Study of Real-road Nitrogen Oxide Emissions of Non-road Vehicles

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Abstract. The exhaust gas pollutants of the non-road vehicles are harmful to the environment. Many non-road vehicles meet the requirements of the regulations in the laboratory. However, the real-road emissions of such vehicles are sometimes higher. Measuring the real-road emissions of non-road vehicles is very important. The real-road emissions are measured by on-Board Diagnostics (OBD), but there are some problems in the data stability of OBD. The NOx emissions of a bulldozer (a type of China IV non-road vehicle) based on both portable emission measurement system (PEMS) and OBD are studied in this article. Experiments contained three working processes: idle, driving, and operating. The nitrogen oxide (NOx) emissions during operating were highest. The NOx emission characteristics of the bulldozer from PEMS and OBD have the similar variation trends. But there are still some differences, including the NOx emission value and response time. The measurement principles and different sampling points between PEMS and OBD are the main factors. An effective data processing method is introduced to reduce the differences of between the data from PEMS and OBD. Briefly, the NOx emissions of the OBD and PEMS were highly consistent. The OBD is reliable and can be widely used in non-road vehicles.

1. Introduction
Diesel engines generally have higher thermal efficiencies than gasoline engines because of their higher compression ratios, leaner combustion, and less air exchange loss (non-throttle). Diesel engines also have better low-speed torque characteristics (Wu et al, 2020). Currently, diesel engines are widely used in vehicles. Non-road vehicles include railroad locomotives, marine vessels, and other equipment used for agriculture, construction, logging, and mining. The diesel engines used in non-road vehicles are a significant source of pollutants, such as NOx, hydrocarbons (HCs), CO, and PM10 (particulate matter (PM) smaller than 10 µm). In China, mobile sources (including vehicles and non-road vehicles) have been viewed as one of the main contributors to air pollution due to the exhaust emissions during the working process of diesel engines (Guo et al, 2020). Among these pollutants, NOx has negative effects on health, and it contributes to the formation of ozone and secondary particles through a series of photochemical reactions (Vaughan et al, 2016). Due to the large number of the non-road vehicles and their wide range of applications, total activity and emissions from these sources are uncertain (Desouza et al, 2020). Therefore, the emissions problem of non-road mobile sources is becoming increasingly serious (Kean et al., 2000).

Laboratory studies on the emissions of non-road vehicles have been conducted. In the United
States, the EPA developed an emissions model of non-road vehicles based on engine testing data (Bray et al, 2019; Perugu et al, 2018; Heather et al, 2020). Lahde et al. (Lahde et al, 2014) used an engine bench test to measure the inorganic element concentration in the exhaust gas of non-road vehicles. Fan et al. (Fan et al, 2018) evaluated carbonyl compound emissions from a non-road-vehicle diesel engine fueled with a methanol/diesel blend.

However, the emissions from an engine bench test and a real road are different (Desouza et al, 2020). The emissions measured under real conditions are always higher. With the development of technology, the portable emissions measurement system (PEMS) (Wang et al, 2020) apparatus is used for measuring real road emissions. These systems have been used by many researchers and centers to carry out exhaust emissions measurements (Ziolkowski et al, 2019). Frey et al. (Frey et al, 2010) carried out a systematic test of the real emission characteristics of non-road vehicles, including an excavator and a loader. Lijewski et al. (Lijewski et al, 2013) used a PEMS to measure the emissions from non-road vehicles, and analyzed the relationship between the emissions and the engine operating parameters. Fu et al. (Fu et al, 2012) used PEMS to conduct measurements and calculated the emissions factors of the gas pollutants and particulates under different conditions, such as idling and other working conditions. Wang et al. (Wang et al, 2020) established the emissions factors and inventory of agricultural machinery in Beijing in 2017 under real-world operation. Lijewski et al. (Lijewski et al, 2013) studied air pollution from the exhaust emissions of non-road vehicles under actual operating conditions by using a SEMTECH DS portable exhaust emissions analyzer. Desouza et al. (Desouza et al, 2020) measured real-world NOx and PM emissions from non-road vehicles in London and compared the NOx emissions of different engine stages. Szymlet et al. (Szymlet et al, 2018) presented a comparative analysis of harmful compounds (CO, CO, HC, NOx, and PM) emitted from passenger cars and non-road vehicles based on data from a PEMS. Guo et al. (Guo et al, 2020) conducted estimations and predictions of NOx and other pollutant emissions from agricultural and construction diesel machinery in China. Pirjola et al. (Pirjola et al, 2017) conducted both real-world and laboratory studies. They analyzed NOx and PM emissions emitted by a non-road vehicle by following a tractor in real-world conditions, and they repeated the same transient tests with a similar engine using an engine dynamometer. In addition, non-road steady-state tests were carried out.

