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About the constructive and functional particularities of spark ignition engines with gasoline direct injection: experimental results

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Abstract: The paper aims to analyze and compare the environmental performances between a gasoline direct engine and a multi-point injection engine. There are analyzed the stages of emission formation during the New European Driving Cycle. The paper points out the dynamic, economic and environmental performances of spark ignition engines equipped with a GDI systems. Reason why, we believe the widespread implementation of this technology is today an immediate need.

1. Introduction
1.1 Organized movements
The actual trend regarding the internal combustion engines is to obtain higher dynamic performances with lower fuel consumption, respecting at the same time the current legislation. In order to compliance with these requirements that become more in more exigent, automotive manufacturers chose to implement on their engines gasoline direct injection and downsizing.

Figure 1. Types of organized mixtures [1].
a) **Swirl motion (Figure 1a)** assumes air mass rotation around the cylinder axis. This type of movement confers a various number of advantages such as: rapid homogenization of the mixture, high flame velocity, ignition stability by orientating the fuel mass towards the spark plug and fast evaporation of the fuel.

b) **Tumble motion (Figure 1b)** assumes tangential rotation of the air mass or mixture in a perpendicular plan on piston head surface. Tumble motion is generated by the circular axis of the intake manifold and maintained by piston head profile.

c) **Squish motion (Figure 1c)** is a radial movement that is obtained at the end of the compression stroke, by step effect when the mixture reaches the piston and cylinder head cavities.

2. **Fuel jet control**
Gasoline direct injection assume guiding the fuel jet that is delivered in the cylinder, in such way as the mixture to be found near the spark plug in order to have a proper ignition.

d) **Wall guiding of the fuel jet (Figure 2a)** assume orientating the fuel mass toward the spark plug using the profiled surface of the piston head.

e) **Air guiding (Figure 2b)** of the fuel jet assume installing air flaps for every cylinder in the intake manifold. The air flaps serve to control the air flow and amplifying the tumble effect of the mixture.

f) **Direct guiding (Figure 2c)** of the fuel mass assume placing the injector near the spark plug. The fuel mass being ignited at short time after the injection. [1]

![Figure 2. Fuel jet control][1]

3. **Experimental results**

3.1 **Technical details**
For the experimental investigations, the following engines with the following parameters were used:

| Table 3.1. Engine specifications. |
|-----------------------------------|
| Engine                          | A         | B         |
| Compression ratio               | 10.2      | 10.9      |
| Idle speed                      | 900rpm    | 900rpm    |
| Total displacement              | 1200cc    | 1600cc    |
| Maximum torque [Nm]             | 190       | 165       |
| Maximum power [kW]              | 85        | 85        |
| Number of cylinders and alignment | 4L        | 4L        |
| Maximum power engine speed [rpm]| 4600      | 5700      |
| Maximum torque engine speed [rpm]| 1900    | 3800      |
In order to highlight the environmental and economic performance, the two selected engines for analysis are similar in terms of dynamic performance as can be seen in table 3.1. Also, they have equipped the same body during the NEDC test cycle.

The experimental investigation was made during a simulation of a New European Driving Cycle (NEDC) on a test bench.

![NEDC](image)

**Figure 3.** New European Driving Cycle.

The New European driving cycle, was first introduced in year 1992, and in the first stage consisted in a 40 second lead time, urban driving cycle and extra urban driving cycle. The 40 seconds leading time was removed in the first part of year 2000 and from that time, the cycle remained unmodified. The main purpose of the NEDC is to assure similar test conditions for all tested vehicles. In order to be able to sell a vehicle, a car has to meet the NEDC requirements. [6] The main characteristics of the New European driving cycle are shown in table 3.2 and the regulated emissions in table 3.3.

| Table 3.2. New European driving cycle characteristics. |
|--------------------------------------------------------|
| **Value**     | **Unit of measure** |
| Urban         | 780                | Seconds |
| Extra-urban   | 400                | Seconds |
| Complete cycle| 1180               | Seconds |
| Distance      | 11015              | Meters  |
| Maximum speed (extra-urban) | 120                | Kilometres/hour |
| Maximum speed (urban) | 50                 | Kilometres/hour |
| Average Speed | 33.6               | Kilometres/hour |
Table 3.3. Regulated emissions.

| Regulated emissions          | Unit     |
|------------------------------|----------|
| Carbon monoxide              | CO       |
| Hydrocarbons                 | HC       |
| Nonmethane hydrocarbons      | NMHC     |
| Oxides of nitrogen           | NOₓ      |
| Carbon dioxide               | CO₂      |

In order to have a vision strictly on the engine emissions, the samples were taken before catalyst.

