Experimental study of NO\textsubscript{x} and CO\textsubscript{2} emissions at load regimes for a passenger car powered by direct injection diesel engine

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Abstract. The paper presents a study of NO\textsubscript{x} and CO\textsubscript{2} emissions for a standard diesel direct injection engine, which equips the Renault-Dacia Solenza 1.9D-SDI cars. The different pollutions levels are analysed between idling regimes and medium and high loads at different speeds and transmission gearboxes. To simulate the load regimes, chassis dynamometer V-Tech Dyno VT-2/B1 was used. The exhaust gases were taken to various operating modes on the chassis dynamometer, specific regimes in urban and extra-urban mode. In the paper, some recommendations are made on operating regimes that would ensure the functioning of the car at a lower polluting level.

1. Introduction

The main legislative instrument to achieve the 2030 objectives of the Clean Air Programme is Directive 2016/2284/EU on the reduction of national emissions of certain atmospheric pollutants which entered into force on 31 December 2016 [1]. Air pollution is an important public health problem in most cities [2]. Without effective measures to mitigate the adverse impacts of motor vehicle use, the living environment in the cities will continue to deteriorate and become increasingly unbearable, [2, 3, 4].

According with ACEA (European Automobile Manufacturers Association), the global vehicle fleet continues to grow. The EU passenger car fleet grew by 5.7% over the last five years. The EU has a total fleet of 259.7 million passenger cars. According to the same Association, Romania had in 2017 the oldest fleet, with vehicles older than 16 years. Out of the total cars running in Romania, over 4 million are 10 years old, [5]. The new Romanian legislation on pollution standards for second-hand cars has as a consequence the import of more than 500,000 used cars in 2018 [6]. The increase in the number of passenger automotives with diesel engine and the intensive traffic in urban areas have a negative effect on environment and human health, [7]. Chana describes in his study the emissions from actual operations and their dependence to the speed or age of the vehicle, [8].

The most important pollutant emissions of diesel engine are nitrogen oxides (NO\textsubscript{x}) and smoke, the carbon dioxide CO\textsubscript{2} being considered a greenhouse effect gas, [9, 10]. Regarding the impact of pollutant emissions on environment [2, 3], special measures are taken in order to reduce as much as possible the pollution produced by diesel engines, especially in the urban areas, [10, 11].

In order to limit the pollutant emissions level at diesel engines, especially NO\textsubscript{x} and soot, the pollution legislations have become more severe, this fact leading to the applying of new active and passive methods for fuels combustion control [12, 13], and using alternative fuel too, [14, 15].
The present paper aims precisely to show the difference between the NO\textsubscript{x} and CO\textsubscript{2} emissions determined at idling speed and the one determined at the load regimes specific to the normal operating conditions in urban and extra-urban mode, in case of a passenger car powered by direct injection diesel engine.

In the case of real operating regimes (operating regimes in load), the NO\textsubscript{x} and smoke level may exceed the maximum smoke and NO\textsubscript{x} level imposed by European anti-pollution legislation, but this thing depends largely on the engine's technical condition, fuel quality and operating regimes. According to this legislation, the level of smoke is measured by free acceleration at idling speed between the minimum and the maximum rotation of engine and the determination of the pollution level for NO and NO\textsubscript{x} is carried out under idling regimes with specified conditions (oil temperature, speed engine), so there are no provisions for the measurement of pollutants in the gasses with the engine in load.

2. Equipment used for experimental studies

The equipment used for experimental determinations includes a car, V-Tech Dyno VT-2 / B1 Chassis dynamometer, an analyzer of exhaust gases and a smoke meter.

The car used in the study, was Renault-Dacia-Solenza 1.9D-SDI with the characteristics indicated in the table 1, from [16].

| Maximum power | Maximum rotation of engine | Engine type | Engine volume | Cylinders number | Type of fuel and fuel system | Environmental standard | Maximum authorized weight |
|---------------|-----------------------------|-------------|---------------|-----------------|-----------------------------|------------------------|--------------------------|
| HP            | rpm]                        | -           | cm\textsuperscript{3} | -               | -                           | -                      | kg                       |
| 63            | 4500                        | F8Q         | 1870          | 4               | Diesel/Standard diesel injection-SDI | EURO III               | 1460                     |

The total emission of nitrogen oxides NO\textsubscript{x}(%vol) and the CO\textsubscript{2} (vol\%) in the exhausts gasses were measured with the Multilyzer STx gas analyser. The analyzer used for the opacity coefficient measure is Johnson Controls – Ultimax 600, 800-65 model.

The roller stand enables the dynamical determination of the engine's power and torque, as well as of the power and torque of the vehicle's engine wheels.

The V-TechDyno VT-2/B1 Chassis dynamometer (figure 1) has been used [17], which has the following features:

- maximum load on the axis 3000 kg;
- number of axes - 1 axis;
- maximum speed 300 [km/h];
- maximum engine power measured 600 [HP];
- minimum external wheel diameter 400 [mm];
- the TELMA eddy-current electric brake with a maximum torque of 800 Nm/1000 rpm, with a precision of 0.1% for inertial mode and 1% for brake mode respectively.

