The impact of exhaust gas recirculation system on the operating parameters of diesel engine in agricultural tractors

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Abstract. This article deals with the results of an experimental study into control of exhaust gas flow through the exhaust gas recirculation system. The discussed technical modifications involve the application of the new exhaust gas recirculation valve, which is the main component of the exhaust gas recirculation system in a diesel engine. The purpose of the exhaust gas recirculation valve is to control the flow of the exhaust gas routed into the intake manifold and then into the combustion chamber. Another focal point in the study was on the relation between the exhaust gas concentration of nitrogen oxide and exhaust gas concentration of particulate matter and the degree of exhaust gas recirculation valve opening. This paper also reports the results of impact of exhaust gas recirculation valve control into another selected engine operation parameters as fuel consumption.

1. Introduction

Despite the fact that the design of a combustion engine is more than one and a half century old, the continuous progress in engineering means that it is still widely used in means of transport including the ships as well as road vehicles and off-road for the transportation of goods and people. The success of engine development over many years stems from the use of adequate fuels, whose potential results from high energy density. This applies to both the volume ratio and the mass index at a high calorific value which is accompanied by easy implementation of engine characteristics. Hence, we can say that progress in civilization is inevitably related to the development of means of transport, and is one of the most important branches of the global economy. The development of civilization also involves an increase in demand for transport means. According to the data from American Environmental Protection Agency, the number of vehicles in 2010 exceeded one billion, and it will continue to grow considerably over the next years, in particular in the developing countries such as China, India, South America and Africa. However, there are serious issues facing the development of internal combustion engines in vehicles. The first is a problem related to the emission of compounds resulting from the combustion process of fuel in engines [1, 2, 3, 4]. Thus, restrictions are being implemented in the form exhaust gas emissions standards such as EURO or Tier. The second major issue is associated with the increased fuel to meet the demand for the growing numbers of vehicles, as the supply of fossil fuels is limited and, consequently, this can limit the development of internal combustion engines. The work associated with overcoming these problems is conducted in various directions. One of the developments involves engine design modifications in the fuel injection system of an internal combustion engine. Examples of new designs include high pressure fuel injection tank and developments in exhaust gas recirculation systems. Other solutions focus on the applicability of new
fuels or fuel mixtures for the supply of diesel engines [5]. These activities have led to significant differences between up-to-date engines used in the ships as well as road vehicles and off-road and the ones installed dozens of years ago.

Both engine parameters and environmental indicators, i.e. emission of harmful substances in the exhaust gases depend on the technical condition. In the case of road vehicles, this problem was partly solved by implementation of procedures of detecting increased emissions of harmful substances in exhaust gases as a result of installation of on-board diagnostic systems. This issue has not been addressed in off-road vehicles (e.g. agricultural tractors). The current legal status imposes liability on to vehicle manufacturers only for the emission of harmful substances in the exhaust of an approved engine, while in the process of operation there is no obligation to test tractors and agricultural machines regularly for emission levels. Therefore, it is reasonable to study the impact of engine design and its operating indicators on the emission/ concentration of harmful substances at exhaust gases.

2. Emission of harmful substances

Requirements are established for contemporary designs of combustion ignition engine in off-road vehicles with regard to the current and future emission standards of harmful substances mainly stating the emission of nitrogen oxides and particulate matter.

| kW/Year | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---------|------|------|------|------|------|------|------|------|------|------|
| 18-36   |      |      |      |      | (7,5)/5,5/0,6 |      |      |      |      |      |
| 37-55   | (4,7)/5,0/0,4 |      |      |      | (4,7)/5,0/0,025 |      |      |      |      |      |
| 56-74   | (4,7)/5,0/0,4 |      |      | 3,3/0,19/5,0/0,025 | 0,4/0,19/5,0/0,025 |      |      |      |      |      |
| 75-129  | (4,0)/5,0/0,3 |      |      |      |      |      |      |      |      |      |
| 130-560 | (4,0)/3,5/0,2 | 2,0/0,19/3,5/0,025 | 0,4/0,019/3,5/0,025 |      |      |      |      |      |      |
| EURO    | STAGE IIIA | STAGE IIIB | STAGE IV |      |      |      |      |      |      |
| emission g/KW·h | (NOx+NMC)/CO/PM | (NOx+NMC)/CO/PM | NOx/HC/CO/PM |      |      |      |      |      |      |

