An assessment of consistence of exhaust gas emission test results obtained under controlled NEDC conditions

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Abstract. Measurements concerning emissions of pollutants contained in automobile combustion engine exhaust gases is of primary importance in view of their harmful impact on the natural environment. This paper presents results of tests aimed at determining exhaust gas pollutant emissions from a passenger car engine obtained under repeatable conditions on a chassis dynamometer. The test set-up was installed in a controlled climate chamber allowing to maintain the temperature conditions within the range from –20°C to +30°C. The analysis covered emissions of such components as CO, CO₂, NOₓ, CH₄, THC, and NMHC. The purpose of the study was to assess repeatability of results obtained in a number of tests performed as per NEDC test plan. The study is an introductory stage of a wider research project concerning the effect of climate conditions and fuel type on emission of pollutants contained in exhaust gases generated by automotive vehicles.

1. Introduction

Harmful impact of transport on the environment includes emissions of gas and dust pollutants generated by combustion engines. Since many years, enormous research effort is put into studies aimed at minimisation of energy consumption and reduction of emissions of pollutants included in exhaust gases. The related progress is reflected in newly introduced emission standards and procedures applicable to combustion engine testing. Passenger cars and lightweight utility vehicles in the European Union are subject to Euro procedures which determine standards for emissions of pollutants in exhaust fumes determined in the course of drive tests under controlled conditions of chassis dynamometers[1].

Limited resources of crude oil which is a basic raw material transformed into petrol and diesel fuel encourage to look for substitution fuels. It is assumed that introduction of such substitutes on commercial fuel markets will not result in emissions of pollutants contained in exhaust gases exceeding the limits set out in currently applicable standards.

The Rzeszów University of Technology’s Department of Combustion Engines and Transport also undertakes a number of research projects aimed at reduction of harmful impact of the means of automotive transport on natural environment. The main topics include combustion engine design improvement and search for alternative fuels. Current activities are focused on evaluation of emission levels characterising individual pollutants contained in passenger car exhaust gases. The related tests are performed on an engine test bench, in actual road conditions, and in controlled climate environment as defined by the European NEDC (New European Driving Cycle) testing procedure. In view of the fact that in most cases, the effect of consecutive design and operation changes on fuel consumption and emission of pollutants is relatively small, the issue of determining precision of tests confirming substantiality seems to be of key importance. For this reason, numerous laboratories
worldwide undertake studies concerning repeatability and reproducibility of results obtained in the course of pollutant emission measurements carried out on engine testing facilities [2–5]. Studies on pollutant emissions performed on chassis dynamometers represent a very complex issue. The obtained results depend, among other things, on behaviour of the operator (vehicle driver) reconstructing the drive test schedule, climate conditions, physicochemical properties of the fuel, and on precision available with the used measuring apparatus. In view of the above, the key issue is repeatability of measurements performed under conditions of repeatability, which include:

- the use of the same test method;
- performing the tests in the same laboratory;
- tests being performed by the same operator;
- performing the tests with the use of the same equipment;
- completing the tests one after another in short intervals.

This paper is a presentation of a study on repeatability of results of tests performed as per the Euro procedure used to determine emissions of pollutants contained in exhaust fumes of petrol engines driving passenger cars.

2. Testing procedure

The tests were performed on ROADSIM 48" Chassis Dynamometer (AVL Zöllner) installed in a controlled climate chamber. The research set-up was constructed in the Automotive Ecology Laboratory run by the Department of Combustion Engine and Transport, Faculty of Mechanical Engineering and Aeronautics, Rzeszów University of Technology. Basic technical data characterising the chassis bench are summarised in table 1. A view of the tested car on the chassis on the research set-up is presented in figure 1, whereas figure 2 is a view of the control room.

