A study on the relationship between vehicle operating conditions and NOx emission characteristics

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Abstract. To address the challenges faced by vehicles during actual operation when passing through traffic lights or intersections, where rapid changes in operating conditions can lead to a decrease in SCR efficiency and an increase in NOx emissions, this study focuses on defining characteristic position scenarios and analyzing the NOx emission characteristics of vehicles when passing through these scenarios based on real-time vehicle conditions. Through the analysis of several specific events, several road condition factors and driver behavior factors that may contribute to increased NOx emissions at characteristic position scenarios are identified. The findings indicate that when vehicles pass through traffic lights and intersections, the main causes of increased NOx emissions are low SCR temperature resulting from prolonged idling or engine shutdown, and high exhaust NOx emissions resulting from sudden excessive fuel injection. The driver behaviors associated with these situations primarily include coasting when approaching intersections, frequent stop-start behaviour due to traffic congestion or road crowding, choosing to shut off the engine for fuel efficiency during prolonged traffic congestion, and aggressive acceleration by stepping on the accelerator when the green light is about to turn red.

Keywords: NOx real driving emission, Characteristic position scenario, Driver behaviour.

1 Introduction

Unlike laboratory testing results, the actual operating conditions of vehicles often exhibit significant deviations from standardized conditions [1]. The diverse operating scenarios of vehicles can result in fluctuations in the combustion temperature and pressure within the cylinder, thereby impacting the emissions of NOx from the engine. Current emission regulations not only impose stricter limits on pollutant emissions but also place increasing emphasis on emissions during real-world driving. The current emission standard in Europe is the Euro 6 standard, which was implemented in 2016 [2]. Under the Euro 6 standard, the testing cycles for vehicles were optimized, replacing the European Steady State Test Cycle (ESC) and European Transient Test Cycle (ETC) with the World Harmonized Steady State...
Cycle (WHSC) and World Harmonized Transient Test Cycle (WHTC). The development of the WHTC and WHSC cycles was driven by the observation that diesel vehicles equipped with SCR systems emitted NOx far exceeding the limits under real-world driving conditions as stipulated by the Euro 4 and Euro 5 regulations [3]. Additionally, the Euro 6 standard introduced requirements for Real Driving Emissions (RDE) testing to better regulate vehicle emissions during real-world driving. In the proposed Euro 7 emission standard, which was released in 2022, stricter limits for NOx emissions were implemented to improve real-world road emissions and address the issue of insufficient control over actual vehicle emissions. Furthermore, the RDE testing requirements were expanded to encompass various scenarios, including low temperatures, extended idling, short trips, start-stop situations, rapid accelerations, and high altitudes.

Currently, there are a large amount of studies focusing on the differences between NOx emissions under real-world operating conditions and those under standard cycles. Joumard et al. [4] selected three sets of driving cycles that could represent real-world scenarios and compared them with the standard cycle. It was found that the standard cycle underestimated emissions from diesel vehicles by 30%. Degraeuwe et al. [5] conducted measurements of actual road pollutants using Portable Emission Measurement Systems (PEMS). The results showed that NOx emissions from diesel vehicles on actual roads were 206% higher than those in the New European Driving Cycle (NEDC). The significant discrepancies with the standard cycle make controlling NOx emissions on actual roads a focal point and challenge in the next phase of environmental protection.

In real-world driving conditions, the post-treatment of Nitrogen Oxides (NOx) is primarily carried out by the Selective Catalytic Reduction SCR system. SCR is currently the most preferred solution for NOx conversion [6]. In the SCR system, NOx is converted to water and nitrogen gas through the use of NH3 generated from urea solution [7]. The high NOx emissions during actual driving are mainly attributed to low SCR efficiency. In real-world driving scenarios, sudden variations in vehicle speed can result in changes in exhaust temperature and fuel injection, causing moments of insufficient NH3 in the SCR system and subsequently leading to increased NOx emissions.

