Research on Calculation Method of Non-Road Mobile Machinery PEMS

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Abstract. In this paper, four typical non-road mobile machinery test objects were used to test the actual operation of the NOx emissions using a portable emission measuring system (PEMS). The NTE method of the United States and the European work-based window method test data were used for processing and analysis of emissions. The research results show that the NTE method cannot be applied to the actual operation emission analysis of four non-road mobile machinery, and the work-based window method can accurately evaluate the emission levels of four non-road mobile machinery.

Keywords: Non-road mobile machinery, PEMS, work-based window method, NTE method.

1. Introduction
The Chinese government is currently paying close attention to the monitoring of air quality and the prevention and control of atmospheric pollution. In order to meet the needs of the national environmental protection strategy, the forthcoming implementation of the “Nonroad Stage IV of China” proposes the use of compliance supervision, requiring the use of portable emission measuring system (PEMS) to detect the real operating emission of in-use non-road mobile machinery [1].

PEMS has been widely used in the testing of real driving emissions of heavy-duty diesel vehicles, and both the United States and the European Union have proposed their own PEMS regulations [2-3]. The two major regulations have large differences in data processing methods, forming an independent emission evaluation method: the US NTE method, the EU uses the average window method. Both methods of data processing for non-road mobile machinery have been applied, but whether the two methods can accurately evaluate the NRMM emissions are urgently needed.

2. Research Method

2.1. Introduction to the US NTE Method
The NTE method defines the NTE zone and NTE events. Engine operating condition that enters the NET zone and lasts for no less than 30 seconds is defined as an NTE event and the emission of the event will be calculated later. The NTE discharge zone consists of an engine external characteristic torque line, an engine 30% maximum power line, an engine 30% maximum torque line, and an engine ESC-15% speed line, as shown in figure 1.

The NTE method ignores the effects of emissions at low speeds and rapid engine speed changes, which is suitable for tests the Steady state operating conditions. For the developed road network and low population density, heavy-duty diesel vehicles in US have long been in the highway driving conditions,
and generally travel at a relatively stable speed, in line with the NTE method. At the same time, the NTE method neglects the low engine speed and the sudden increase and decrease of the engine speed, which reduces the impact of the driver’s bad driving habits on the emissions and improves the pass rate of the test.

![Figure 1. Definition of NTE area.](image)

2.2. Introduction to the European Average Window Method (AWM)

The Joint Research Centre (JRC) of European Commission (EC) believes that the NTE method does not apply to the actual driving conditions of European heavy-duty vehicles and proposes “average window method” that divides the entire emissions according to window periods and calculating the emission of each window. The window period can be selected to accumulate work, cumulative CO2 emissions, and the time window directly [4].

Compared with the NTE method, the average window method incorporates the emission of non-NTE condition into emissions calculations, and is more suitable for heavy-duty diesel vehicles that often operate at low and medium loads, such as buses and garbage trucks. At the same time, the engine idle speed condition and load sudden change condition are included in the emission calculation, which is more suitable method for the complex road networks and dense populations in EU.

2.3. Test Equipment

The test equipment used was the Sentech-ECOSTAR PEMS manufactured by Sensors, USA. The entire equipment consists of a gas analysis module, a sampling control system, a pitot tube flow meter, a weather station, and a GPS system. The gas analysis module applies non-dispersive infrared analysis (NDIR) to measure carbon monoxide (CO) and carbon dioxide (CO2) content, and uses non-dispersive ultraviolet (NDUV) to measure nitrogen oxide (NOx) emissions. The engine operating condition signal is provided directly by the engine ECU [5].

2.4. Sample Selected

According to the data in the “China Motor Vehicle Environmental Management Annual Report-2018” issued by the Ministry of Environmental Protection: China's non-road mobile machinery's nitrogen and oxygen emissions mainly come from construction machinery and agricultural machinery, in which construction machinery NOx emissions account for non-road mobile machinery nitrogen oxidation. 37.5% of total non-road emissions, agricultural machinery NOx emissions accounted for 32% of total non-road mobile machinery NOx emissions. Forklifts, loaders and excavators in construction machinery accounted for the top three in terms of quantity, accounting for 41.8%, 27.3% and 26.8% respectively. Tractor accounts for the vast majority of agricultural machinery, accounting for 49%. Based on this, we chose forklifts, loaders, excavators and tractors as test samples, as shown in table 1.
Table 1. Test sample parameters.

| NO.   | Type     | Power (kW) | Rotating speed (rpm) |
|-------|----------|------------|----------------------|
| Sample 1 | Forklift | 85         | 2200                 |
| Sample 2 | Loader   | 162        | 1800                 |
| Sample 3 | Excavator | 162      | 2000                 |
| Sample 4 | Tractor  | 110        | 2200                 |

The test conditions use the actual working conditions common to the machine, and the loading conditions are based on the actual conditions of the operation. The test method is required to be carried out in accordance with the non-road PEMS requirements in the European Stage V. In order to obtain sufficient data samples, the test time is required to achieve mechanical 5 times NRTC cycle work or 2.5 hours, whichever comes first. Data processing method is processed according to the work-based window method specified in the US NTE method and the EU non-road Stage V.

3. Analysis of Results

3.1. Data Analysis
The non-road mobile machinery has a high load during actual operation, and all of them have completed 5 times of cycle work accumulation within 2 hours. The mechanical operation cycle is single, and the single operation cycle time is short. The whole test collects a large number of single operation cycle discharge samples, which can truly reflect the actual operation discharge of the machine. Table 2 records the test results.

