The evaluation of NO\textsubscript{x} emissions in RDE tests including dynamic driving conditions

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Abstract. Nowadays, one of the most critical roles of both legislators and society itself is to look after the future of our environment. There are many reasons for the deterioration of air quality. Unfortunately, pollution from the automotive sector is still widely regarded as one of them. For this reason, the European Commission has been improving testing procedures for years, including more and more advanced measurement capabilities and extending testing to include further exhaust gas compounds. The object of the article is to assess the actual emission of nitrogen oxides (NO\textsubscript{x}) from two passenger cars equipped with gasoline engines. The authors carried out the tests according to the guidelines of the Real Driving Emissions (RDE) test procedure with the use of PEMS (Portable Emissions Measurements System) mobile measuring equipment. The influence of dynamic conditions (such as vehicle speed, acceleration and product of vehicle speed and acceleration) during the tests on NO\textsubscript{x} emissions was determined and the areas in which this relation was the most visible were estimated.

1. Introduction

Understanding the issue of vehicle emissions is essential in order to develop more precise legislation and increase the effectiveness of its application in practice. The aim of this article is the assessment of nitrogen oxides (NO\textsubscript{x}) emissions from passenger cars, which, especially in urban agglomerations, is still a challenge for the European Commission. Legislators have been introducing increasingly restrictive legislation for years. Thanks to them, discrepancies between the emission results obtained in lab conditions and those obtained in actual operation are strictly controlled. The Commission Regulation (EU) 2018/1832 of 5 November 2018 [1] introduced the package 4 of the Real Driving Emissions (RDE) test procedure, which complemented this procedure. This procedure is crucial because it concerns exhaust emissions under real driving conditions. Moreover, it includes measurements of the most problematic exhaust compounds (such as nitrogen oxides and solid particulates). This is not the end of the changes, as implementing Regulations [2, 3] have introduced improvements in the determination of CO\textsubscript{2} values for certain categories of new light vehicles. In this article, the authors focused only on NO\textsubscript{x} emissions so other compounds are not analysed.

So far, many scientists have published publications on vehicle emissions under real traffic conditions. However, the RDE test procedure is very complicated, has several requirements to meet, and at the same time takes place under varying road conditions. It raises many questions, e.g. how to design a methodology for testing RDE tests and what to test so that the results of the compared parameters are reliable. It is essential both to select suitable test objects and to focus on the specific requirements of the
RDE test procedure (and their detailed analysis). The authors of the article [4] stated that comparing vehicles based on their age is not a goal because it does not fully reflect the changes in the level of road emissions of particular exhaust compounds. In turn, the author [5] concluded that it is necessary to focus more on the analysis of dynamic parameters in the urban part. In her opinion, the current form of the RDE test does not fully reflect driver behaviour especially in congested cities. A detailed analysis of parameters such as fuel type, driving dynamics, topography or driver's behaviour is essential because these parameters currently contribute to differences in emissions of on-road tests. The authors of the article [6] checked the influence of the road slope and driving style on the NOx and CO2 emission values. According to them, the difference in NOx emissions between normal and aggressive driving style is up to 55%. The authors of the article [7] attempted to evaluate the impact of the RDE test dynamic conditions Relative Positive Acceleration (RPA) and 95th percentile of vehicle speed (v) and acceleration (a) product, as defined in the RDE test requirements. They were focused on the road emission of exhaust compounds from gasoline engines. They also noticed that for a passenger car with a gasoline engine, the dynamics of the test (RPA values) is connected with on-road exhaust emissions of carbon monoxide (CO), carbon dioxide (CO2), NOx, and hydrocarbons (HC). For the second dynamic test parameter (95th percentile values of v·a), the increasing 95th percentile values of v·a results in a decrease of CO, CO2, NOx, and HC on-road exhaust emissions. A detailed analysis of the dynamic parameters obtained during tests under real traffic conditions will allow for better correlation between the RDE test and the test carried out in laboratory conditions. It will allow for better design of the test. Moreover, understanding these exhaust gas details is particularly important from the perspective of the further development of test procedures under real traffic conditions, not only for vehicles equipped with gasoline or diesel engines but also for alternative [8-9] vehicles, which are increasingly emerging on the European market.

