# Heavy-duty vehicle emission characteristics based on the remote-monitoring three-bin moving-average window method

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**Abstract:** A three-bin moving average window (3B-MAW) model was proposed and compared with the work-based window method (WB-WM) to investigate the on-road emission characteristics of heavy-duty vehicles. The invalid data of remote monitoring were mainly composed of the NOx sensor's abnormal data and the uploaded data after the engine shutdown. In the 3B-MAW model, each data was attributed to one, two or three bins. The percentage of the three bins were linked to the vehicle's real driving conditions. In order to gain the emission calculation accuracy and a smaller scale of required data, the value of the four main parameters, i.e., the minimum window number, the window width, the first cut-off and the second cut-off are set around 2 400 s, 300 s, 6% and 20%, respectively. Since the window power is no longer required, the 3B-MAW method is able to capture the low load emission characteristics more effectively, compared to the WB-WM. Therefore, the 3B-MAW method is a more appreciate approach to analyse on-road random driving conditions.

**Key words:** Heavy-duty vehicle; moving average; remote monitoring; work-based window method.

## 1. Introduction

Heavy commercial vehicles have always been the focus of emission monitoring. According to the "2022 China Mobile Source Environmental Management Annual Report" by the Ministry of Ecology and Environment, the emissions of nitrogen oxides (NOx) and particulate matter (PM) from diesel vehicles in China accounted for over 80% and 90% of the total vehicle emissions in 2021, respectively [1].

In order to better control the emissions of heavy-duty vehicles, China's six stage emission standards for heavy-duty vehicles [2] have added remote emission monitoring and actual road driving measurement methods. Among them, remote emission monitoring requires vehicles to install on-board terminals throughout their entire life cycle, send data as required, and be received by the ecological environment regulatory department and the remote platform of the production enterprise. The study by Sun Yilong et al. [3] found that the data and emission values obtained from remote monitoring are consistent with the experimental test data. In 2021, the Ministry of Ecology and Environment issued the Technical Specification for Remote Monitoring of Heavy Vehicle Emissions [4], further explaining the relevant technical requirements. At present, there are problems with low data quality and slow progress in data application models in remote data [5]. How to use the emission big data received by remote platforms to establish a monitoring model and achieve limited monitoring of vehicle emission levels is currently a research focus [6]. Cheng Xiaozhang et al. [7] from Hefei University of Technology found that NOx emissions are influenced by both vehicle speed and acceleration. By dividing the remotely monitored NOx emissions into four operating conditions and screening them using statistical principles, high emission diesel vehicles are identified. Xu Weibiao et al [8]. from Shanghai University of Engineering and Technology proposed a high emission vehicle recognition algorithm driven by NOx concentration distribution characteristics, which clusters vehicle NOx emissions through system clustering method. Zhang Xinyu et al. [9] from Jianghuai Automobile proposed a selective catalytic reduction (SCR) conversion efficiency algorithm based on remote data, an analysis method for the impact of user behavior on SCR, and a judgment method for SCR sulfur poisoning and hydrocarbon poisoning。

On the other hand, the actual road driving measurement uses a portable emission measurement system (PEMS) equipment to conduct actual road emission testing of vehicles according to specific operating conditions, and refers to European standards to use the work based window method (WB-WM) for emission calculation and judgment. In WB-WM, the average window power of the

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effective window is required to be greater than 10%. Therefore, this method cannot effectively monitor emissions under low load conditions, and for some test results, if the effective window ratio is low, a larger proportion of test data will be sacrificed, and the test conditions cannot correspond well with the actual operation of the vehicle. The research results of Lv Liqun et al.[10]from Beijing University of Technology indicate that the current WB-WM can eliminate up to 46.68% of the NOx high specific emission window in the emission assessment process, significantly underestimating the actual NOx emissions of heavy-duty diesel vehicles under actual road conditions, especially urban congested road conditions. P. of the Joint Research Center of the European Commission In the research results of Mendoza Villafeuerte et al.[11], up to 85% of NOx emission results were not included in the calculation of results. At present, international efforts are also being made to improve and upgrade this testing method. Zhang Xiaowen et al.[12]from the China Automotive Technology Research Center proposed a fuel consumption based window partitioning method for PEMS testing, which can reduce NOx emission deviation by 6% compared to WB-WM。

C.Sharp et al[13] from the Southwest Research Institute in the United States found through extensive data analysis that operating conditions with a load of less than 20% account for a higher proportion in the operation of heavy-duty vehicles. Therefore, the California Air Resources Board (CARB) passed ultra-low NOx emission regulations in 2020, which proposed the requirement for low load cycle (LLC) and a new type of heavy-duty vehicle emission monitoring method, namely the three in moving average window (3B-MAW) method[14]. This method uses a fixed moving window of 300 seconds, calculates the corresponding load ratio based on the CO2 emissions of each window, and divides the window that moves every second into idle zone, low load zone, and medium to high load zone based on the load ratio. And requirements were made for the emission limits of three zones. G Sadek [15] found that there is a trade off relationship between NOx and CO2 in the low load and medium to high load regions of the 3B-MAW method. The 3B-MAW method can effectively correspond to engine emission cycles, such as LLC cycles for low load zones, federal test procedures (FTP) and ramped mode cycles (RMC) for medium to high load zones. Therefore, compared to the current WB-WM, it can better monitor low load conditions. In summary, the 3B-MAW method can effectively improve the efficiency of using emission data and monitor low load conditions.