![Figure 1. A view of the car on the research set-up.](image)

| Table 1. Basic technical data of AVL ROADSIM 48" Chassis Dynamometer [6]. |
|---------------------------------------------------------------|
| Analysed quantity                  | Value                                   |
| Dimensions (Length / Width / Height) | 3,600 mm / 1,600 mm / 1,300 mm            |
| Roller diameter                    | 1,219.2 mm                               |
| Roller mass                        | 765 kg                                   |
| Rated power                         | 153 kW                                   |
| Instantaneous power                | 258 kW                                   |
| Maximum speed                      | 200 km/h                                 |
| Inertia simulation range            | 454 kg … 2,722 kg                        |
| Maximum continuous tractive force  | 5,987 N                                  |
| Maximum instantaneous tractive force| 10,096 N                                 |
| Ttractive force measurement error   | ≤0.1 %                                   |
| Speed measurement error            | ≤0.02 km/h                               |
| Distance measurement error         | 0.001 %/m                                |
| Maximum axle load                  | 2,000 kg                                 |
The subject of the test was a passenger car manufactured in 2003 with total mileage of about 60,000 km and other basic technical data summarised in table 2. To ensure that the resistance to motion observed on chassis dynamometer are as close as possible to those occurring in actual road conditions, an on-road coasting tests were performed within the speed range from 130 km/h to car stoppage. To measure the coasting parameters, a measuring set-up with DATRON DLS-2 optoelectronic sensor system. A view of the car in the course of the road test with the sensor mounted on it is presented in figure 3. Based on the determined coasting times, the following formula was derived for the resisting force on the car:

\[
F_r = 155.11 - 1.2343V + 0.4685V^2
\]

(1)

where \( F_r \) is the total resisting force representing combined rolling resistance and air drag (N) and V is the driving speed (km/h).

| Parameter                        | Value                                    |
|----------------------------------|------------------------------------------|
| Length / Width / Height          | 4,665 mm / 1,760 mm / 1,445 mm           |
| Wheelbase                        | 2,670 mm                                 |
| Weight                           | 1,430 kg                                 |
| Engine type                      | Petrol (gasoline)                        |
| Fuel System                      | Multi-point injection                    |
| Engine displacement              | 1998 cm³                                 |
| Engine power                     | 115 kW @ 6,000 rpm                       |
| Engine torque                    | 190 Nm @ 4,500 rpm                       |
| Number of cylinders              | 4                                        |
| Number of valves                 | 16                                       |
| Wheel drive                      | Front                                    |
| Number of gears (manual transmission) | 5                                      |
| Tire size                        | 205/55 R16                               |
The tests were carried out in an air-conditioned chamber in which temperature of 21°C and relative humidity of 40% were maintained. According to the test procedure determined in the applicable regulation [1], the car was stabilised in the chamber before the test for a period of at least 6 hours. The test was carried out as per Type 1 test plan (verifying the average exhaust emissions after a cold start). To measure emissions, AMA i60 Exhaust Measuring System equipped with CVS i60 Exhaust Gas Dilution System (both devices by AVL) were used.

Emissions are tested over the NEDC chassis dynamometer procedure. Part one of the test is made up of four elementary urban cycles (ECE). Each elementary urban cycle comprises fifteen phases (idling, acceleration, steady speed, deceleration, etc.). Part Two of the test is made up of one extra-urban cycle (EUDC). The extra-urban cycle comprises 13 phases (idling, acceleration, steady speed, deceleration, etc.). During the test, the exhaust gases were diluted and a proportional sample collected in bags. The exhaust gases of the vehicle tested were diluted, sampled and analysed, and the total volume of the diluted exhaust were measured.

3. Research results

Results concerning content of toxic pollutants in the exhaust gas obtained in consecutive tests carried out as per Type 1 test plan are summarised in table 3 and illustrated in figure 4.

For the obtained emission measurement results, an analysis concerning accuracy of the obtained values was performed. To characterise quantitatively the accuracy of a measuring method, two fundamental terms, “trueness” and “precision”, are commonly used [7, 8].

The trueness determines the closeness of the mean of a set of measurement results obtained from a large sequence of tests and an adopted reference value. Precision is defined as the closeness of agreement between independent measurement results obtained under stipulated conditions. Precision depends on the distribution of random errors and is not referred to any actual value. Usually, precision is characterised quantitatively by means of the standard deviation of measurement results, value of which is the smaller the largest is precision of the measuring apparatus.