2.Methodology

The tested objects in real driving conditions were accessible in the European cities. There were two passenger cars (#1 and #2) equipped with a gasoline engine, meeting the Euro 6c (#1) and Euro 6d-temp (#2) emissions standard (Table 1). The fulfilled requirements of the RDE test procedure are marked green. A characteristic feature of the vehicles tested were similar engine operating parameters (engine power, torque and displacement). Moreover, their curb weight was similar.

According to the latest legislative requirements of the RDE test procedure, the research route was designed and divided into three sections (in urban, rural, and motorway conditions). The authors carried out the test drives on the same research route in the city of Poznan and its surroundings. There were three tests for each passenger car. All the test drives were made by the same driver and under similar weather conditions. The air temperature was 26 ° C, so during the tests, the air conditioning was switched on. Following the requirements of the RDE test procedure, the values obtained during cold start have been included in tests. The road tests were not conducted in a biased manner, i.e. the driver's driving style was regular (neither too aggressive nor too slow). However, each journey was characterised by different, unpredictable road conditions during the test (e.g. random situations on the road or temporary changes in traffic) which had an influence on the results obtained. It is worth noting that despite the occurrence of these events, the requirements of the RDE test procedure have been maintained. All the tests were by the RDE test procedure; examples of results for both vehicles are shown in the table 2.

For measuring the concentration of NOx, a mobile measuring apparatus of the portable emissions measurement system (PEMS) type (Semtech DS) was used. Besides, the Global Positioning System (GPS) signal was recorded at a frequency of 1 Hz during testing. The research equipment used was compliant with the European Union requirements concerning the measurement of harmful exhaust compounds from passenger cars under real traffic conditions.
Table 1. Characteristics of vehicle/engine used in testing.

|                | #1       | #2       |
|----------------|----------|----------|
| Displacement [dm³] | 1598     | 1598     |
| Mileage [km]     | 15000    | 40000    |
| Curb weight [kg] | 1320     | 1300     |
| Emissions standard | Euro 6c  | Euro 6d-temp |
| Max power [kW] at [rpm] | 81/5500 | 97/6400 |
| Max torque [Nm] at [rpm] | 152/4500 | 160/4400 |

Table 2. RDE results obtained during tests (examples): a) vehicle #1, b) vehicle #2.

| ROUTE CHARACTERISTICS | Urban | Rural | Motorway | Total |
|-----------------------|-------|-------|----------|-------|
| Trip distance         | 15 km | 15 km | 15 km    | 41 km |
| Trip duration         | 90-120 min |       |          |       |
| Cold start duration   |      |      |          |       |
| Distance share        | 29.4% | 20.4% | 20.4%    | 22.4% |
| Average speed         | 30-40 km/h | 77-74 km/h | 130-166 km/h | 47-81 km/h |
| RCA (m/s²)            | > 0.15 | > 0.05 | > 0.05   | > 0.16 |
| 95%-percentile (V+Vₐ) [m/s²] | > 17.060 | > 24.780 | > 28.920 |       |

| ROUTE CHARACTERISTICS | Urban | Rural | Motorway | Total |
|-----------------------|-------|-------|----------|-------|
| Trip distance         | 14 km | 14 km | 14 km    | 42 km |
| Trip duration         | 90-120 min |       |          |       |
| Cold start duration   |      |      |          |       |
| Distance share        | 29.4% | 20.4% | 20.4%    | 22.4% |
| Average speed         | 30-40 km/h | 77-74 km/h | 130-166 km/h | 47-81 km/h |
| RCA (m/s²)            | > 0.14 | > 0.05 | > 0.05   | > 0.16 |
| 95%-percentile (V+Vₐ) [m/s²] | > 17.400 | > 24.780 | > 28.920 |       |

3. Results

In the first stage, the aim of the analysis was dynamic parameters (such as vehicle speed (V), engine speed (n), vehicle acceleration (a), engine load (Z), exhaust gas temperature temperature (Tₑₐₓₜₐₜ)) and the instantaneous NOₓ emissions intensity (Eₑₐ₇ₑₐₙₐ) during the tests. Fig. 1a–j shows examples of results obtained during one of the tests of vehicles #1 and #2. Even though the carried out tests were on the same test route, by the same driver, theoretically the same driving style, the results differ. The speed profiles of the vehicle and the instantaneous NOₓ emissions intensity are different. The passenger car #1 has significantly higher values of this exhaust compound. The maximum values reaches almost 12 mg/s and they are observed in the urban part (V ≤ 60 km/h) during accelerations.