The data acquisition system that equips the V-TechDyno VT-2/B1 Chassis dynamometer is shown in figure 2.

To perform the load tests, the road test method was used (figure 3). This mode simulates road condition, driving and changing gears at the same way as on the road. Basic data should be written to the software as weight, aerodynamic coefficient C\textsubscript{x} value and front area. During acceleration, the brakes will apply the proper load on dyno rolls – this will enable to simulate air and traction resistances. This mode also gives the possibility to simulate hills.
The determinations were made for the horizontal road, in the 2\textsuperscript{nd}, 3\textsuperscript{rd}, 4\textsuperscript{th}, and 5\textsuperscript{th} gears of the gearbox, at the usual travel speeds of (25 – 150) km/h and in the range of (1500 – 4000) rpm, which is the specific operating range for the diesel engine and the car powered with diesel engine.

In accordance to the European provisions, for diesel-fuelled cars, at the periodic technical inspection [18], the smoke index is checked, which must fit as follows:

- For natural aspirated diesel engines, the smoke index $k \leq 2.5 \text{ m}^{-1}$.
- For turbocharged diesel engines with pollution norms up to and including EURO 3, the smoke index $k \leq 3 \text{ m}^{-1}$.
- For turbocharged diesel engines that have the pollution standard EURO 4, EURO 5, EURO6, the smoke index $k \leq 1.5 \text{ m}^{-1}$.
- Carbon dioxide is not yet legislated.
In terms of the limit for NOx, according to the Euro standard, that is 0.5 [g/km] for EURO 3, 0.25 [g/km] for EURO 4, for EURO 5 is 0.18 [g/km], respectively 0.08 [g/km] for EURO 6, but these are only determined when homologate a new automotive model for establish and verify the EURO norm.

The paper aims to show the difference between the smoke index, NOx and CO2 emissions determined in the idling regimes and the ones determined at the load regimes of engine, in urban and extra-urban mode, for a passenger car powered by direct injection diesel engine.

The roller stand enables the dynamical determination of the engine's power and torque, as well as the power and torque of the vehicle's engine wheels.

3. Experimental determinations

Using the equipment presented, experiments were carried out for measuring the CO2 and NOx emissions and also the opacity coefficient at idling regimes and load regimes.

For engine idling at various speeds, a regime which is not representative of the operation of engine because it represents a maximum of 5% of the total running time, the following were found, according to the graphs in figure 4, 5, 6:

- At speeds above 2500 rpm, CO2 emissions increase by up to 37% compared to those measured at speeds below the above-mentioned value, (figure 4);
- At speeds above 2500 rpm, NOx emissions increase by up to 66% as compared to those measured at speeds lower than the value mentioned, figure 5;
- The maximum value of the measured smoke index of 0.18 m-1 (figure 6), is 14 times smaller than the maximum admissible limit accepted by European legislation, under the specified conditions and 7.4 times lower than the one measured directly by acceleration between minimum and maximum at idling regime. However, this value was measured in a stabilized idle mode, not through acceleration from a minimum to a maximum speed;
- The maximum value of the smoke index obtained, measured according to legislative provisions and presented in figure 7, was 1.8 times lower than the maximum admitted limit for this euro category and type of engine.

![Figure 4. Emissions of CO2 for idling regimes.](image1)

![Figure 5. Emissions of NOx for idling regimes.](image2)
For the idle mode, which is not specific to the operation of cars because it represents a maximum of 5% of the service life, the conclusion is as follows: in situation of good technical condition of the diesel engine (with proper adjustment of the fuel system and with a normal compressing in the engine mechanism), the engine having the appropriate thermal regime (coolant temperature of at least 80°C), the level of CO₂, NOₓ and smoke pollution is low, below the limits imposed by the legislation and in order to reduce them, it is recommended the idling speed in the range of (800 – 1500) rpm, which also holds true for real life situations.

For the functioning of the indicated diesel engine in the load regime, i.e. the urban and off-road operation of the car, based on the analysis of the variations shown in figures 8, 9, 10, the following findings can be mentioned:

- as far as CO₂ emissions are concerned:
  - The smallest emissions were recorded for 2nd gear operation in the range of (25-40) km/h, corresponding to (1500-2500) rpm for the engine, and around the speed of 70 km/h for 3rd gear operation, ie 3000 rpm for the engine.
  - The CO₂ emission reduction tendency was also found for operation within the (2500-3000) rpm range, which corresponds to the (50-70) km/h speed range for the 3rd gear, (70-90) km/h for the 4th gear and (90-110) km/h for 5th gear operation. This aspect of reducing CO₂ emissions is explained by the fact that within the speed range (2500-3000) rpm, the economic zone is located, the engine having a lower consumption than for other speed ranges.
  - When the engine runs above 3200 rpm, CO₂ emissions increase too as it exits the economic zone. The highest CO₂ emissions are encountered in the 5th gear drive, at speeds over 120 km/h, respectively above (3200-3500) rpm. When running in the 5th gear at speeds above 120 km/h, the CO₂ emissions are of (12.5-14) %, being (35-55)% higher than emissions from the a 4th or a 3rd gear run respectively.