Repeatability is the precision under the repeatability conditions being met. To evaluate repeatability, the following quantities were determined:

- average values of measurement results \( x_{\text{av}} \);
- minimum values \( x_{\text{min}} \) and maximum values \( x_{\text{max}} \);
- the range \( R_x \);
- the standard deviation of repeatability \( s_r \);
- the repeatability limit \( r \);
- the relative standard deviation of repeatability \( \text{RSD}_r \);
- the coefficient of variation \( \text{CV} \);
- ratio of the range to the repeatability limit.
### Table 3. Emission results (bag emissions) and the limits (Euro 4 standards).

| Pollutants | Test 1 (g km$^{-1}$) | Test 2 (g km$^{-1}$) | Test 3 (g km$^{-1}$) | Test 4 (g km$^{-1}$) | EU Emission Standards for Passenger Cars using gasoline engines (g km$^{-1}$) |
|------------|-----------------------|-----------------------|-----------------------|-----------------------|--------------------------------------------------------------------------------|
| THC        | 0.046                 | 0.046                 | 0.051                 | 0.046                 | 0.1                                                                              |
| NMHC       | 0.041                 | 0.041                 | 0.046                 | 0.042                 | —                                                                                |
| CH$_4$     | 0.0047                | 0.0048                | 0.0049                | 0.0042                | —                                                                                |
| NO$_X$     | 0.02                  | 0.019                 | 0.016                 | 0.019                 | 0.08                                                                             |
| CO         | 0.439                 | 0.441                 | 0.448                 | 0.428                 | 1.0                                                                              |
| CO$_2$     | 201.411               | 202.796               | 203.332               | 202.615               | —                                                                                |

**Figure 4.** Results of THC, CH$_4$, NMHC, NO$_X$, CO, and CO$_2$ emissions for NEDC tests.
The repeatability standard deviation is a measure of spread of test results obtained under repeatability conditions defined by the formula:

\[ s_r = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - x_{av})^2} \]  

(2)

where \( s_r \) is the repeatability standard deviation, \( x_i \) — result of \( i \)-th measurement, \( x_{av} \) — arithmetic mean of \( n \) measurement results taken into account.

The repeatability limit \( r \) is defined as a quantity which at the 95% probability level is not exceeded by the absolute value of the difference between two test results obtained under repeatability conditions.

In case of standardised methods used in laboratory practice, at least two parallel determinations are performed and the absolute value of difference between the results are compared with certain critical value known as the repeatability limit and defined by the formula [9]:

\[ r = 2.8 \cdot s_r \]  

(3)

where \( s_r \) is the repeatability standard deviation determined for all measurements.

It is recommended that the absolute value of difference between measurement results does not exceed the repeatability limit \( r \). It this is the case, both results are considered correct, and the mean value of the two is presented as the final result.

The relative standard deviation repeatability \( RSD_r \) is defined as:

\[ RSD_r = \frac{s_r}{x_{av}} \]  

(4)

The corresponding non-dimensional relative value which also can be used to characterise non-repeatability of elements of a set is the coefficient of variation \( CV \) defined as:

\[ CV = \frac{s_r}{x_{av}} \times 100\% \]  

(5)

### Table 4. Parameters of repeatability analysis.

| Parameter   | Values for THC | Values for CH4 | Values for NMHC | Values for NOx | Values for CO | Values for CO2 |
|-------------|----------------|----------------|-----------------|----------------|---------------|---------------|
| \( x_{min} \) (g/km\(^{-1}\)) | 0.04594         | 0.005          | 0.04299         | 0.01857        | 0.43924       | 202.538       |
| \( x_{max} \) (g/km\(^{-1}\)) | 0.04594         | 0.004          | 0.04149         | 0.01569        | 0.42776       | 201.411       |
| \( R \) (g/km\(^{-1}\)) | 0.0506          | 0.005          | 0.04601         | 0.02053        | 0.48467       | 203.331       |
| \( s_r \) (g/km\(^{-1}\)) | 0.00466         | 0.001          | 0.00452         | 0.00484        | 0.02091       | 1.92          |
| \( RSD_r \) | 0.04639         | 0.06           | 0.04782         | 0.1104         | 0.01971       | 0.004004      |
| \( CV \) (%)    | 4.63915         | 6.59           | 4.78203         | 11.0403        | 1.97151       | 0.40045       |
| \( CNR \)      | 0.046           | 0.066          | 0.048           | 0.11           | 0.020         | 0.004         |
| \( r \) (g/km\(^{-1}\)) | 0.00615         | 0.00086        | 0.00576         | 0.00574        | 0.02425       | 2.27097       |

Guidelines concerning assessment of pollutant emissions published in works [3,4] include also a proposal to use the coefficient of non-repeatability \( CNR \) defined by means of formula:

\[ CNR = \frac{s_r}{|x_{av} - RV|} \]  

(6)

where RV is a reference value. According to [3], the reference value equals 0 for emissions of pollutants.