Currently, there are numerous studies focusing on the characteristics of NOx emissions during real-world driving. For instance, Georgios et al. [8] found a positive correlation between NOx emissions and road gradient. Wang et al. [9] analyzed the impact of traffic conditions on bus emissions and emphasized the significant influence of delay time and speed in urban operating conditions. Song, Guo, and Wang [10-12] conducted tests on actual road emissions from heavy-duty vehicles under different loads, ambient temperatures, and altitudes, revealing the effects of load, ambient temperature, and altitude on vehicle emissions. Additionally, Wang et al. [13] analyzed remote monitoring data to investigate the operational and emission characteristics of Euro 6 heavy-duty diesel vehicles under low load conditions. Their findings suggested that prolonged operation under low load conditions in urban diesel vehicles results in higher NOx emissions. Based on the actual driving characteristics of vehicles, the study recommended the development of control methods for NOx emissions specifically targeted at low load conditions. Lyu et al. [14] conducted real-world road emission tests on China's National VI heavy-duty diesel vehicles using Portable Emission Measurement Systems (PEMS) and analyzed the NOx emission characteristics using the power-based window method. The results revealed significant uncertainty in NOx emissions during actual driving processes.

The aforementioned researches demonstrate that the historical driving behavior of vehicles has a certain impact on the state of the SCR system. Analyzing the vehicle's historical operational data can help analyze the characteristics of NOx emissions. However, during actual driving processes, the uncertainty of current driving behavior makes it extremely difficult to optimize control based on the system's state and current operational
requirements. Nevertheless, in real-world driving scenarios, there are certain characteristic positions where the uncertainty of driving behavior is higher than on flat roads. For example, when vehicles pass through traffic lights or intersections, which are very common situations, behaviors such as sudden acceleration, abrupt braking, or coasting could occur, which may incur a decreased SCR efficiency. These variations primarily depend on road conditions and driver behaviors, which cannot be identified through analyzing vehicle operational data alone. A detailed investigation into such scenarios and determining the conditions under which vehicles produce high NOx emissions at these characteristic positions is of significant importance for timely adjusting SCR control strategies and reducing real-world NOx emissions.

2 Experimental data acquisition

2.1 Acquisition of vehicle driving data

In this study, vehicle driving data was collected using a remote data monitoring platform. This platform utilizes the vehicle's data link to retrieve real-time parameter information. The communication between the data monitoring platform and the vehicle can be established through on-board communication devices, wireless sensor networks, or other communication technologies. Through this communication method, the platform can gather parameter data such as driving time, speed, mileage, and rotation speed of the vehicle.

To collect data from multiple days of vehicle operation, a freight vehicle was chosen as the research subject, as depicted in Figure 1. The vehicle was monitored on the platform, which complies with Chinese regulations for remote monitoring data acquisition. This platform enables the acquisition of the vehicle's driving information for different dates, including parameters such as driving time, speed, mileage, and rotation speed. The key parameters used in this study are presented in Table 1.

![Fig. 1. Monitored vehicle.](image)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Unit</th>
<th>Feature</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>s</td>
<td>Exhaust gas flow rate</td>
<td>mg*h⁻¹</td>
</tr>
<tr>
<td>Speed</td>
<td>Km*h⁻¹</td>
<td>Fuel Injection</td>
<td>g*h⁻¹</td>
</tr>
<tr>
<td>Engine Rotation Speed</td>
<td>r*min⁻¹</td>
<td>Upstream NOx Concentration</td>
<td>ppm</td>
</tr>
</tbody>
</table>
By continuously monitoring the vehicle and recording its driving data, a dataset of nearly 200,000 data points was accumulated. These data encompass diverse operating scenarios, including both suburban and urban areas. The data acquisition method employed ensures the reliability and representativeness of the dataset, making it possible to conduct rigorous scientific research and perform comprehensive data analysis.