This article applies the 3B-MAW method to the analysis of remote emission monitoring data, and conducts research and analysis on data cleaning, model characteristics, parameter effects, and emission results using remote monitoring data from six different types of heavy-duty vehicles. Finally, a comparative study was conducted between the actual vehicle road emission test and WB-WM.

## 2. Remote monitoring 3B-MAW model

### 2.1 Computation model

The 3B-MAW calculation model for remote monitoring of heavy vehicle emissions proposed in this article is shown in Figure 1.

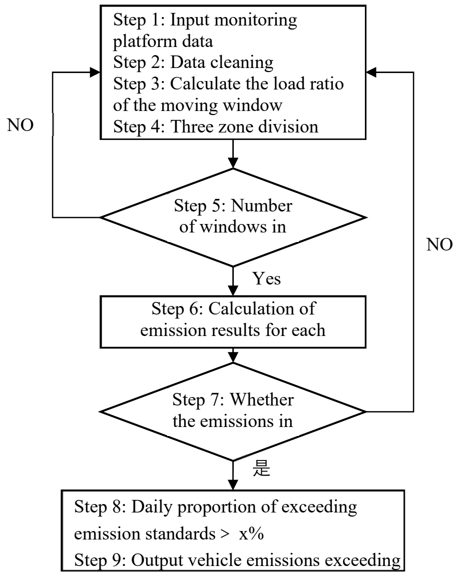


Figure 1 Vehicle Emission Calculation Method Based on 3B-MAW

The calculation steps are:

Step 1: Enter monitoring platform data. Using the daily monitoring data of each vehicle on the remote monitoring platform as input, if the data volume is insufficient, it will be supplemented day by day.

Step 2: Data cleaning. Filter and eliminate remote monitoring data, and the effective data filtering conditions are shown in Section 2.2 of this article.

Step 3: Calculate the load ratio of the moving window. The calculation basis for dividing effective data into moving windows is shown in Section 3.1 of this article. The load ratio of each moving window is

$$\lambda = \frac{3\,600\ \mathrm{s}\sum_{t=1}^{t_{\mathrm{win}}}\left(\dot{m}_{\mathrm{CO_2}}\Delta t\right)}{M_{\mathrm{CO_2}}P_{\max}t_{\mathrm{win}}}. \quad (1)$$

Among them: Mco2 is the CO2 test result of this vehicle model according to Appendix L of GB17691-2018; Pmax is the rated power of the vehicle's engine; twin is the duration of the moving window, recommended as 300 seconds; Δt is the sampling interval, One second for remote monitoring; $\dot{m}_{\mathrm{CO_2}}$ is the instantaneous CO2 mass emission of the vehicle, which can be calculated according to formula (2) for diesel vehicles。

$$\dot{m}_{\mathrm{CO_2}} = \frac{44 q_{\mathrm{v}} \rho_{\mathrm{d}}}{13.86 \times 3600}. \quad (2)$$

In the equation: $q_v$ is the fuel volume flow rate of the engine, in L·h-1, Upload data items for remote monitoring; $\rho_d$ is the density of diesel fuel,in g·L-1; 44 is the relative molecular weight of CO2;The hydrocarbon mass ratio in diesel fuel is 12:1.86。

Step 4: Three zone division. Calculate the window load ratio according to step 3 λ Divide each mobile window into different types.$\lambda \leq 6\%$ are divided into idle zones,6% $< \lambda \leq 20\%$ are divided into low load areas，$\lambda > 20\%$ are divided into Medium to high load areas.

Step 5: Confirm that the cumulative number of windows in each area is greater than or equal to the minimum required number of windows nmin =2400, otherwise supplement the previous day's data and return to step 1.

Step 6: Calculate the emission values for the three zones. For low load areas and medium to high load areas, calculate the specific emissions according to formula (3).

$$E_{a,b}=\frac{M_{\mathrm{CO_2}}\sum_{k=1}^{n_b}\sum_{t=1}^{t_{\mathrm{win}}}\left(\dot{m}_a\Delta t\right)}{\sum_{k=1}^{n_b}\sum_{t=1}^{t_{\mathrm{win}}}\left(\dot{m}_{\mathrm{CO_2}}\Delta t\right)}. \qquad (3)$$

In the equation:$E_{a,b}$ is the specific emission of the area, in g·(kW·h)-1;a represents emissions，It can be HC, CO, NOx, and PM, and for current remote monitoring requirements, it generally refers to NOx;b represents the type of zone, which can be low load zone or medium high load zone; nb represents the number of windows in zone b，$n_b \geq n_{\min}$;$\dot{m}_a$ is the instantaneous mass emission of emissions, in g·s-1。

For the idle zone, calculate the emission flow rate according to formula (4).

$$E_{a,\mathrm{idl}}=\frac{3\ 600\sum_{k=1}^{n_{\mathrm{idl}}}\sum_{t=1}^{t_{\mathrm{win}}}\left(\dot{m}_a\Delta t\right)}{\sum_{k=1}^{n_{\mathrm{idl}}}\sum_{t=1}^{t_{\mathrm{win}}}\left(\Delta t\right)}. \qquad (4)$$

In the equation: $E_{a,\mathrm{idl}}$ is the mass flow rate of emissions a in the idle zone,in g·h-1; $n_{\mathrm{idl}}$ is the number of windows in the idle zone.

Step 7: Verify whether the emissions in Zone 3 exceed the limit values (see Section 3.3 of this article for a discussion of the limit values). If there is an area exceeding the emission limit, it will be recorded as exceeding the emission limit on that day. Return to step 1 to calculate the next day's emission situation.