Values of the calculated repeatability measures are summarised in table 4. Plots in figure 5 represent results concerning the repeatability limits \( r \) and absolute differences \( \Delta \) between two results of emission measurements under repeatability conditions for the analysed exhaust gas components. Figure 6 shows values of the coefficient of non-repeatability \( CNR \) for measurements of the mass emission of the
analysed exhaust gas component throughout the test. To illustrate repeatability of measurements, ratio of the measurements range \( R \), to the repeatability limit \( r \) was also calculated (figure 7).

![Figure 5](image)

**Figure 5.** Values of repeatability limits \( r \) and absolute differences \( \Delta \) between two results of emission measurements of the analysed exhaust gas components over the whole test.

![Figure 6](image)

**Figure 6.** Values of the non-repeatability coefficient for mass emissions of the analysed exhaust gas components over the whole test.
4. Conclusions

Analysis of the obtained results indicates that the performed measurements can be considered repeatable. Emission differences for all the measured toxic components evaluated in two measurements did not indicate any exceedances with respect to the repeatability limits $r$.

It is therefore possible under repeatability conditions to assume that on the examined research set-up, measurement results will be repeatable. The spread of pollutant emission values measured in the tests was characterised by the following values of the range $R_k$:

- $R_k = 0.00466$ g/km for THC ($r = 0.00615$ g/km$^{-1}$);
- $R_k = 0.001$ g/km for CH$_4$ ($r = 0.00086$ g/km$^{-1}$);
- $R_k = 0.00452$ g/km for NMHC ($r = 0.00576$ g/km$^{-1}$);
- $R_k = 0.00484$ g/km for NO$_X$ ($r = 0.00574$ g/km$^{-1}$);
- $R_k = 0.02091$ g/km for CO ($r = 0.0245$ g/km$^{-1}$);
- $R_k = 1.92$ g/km for CO$_2$ ($r = 2.027097$ g/km$^{-1}$).

The coefficient of variation CV for the analysed exhaust gas components is less than 10%, except for NO$_X$ for which CV $= 11.04\%$ which is the evidence of repeatability of the results being at the acceptable level [2].

It should be noted that in the case when the adopted ultimate test result is the mean value of individual measurement results the number of which exceeds 2, then the repeatability limits will change and they can be calculated with the use of appropriate formulae according to [9].

Values of the coefficient of non-repeatability CNR were smallest for CO$_2$, both for the whole test and for its individual parts. The highest values of the coefficient were obtained for the CH$_4$ mass emission in the second part of the test, whereas in case of the mass emission observed in the course of the whole test, the largest values CNR value was obtained for the mass emission of NO$_X$.

Taking into account the range-to-repeatability limit ratio (figure 7), the largest value of the coefficient amounting to about 0.86 was obtained for CO emission. It can be however noted that values of the coefficient characterising other analysed exhaust gas components are similar and their values fall into the range from about 0.76 to about 0.86.

It can be easily seen from the graph representing requirements concerning the number of tests to be performed with respect to exhaust gas pollutants subject to limitations (figure 8) that is the result obtained from the first test is on the level equal to or less than 0.7 L for all pollutants, such result is considered final (regardless of repeatability of the measurement). In other cases (figure 8), the average from two or three tests is adopted to be the final result, whereas possible measurement results can be characterised with a large spread and thus exceed the determined repeatability limits.

\section*{Figure 7.} Values of ratio of the range $R_k$ to the repeatability limit $r$ of the analysed exhaust gas components over the whole test.
Figure 8. Flow chart for Type I Approval (Vi — emission value from i-th test, L — the limit value as per emission standard) [1].

To sum up, in consecutive assessments concerning exhaust gas emissions concerning e.g. dependence of pollutant levels on the vehicle operating mileage, it will be possible to consider results of any two measurements falling into the repeatability limits determined with the use of the same measuring set-up as representative ones.
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