### 2.2 Calculation of NOx emissions

The NOx emissions calculation method employed in this study involved on-road testing using Portable Emissions Measurement Systems (PEMS), and the Power-Based Window (PBW) method was utilized to calculate specific NOx emissions. The PBW method involves dividing the testing data into a series of subsets, referred to as windows. Each window is defined starting from the point of valid data and accumulates power until it reaches a predetermined portion of the engine's World Harmonized Transient Cycle (WHTC) power. A window is considered valid if its average power exceeds 20% of the maximum engine power. The length of each window is determined using the following formula.

\[
W(t_{2,i}) - W(t_{1,i}) \geq W_{\text{ref}}
\]  

(1)

In the equation, \(W(t_{j,i})\) represents the accumulated power of the engine from the beginning of the data up to time \(t_{j,i}\), and \(W_{\text{ref}}\) represents the power of the WHTC cycle. The NOx specific emission is calculated as the ratio of the total NOx emissions to the accumulated power in each window, and the calculation formula is as follows.

\[
e_p = \frac{m_{\text{gas}}}{W(t_{2,i}) - W(t_{1,i})}
\]  

(2)

In this equation, \(m\) represents the total amount of NOx emissions in the window, and \(e_p\) represents the NOx specific emissions.

In the context of China's sixth emission standard, a list-based method for calculating mass emissions was introduced, with the following formula:

\[
m_{\text{gas}} = u_{\text{gas}} \times \sum_{i=1}^{n} c_{\text{gas},i} \times q_{\text{mew},i} \times \frac{1}{f}
\]  

(3)

where \(u_{\text{gas}}\) represents the ratio of the pollutant component's density to the exhaust density, with a reference value of 0.001587, \(c_{\text{gas}}\) denotes the instantaneous concentration of the pollutant component, \(q_{\text{mew},i}\) represents the instantaneous mass flow rate of the exhaust, and \(f\) corresponds to the sampling frequency.

To perform the calculations, the list-based method and the power-based window method were employed. These methods allowed for accurate determination of the NOx emission characteristics based on the collected data.
3 The construction of vehicle characteristic scenarios

When vehicles pass through situations such as traffic lights or transactions, there are often corresponding changes in driver behavior, such as sudden braking, rapid acceleration, or prolonged idling. Consequently, the operating parameters of the vehicle, such as speed and acceleration, experience significant variations in the vicinity of these situations. These variations can have an impact on the functioning of the SCR system, resulting in a decrease in NOX conversion efficiency. Thus, in this study, traffic lights and transactions are defined as characteristic position scenarios.

By utilizing GPS information, the vehicle's trajectory is reconstructed on a map, facilitating a comprehensive search of the trajectory. This search enables the identification of instances when the vehicle passes through traffic lights and transactions, which serve as reference points for constructing the characteristic position scenarios. By employing this methodology, the study aims to analyze and characterize the vehicle's behavior when passing through these specific scenarios.

When a vehicle encounters a traffic light or a transaction, it is highly probable that its operating state will undergo a change. In this research, traffic lights and transactions are defined as characteristic position. To identify all characteristic positions during the driving process, GPS information is utilized to restore the vehicle's running trajectory on a map. The trajectory is then traversed and searched to determine the specific moment when the vehicle passes through a traffic light or a transaction.

The frequency of vehicle data collection is 1 Hz. To facilitate calculations, the vehicle's travel time is reset to 1, 2, ..., n. Based on the latitude and longitude information of the vehicle, the driving trajectory is plotted on the map, and select driving trajectories are illustrated in Figure 1.

It can be concluded from Figure 2 that the vehicle traversed three transactions (which marked as point 1, 2, and 3) and two traffic signals, which located at the second transaction and the third transaction. During actual driving, the process of passing through a traffic signal or a transaction can last for a certain duration. Therefore, the vehicle’s state within 100 meters of the traffic signal or transaction, including 50 meters before and after it, is considered the characteristic event at the characteristic position.

In the dataset used for this study, the vehicle passed through 338 traffic signal intersections and 237 transactions, resulting in a total of 468 characteristic positions. Since the processes of passing through a traffic signal and a transaction overlap to some extent, the number of characteristic positions is less than the sum of the individual counts of traffic signals and transactions.

![Fig. 2. Partial driving track.](image)
Figure 3 depicts the distribution of average speed under characteristic position scenarios. The speed distribution graph reveals a preference for lower speeds, with the intervals of 1-2 m/s, 2-3 m/s, and 3-4 m/s having the highest frequencies. However, the frequency of the lower speed distribution does not significantly differ from that of the mid-to-high speed distribution. This can be attributed to the fact that not every characteristic event experiences congestion. For instance, at an unobstructed green light intersection, the vehicle's speed would remain relatively constant.