Step 8: If the daily proportion of the vehicle exceeding the limit is greater than x%, the vehicle is deemed to be a suspected vehicle exceeding the limit. 0<x<100, can be selected according to actual regulatory needs, which is not within the scope of this article and does not affect the conclusion of this article.

### 2.2 Model Features

Through the above description, the following characteristics of the 3B-MAW calculation model can be learned:

1) Suitable for verifying the actual driving emission level of vehicles, there are no requirements for driving conditions and window movement direction.

2) The load ratio is characterized by CO2 emissions, and the monitoring load range is wide, without considering the load situation.

3) After data cleaning, even if the data is discontinuous, it can be applied to calculations to improve data usage efficiency.

## 3. Vehicle selection and data cleaning

### 3.1 Vehicle selection

The remote monitoring data used for model research in this article mainly comes from the six heavy-duty vehicles shown in Table 1, covering different vehicle types, masses, and power levels of trucks, tractors, and buses. Each vehicle was selected for four consecutive weeks of remote monitoring data. Due to the different frequency of vehicle usage, the total amount of data varies, with truck 3 having the largest data volume of approximately 267 hours. The remote monitoring of vehicles is wirelessly transmitted through on-board terminals in accordance with the national emission standards of 6, and received and recorded through software platforms. The driving conditions and loads of the vehicles are daily operating conditions (traffic conditions are random).

Table 1 Vehicle Parameters

| Name | Classification | Maximum total mass / t | Volumetric displacement / L | Rated power / kW | $M_{\mathrm{co_2}}$/[g·(kW·h)$^{-1}$] | Data volume / s |
|---|---|---|---|---|---|---|
| Truck 1 | N2 | 4.5 | 2.29 | 96 | 670.2 | 258 196 |
| Truck 2 | N3 | 18.0 | 4.58 | 162 | 583.9 | 222 072 |
| Truck 3 | N3 | 31.0 | 9.50 | 289 | 609.1 | 739 538 |
| Traction 1 | N3 | 18.0 | 10.52 | 327 | 602.7 | 963 274 |
| Traction 2 | N3 | 25.0 | 12.90 | 426 | 552.0 | 784 589 |
| Bus 1 | M3 | 16.0 | 7.80 | 235 | 696.4 | 204 990 |

### 3.2 Data cleaning

The remote monitoring data of each vehicle has been cleaned, and the screening principles for effective data are as follows:

1) The altitude at which the vehicle is driven is less than 2500 meters, which means that the atmospheric pressure is approximately greater than 74 kPa (under the PEMS test conditions of the National VI Emission Standard);

2) The engine is in a non shutdown state, that is, the engine speed is greater than 500 r/min (with no emissions when the engine is turned off);

3) The engine is in a hot engine state, that is, the coolant temperature is greater than 70°C (under the analysis conditions of PEMS test data in the sixth emission standard of China);

4) The vehicle NOx sensor is able to transmit valid NOx emission values normally (there is no NOx effective value during the dew point detection process).

Taking the 2400 second operation data of truck 1 as an example, Figure 2 shows the distribution of valid and invalid data. It can be seen that after the vehicle has stopped for a period of time, the engine coolant temperature may be lower than 70°C, and the vehicle has not fully warmed up, so the data at this time will be excluded. After the water temperature rises to above 70°C, it still takes some time for the NOx sensor to start transmitting valid data, and invalid NOx data also needs to be removed.

Figure 3 shows the data deletion statistics of the selected 6 heavy-duty vehicles. It can be seen that the proportion of data deleted is the smallest due to a speed less than 500 r/min. For truck 1 and traction 1, the proportion is as high as 17.5% and 22.6%, respectively, because although the engine of these vehicles has stopped, the vehicle has not been powered off, causing the on-board terminal to continue transmitting data, which is not necessary for analysis and therefore needs to be removed. Due to the water temperature being less than 70°C and the NOx sensor not transmitting data properly, the proportion of deleted data is related to the actual driving conditions of the vehicle. Overall, based on the effective data screening principles mentioned above, an average of approximately 32.1% of the data has been excluded.

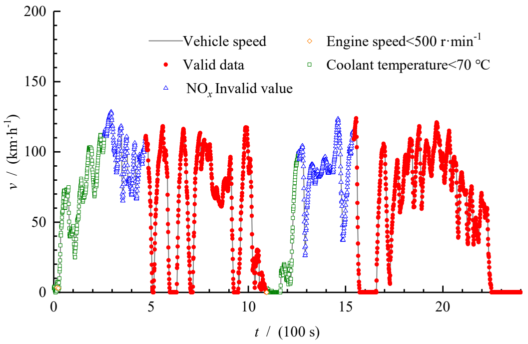


Figure 2 Example of invalid and valid data distribution

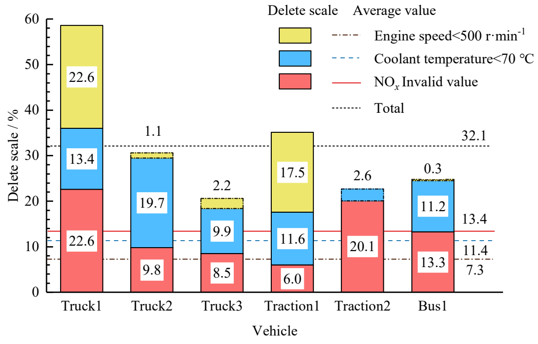


Figure 3 Data deletion ratio

## 4. Calculation Results and Discussion

### 4.1 Research on Model Characteristics

Taking the 3600s data of truck 1 as an example, Figure 4 shows the variation of vehicle speed and calculated load ratio over time. Each point on the load ratio curve represents the calculated load ratio of the moving window after that point for 300 seconds, as shown in the box area in the figure. It can be seen that there is a certain correlation between the change in load ratio curve and the speed curve. According to the CARB file[14], using $CO_2$ emissions to calculate the load is more accurate than collecting on-board diagnostic (OBD) load data compared to traditional PEMS tests. The original vehicle OBD load data was not accurate at low loads.