In addition to PEMSs, on-board diagnostics (OBD) technology has been introduced to make diagnoses and report the health status of engines (including the after treatment device) (Zheng et al, 2020). In China’s mobile emissions regulations, both PEMSs and OBD are required. OBD consists of a remote control system and various sensors to monitor the emissions and other components of the engine. In 1994, the Society of Automotive Engineers formulated unified standards for OBD systems. Based on this, the OBDII came into being. Recently, the OBDIII has been developed. Compared to the OBDII, it has faster response times (Yao et al, 2014). Hitachi, Volvo, and some other enterprises have equipped their products with remote control and data transmission systems. The National University of Singapore, Stanford University, and other research institutions have developed an open remote fault diagnosis center (Schubert et al, 2000). Jiang et al. (Jiang et al, 2021) conducted an evaluation of the emissions benefits of OBD-based repairs for potential applications in a heavy-duty vehicle inspection and maintenance program. A series of studies have been conducted on the exhaust emissions based on the OBD. Yang et al. (Yang et al, 2016) evaluated real-world CO2 and NOx emissions for public transit buses using an OBD approach. Bu et al. (Bu et al, 2010) designed a new OBDII configuration for the SCR system of diesel vehicles. Wang et al. (Wang et al, 2020) analyzed the NOx emission characteristics of non-road vehicles based on remote monitoring technology. Rymaniak et al. (Rymaniak et al, 2020) discussed the determination of engine torque to calculate the work performed by non-road vehicles when determining specific exhaust emissions.

There have been several studies involving both PEMS and OBD technology. Bishop et al. (Bishop et al, 2016) used data from these two systems to create engine maps of fuel use and emissions of NOx, CO2, and CO. Rosero et al. (Rosero et al, 2020) created engine efficiency and emissions maps by combining transient-state engine data obtained from a PEMS and OBD. Junepyo et al. (Junepyo et al, 2019) used both OBD and a PEMS to evaluate real driving emissions for Euro 6 light-duty diesel vehicles equipped with lean-burn NOx trap (LNT) and selective catalytic
reduction (SCR) sold in Korea. To judge the reliability of OBD, He et al. (He et al., 2020) compared the data from both a PEMS and OBD. They found that the instantaneous fuel consumption data and carbon-balance fuel consumption data of OBD remote monitoring equipment agreed within 10%, which proved that OBD remote monitoring has good accuracy. Cheng et al. (Cheng et al., 2019) used PEMS testing to evaluate on-board sensing-based NOx emissions from heavy-duty diesel vehicles in China. Tan et al. (Tan et al., 2019) conducted a heavy-duty in-use compliance program and proved that the on-board NOx sensor data is useful.

The data alignment can be used as an effective method to process the data from PEMSs and OBD and to analyze and reduce the errors. Chatzimparmpas (Chatzimparmpas, 2021) used performance metrics to complete the alignment of data, algorithms, and models for stacking ensemble learning. Eriksson et al. (Eriksson et al., 2021) developed a new method for time alignment and time calibration of the time-of-flight neutron spectrometer at the Joint European Torus (JET). Borghi (Borghi, 2017) introduced novel real-time alignment and calibration of the Large Hadron Collider (LHCb) detector and its performance.