![Average speed distribution](image)

**Fig. 3.** Average speed distribution.

### 4 Analysis of NOx emission characteristics

#### 4.1 NOx emission characteristics under characteristic position scenarios

In section 3, characteristic positions were identified. However, with the present of some real-time road conditions such as traffic lights and transactions, the vehicle speed did not exhibit a concentrated distribution trend at these characteristic positions. Figure 4 presents the average NOx emissions for each characteristic position, both upstream and downstream. Across all characteristic positions, the average upstream NOx emissions was 273 ppm, while the average downstream NOx emissions was 32 ppm, resulting in an average conversion efficiency of 88.3%. The lower upstream NOx concentration can be attributed to the low load operating condition of the vehicles at the characteristic position, which leads to a lower temperature within the engine cylinder and consequently lower exhaust NOx emissions.
Since parts per million (ppm) is a concentration unit representing a relative value, it cannot describe the absolute quantity of NOx emissions accurately. Therefore, the NOx emissions and specific emissions were calculated using the method outlined in the National VI standard. It should be noted that sensor malfunctions may occur intermittently due to interference from actual road conditions. Our analysis revealed that NOx emissions within the emission range of 0-0.05 g/s accounted for 99.16% of the total emissions, thus defining this range as the effective range. Additionally, NOx emissions within the 0-0.01 g/s range accounted for 88.12% of the total emissions, indicating that vehicles can effectively control NOx emissions to a reduced level in most characteristic driving events.

Figure 5 illustrates the distribution of NOx emissions in relation to speed and acceleration. This distribution was obtained by statistically analyzing the relationship between NOx emissions and the current speed and acceleration during characteristic driving events. Notably, in the high acceleration region, with the speed ranges from 5-15 m/s, higher NOx emissions were observed due to the engine operating under increased load to provide greater power. This results in higher combustion temperatures and subsequently higher NOx emissions.

According to the actual range of NOx emissions, emissions exceeding 0.03 g/s were classified as high level emissions, emissions ranging between 0.01 g/s and 0.03 g/s were classified as medium level emissions, and emissions below 0.01 g/s were classified as low level emissions.
Fig. 5. Relationship between NOx instantaneous emission speed and acceleration.

Figure 5 demonstrates a strong correlation between NOx emissions and vehicle driving speed and acceleration. In order to delve deeper into the relationship between NOx emissions and vehicle operating conditions when passing through characteristic positions, Figure 6(a) depicts the driving trajectories of vehicles in each characteristic event. The color of the trajectories corresponds to the average NOx emission rate. It is crucial to note that in this figure, the coordinate origin signifies the initial position of the vehicle when passing through the characteristic position, rather than the position of the intersection itself.
(a) Trajectories in each characteristic event (b) Relationship between accelerations and total NOx emissions (c) Relationship between accelerations, minimum speed and total NOx emissions

**Fig. 6.** Total NOx emissions in each characteristic event.

Figure 6(b) presents the relationship between total NOx emissions, maximum acceleration, and minimum acceleration of the vehicle in each characteristic position scenario. Furthermore, Figure 6(c) adds the minimum speed to Figure 6(b). Through the analysis of both Figure 6(b) and Figure 6(c), it can be concluded that high NOx emissions are more likely to occur in characteristic positions when the vehicle operates at a small minimum speed and a medium or large maximum acceleration, which may indicate a stop-start process at the crossroad. Conversely, when the vehicle passes through characteristic positions without stopping, while maintaining a lower speed and lower maximum acceleration, indicating less aggressive acceleration by the driver, the NOx emissions will not be too high.