Both cars have similar exhaust gas temperature profiles. During the tests of car #1, the exhaust gas increases by almost 170 °C and for car #2 by almost 202 °C. The engine load values of the #1 car engine do not exceed 55%, while the #2 car engine is up to 100%.
Fig. 1. Profiles of: a), b) vehicle speed, c), d) engine speed, e), f) vehicle acceleration, g), h) exhaust gas temperature and the instantaneous NOx emissions intensity obtained during the tests for vehicles #1 and #2 (examples)
Fig. 1. Profiles of: i), j) engine load and the instantaneous NO\textsubscript{x} emissions intensity obtained during the tests for vehicles #1 and #2 (examples)

The next step in analysing the obtained results was to determine the instantaneous NO\textsubscript{x} emissions intensity in terms of acceleration, the product of vehicle speed and acceleration, vehicle speed and exhaust gas temperature values. The results were divided into 3 parts: in urban, rural and motorway conditions. In both cases, the highest values of instantaneous NO\textsubscript{x} emissions intensity are achieved in the urban part. For car #1 the value reaches almost 12 mg/s, and for car #2 it is three times lower (Fig. 2a–b). The average instantaneous emissions intensity in the urban, rural and motorway sections reach the following values (0.55 mg/s, 0.44 mg/s, 0.28 mg/s, respectively) for car #1. This observation confirms the need to reduce them, as especially in urban agglomerations people are directly exposed to their negative impact the most. Fig. 2c–d show the acceleration range, which is from -4 m/s\textsuperscript{2} to 4 m/s\textsuperscript{2} (#1). In the case of vehicle #2, the values of instantaneous emission intensity are more cumulative, and they are in the range of slightly lower vehicle acceleration (between -2 m/s\textsuperscript{2} to 2 m/s\textsuperscript{2}). This drive test is more fluent and includes more acceleration changes. The average instantaneous emissions in the urban, rural and motorway parts reach the following values (0.20 mg/s, 0.32 mg/s, 0.53 mg/s, respectively).

Fig. 2. Emissions of NO\textsubscript{x} in the relation to: a), b) vehicle acceleration, c), d) vehicle speed and acceleration product divided into urban, rural and motorway conditions for car #1 and #2.
It was observed that during tests of the car #1, the mass of NO\textsubscript{x} emitted in the urban, rural and motorway parts is 70%, 22%, 8%, respectively. Whereas during the car #2 test the values are 54%, 22%, 24%, respectively. Fig. 3 shows the results of the instantaneous NO\textsubscript{x} emissions intensity in terms of the vehicle speed test (Fig. 3a,b) and the exhaust gas temperature (Fig. 3c,d). All results are divided according to the section of the test, i.e. urban, rural and motorway parts. A detailed analysis of the exhaust gas temperature obtained during the tests is discussed in the further part of this article.

![Fig. 3. Emissions of NO\textsubscript{x} in relation to: a, b) vehicle speed, c, d) exhaust temperature for car #1 and #2.](image)

Fig. 4 show the distribution of engine load results obtained during both RDE tests. In the case of car #1 the engine operates in lower values (up to 60%). While engine load values of car #2 reaches 100%. A detailed analysis of the engine load in terms of NO\textsubscript{x} emissions intensity obtained during the tests is discussed in the further part of this article.

![Fig. 4. Engine load obtained during tests: a) vehicle #1, b) vehicle #2.](image)
Figure 5 show the results of the dynamic conditions specified in the RDE test procedure. As required, this parameter is calculated for each part of the test. The graphs show averaged results. All results are in accordance with the RDE procedure (Fig. 5a–b), i.e. the results of the RPA parameter do not exceed a minimum value. The RPA results obtained during the tests of the car #1 in the urban, rural and motorway parts are 0.21 m/s², 0.08 m/s², 0.13 m/s², respectively. For the second parameter, i.e. 95th percentile of V·a, the results obtained did not exceed the maximum value (Fig. 5c–d), i.e. they complied with the Regulation [1]. The results are as follow 12.24 m²/s³, 13.64 m²/s³, 16.18 m²/s³, respectively. While for vehicle #2 results are as follow 0.24 m/s², 0.09 m/s², 0.09 m/s² respectively. For the second parameter, i.e. 95th percentile of V·a, the following results were obtained 12.80 m²/s³, 15.79 m²/s³, 16.63 m²/s³, respectively.