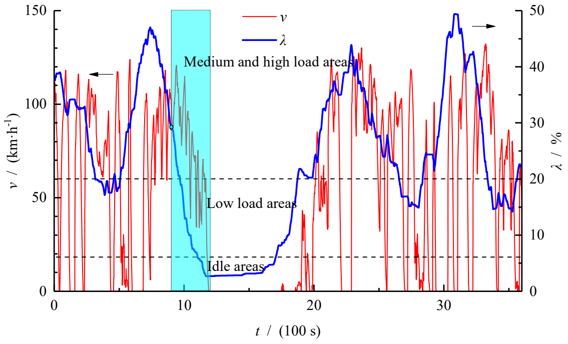


Figure 4 Average Moving Window

From Figure 4, it can be seen that each data point is contained by 300 consecutive moving windows, and as the load ratio of the moving windows changes, each data point may fall within one, two, or three types of zones.

Figure 5 shows the proportion of data points from different vehicles in different areas. It can be seen that the probability of data points falling within the three zones simultaneously is relatively low. The data falls within several zones and is related to the driving conditions and loading conditions of the vehicle. The simpler the driving conditions, such as heavy trucks, tractors, and buses, the higher the proportion of data points falling within one type of zone.

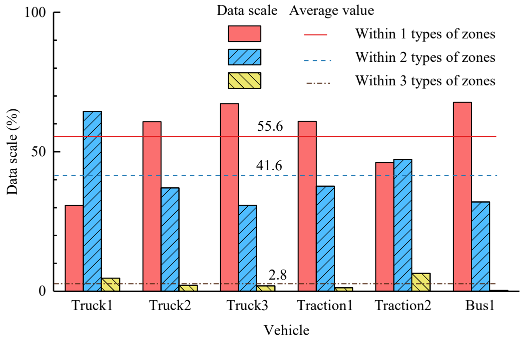


Figure 5 Proportion of data points falling simultaneously in 1, 2, or 3 zones

As shown in Figure 6, the daily transportation and driving conditions of different vehicles can be seen from the proportion of the three zones of the moving window. For example, the proportion of moving windows in the medium to high load areas of Truck 1, Truck 2, and Tractor 2 is greater than 50%, indicating that their daily transportation volume is large or their average driving speed is fast. For truck 3, traction 1, and passenger car 1, the proportion of moving windows in low load areas is higher.

Figures 7 and 8 respectively show the average vehicle speed and average exhaust temperature for each zone. Due to the fact that the division of the three zones is mainly based on the window load ratio, as the window load ratio increases, the average window speed and average exhaust temperature (SCR inlet temperature) also show an upward trend.

For the vehicles studied in this article, the average SCR inlet temperatures in the idle zone, low load zone, and medium to high load zone are 186.7, 253.6, and 310.3℃, respectively. The NOx conversion efficiency of SCR increases with the increase of catalyst temperature in the range of 180~300℃. In the emission comparison in section 3.3 of this article, it can be seen that NOx emissions in the medium to high load areas are more likely to be lower than those in the low load areas. Therefore, the 3B-MAW model can better reflect the operational characteristics of vehicles under different loads.

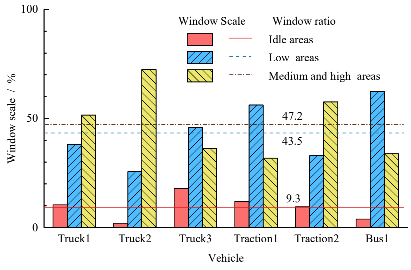


Figure 6 Moving Window Three Zone Division Ratio

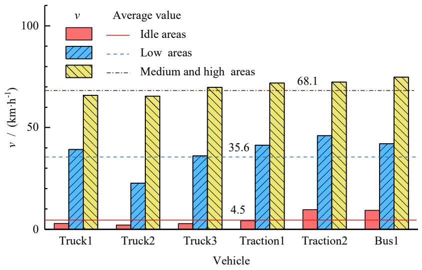


Figure 7 Average Speed of Three Zones

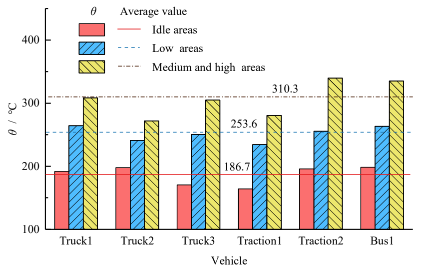


Figure 8 Average SCR inlet temperature in three zones

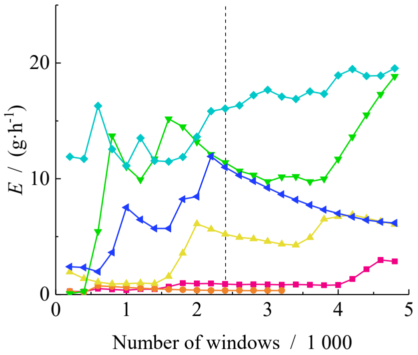
## 4.2 Model parameter research

From the description process of the calculation model in Section 1.1, it can be seen that the three zone moving average window calculation model has four main control parameters, namely the minimum number of windows (default nmin=2400), window width (default twin=300 s), the division line for idle and low load areas (the first division line, default value is 6%), and the division line for low load and medium high load areas (the second division line, default value is 20%). This section investigates the influence of various main control parameters on the calculation results and the selection basis.