### 4.2 Analysis of high NOx emission scenarios

Figure 6(a) illustrates the driving trajectories in various characteristic events, highlighting noticeable differences in NOx emissions among them. Figure 7 makes a comparison between medium-high NOx emission events and other events. Although only 4% of all characteristic events fall into the medium-high NOx emission category, they contribute to 50% of the total NOx emissions in all characteristic events. Therefore, conducting further investigations into these specific high NOx emission situations can greatly assist in optimizing the SCR control strategy.
Figure 6(b) and Figure 6(c) indicate that NOx emissions in characteristic events are not strongly correlated to minimum accelerations. Therefore, the subsequent analysis in this study will primarily focus on the analysis of maximum accelerations of vehicles.

As mentioned in section 3.1, high NOx emissions are more likely to occur when the vehicle operates at a small minimum speed and a medium or large maximum acceleration. Figure 8(a) illustrates the relationship between maximum accelerations, minimum speed, and total NOx emissions in each characteristic event.

**Fig. 8.** (a) Relationship between maximum accelerations, minimum speed and total NOx emissions (b) relationship between maximum acceleration, accelerate duration, and total NOx emissions.
The event points with the highest total NOx emissions in Figure 8(a) are concentrated along the x-axis. To provide more detailed information about these points, Figure 8(b) depicts the relationship between maximum acceleration, accelerate duration, and total NOx emissions.

To further investigate the driving behaviors that contribute to high NOx emissions in these scenarios, some specific high-NOx-emission events were selected for detailed analysis. These events are marked as number 1 to 3 in Figure 8(a) and Figure 8(b).

Event 1 has a maximum acceleration of a medium value, 1.1 m/s², and a minimum speed down to 0 m/s, which indicates that in event 1, the vehicle stopped at the crossroad waiting for the traffic signals. The detailed information of event 1 is shown in Figure 9(a).

It is evident that a significant portion of NOx emissions in this event occurred during the vehicle's startup phase when the traffic light turned green, with a tailpipe NOx emission up to 0.164 g/s. At this moment, when the driver pressed the accelerator pedal, a large amount of fuel was instantaneously injected into the engine, while the SCR system did not respond by injecting NH3 accordingly. This imbalance between fuel injection and NH3 injection resulted in lower SCR efficiency, with a NOx conversion efficiency lower than 50%, and an increase in tailpipe NOx emissions, leading to significant NOx emissions during this phase.

In Figure 9(b), the variation in SCR temperature in event 1 is illustrated. It is evident that due to the vehicle coasting for over twenty seconds before coming to a stop and idling for ten seconds while waiting for the traffic light, the SCR temperature, which initially was not very high, dropped below 200 °C. As a result, despite the sudden increase in raw NOx emissions, the SCR system was unable to immediately inject NH3 due to the low temperature. This low temperature condition contributed to the high NOx emissions observed in this specific event.
In event 2, the minimum speed of the vehicle did not drop to 0, and the vehicle went through an accelerate period lasting over 10 seconds with a maximum acceleration lower than 0.5 m/s², indicating that the vehicle crossed the intersection in a relatively smooth manner. Figure 10(a) provides detailed information about event 2. From Figure 10(a), it can be observed that the high NOx emissions in this event are attributed to the lack of corresponding NH3 injection by the SCR system when the exhaust NOx level increases. This is because the SCR operates at a temperature below 200°C throughout this event. To identify the reason behind this, Figure 10(b) retraces the vehicle's operating conditions for 800 seconds before event 2.

Based on Figure 10(b), it is evident that the vehicle encountered prolonged start-stop cycles before entering this characteristic event, likely due to traffic congestion. The extended idling periods resulted in consistently low SCR temperatures. Even though the vehicle passed through the characteristic event at a relatively low and constant speed, the low SCR efficiency would still lead to a high NOx emission of 0.105g/s.

Furthermore, Figure 10(b) highlights a sudden drop in SCR temperature, accompanied by the vehicle speed and fuel injection dropping to zero at approximately 700 seconds before event 2. This occurred because the driver turned off the engine at that time, causing the onboard data acquisition system to cease functioning. According to the timestamp data, the engine remained off for a duration of 196 seconds at that location, resulting in a decrease in SCR temperature by nearly 40°C. This incident also contributed to the low SCR temperature observed during the event.

**Fig. 9.** (a) Detailed information of event 1 (b) Temperature information of event 1.
Fig. 10. (a) Detailed information of event 2 (b) Temperature information before event 2.