3.2 NEDC Results

In the figures 3.1, 3.2, 3.3 and 3.4 are presented the hydrocarbons, carbon monoxide, nitrogen oxides and respectively carbon dioxide emissions results during the NEDC for the entire test.

Figure 3.1. Hydrocarbons emissions during the NEDC.

Hydrocarbons are organic compounds formed by hydrogen and carbon, which can be found naturally in fossil fuels. Hydrocarbons are the primary element of oil, coal and natural gas. In the car exhaust system, hydrocarbons can be found in a various number of forms such as C₆H₆, C₈H₁₈ etc. with diversified effects on the human body.

Figure 3.2. Carbon monoxide emissions during the NEDC.
Carbon monoxide is a colorless, odorless, tasteless, highly toxic and explosive gas. It is highly toxic, even in low concentrations, for human organism due to its characteristics to prevent red blood corpuscles to transport oxygen. In open field, carbon monoxide atoms will oxidize into carbon dioxide after a short period of time. Carbon monoxide are compounds formed with one atom of carbon and one atom of oxygen connected by a triple bond.

Nitrogen oxides are various compounds of nitrogen \( N_2 \) and oxygen \( O_2 \) such as \( NO, NO_2, N_2O \) etc. Nitrogen oxides are the results of high pressure and temperatures inside the engine cylinders. A slightly increase of these emissions are related to the actions taken in account to reduce the fuel consumption such as the decrease of the quantity of the injected fuel which leads to air excess in the cylinder.

Carbon dioxide is a colorless, non-flammable gas which consist of a carbon atom double bounded to two atoms of oxygen. It can be found naturally in Earth’s atmosphere from sources such as volcanoes, wild fires, hot springs etc. In case of internal combustion engine, emissions are produced due the burning of the fossil fuel. Carbon dioxide depletes the Earth ozone layer which conducts directly to increase of greenhouse effect and global warming. [4]

For a detailed analysis, the two specific areas of the NEDC cycle were analyzed: the urban cycle and the extra-urban cycle. The urban area is characterized by 3 cycles of speed that is repeated 4 times.
The first part of the cycle will be examined as the urban cycle because also contains the engine start and catalyst warm up phase. The extra-urban area it will be analyzed completely.

### 3.3 Urban cycle and starting phase

The urban cycle has a duration of 780 seconds, characterized by transitional and stabilized phases, with a top speed of 50 km/h.

![Urban (HC)](image)

**Figure 3.5.** Hydrocarbons emissions during the first part of NEDC.

During the urban cycle, slightly increased values of hydrocarbons can be observed for engine A in figure 3.5. Since the injection is made directly into the cylinder and the combustion is degraded until the engine reaches its operating temperature explains the increase of the emissions.

![Urban (CO)](image)

**Figure 3.6.** Carbon monoxide emissions during the first part of NEDC.
On the terms of direct injection, homogenization time is diminished compared with indirect injection engines, so a part of the injected dose not burn, also organized movements in the cylinder have strong influence on the quality of the mixture in terms of homogenization.

For example, at low velocities of air movements, the mixture is not completely homogenized and high velocities may involve oil film driving with direct impact on the emissions.

On the engine start phase, a high peak of hydrocarbons can be seen for both engines, on this phase a large dose of fuel is injected in order to run the engine on all conditions.

Carbon monoxide emissions result from incomplete fuel combustion generally generated by excessive enrichment of the mixture or due to incomplete homogenization of the fuel.

Due the small amount of time available for the homogenization, some fuel particles are not found near oxygen molecules, required for oxidation.

As it can be observed in figure 3.6, on the first part of the cycle the carbon monoxide emissions are higher due the degraded combustion. In the last part of the chart, the emissions get stabilized at lower values.

![Figure 3.7. Nitrogen oxides emissions during the first part of NEDC.](image)

![Figure 3.8. Carbon dioxide emissions during the first part of NEDC.](image)
Regarding nitrogen oxides emissions, lower values of nitrogen oxides for engine A can be observed in figure 3.7 since the fuel is delivered directly into the cylinder, some of the heat is absorbed by the fuel for vaporization, resulting in a lower temperature in the combustion chamber. Significant amounts of nitrogen oxides can be observed in transitional phases, due difficulty to control the richness at 1.[3]

Carbon dioxide emissions are greenhouse emissions, thus not regulated by NEDC. However, they play an important role, they reflect fuel consumption and represents a marketing plan. Although both engines are equipped with stop and start, it does not come into operation in the first 80 seconds as the engine is in catalyst heating phase. In figure 3.8 it can be observed that in the 100 seconds mark, the CO$_2$ emissions are 0g/km due the activation of start and stop system

3.4 Extra-urban cycle
The extra-urban cycle has a duration of 400 seconds, characterized by transitional and stabilized phases, with a top speed of 120 km/h.