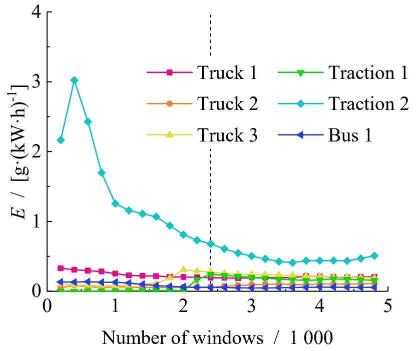
1) Minimum number of windows.

By setting the minimum number of windows, on the one hand, the emission results of multiple windows can be averaged to further assess the vehicle's emission situation, and on the other hand, the amount of data calculated can be effectively controlled.

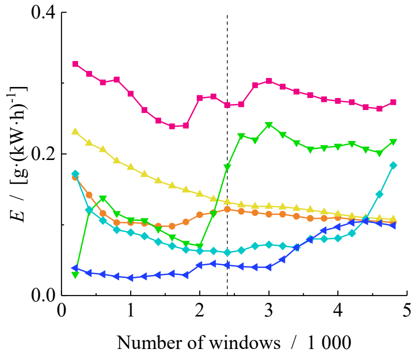
As shown in Figure 9, when the number of windows is less than 2400, due to the small number of windows for average calculation, the emission calculation results of some test samples in the three zones fluctuate significantly. After the number of windows exceeds 2400, the trend of the three zone emission calculation results for most vehicles is relatively flat, while for some vehicles (such as tractor 2 and passenger car 1), there is still a certain degree of fluctuation.



(a) Idle zone



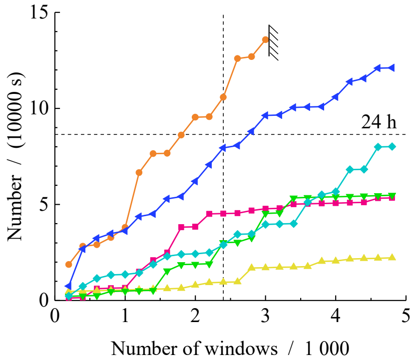
(b) Low zone



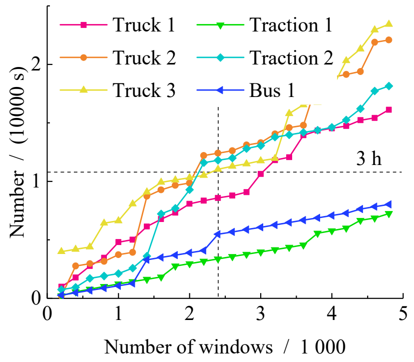
(c) Medium and high zone

Figure 9 Impact of Window Quantity on NOx Emission Results

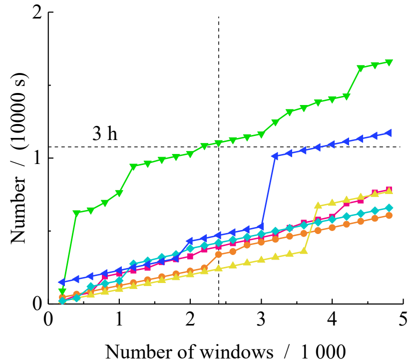
As shown in Figure 10, as the number of windows increases, the total amount of data to complete the three zone calculation (after cleaning) rapidly increases. Especially for the idle zone, due to the low proportion of vehicles falling into the idle zone during driving (see Figure 6), the data required to complete the idle zone calculation increases rapidly. From Table 3, it can be seen that the average daily running time of the vehicle is around 2-10 hours. Therefore, in order to ensure that the model calculation is completed using the same day's data as much as possible, the number of windows should not be too large. Based on the analysis results in Figure 9, setting the minimum window number to 2400 can achieve relatively stable emission results without causing too much data required to complete the model calculation.



(a) Idle zone



(b) Low zone



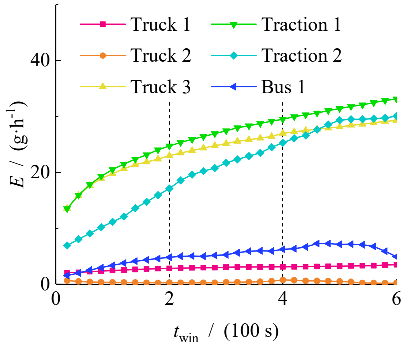
(c) Medium and high zone

Figure 10: The impact of the number of windows on the amount of calculated data

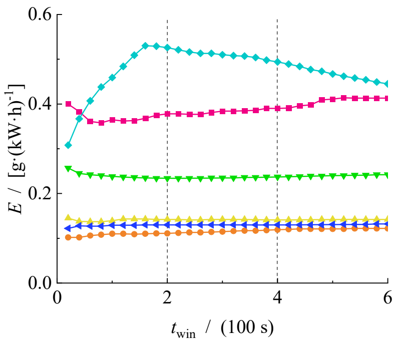
2) Window width.