There have not enough studies on PEMS tests of the non-road vehicle emissions, and the OBD system has not been widely used in non-road vehicles yet. Thus, the use of both a PEMS and OBD to analyze the NOx emissions characteristics of non-road vehicles, such as a bulldozer, is essential and necessary. In addition, the data from these two different sources can be compared to judge whether OBD remote monitoring systems are reliable. The previous comparisons have not been thorough and comprehensive. In this article, the errors between these two measurement systems are deeply analyzed. The accuracy of the NOx sensors is evaluated, and data alignment is used to eliminate the response time error between two devices.

2. Experiment Device

2.1 Bulldozer
The research object of this paper was a 240-HP bulldozer. The bulldozer’s parameters are shown in Table 1. The relevant parameters of the engine are shown in Table 2.

| Table 1. Parameters of the bulldozer                        | Engine model | WP12G |
|------------------------------------------------------------|--------------|-------|
| Performance parameters                                     | Grounding length (mm) | 3050  |
|                                                            | Grounding pressure (kPa) | 67.4  |
| Dimensions                                                 | Length (mm)  | 6084  |
|                                                            | Width (mm)   | 3640  |
|                                                            | Height (mm)  | 3192  |
| Walking performance parameters                              | Forward speed| 0-11 CVT |
|                                                            | Reverse speed| 0-11 CVT |
|                                                            | Climbing ability (°) | 30°   |
|                                                            | Blade form   | Half u shovel |
|                                                            | Blade width x height (mm) | 3640 × 1580 |
| Working device                                             | Blade capacity (m³) | 6.5   |
|                                                            | Blade lifting height (mm) | 1247  |
|                                                            | Cutting depth of blade (mm) | 540   |
Table 2. Engine parameters of the bulldozer

| Model | WP12G |
|-------|-------|
| Cylinder diameter × stroke (mm) | 126 × 155 |
| Total displacement (L) | 11.596 |
| Structural style | In-line, six cylinder, supercharged |
| Technology roadmap | CR + DOC + DPF + SCR |
| Rated power (kW) | 338 |
| Rated speed (r/min) | 1900 |
| Maximum torque (N·m) | 2110 |
| Maximum speed (r/min) | 1000–1400 |

2.2 Equipment
A Horiba OBS-ONE device was used to test the NOx emissions of a bulldozer (PEMS test). This equipment was composed of different modules, which were controlled by an integrated device management controller (Gómez et al., 2021). This device could measure and record emission concentrations (CO, CO₂, total hydrocarbon (THC), NOx, NO₂), exhaust flow, global positioning system (GPS) data, and environmental conditions (atmospheric temperature, humidity, and pressure) during the test. The measurement ranges of the HORIBA OBS-ONE analyzer are shown in Table 3.

Table 3. Measurement range of the HORIBA OBS-ONE

| Compound measured | Measurement range |
|-------------------|-------------------|
| CO                | 0–0.5 to 0–10 vol% |
| CO₂               | 0–5 to 0–20 vol%  |
| NO, NOx, NO₂      | 0–100 to 0–3000 ppm |
| THC               | 0–100 to 0–10,000 ppmC |

The OBD system could monitor the operation of the engine and many other parts in real time, such as the diesel oxidation catalyst (DOC), diesel particulate trap (DPF), and selective catalytic reduction (SCR). The OBD has two purposes: one is to provide maintenance people with a monitor interface, and the other is to determine whether the engine meets the environmental protection requirements for environmental protection departments (Röthlein and Gail, 2007). It contains diagnostic software and is designed to operate on the CAN (Controller Area Network) Protocol. With the help of the CAN Protocol, the system could be connected to the scanning tools (NOx sensor and temperature sensor) and other external hardware.

2.3 Experimental Design
The experiments included PEMS tests and OBD monitoring. As shown in Figure 1, a trailer was towed behind the bulldozer, and the test equipment was placed in the trailer to obtain real-time measurements of the emission characteristics of the bulldozer under real road conditions. An OBD system was also equipped on the bulldozer to obtain data.

