Measurements of particulate emissions from Euro 5/6 passenger cars in different drive settings

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Abstract. The article presents the particulate emission measurements of passenger cars that meet the latest emission norms, the development of which has so far been dictated by requirements of downsizing. The comparison was made based on the selected vehicles equipped with spark-ignition engines, which are an example of reducing the displacement volume while maintaining the operational parameters of the drive units. Particle emissions were measured during tests in real traffic conditions. The change in the vehicle's emission category caused an increase in requirements regarding emitted particles number from these engines. As a result, the introduction of particulate filters into exhaust after-treatment systems of gasoline engines (so far only three-way catalytic converters have been used) became necessary. Comparisons of the mass and particles number and their dimensional distribution for vehicles of different ecological classes, and also engines before and after downsizing were the basis for making conclusions about the direction of changes in traditional propulsion units in modern vehicles.

1. Introduction

Despite constant changes in legislation, road transport is still considered the most important source of hydrocarbons, carbon monoxide, carbon dioxide, nitrogen oxides, and particulate matter emissions. These compounds cause not only the deterioration of air quality but also the human health condition. This effect is particularly visible in many urban areas. It has led legislators to adopt more stringent pollutant emission standards for the automotive sector worldwide [6]. For example, by 2021, the limits on carbon dioxide emissions will have been reduced to 95 g/km. Unfortunately, the growing number of passenger cars moving within the European Union is becoming a real issue. That is the reason to develop better key emission control strategies [11].

Increasingly stringent environmental requirements have resulted in significant changes in the exhaust emissions evaluation from motor vehicles [7, 9]. It was considered that type approval tests carried out in laboratory conditions (on a chassis dynamometer) are not sufficient. They are performed under strictly defined conditions (such as temperature, humidity), and the lack of unpredictability factor causes that the results of exhaust emissions do not match those of traffic conditions. Introducing the equivalent exhaust emissions testing in real traffic conditions has amended that. Such real traffic conditions may be characterized by variability of parameters (in an extent as limited by standards). At the same time,
the values of exhaust emissions cannot be higher than those specified in the relevant regulations. The tests are possible to perform by using PEMS type mobile research equipment [17].

According to the Commission Regulation 2016/646 [1] of 20 April 2016 amending Regulation 692/2008 [3] a new emissions norm Euro 6d-Temp has been established. The requirements of this norm are an extension of the Euro 6 emissions norm regarding road exhaust emissions of nitrogen oxides and the particle number emissions for passenger cars equipped with gasoline engines, as well as introducing conformity factors (excess emissions) which have been given the value of 1.43 (from 2020). The Real Driving Emissions procedure has been introduced in the European Union by Regulation 2017/1151 [4] and updated by Regulation 2017/1154 [5] (Fig. 1).

Figure 1. The RDE test requirements [2].

For practical purposes, the RDE procedure has been developed in four separate packages [6, 15]. The first package, which was adopted in May 2015 (Fig. 2), defined the general RDE test procedure. The second package, which was adopted in October 2015, introduced the NOx Conformity Factor (CF). From September 2020, RDE emissions of new car models need to meet an NTE (Not-To-Exceed) emissions limit and the conformity factor for NOx emissions equal to 1.43 (an extra 43 per cent tolerance in emission value compared to the current NOx limit of 60 mg/km – in the case of a spark-ignition engine). Package 3 introduced both conformity factor for particle number and RDE cold start emissions [14, 16]:

- max vehicle speed ≤ 60 km/h,
- average vehicle speed (including stops) 15–40 km/h,
- total stop time < 90 s,
- idling after ignition 15 s,
- idling after vehicle conditioning for cold start testing driven for at least 30 min followed by soak duration in the range of 6 to 56 hours.

Package 4 has added not only In-Service Conformity RDE testing but also market surveillance.

Figure 2. Requirements for type approval tests and real operating conditions for passenger vehicles in 2015-2023 [12, 13].
However, the biggest challenge for designers is still the emission of solid particles [8, 10]. The particulate matter (PM) reduction was mainly due to the use of particle filter (GPF). The effectiveness of using such filters, in this case, is 99.9%, while the reduction in particle number (PN) is about 95%.