![Graphs showing RPA and V·a results for cars #1 and #2.](image)

**Fig. 5.** The results of the dynamic conditions: a), b) RPA, c), d) 95th percentile of V·a for cars #1 and #2.

Based on the results obtained, two-dimensional characteristics of NOx mass and shares in coordinates of engine speed and load were determined (Fig. 6, 7). For #1 the highest mass values are achieved in the range of n = 800–2800 rpm, Z = 0–40%; max value is almost 373 mg (n = 1600–2000 rpm, Z = 10–20%). However, in the case of passenger car #2, engine load range was greater, i.e., from 30 to 100%. The highest values of NOx mass are achieved in the range of n = 2000–2800 rpm, Z = 70–100%; the maximum value is about 170 mg (n = 2000–2400 rpm, Z = 80–90%). The emission shares have a similar distribution.

In the case of NOx mass and shares in coordinates of exhaust gas temperature and engine load, the highest values of emitted NOx mass for car #1 are achieved in the range of T_exh = 90–180 °C, Z = 0–40% The maximum value reaches almost 581 mg (n = 1600–2000 rpm, Z = 10–20%). However, in the case of passenger car #2, engine load range was greater, i.e., from 30 to 100% (Fig. 8). The highest values of emitted NOx mass are achieved in the range of n = 90–210 °C, Z = 30–100%. The maximum value is almost 135 mg (T_exh = 180–210 °C, Z = 80–90%). As expected, the largest shares of NOx mass are observed in the exhaust temperature range between 120 and 150 °C (during tests the car #1). In the case of test #2, the exhaust temperature is up to 240 °C (Fig. 9). Fig. 10 presents a summary of the on-road emission of NOx for the cars tested.
Figure 6. The comparison of NO$_x$ emissions mass in both tests in the coordinates of the engine speed and load: a) #1, b) #2.

Figure 7. The comparison of NO$_x$ emissions shares in both tests in the coordinates of the engine speed and load: a) #1, b) #2.

Figure 8. The comparison of NO$_x$ mass in both tests in the coordinates of exhaust gas temperature and engine load a) #1, b) #2.
Figure 9. The comparison of NOx emissions intensity in both tests in the coordinates of exhaust gas temperature and engine load a) #1, b) #2.

Fig. 10. On-road emission of NOx for both passenger cars.

4. Conclusions

Since 2017, there are two emission tests WLTC (Worldwide Harmonized Light Vehicles Test Cycle); under laboratory conditions and RDE (under real driving conditions) in the European Union legislation regarding passenger cars. The reason for complementing the RDE test was to complement the WLTC laboratory test. In combination, these tests form a complete emission test reflecting the engine parameters during the actual operation. Moreover, the RDE test considers many unpredictable traffic situations, e.g., ambient conditions, driver behaviour, traffic congestions, and random events occurring during the test drive. Thanks to which it reflects the conditions of real driving much better. Furthermore, the use of increasingly advanced exhaust after-treatment systems, as well as the introduction of restrictive legislation, allows the reduction of NOx emissions.

The aim of this article was the assessment of nitrogen oxides (NOx) emissions from passenger cars during tests in real driving conditions. Two gasoline passenger cars of different emission classes were used for the tests; Euro 6c (#1) and Euro 6d-temp (#2). The results obtained indicate that most nitrogen oxides mass is emitted in the urban part of the RDE test; regardless of the emissions standard. After analysing the results of the instantaneous NOx emissions intensity, it was observed that despite the #2 vehicle was operated on parameters higher than #1 (higher engine speed and engine load), its NOx emission intensity is lower. The obtained results were compared with the results of publications[10, 11], where the test objects met the previous emissions standard (Euro 6b). It confirmed that results obtained in this article are caused by the higher conversion efficiency in the catalytic converter. Therefore the next
generation of Euro 6d-Temp emission class vehicles is much better in terms of NO\textsubscript{x} reduction than the previous one.

**Founding**

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