Table 2. Sample test result.

| NO.   | Test duration (s) | Multiple of accumulated work | Average emissions (g/kWh) | Average load |
|-------|-------------------|------------------------------|---------------------------|-------------|
| Sample 1 | 4272              | 5.0                          | 4.64                      | 52.7%       |
| Sample 2 | 6340              | 5.7                          | 3.09                      | 41.0%       |
| Sample 3 | 3821              | 6.2                          | 2.06                      | 74.4%       |
| Sample 4 | 3830              | 5.4                          | 3.05                      | 62.1%       |

The working mode of the sample 1 is the V-line operation method, and the main work flow is: lifting, load-weight walking, unloading, no-load walking. The entire work cycle is usually about 25 seconds. There are a large number of sudden changes in the speed load during the work. The sample 1 has a higher load during lifting and weight-bearing walking during actual operation, and the load of unloading and no-load walking is lower, and the working point covers almost the entire engine map, as shown in figure 2.

The working mode of the sample 2 is also the V-line operation method, and the main work flow is: loading, loading walking, unloading, no-load walking. The entire work cycle is usually around 40 seconds. There are a large number of sudden load changes in the work. The sample 2 has a higher load during lifting and weight-bearing walking during actual operation, and the load of unloading and no-load walking is lower. During the loading process, the engine may run on the external characteristics of the engine, and the working condition point covers almost the entire engine map, as shown in figure 3.

The working mode of the sample 3 is a fixed work excavation. The time of each digging action is 5-10 s, and the level of single excavation loading is also very much related to the operator’s choice. Therefore, the engine is in a working condition with a constant speed changing load. Figure 4 show the operating points distribution.
The working mode of the sample 4 is towing and walking. Working under heavy load conditions, the engine often works on the outside engine characteristics. The tractor is in a low-load condition when it turns its head, which is close to the idle condition, as shown in figure 5.
3.2. Emission Results under the NTE Method

The number and proportion of NTE events processed by the sample according to the NTE method are listed in Table 3.

| NO.  | Number of NTE events | Data utilization | Maximum emissions (g/kWh) |
|------|----------------------|------------------|---------------------------|
| Sample 1 | 3                    | 4.1%             | 0.36                      |
| Sample 2 | 0                    | 0%               | —                         |
| Sample 3 | 15                   | 90.6%            | 2.07                      |
| Sample 4 | 18                   | 61.7%            | 5.43                      |

It can be seen from Table 3 that the sample 1 and the sample 2 are difficult to generate an NTE event during the actual operation. Although the average load rate of the sample 1 and the sample 2 is high, a large number of operating points are in the NTE zone. The single cycle operation time of the sample 1 and the sample 2 is very short, generally 20s-40s, and an NTE event cannot be formed. Even if an NTE event is formed, the actual emission of the machine cannot be reflected because the sample size is too small: the maximum emission of the NTE event of the sample 1 is 0.36 g/kWh, and only the average emission of the sample 1 is 7.8% of the 4.64 g/kWh. More NTE events were formed in the test of the sample 3 and the sample 4, and the time of the NTE event accounted for a higher proportion of the entire test time, reaching 90.6% and 61.7%, respectively, which can fully reflect the mechanical emission level. However, the NTE event emissions of the sample 3 at the sample 4 are substantially less than the test emission average. The emissions calculated using the NTE method are relatively loose.

Figure 6 shows that all the NTE event emissions of the sample 3 fluctuated less because the engine of the sample 3 was always operating at a fixed speed and the load per action was similar, with little change in the operating conditions of the single operating cycle. Sample 4 showed two high-emission events in the second half of the test. The two NTE times lasted for 45 s and 38 s, respectively, named event A and event B. By study the operating conditions of events A and B, it can be found from Figure 7 that the operating conditions of these two events all run on the external characteristic curve of the engine, which has the highest burst pressure and the highest heat release rate. At the same time, since the operating conditions of these two events basically run the high-speed range of the engine, the engine's air-fuel ratio at this time is relatively high. Therefore, it can be concluded that the combustion conditions in the engine cylinders in events A and B are high temperature and rich in oxygen, which is a condition for easy formation of nitrogen oxides. It’s normal to appear a sudden emission rise.
3.3. Emission Results under the Work-Based Window Method

The number and proportion of windows processed according to the work-based method are:

| NO.  | Number of windows | Test duration (s) | Data utilization |
|------|-------------------|-------------------|------------------|
| Sample1 | 3385               | 4272              | 99.9%            |
| Sample2 | 5231               | 6340              | 99.9%            |
| Sample3 | 3201               | 3821              | 99.9%            |
| Sample4 | 3149               | 3830              | 99.9%            |

As shown in Table 4, using the work-base window method, the test data was almost completely included in the calculation, and the data utilization rate was high, which could comprehensively reflect the discharge of the mechanical operation. The work-based window method produces a large number of data windows that can be used for calculations to ensure a sufficient sample size. The result of the work-based window approach is to calculate the average emissions over the window time, so it is possible to effectively avoid sudden changes in emissions or equipment errors. The average load rate of the prototype during the test was higher, both higher than 40%. Figure 8 shows the minimum window time for all test samples is above 600 seconds, avoiding the effects of transient emissions peaks and test equipment drift on actual emissions.
Figure 8 NTE event emission distribution for sample 3 and sample 4.

4. Conclusion
The real operating cycle time of non-road mobile machinery is short, and the load changes drastically and rapidly. The actual operating conditions of some non-road mobile machines are difficult to generate NTE events.

Most of the NTE event emissions are below average emissions. Part of the NTE emissions are suddenly increased in a short time. This will have a large impact on the overall emissions calculation, resulting in an incorrect emissions assessment.

The work-base window method is used to calculate the high utilization rate of non-road mobile machinery emission data, to avoid the adverse effects of mechanical emission mutations and to reflect the changes of mechanical working conditions to a certain extent, and to accurately reflect the true emission level of machinery.

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