 shows the comparison between the OBD fuel flow rate and fuel consumption rate calculated based on carbon balance. The fuel consumption rates of the vehicle calculated based on the carbon balance method are consistent with the trend of the OBD fuel flow rate, but the transient fluctuation of the calculated fuel consumption rates based on the carbon balance is significantly reduced compared with the OBD fuel flow rate. The main reason is that the OBD fuel flow rate is calculated based on the vehicle engine fuel injection quantity per operation cycle and changes with the engine operating conditions, but the exhaust gas is mixed in the exhaust pipe and diluted by the air in the CVS system, and the transient fluctuation of the calculated vehicle fuel consumption rates is significantly reduced. Therefore, the OBD fuel flow rates can better reflect the transient operating characteristics of the vehicle and engine.

The results of vehicle fuel consumption per hundred kilometers calculated based on the OBD fuel flow rate, fuel flow meter, and carbon balance method over the CHTC-HT driving cycle are compared and shown in Table 4.

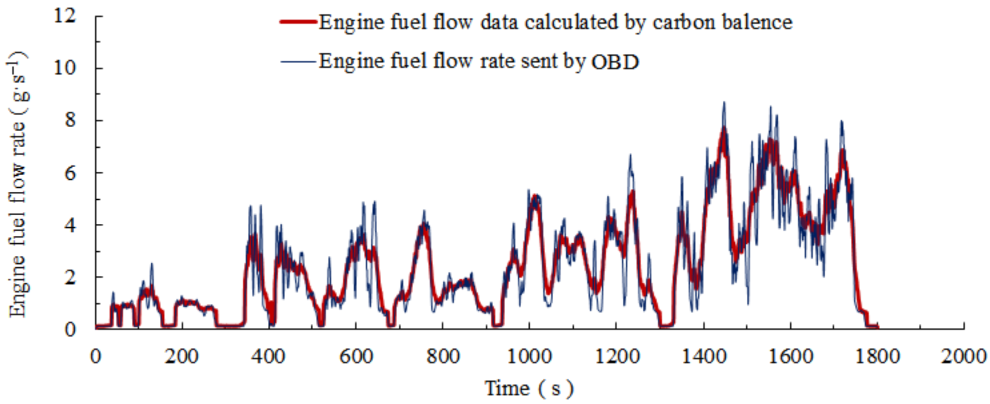


Figure 5. Comparison between the OBD fuel flow rate and the fuel flow rate calculated based on carbon balance.

Table 4. Comparison of vehicle fuel consumption over the CHTC-HT driving cycle.

Number of Tests	**Vehicle Fuel Consumption per 100 km (L·(100 km)$^{-1}$)**			**Deviation from the Calculated Data Based on OBD Data (%)**	
	Calculated Results Based on OBD Data	**Calculated Results by Carbon Balance Method**	**Fuel Flow Meter Test Results**	**Calculated Results by Carbon Balance Method**	**Fuel Flow Meter Test Results**
Test 1	29.56	29.24	29.35	−1.08%	−0.71%
Test 2	29.08	28.85	29.42	−0.79%	1.17%
Test 3	28.92	28.26	29.13	−2.28%	0.73%
Mean value	29.19	28.78	29.30	−1.38%	0.39%

The vehicle fuel consumptions per hundred kilometers calculated based on the OBD fuel flow rate are in good agreement with the fuel flowmeter test results, with a maximum relative error of about 1.17%, and the average deviation of the three measurements is only 0.39%. In addition, the relative error between the fuel consumptions per hundred kilometers calculated based on the OBD fuel flow rate and the fuel consumptions per hundred kilometers calculated using the carbon balance method is about 2.28%, and the average deviation of the three measurements is 1.38%. The fuel consumption results calculated by the carbon balance method are relatively small, which may be due to the influence of condensation of exhaust emission components and the influence of PM emissions containing carbon elements not included in the calculation of vehicle fuel consumption. The experimental results show that the method of calculating fuel consumption based on the OBD fuel flow rate has sufficient measurement accuracy and can be used to calculate vehicle fuel consumption.

Although the vehicle fuel consumptions calculated based on these three methods are very close, there are still some deviations. The possible reasons are as follows:

(i) Test instruments, including fuel flowmeter, emission analyzer, and CVS dilution system, have measurement errors that may affect test results.

(ii) The control accuracy of ECU fuel injection quantity is affected by many factors, such as injection pressure, injection pulse width, injector needle valve inertia, and control system voltage, resulting in a difference between the actual injection quantity and the target injection quantity, which may lead to deviations in the fuel flow rate transmitted by ECU through OBD and affect the vehicle fuel consumption results calculated based on the instantaneous fuel flow rate.

(iii) These three test methods of vehicle fuel consumption are based on different sampling principles, which may have some influences on the test results.

4. Conclusions

The OBD data of heavy-duty diesel vehicles were used to calculate vehicle NOx and CO_2 emissions, and they are validated by testing a heavy-duty truck's emissions and fuel consumption on the chassis dynamometer over the CHTC-HT driving cycle.

The calculated NOx and CO_2 emissions based on the OBD data are consistent with the NOx and CO_2 emissions measured by the emission analyzer. The calculated NOx emission factors based on OBD data in the three CHTC-HT driving cycles are very close to the measured NOx emission factors by the emission analyzer with a maximum error of 2.24% and an average error of 0.74%. The calculated CO_2 emission factors per unit mileage based on OBD data are also very close to the measured CO_2 emission factors by emission analyzer with the maximum error of 2.3%, and the average error is 1.68%. The OBD data of heavy-duty diesel vehicles can be used to calculate vehicle NOx and CO_2 emissions and has sufficient prediction accuracy.

The fuel consumption of the heavy-duty diesel truck was measured using three methods including accessing vehicle fuel flow rate by OBD, using a fuel flowmeter, and using carbon balance. The measured vehicle fuel consumptions obtained by the three methods are very close. For the test results of the CHTC-HT cycle, the maximum relative error between the results calculated based on the OBD data and the result tested by the fuel flowmeter is 1.17%, and the average deviation of the three measurements is only 0.39%. The maximum relative error between the results calculated based on OBD data and the results calculated based on carbon balance is 2.28%, and the average deviation of three measurements is 1.38%. The experimental results further prove that the OBD data of heavy-duty vehicles can be used to calculate vehicle fuel consumption and CO_2 emissions.

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Nomenclature

ASC	Ammonia slip catalyst
CAN	Controller area network
CBD	Chemiluminescent detector
CCP	CAN Calibration Protocol
CEM	Comprehensive modal emissions model
CHTC-HT	China heavy-duty test cycle-heavy-duty truck
CI	Compression ignition
CO	Carbon monoxide
CO_2	Carbon dioxide
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
ECU	Electronic control unit
HC	Hydrocarbon
HD	Heated flame ionization detector

HDDV	Heavy-duty diesel vehicle
HDV	Heavy-duty vehicle
NDIR	Non-dispersive infrared detection
NOx	Oxides of nitrogen
OBD	On-board diagnostics
OBFCM	On-board fuel and energy consumption monitoring
OBM	On-board monitoring
PM	Particulate matter
RED	Infrared detector
SCR	Selective catalytic reduction
THC	Total hydrocarbons
US EPA	US Environmental Protection Agency

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