This model adopts a fixed time width moving window. According to the US CARB report[16], a window width of 300 seconds can provide better filtering performance compared to the 30 second window currently tested by the US NTE (Non to Exceed), without causing distortion due to being too long[14].

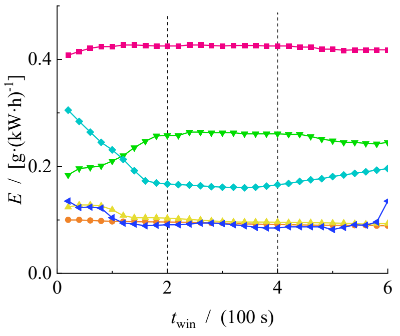
As shown in Figure 11 (with a fixed number of 2400 windows), when the window width is less than 200 seconds, the filtering effect on emission data is not significant due to the narrow window, resulting in rapid changes in emissions for most vehicles. When the window width is greater than 400 seconds, due to the excessive width of the window, the included operating conditions fluctuate greatly, leading to distorted fluctuations. However, when the window width is between 200 and 400 seconds, the emission results of most vehicles are relatively stable.



(a) Idle zone



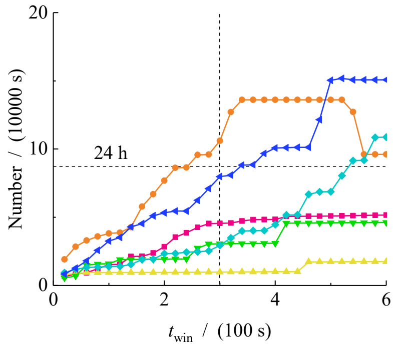
(b) Low zone



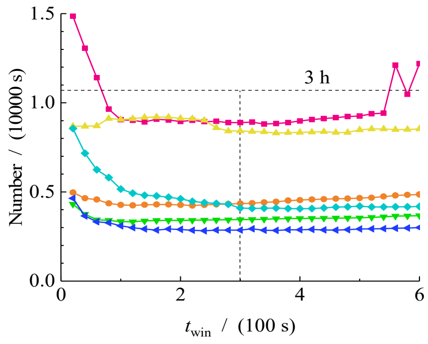
(c) Medium and high zone

Figure 11 Impact of window width on emission results

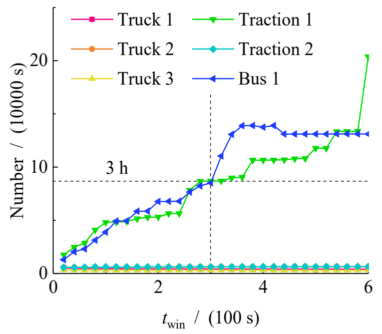
As shown in Figure 12 (with a fixed number of 2400 windows), the window width has a significant impact on the amount of emission calculation data in the idle zone and medium to high load zone. The reason is that when the operating load per second in a moving window is relatively low or high, it is divided into idle or medium to high load zones. As the window width increases, the window contains more changes in operating conditions, and the probability of consistently low or high operating conditions is also decreasing. Therefore, more data is needed to achieve the minimum number of windows required by the model. For example, for traction 1 and passenger car 1, it can be seen from Figure 6 that the proportion of high load areas in both operating conditions is relatively low. Therefore, as the window width increases, the amount of data required for the two to accumulate 2400 medium to high load areas also rapidly increases. Therefore, similar to the analysis of the minimum number of windows, in order to minimize the amount of data required for model calculations, the window width should not be too long, and 300 s is a more suitable value.



(a) Idle zone



(b) Low zone

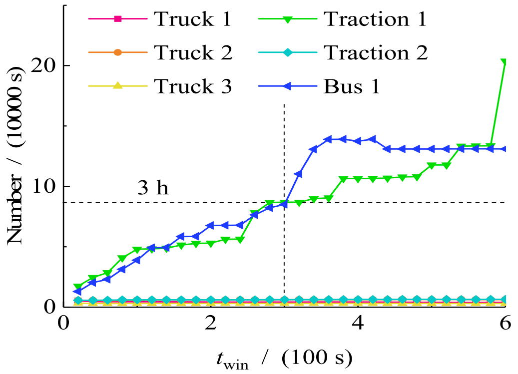


(c) Medium and high zone

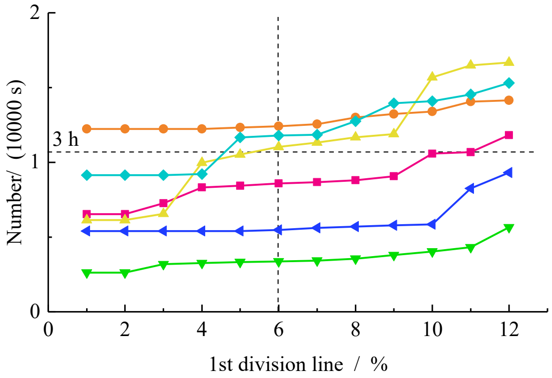
Figure 12 Impact of window width on calculated data volume

3) Load ratio dividing line.

According to the US CARB report[16], the reason for setting the first division line at 6% is that it corresponds to the test results of LLC cycles (LLC load ratio is generally 5-7%). From the perspective of model principles, the first division line mainly affects the division and calculation of idle zone and low load zone. As shown in Figure 13, when the first partition line is less than 6%, the probability of the window falling into the idle zone rapidly decreases, resulting in a rapid increase in the computational complexity required to complete the model. When the first division line is greater than 6%, the amount of data to complete the calculation of low load areas also shows an upward trend. Therefore, considering both the low load cycle requirements and the required data volume, it is more reasonable to set the first division line at around 6%.