- with regard to the smoke index (opacity of the exhaust gas), according to figure 10:
  - For the full speed range of (25-100) km/h, for the run in the 2nd, 3rd and 4th gear at stabilized speeds, the smoke index does not exceed 0.22 m⁻¹, which represents a reduced value, 6 times lower than the index of smoke measured in acceleration (figure 7), according to the legislative provisions.
  - When running in the 5th gear at stabilized speeds above 100 [km/h], the smoke index increases up to 7 times as compared to the less polluting regimes indicated previously, however it never exceeds the smoke index measured in acceleration (figure 7), according to the legislative provisions.
• In situation of good technical condition of the diesel engine, the engine having the appropriate thermal regime (coolant temperature of at least 80°C), the smoke level is low if run at approximately constant speeds (stabilized regimes), the pollution level being just below the one recorded at idle and acceleration from minimum to maximum regimes, according to the legislative provisions [18].

- with regard to NO\textsubscript{x} emissions:
  • The smallest emissions of (0.005 - 0.015) % are achieved for 2\textsuperscript{nd}, 3\textsuperscript{rd}, and 4\textsuperscript{th} gear operation, for engine operation within the (2000-3000) rpm range. Speed ranges that produce minimal pollution and which are recommended for operation are: (25-45) km/h in the 2\textsuperscript{nd} gear, (45-65)km/h for the 3\textsuperscript{rd} gear operation, and (60-75) km/h for the 4\textsuperscript{th} gear, respectively.
  • Running at approximately constant speeds, within this speed range of (25-75) km/h, which is specific to urban driving, with engine at the appropriate heat regime, lead to quite low NO\textsubscript{x} emissions.

Figure 8. CO\textsubscript{2} emissions depend of speed and gear.

Figure 9. NO\textsubscript{x} emissions depend of speed and gear.

Figure 10. Smoke emissions depend of speed and gear.
• This aspect of NO\textsubscript{x} reduction is explained by the fact that, in the (2000-3000) rpm range, the economical operating area is situated, with the economic pole around the speed of 2500 rpm, the engine having a lower consumption than for other speed intervals. For the indicated speed range, even if the amount of O\textsubscript{2} is quite high, ranging from 7 to 15 % as shown in figure 12, however, due to lower gas temperature, average loads being considered (the exhaust gas temperature did not exceed 200\textdegree C, as shown in Figure 11), the NO\textsubscript{x} emissions are at minimum values.
• Running at steady speeds above 75 km/h in the 4\textsuperscript{th} gear and above 120 km/h respectively in the 5\textsuperscript{th} gear, NO\textsubscript{x} emissions may increase three times as compared to the regimes with low pollution indicated above. This is explained by the increased fuel consumption and flue gas temperature (exhaust gas temperature exceeded 220\textdegree C, as shown in figure 11). The influence of temperature has a more important role in NO\textsubscript{x} formation than oxygen does, because these emissions increase even if the amount of O\textsubscript{2} is reduced by about 50% for the 4\textsuperscript{th} gear and (3-5) times for running in the 5\textsuperscript{th} gear, as shown in figure 12.

4. Conclusions
According to the experimental results, conclusions are as following:
• In order to ensure the lowest pollutant values, it is recommended to operate the engine in the range of (2000-3000) rpm, which is the economic pole in the speed range of 2500 rpm. Engine operation in the recommended range allows you to run at speeds of (25-75) km/h on the 2\textsuperscript{nd}, 3\textsuperscript{rd} and 4\textsuperscript{th} gear, which is specific to urban operation.
• Speed ranges that produce minimal pollution and which are recommended for operation are: (25-45) km/h on 2\textsuperscript{nd} gear of the gearbox, (45-65) km/h for running on the 3\textsuperscript{rd} gear of the gearbox and (60-75) km/h for the 4\textsuperscript{th} gear.
• When running at constant speeds above 75 km/h on the 4\textsuperscript{th} gear and above 120 km/h respectively on the 5\textsuperscript{th} gear, the NO\textsubscript{x} emissions will increase up to 3 times as compared to the low pollution regimes indicated, and the smoke index increases up to 7 times.
• The highest emissions of CO\textsubscript{2}, NO\textsubscript{x} and smoke have been recorded for the 5\textsuperscript{th} gear at speeds above (100-120) km/h, running regimes specific to extra-urban operation.
• In situation of good technical condition of the diesel engine, the engine having the coolant temperature of at least 80°C, if run at approximately constant speeds (stabilized regimes) in urban mode, the pollution is reduced compared to the one achieved in dynamic driving.

• It is advisable to avoid sudden accelerating, running at approximately constant speeds in the (25-75) km/h speed range, which will ensure a minimum level of CO₂, NOₓ and smoke pollution, below the values obtained for acceleration at idle regime when running between the minimum and maximum possible speeds.

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