The article concerns the comparison of the change in the number of solid particles and their dimensional distribution in road tests for two categories of vehicles – Euro 5 and Euro 6d-Temp, in which engines with different technical parameters were used, however, assembled in the same vehicles. The analysis for various drive settings (Eco, Comfort, Sport) was made. The presented field of research has not been published in reference to the RDE tests so far, and the results obtained may be used for further studies which develop the subject.

2. Measurement methodology in real traffic conditions

2.1. Test vehicles

The article presents the research results of the number of particles in RDE tests for two passenger cars equipped with spark-ignition engines with direct fuel injection. The main requirement for selected research objects was the difference in engine emissions class – they meet the Euro 5 and Euro 6d-Temp emissions standard. The second vehicle was equipped with smaller engine displacement and a gasoline particulate filter (GPF). Other criteria, including the curb weight of vehicles and the type of propulsion, were similar in construction. Detailed technical data of vehicles is presented in Table 1, and the characteristics of their engines – in Figure 3.

| Table 1. Characteristics of engine/vehicle used in testing |
|------------------------------------------------------------|
| Parameter | Euro 5 | Euro 6d-Temp |
| --- | --- | --- |
| Cylinder number, arrangement | 4, in series | 4, in series |
| Displacement [cm\(^3\)] | 1991 | 1497 |
| Engine | standard | downsized |
| Max. power [kW] / [rpm] | 135/5500 | 135/5800 |
| Max. torque [Nm] / [rpm] | 300/1200–4000 | 350/1200–4000 |
| Fuel injection | direct injection | direct injection |
| Three Way Catalyst | yes | yes |
| Gasoline Particle Filter | no | yes |
| Gearbox | 7, automatic | 9, automatic |
| Vehicle curb weight [kg] | 1570 | 1635 |
2.2. Measuring equipment

This section describes a complete system for measuring the emission of pollutants emissions in RDE tests, while the article describes test results obtained only with the equipment for measuring the number of particles. The testing apparatus is presented in Figure 4. A portable Semtech DS analyser and Engine Exhaust Particle Sizer Spectrometer were used for the measurement of exhaust emissions from vehicles. It allowed measurements of CO, CO₂, HC, NOₓ and PN. In terms of benchmarking and quality control, zero-span checks were performed before and after each measurement. Linearisations of the equipment were carried out every three months (manufacturer's requirement). Post-processing plausibility checks were made on all data, focusing on CO₂ to ensure that the data collected were realistic. The emissions measurement equipment had a maximum mass of 46 kg (PEMS Gas and PN = 25 kg), together with an additional power supply (generator) – 21 kg.

![Diagram of the measurement system used for testing](image)

**Figure 4.** Diagram of the measurement system used for testing (a) and mobile exhaust gas analyzer with marked flue gas flow (b) for the measurement of gaseous compounds and particulates; T – ambient temperature, Rh – air humidity, OBD – On-Board Diagnostic.

3. Results and analysis

Measurements of the particle number were made in the RDE test during the urban part (taking into account the cold start of the engine), rural and motorway. Figure 5 also indicates the road category (U/R/M) during such a test. The parameters for the validity of the test were met during all test drives. Figure 6 shows the dynamic parameters of such tests, which indicate the differentiation of individual modes of the propulsion system in vehicles.
Figure 5. Example of vehicle speed during RDE test and indication of road category.

The values of the 95th percentile of the product of vehicle speed and positive acceleration for all tests were varied, as well as the relative positive acceleration values were also different (Figure 6). It was a premise to state that the dynamic driving conditions of the tests were not identical. On this basis, the comparison of the number of particles during such tests is possible to make.

Figure 6. Dynamic driving parameters during RDE tests: a) 95th percentile of the product of the vehicle speed and positive acceleration and b) relative positive acceleration.