The trailer contained the following components: the OBS-ONE device, a generator, two gas cylinders, and two computers. The generator mainly supplied power for the OBS-ONE. One gas cylinder was filled with high-purity nitrogen, and the other cylinder was filled with standard gas, which was used to zero and calibrate the PEMS equipment before the experiment. One of the two computers was responsible for collecting PEMS data, and the other was used to collect OBD data.
The cycle test included three different working processes (idling, driving and operating). Each experiment at the specified working processes lasted 300–500 s. The working conditions of the bulldozer could be roughly judged by the exhaust flow (Liu et al., 2020) in the OBD data (Figure 3).

The average exhaust flows during the idling, driving, and operating processes were about 16.21,
41.35, and 78.23 g/s. On this basis, the working processes can be distinguished, and the pollutant emission characteristics under different working processes can be studied.

3. Result and Discussion

3.1 NOx Emission Characteristics Based on Portable Emissions Measurement System (PEMS)

The curves of the NOx emissions and the exhaust flows were plotted in the same figure to distinguish the working processes. The data of the exhaust flows was obtained from the PEMS. Since the PEMS only collected part of the exhaust, a correction factor was used to match it to the exhaust flow in the OBD.

In Figure 4, the curve of the NOx concentration in the idling process was relatively stable and increased slightly with time, because the temperature rise of the diesel engine contributed to the formation of NOx (Song et al, 2021).

![Figure 4. Exhaust flow and NOx emission concentration of bulldozer in idling process.](image)

As shown in Figure 5, the overall NOx emission concentration in the driving process was higher than that in the idle process, which was mainly because the load increased in the driving process, the diesel engine underwent lean combustion, and the whole cylinder temperature was higher. As a result, the NOx emissions increased (Oumlzguumll and Bedir, 2019). Due to unstable combustion and other factors, the NOx concentration showed an unstable trend.
Figure 5. Exhaust flow and NOx emission concentration of bulldozer in driving process

In the operating process (Figure 6), the emission concentration of NOx was significantly higher than that in the idle and driving processes. In the operating process (25–330 s), the concentration of NOx first increased, then tended to be stable, and finally decreased. Since the bucket began to shovel soil, the load increased, which increased the maximum combustion temperature of the diesel engine. As a result, the NOx emissions increased. However, when the load exceeded a certain limit, the oxygen content in the combustion chamber decreased relatively. This led to a decrease in the NOx concentration (Masoud et al, 2020).

Figure 6. NOx emission concentration of bulldozer in operating process
Table 4. NOx emissions of bulldozer under different working processes

| Construction machinery | Process | NOx emission concentration $\varphi$ (ppm) | Exhaust flow Q (g/s) | NOx emission rate (g/s) |
|------------------------|---------|------------------------------------------|---------------------|------------------------|
| Bulldozer             | Idling  | 202.40                                   | 20.67               | 0.0042                 |
|                        | Driving | 420.31                                   | 42.01               | 0.0177                 |
|                        | Operating | 706.68                                | 80.36               | 0.0568                 |

The average NOx emission rate (g/s) was calculated, and the results are shown in Table 4. The NOx emission rate was highest in the operating process.

3.2 Comparison of NOx Emissions Based on PEMS and OBD

3.2.1 Data comparison
Although the NOx emission characteristics based on the OBD data were similar to those based on the PEMS data, there were still some differences between the data from these different sources, as shown in Figure 7.

![Figure 7. Comparison of NOx concentration by PEMS and OBD](image)

The data acquisition frequency of the OBD was 0.1 Hz, and that of PEMS was 1 Hz (Cha et al., 2019). The data from both had some degree of fluctuation, which caused their variation trends to be unclear. The OBD data were smoothed for 40 s, and the PEMS data were smoothed for 400 s. In this way, the data acquisition frequencies of the OBD and PEMS were the same, and the curves of these two data sets could be compared more clearly.
Figure 8. Comparison of NOx concentration by PEMS and OBD after smoothing

Figure 8 shows that the NOx emission concentrations collected by the PEMS and OBD had many similarities, described as follows.

1. The variation trends of the NOx emission concentration data collected by the PEMS and OBD technology with time were roughly the same, and the distribution of the data in the rising and falling sections of the two curves were almost the same (Söderena et al., 2020).

2. The distribution of extreme points in the data collected by the PEMS and OBD were roughly the same. However, there were some differences between the data collected by the PEMS and OBD, described as follows.