Figure 11 provides detailed information about event 3, which is located near event 2 in Figure 8(a) and Figure 8(b). However, as is shown in Figure 11, the situations in event 3 and event 2 are distinctively different. In event 3, the vehicle passed through the intersection with sustained acceleration within a very short period of time. The vehicle's speed rose by 100%
after passing through the characteristic position, and there was a significant amount of fuel injection at the intersection. This situation is likely a result of the driver's attempt to take advantage of the green light by aggressively stepping on the accelerator pedal to swiftly pass through the intersection, leading to a sudden increase in exhaust NOx emissions, which was as high as 0.59 g/s. Despite the immediate injection of NH3 by the SCR system, the excessive exhaust NOx emissions still caused an increase in tailpipe NOx emissions, which would reach to 0.14 g/s.

Based on the analysis above, two main factors contribute to excessive NOx emissions in characteristic position events are identified. One is low temperature, which leads to the cessation of ammonia injection by the SCR system and a decrease in SCR conversion efficiency, the other is the sudden occurrence of excessive fuel injection during normal driving, resulting in an instant increase in original emissions.

Driver behaviors that contribute to low SCR temperatures primarily include prolonged periods of coasting or idling, as well as engine shutdown. Coasting behavior may occur when the vehicle is about to reach an uncrowded intersection, and the driver determines that the vehicle can coast to this intersection. Prolonged idling may occur when the vehicle is unable to pass through an intersection within a short period, which could be due to traffic congestion or a long line of vehicles waiting for a traffic light. Engine shutdown mainly occurs in congested traffic situations. To improve SCR efficiency in such scenarios, measures such as increasing the idle fuel injection rate or adjusting the fuel injection phase can be taken to raise the exhaust temperature during prolonged idle conditions or after engine shutdown and restart, helping the SCR reach 200°C as early as possible.

Driver behavior that leads to excessive fuel injection during SCR operation is primarily aggressive acceleration. This situation is likely to occur when the green light is about to turn
red. To reduce NOx emissions in such situations, it would be better if road traffic signal information could be integrated. When it is detected that the green light is about to turn red, timely increasing the amount of ammonia injection would be beneficial in reducing NOx emissions.

5 Conclusions

Based on the analysis of actual road data, this study has defined traffic lights and transactions as characteristic position scenarios, and analyzed the NOx emission characteristics in these scenarios. The key conclusions drawn from the study are as follows:

(1) Characteristic position scenarios were defined by utilizing GPS information to identify specific 50-meter stretches before and after traffic lights and transactions. The analysis in NOx emission characteristics in characteristic position scenarios shows that higher NOx emissions are more likely to occur when the minimum speed is down to 0 and the maximum acceleration reaches over 1 m/s², which may indicate a stop-start process at the crossroad.

(2) Through the analysis of typical high NOx emission characteristic events, the main reasons for increased NOx emissions at intersections have been identified. These reasons include prolonged idling periods or engine shutdown, which can lead to low SCR temperatures and a potential cessation of NH3 injection, and sudden excessive fuel injection which would result in high exhaust NOx emissions, with exhaust NOx emissions reaching more than 0.5 g/s, leading to high tailpipe NOx emissions.

(3) Driver behaviors that may contribute to increased NOx emissions in characteristic position scenarios were analyzed, including coasting in neutral gear when approaching intersections, frequent start-stop due to congestion or road crowding, choosing to shut off the engine for fuel efficiency during prolonged traffic congestion, and aggressively accelerating by stepping on the accelerator when the green light is about to turn red. Note that when facing the same road conditions, different drivers may employ different driving strategies. For instance, when approaching a red light, some drivers may drive up to the intersection before decelerating, while others may choose to coast. Similarly, when a green light is coming to an end, some drivers may choose to accelerate and rush through, whereas others may prefer to stop and wait for the next green light. Therefore, in addition to analyzing objective road conditions, it is crucial to analysis the driver's driving styles to optimize SCR control strategies. It is advisable to take both factors into account when designing SCR control strategies in the future works.

Reference