When the driver used the Eco mode (the lowest values of driving dynamics), the number of particulates related to the road emissions indicated that this emission was close to the value of the emission obtained in the Sport mode (for both vehicles tested). It was mainly because, in the Eco mode, the Start-Stop system is activated, which reduced fuel consumption when the vehicle stops. Unfortunately, this has consequences in the form of increased particle emissions during the subsequent engine starts (Figure 7). In the Comfort and Sport mode this function was inactive, which meant that for a vehicle with Euro 5 emission class (without GPF), emissions of the particulate number were the highest in the Sport mode (approx. 100 times for Euro 5 vehicle). However, for a vehicle with Euro 6d-Temp emission class (with GPF), the differences in the level of particle emissions during different driving modes were small.
Figure 7. Particle number during road tests for various vehicle emission categories in the individual parts of the test, and the entire test.

The analysis of particulate emissions during the cold start, concerning the entire test, shows that the largest share of the cold phase (calculated here as 300 s from engine start) occurs for a vehicle with Euro 5 emission class in the Eco mode. The share of the cold start phase in the entire RDE test is by 17%. It indicates a high emission of particulate matter in the initial period of engine operation. This share decreases as the vehicle dynamics increases (from 17% to 8% – in the Sport mode). For Euro 6d-Temp emission class vehicles, these values were similar – regardless of the driving mode, they are approximately 3–4%. It demonstrates the high efficiency of reducing the number of particles in the initial phase of engine operation – this is the result of using a particulate filter (Figure 8). Detailed differences are shown in Figure 9, where the particle size distribution of the tested vehicles was compared. For the Euro 5 emission class vehicle, the concentration of particulate matter is significantly higher (around 70–100 times) than for the Euro 6d-Temp emission class vehicle equipped with a particulate filter.

Figure 8. The share of the number of particulates during cold start phase in relation to the number of particulates in the entire RDE test for different driving modes of vehicles with different engine emission class.
Figure 9. Size distribution of solid particles during testing of Euro5 / Euro 6 vehicles.

A thorough analysis indicates different characteristic size distribution of the emitted particles of both vehicles. For the vehicle with Euro 5 emission class, it is in the range of 34–45 nm, while for the vehicle with Euro 6d-Temp emission class equipped with a particulate filter it is 45–60 nm.

Comparing the particle size distribution for the appropriate driving modes in the RDE test and during a cold start phase, the same relations can be noticed several times higher concentration of solid particles during cold start for particles of all size range. This correlation shows that the particulate emissions during the cold start phase are not only relevant for vehicles without particulate filters but also equipped with such devices. The most significant differences can be observed after starting the Start&Stop system (Eco mode).

4. Summary

Vehicle design solutions are a consequence of changes introduced in the exhaust toxicity regulations. The application of increasingly stringent requirements regarding the permissible value of the particulate number has forced the designers to introduce the particulate filters into the exhaust after-treatment systems of gasoline engine vehicles.
The tests performed on the influence of different vehicle settings on particulate emissions indicate that the use of different propulsion system operation practices has a significant impact on their results. For a Euro 5 vehicle, a change in driving mode (e.g. Comfort/Sport) results in an approximately 100-fold change in particle numbers (in nearly all parts of the RDE test). Significantly lesser differences were observed for a Euro 6d-Temp vehicle equipped with a particulate filter.

Similarly, the proportion of particle emissions during a cold start was also reported for the whole RDE test. For a vehicle without a particulate filter, this is between 8% and 17% (for the Sport/Eco driving mode, respectively). In contrast, for a Euro 6d-Temp vehicle, this share is only 3–4% (regardless of the driving mode).

These conclusions are confirmed by an analysis of the number of particles according to particle diameter; in each driving mode, a significantly higher number was recorded during the cold start phase. The authors of the article compared vehicles of different emissions class in terms of particulate emissions in road tests. At the same time, they pointed out that the use of particulate filters in gasoline engines with direct fuel injection allows to 100-fold reduce of particle number. The effectiveness of such a solution has also been confirmed in the analysis of particle size distribution. It shows that such filters can significantly reduce the concentration of particles of all sizes. It should be added that particulate emissions during cold start phase are significant in both cases, for vehicles without particulate filters and for cars equipped with such devices. In addition to the above, the most significant differences are visible when the system Start&Stop (Eco mode) is activated.

**Founding**

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