Figure 1. Emission limits for off-road vehicles engines in Europe [4]

Currently manufactured engines have to meet the emission requirements defined in Non-Road Stationary Cycle and Non-Road Transient Cycle. However, as noted in the introduction, these provisions do not resolve issues relating to the vehicles already in operation. The papers [1, 2, 3, 4] contains reports of studies conducted with regard to tractors and agricultural machinery, construction machinery performed under actual working conditions.

The analysed time of machine work was more than 1000h, during which a combustion engine operated at different loads i.e. 34 % of time idling and only about 16 % of the time the engine reaches ¾ its maximum output and about 2 % corresponds to its full capacity. In actual working conditions, the proportion of rotational speed ranges is distinct the conditions in the standard. The current standard in Europe for off-road vehicles is dependent on engine power output, and for engines with the power output exceeding 130 kW there are already new standards stated as STAGE IV from 2014. For internal combustion engines with a power smaller than 130 kW, the previous standard STAGE 3B also deals with the engines with in-line injection pumps with modified engine power control system, and including programmable control exhaust gas recirculation valve. This is particularly important in the actual working conditions of internal combustion engines of off-road vehicles, as they operate mostly in the conditions of dusty environment, variable terrain and load. We have to deal with engine parameters such
as engine speed, injection parameters (injection timing, number of phases), the pressure in the intake manifold or the timing of the exhaust gas valve opening, which have to respond to instantaneous changes in the actual conditions. Such engines are characterized by high durability and reliability, good parameters of engine operation and demonstrate a significant tolerance to the quality of used fuel including the possibility of using alternative fuels with a low unitary fuel consumption of 215 g/kW·h.

3. Analysis of the exhaust gas recirculation system

Exhaust gas recirculation system works by recirculating a portion of the exhaust gas into the combustion chamber from the combustion process, which results in improvement of the operating parameters of internal combustion engine including in particular the exhaust gas concentration of harmful compounds. However, care must be taken that the volume of recirculated exhaust gas is not too high, which can lead not only to increased particulate exhaust gas concentration, but also to the deterioration of the dynamic properties of the motor [6, 7, 8].

![Figure 2. Influence of exhaust gas recirculation valve position on concentration of NOx and PM (1100 rpm and 100Nm) [6]](image)

When we consider the relation in [6] (Figure 2), we can note that a compromise should be sought between nitrogen oxides and particulate exhaust gas concentration, which are dependent on each other to some extent. The relation significantly depends on the degree of exhaust gas recirculation, which can be stated in the following form [9]

\[
SRS_{EGR} = \frac{m_{EGR}}{m_{EGR} + m_{AIR}} \cdot 100\%
\]  

(1),

\[
\dot{m}_{EGR} \quad \text{mass flow rate of recirculated gas, [m}^3\text{s}^{-1}],
\]

\[
\dot{m}_{AIR} \quad \text{mass flow rate of of intake air [m}^3\text{s}^{-1}].
\]