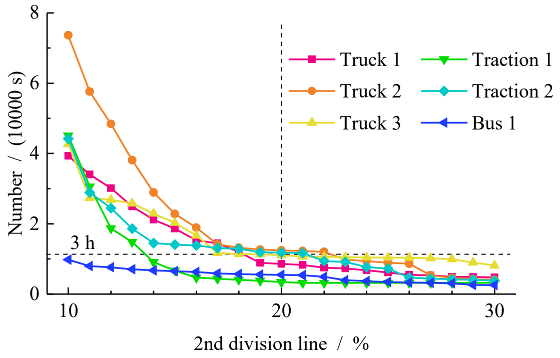
(a) Idle zone



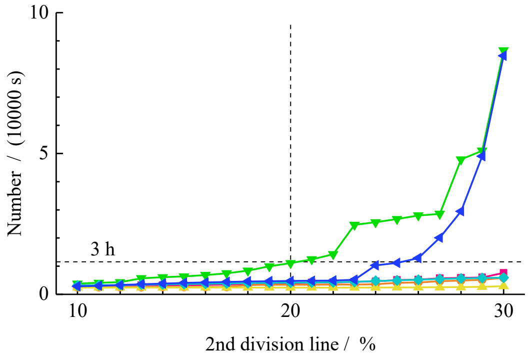
(b) Low zone

Figure 13: The impact of the first partition line on the calculation of data volume

The second division line is determined based on the average load ratio of the FTP cycle, which is approximately 20% [16]. Similar to the principle of the first division line, the second division line mainly affects the division and calculation of low load areas and medium to high load areas. As shown in Figure 14 (with a fixed number of 2400 windows), when the second partition line is around 20%, the required data volume for medium to high load and low load areas is basically controlled within 3 hours. When the second division line increases or decreases from 20%, the computational data volume in the medium to high load area and the low load area increases rapidly, respectively. Therefore, selecting 20% as the second dividing line can minimize the data demand.



(a) Idle zone



(b) Medium and high zone

Figure 14: The impact of the second partition line on the calculation of data volume

## 4.3 Emission Results

As shown in Table 2, the CARB report in the United States[14] proposes a limit value for the three zone moving average window model, which is the product of the consistency factor (CF) and the corresponding cycle condition limit value, and CF and condition limit values will continue to be tightened over time. G. of WVU Sadek proposed two recommended limits for 2010 and 2024 in his research.

Table 2 NOx Emission Limits for Three Zones

| partition | limiting value | |
|---|---|---|
| | CARB | WVU |
| Idle zone | CF×IDLE limiting value | 15~45 $g\cdot h^{-1}$ |
| Low zone | CF×LLC limiting value | 0.4 $g\cdot(kW\cdot h)^{-1}$ |
| Medium and high areas | CF×FTP/RMC limiting value | 0.1~0.4 $g\cdot(kW\cdot h)^{-1}$ |

As shown in Figure 15, there are significant differences in the emission flow calculation results for different vehicles in the idle zone, ranging from 0 to 40 kg/h. Therefore, it is necessary to have specific emission limit requirements for the idle zone in future emission standards. The specific emissions in the medium to high load zone are close to or lower than those in the low load zone, because the post-treatment temperature in the medium to high load zone is higher (see Figure 11) and the conversion efficiency of NOx is higher. For low load areas, except for the high

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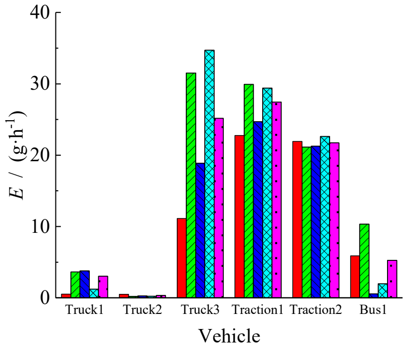
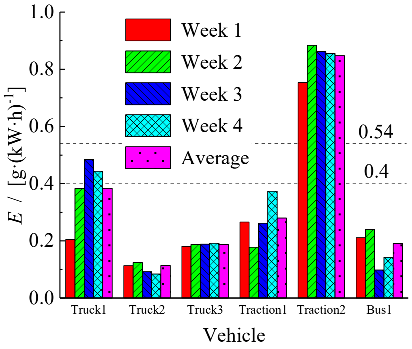
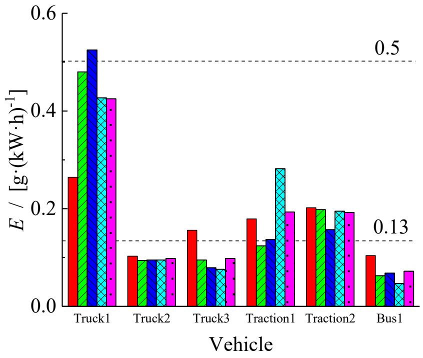
emissions of traction 2, the emission results of other vehicles are basically controlled below 0.5 g/(kWh), which is close to the limits of CARB (0.54 g/(kWh) and WVU (0.4 g/(kWh)) in 2024. However, considering that there are no emission requirements for low load areas in China, their limits can be appropriately relaxed. For high emission areas, the emission results of truck 1 are significantly higher than those of other vehicles, while the emissions of other vehicles are basically below 0.3 g/(kWh). Without considering the degradation coefficient of in use vehicles, there is still a certain gap between some vehicles and the 0.13 g/(kWh) requirement of the CARB in 2024.