![Figure 3.9. Hydrocarbons emissions during the last part of NEDC.](image)

![Figure 3.10. Carbon monoxide emissions during the last part of NEDC.](image)
Regarding emissions of hydrocarbons over the extra-urban cycle, values are close to each other, slightly higher values can be observed in figure 3.9 for engine A. The main source of these emissions is given by direct injection, another source of hydrocarbons is due to the overlap between the valves at high and medium load. Since the engine, A is equipped with dual VVT, during which the time when the valves are overlapping a part of the fuel reach the exhaust manifold before the start of ignition.

Just as in the first part of the cycle the carbon monoxide emissions have higher values for transitional phases, and it gets stabilized at lower values during stabilized phases as can be observed in figure 3.10. The carbon monoxide emission have higher emissions during the acceleration phase due the constant changes of the external and internal factors. External factors such as road load, air friction, rolling resistance etc and internal factors such as internal aerodynamics of the mixture, engine load, fuel and air quantity, poor control of the mixture. On the stabilized phases, the fuel-air quality can be controled more precisely due the constant engine load, with visible effect on the carbon dioxide emissions. The HC and CO emissions have higher peaks in case of engine A mostly because the the fuel is delivered entierly into the cylinder, and a higher torque request of the driver translates in the quantity of fuel injected.

![Extra-Urban (NOx)](image)

**Figure 3.11.** Nitrogen oxides emissions during the last part of NEDC.

![Extra-Urban (CO2)](image)

**Figure 3.12.** Carbon dioxide emissions during the last part of NEDC.
On the extra-urban cycle, due the high engine load and engine speed, the richness factor is slightly increased from 1.0 to 1.2 in order to decrease the combustion temperature and to cool down the catalyst convertor. [2] Due the excess of fuel, absence of air and decrease of temperature the nitrogen oxides are maintained slightly to constant levels with lower values for engine A as can be observed in figure 3.11. At the same time, the increasing of the richness factor have direct effects on the CO and HC emissions which can be seen in figures 3.9 and 3.10.

Carbon dioxide emissions, which can be observed in figure 3.12, have similar values for the both engines due the same amount of fuel burned in order to achieve the target torque needed to power the vehicle. As it was mentioned before, the transitional phases are the areas where the biggest amount of emissions are produced.

3.5 NEDC emissions results

The quantities of emissions from NEDC cycle tests are shown in the table 3.4:

| Engine A | Engine B |
|----------|----------|
| Emissions [mg] | Enviromental performance [%] | Emissions [mg] |
| HC | 16167 | 19.34% ↑ | 13040 |
| CO | 67417 | 20.27% ↑ | 53749 |
| NOx | 17202 | 16.35% ↓ | 20015 |
| CO2 | 1481 | 0.34% ↑ | 1476 |

It can be noticed that by reducing displacement with 400cc, implementation turbocharging and direct injection was obtained a increase of dinamic performances but at the same time a increasing of emissions and a increase of a greenhouse gas. Due to the implementation of the three way catalyst, these values are treated with a efficiency of 98%.

The final emissions are presented in table 3.5.

| Engine A | Engine B |
|----------|----------|
| Emissions after TWC [mg] | Enviromental performance [%] | Emissions after TWC [mg] |
| HC [mg] | 510 | 2.35% ↑ | 498 |
| CO [mg] | 3643 | 4.39% ↓ | 3803 |
| NOx [mg] | 126 | 3.17% ↓ | 130 |
| CO2 [mg] | 1590 | 0.25% ↑ | 1586 |

4. Conclusions

At the present stage, the legislative requirements regarding environmental performances are becoming more and more exigent. In order to compliance with these requirements, the best solution is the implementation of the direct injection. Direct fuel injection systems allow the car manufacturers to apply various strategies such as: stratified injection, multi-injection, fuel injection in admission or compression stroke.

In our tests even if the engines are fitted with different type of injection systems, both engines work with homogenous mixtures and the fuel is delivered during the admission stroke. Due the direct injection of the fuel, a increase of HC and CO emission with 20% can be observed for engine A. In case of NOx emissions, a decrease with 16% can be observed for engine A, due the vaporization of the
fuel injected and combustion temperature. The CO$_2$ levels are the same due to the same amount of fuel required to power the same vehicle configuration.

Future work will focus mainly on the analysis of organized and turbulent air-fuel mixture movements inside the cylinder by using Particle Image Velocimetry and Computational Fluid Dynamics simulation.

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