As a result of changes in the degree of exhaust gas recirculation, we can expect to face a change in various indicators of engine operation, e.g. fuel consumption, level of noise as well as changes in smooth engine operation [11]. The standard design of exhaust gas recirculation system has its limitations, which involves the lack of flexibility in the degree of exhaust gas recirculation control [7, 8, 10]. The results of simulations based on the values of selected exhaust gas recirculation system parameters are shown in Figure 3 and deal with the standard exhaust gas recirculation system design. The calculations account for a differential pressure between the intake and the outlet nozzle of 0.05 MPa which was experimentally determined in a prototype exhaust gas recirculation valve. The value corresponds conform to the recorded results during engine testing with a standard exhaust gas recirculation system.
By analysing these data, we can note that in standard design of exhaust gas recirculation system, the maximum possible exhaust gas recirculation degree can be achieved with a small valve opening of approx. $1.3 \times 10^{-3}$ m which representing approx. 25% of the total exhaust gas recirculation valve’s stroke amounting precisely to $5 \times 10^{-3}$ m (Figure 3). The studies and simulations using the original configuration of the exhaust gas recirculation system with a proportional valve resulted in identification of the need to modify its configuration.

A wider range of adjusting the volume of recirculated exhaust gas can provide a better use of exhaust gas recirculation system, but under the condition of increasing the resolution of the control system of the exhaust gas recirculation valve. In connection of the limited range of the control of the recirculated exhaust system, a modification is proposed involving an increase of the cross section of the tube connecting exhaust gas recirculation valve with the intake manifold of the engine and a simultaneous increase of resolution control the degree of exhaust gas recirculation (number of steps of the exhaust gas recirculation valve).

There was an increase of sectional area of the tube coupling the outlet manifold to the exhaust gas recirculation system from $0.95 \times 10^{-6}$ m$^2$ to $3.46 \times 10^{-6}$ m$^2$, hence, its inner diameter increased from $11 \times 10^{-3}$ m to $21 \times 10^{-3}$ m. Simultaneously, due to the use of a ribbed tube coupling EGR with the intake manifold with a larger diameter, we can expect to improve the cooling of recirculated exhaust gas flow.

### 4. Experimental studies of modified exhaust gas recirculation system

Emission of harmful substances in the exhaust gas in the original design was controlled using exhaust gas recirculation valve with two states ON/OFF, and controlled by an electromagnetic actuator. Exhaust gas recirculation system was also equipped with an additional bypass channel. Engine operation with a binary exhaust gas recirculation valve, at steady operating conditions has a significant impact on the exhaust gas concentration of harmful substances. For the bimodal valve and drawing attention to Fig. 2, three speed ranges for measuring fuel consumption, nitrogen oxides and particulate matter concentration were selected. Measurement points are listed in table 1.

| Speed Range | Fuel Consumption | NOx | PM |
|-------------|------------------|-----|----|
| 800 rpm     | 3.2 g/kWh        | 0.4 ppm | 0.03 g/kWh |
| 1000 rpm    | 3.4 g/kWh        | 0.5 ppm | 0.04 g/kWh |
| 1200 rpm    | 3.6 g/kWh        | 0.6 ppm | 0.05 g/kWh |
| 1400 rpm    | 3.8 g/kWh        | 0.7 ppm | 0.06 g/kWh |
| 1800 rpm    | 4.0 g/kWh        | 0.8 ppm | 0.07 g/kWh |
| 2200 rpm    | 4.2 g/kWh        | 0.9 ppm | 0.08 g/kWh |

Table 1. Engine test measuring points.
Taking into account (tab. 1) selected 3 engine rotational speed ranges (idle engine crankshaft speed range: point 1 - 2, maximum torque range: point 3 - 5, range corresponding to the maximum engine power: point 6 - 8) concentration of nitrogen oxides, particulate matter tests were carried out as 8-point test. The research was carried out on a test bench (Figure 4a) using a compression ignition engine Zetor Z1505 (Figure 4b).

| Point no | T [N·m] | n [min⁻¹] |
|----------|---------|-----------|
| 1        | 0       | 850       |
| 2        | 100     | 900       |
| 3        | 100     | 1400      |
| 4        | 265     | 1400      |
| 5        | 396     | 1400      |
| 6        | 41      | 2000      |
| 7        | 208     | 2000      |
| 8        | 311     | 2000      |

Figure 4. Diesel engine: a) coupled with an electrodynamic brake used for testing, nominal power output of 90 kW - defined according to procedure 24 ECE R 03; b) the exhaust gas recirculation system is additionally equipped with the nitrogen oxides / oxygen sensor and AVL pressure sensors, located in a test engine's cylinder and fuel system.