1. In the bulldozer operating stage, the data value monitored by the OBD was relatively larger. The maximum concentration detected by the OBD was about 1000 ppm, while the maximum concentration detected by the PEMS was about 800 ppm.

2. The OBD sensor could respond faster. Thus, the PEMS data variations occurred after the OBD data variations.

3. The data monitored by the PEMS was more accurate. The PEMS data were measured by the OBS-ONE gas analyzer. Before the experiment, it was necessary to use a standard gas with a known concentration to zero and calibrate the measuring equipment. Therefore, the NOx emission concentration measured by the OBS-ONE was relatively more accurate. The NOx sensor had a poor working environment and a certain reading drift, so the relative error was large.

3.2.2 NOx emission errors and time alignment
The average error and absolute average error of the NOx emission data from the PEMS and OBD are shown in Table 5.

| Error types   | Average error (ppm) | Absolute average error (ppm) |
|---------------|---------------------|-----------------------------|
| Idling        | 4.83                | 96.00                       |
| Driving       | -4.52               | 59.79                       |
| Operating     | 302.00              | 303.77                      |

The time responses of the data measured by the PEMS and OBD were always different, because the two devices had different sampling locations and it took time for the airflow to pass between the
two sampling points. The environment temperature also influenced the time response differences. Furthermore, there were differences between the self-response times of the OBD and the PEMS, which were due to the operating principles of these devices. To study the errors caused by these time differences, the method of time alignment was used (Guo et al., 2020). First, the data measured by the OBD was shifted back 50 s and then compared with the data measured by the PEMS (Figure 9). The data measured by the OBD were shifted backward 100 s and then compared with the data measured by the PEMS (Figure 10).

Figure 9. Comparison of NOx concentration by PEMS and OBD after shifting by 50 s

Figure 10. Comparison of NOx concentration by the PEMS and OBD after shifting by 100 s

The time delay was different in different processes. Thus, shifting the OBD data for all the processes by the same amount of time could not reduce the error to the greatest extent. The data of the OBD in different processes could be shifted back by different amounts of time. Based on Figure 8, the OBD data should be shifted back 100 s from 0 to 900 s, shifted back 50 s from 900 to 1500 s, and not be shifted from 1500 to 2050 s.
As shown in Figure 11, the time variations of the OBD and PEMS data were more consistent after comprehensive shifting. The PEMS equipment was delayed because of its own operating principle, the insufficient preheating, and the backward sampling location. According to the operating principle of the NOx sensor, the sensor must heat the exhaust gas, pump oxygen, and transfer NOx into N₂ and O₂ before measuring. Time is required to complete these processes (Ritter et al., 2019; Masoud et al., 2018). As a result, the OBD system also had a time delay. In a changing working environment, the time response differences of these two kinds of data are uncertain and vary with time. Therefore, shifting some of the OBD data by certain amounts of time can better reduce the errors.

The relationship between the errors and the different data shifting processes is shown in Table 6. After the OBD data were comprehensively shifted, the absolute average errors were the minimum for all the working processes.

**Table 6. Relationship between the errors and the data shifting processes**

| Data processing | Unprocessed | Shifted 50 s | Shifted 100 s | Comprehensive shifting |
|-----------------|-------------|--------------|---------------|------------------------|
| Absolute average errors (ppm) | 138.51 | 126.30 | 129.56 | 114.04 |

4. Conclusion
The NOx emission concentration of the bulldozer was relatively stable in the idling and driving processes. It increased significantly in the transition to the operating process, then maintained a certain value, and finally decreased.

The NOx emission concentration data of a bulldozer collected by the PEMS and OBD have the same variation trends with time. Meanwhile, there were still some differences, especially in the bulldozer operating stage.

The response times of these two systems were different. Thus, the OBD data were shifted relative to the PEMS data to complete the time alignment. The results showed that the average error was the smallest when shifting the OBD data in the idling, driving, and operating processes by for 100, 50,
and 0 s, respectively.

This study proved that the OBD system is reliable and can be widely used for monitoring the emissions of non-road vehicles.

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6. References

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