(a) Idle zone



(b) Low zone



(c) Medium and highzone

Figure 15 Emission Results

## 5. Comparative study with WB-WM

This article selected 5 test sample vehicles, with sample parameters and testing conditions shown in Table 3. Among them, sample vehicles 1 to 3 were tested using the PEMS testing conditions required in the GB17691-2018 heavy-duty vehicle six stage standard, while sample vehicles 4 and 5 were tested using random operating conditions close to actual operation. Each test sample vehicle obtained vehicle operation data through remote monitoring.

Table 3 Sample Vehicle Parameters and Test Conditions

| prototype car | Maximum total mass / t | displacement / L | Cyclic work / (kW·h$^{-1}$) | load / % |
|---|---|---|---|---|
| 1 | 4.5 | 2.49 | 10.0 | 94.3 |
| 2 | 4.5 | 2.29 | 6.7 | 82.8 |
| 3 | 10.5 | 5.19 | 10.5 | 40 |
| 4 | 31 | 7.8 | 22.3 | 0 |
| 5 | 49 | 13.0 | 36.0 | 90 |

As mentioned earlier, the main difference between WB-WM and 3B-MAW methods lies in the assessment of low load conditions and the analysis method of emission data. The applicability and strict limit of the two methods are analyzed from these two perspectives. WB-WM was used to calculate the effective window (with an average power greater than 20% of the maximum engine power) and the average emission results for all windows. The 3B-MAW method was also used to analyze the test results, as shown in Table 4.

It can be seen that for sample vehicles 1-3 using PEMS operating conditions, the number of idle zone windows ranges from 0 to 396, which does not meet the requirement of nmin=2400. This indicates that the current PEMS testing conditions are not fully suitable for calculation using 3B-MAW due to the lack of idle operating conditions, and the proportion of idle operating conditions needs to be increased. From the results of sample vehicle 4, it can be seen that if tested under random operating conditions, the average emission of all windows in WB-WM is 453.7 mg · (kW · h) $^{-1}$, while the average emission calculated using an effective window is only 30.11 mg · (kW · h) -1, because the window power threshold filters out low load conditions with higher emissions. Therefore, the WB-WM method is not suitable for evaluating the emission levels of actual road conditions. In addition, for sample vehicle 3, the emission results of the low load and high load areas calculated using the 3B-MAW method exceeded the limits in Table 2, while the results calculated using WB-WM did not exceed the regulatory limit (690 mg · (kW · h) -1). The emissions of sample vehicle 5 are relatively poor, and the results of both calculation methods exceed the limit requirements. Therefore, in the application process of 3B-MAW, the design of emission limits can make its calculation method more rigorous compared to WB-WM.

Table 4 Comparison of 3B-MAW method and WB-WM test results

| | | WB-WM | | | 3B-MAW | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| prototype car | Effective data volume /s | Window pass rate /% | Average emissions / [g·(kW·h)$^{-1}$] | | Idle zone | | Low load zone | | Medium and high area | |
| | | | Active Window | All Windows | Number of windows | emission /[g·h$^{-1}$] | Number of windows | emission /[g·(kW·h)$^{-1}$] | Number of windows | emission /[g·(kW·h)$^{-1}$] |
| 1 | 8 537 | 100 | 0.006 7 | 0.007 1 | 0 | — | 5 527 | 0.12 | 2 710 | 0.004 |
| 2 | 6 429 | 100 | 0.229 6 | 0.189 1 | 396 | 0.47 | 2 646 | 0.77 | 3 087 | 0.130 |
| 3 | 9 975 | 80 | 0.591 1 | 0.619 6 | 305 | 9.42 | 6 789 | 0.64 | 2 581 | 0.480 |
| 4 | 8 588 | 100 | 0.030 1 | 0.453 7 | 2 821 | 29.02 | 2 665 | 0.09 | 2 802 | 0.007 |
| 5 | 13 510 | 0 | 2.776 2 | 2.714 1 | 2 534 | 58.15 | 4 776 | 3.38 | 5 900 | 1.880 |

## 6. Conclusion

This article focuses on the application of the Three Zone Moving Average Window (3B-MAW) method in remote monitoring of heavy vehicle emissions, including model establishment, data cleaning, model characteristics, parameter effects, and comparison with the power based window method. The following conclusions are drawn:

1) If a vehicle is driven at an altitude of less than 2500 meters, with an engine speed greater than 500 r/min, a coolant temperature greater than 70 °C, and a NOx sensor transmitting valid data as data screening criteria, approximately 32.1% of remote monitoring will be deleted.

2) In the 3B-MAW model, the proportion of three zones is related to the actual driving conditions of the vehicle. The average vehicle speed and post-processing average temperature in the medium to high load area are relatively high. In order to ensure both the accuracy of emission calculation and the required amount of data, the minimum number of windows, window width, 1st and 2nd partition lines should be set around 2400, 300 s, 6%, and 20%, respectively.

3) If the actual road PEMS operating conditions are to be analyzed using 3B-MAW data, it is necessary to increase the proportion of idle operating conditions. Due to being not limited by the window power threshold, compared to the power based window method, 3B-MAW can better reflect low load emissions and is more suitable for analyzing random driving conditions on actual roads.

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