Figure 5 illustrates the harmful substances concentration at exhaust gases of tested engine for the steady operation states at the speeds of NO\(_x\) and PM. The measurements made for the binary exhaust gas recirculation valve confirm the correlation between the emissions of nitrogen oxides and particulates matter, as shown in Fig. 3, but in a wider range of variations in engine rotational speed. Fig. 3 shows this in terms of constant speed and unchanging load. From the data presented, it is clear that in the low load range, where the compression ignition engine is operating with a large amount of air, the nitrogen oxide in-exhaust gas concentrations play a greater role. The opening of the exhaust gas recirculation valve results in a significant value reduction at each measurement point. However, increasing the load and thus enriching the air / fuel mixture results in a slight increase in particulate matter concentrations for the closed valve and a very significant about 17 times increase in particulate matter concentration in
the exhaust gas (29.3 to 496.0 mg·m⁻³), of not fully loaded engine. At the same time, there were slight changes in fuel consumption at the surveyed points.

Figure 5. Influence of the exhaust gas recirculation valve opening at selected engine speed range and engine load at concentration in exhaust gases: a) nitrogen oxides, b) particulate matter.

Whereas we can confirm the phenomenon described in the literature regarding the lack of a relation between the exhaust gas concentration of nitrogen oxides and particulate matter concentration at exhaust gases – we know that in the conditions of a low particulate exhaust gas concentration and at the same time there is a high exhaust gas concentration of nitrogen oxides and vice versa [12].

Therefore, we applied a new programmable valve manufactured by Auto Power Electronic company in the place of a serial two-state exhaust gas recirculation valve, whose role is to provide a continuous control of the volume of the recirculated exhaust gas.

Figure 6. Modified exhaust gas recirculation system valve with an gas outlet

A programmable exhaust gas recirculation valve is equipped with a microprocessor-based control system with an implemented adaptive control algorithm and predictive control algorithm with a linear indicator of the control quality. A microcontroller system communicates with the opening degree of the exhaust gas recirculation valve via a controller area network bus, and thus feedback is provided in communication [6, 9, 13].

An external exhaust gas recirculation valve control system transmits a set command with the position demand of the valve and after an adequate verification the microcontroller sets the new position of the valve and then sends feedback signal with the current position of the valve and the actual conditions necessary for its diagnosis [7, 10]. The initial design of the valve has 17 programmable steps whereas the number of steps is 40 in the final version, which can be optionally divided into any range of the exhaust gas recirculation valve opening from 0·10⁻³ m to 5·10⁻³ m.
Based on design assumptions, the emission of nitrogen oxides and particulate matter was measured in the conditions of the modified exhaust gas recirculation system (Figure 6). New exhaust gas recirculation valve was programmed for 10 steps and the gas outlet diameter increased from $10\cdot10^{-3}$ m to $22\cdot10^{-3}$ m, which leads to more than four times greater cross-sectional area. The measurements were repeated for the engine in quasi-stationary conditions under the same engine speeds and loads.

Figure 7 contains a chart with the changes in exhaust gas concentrations of nitrogen oxides and particles exhaust gas concentration as a function of the position of the EGR valve for variable load and fixed speed of 900 rpm.

**Figure 7.** Influence of exhaust gas recirculation valve position for engine speed 900 rpm and engine load range of (10 ÷ 180) N·m on the exhaust gas concentration of: a) nitrogen oxides, b) particulate matter.

The bold line represents the load of 100 N·m and a synthetic comparison of exhaust gas concentration of nitrogen oxides and particulate matter at n - 900 rpm and 100 Nm load is shown in Figure 8. We can note the range of exhaust gas recirculation valve control, which increased to 50% of open in relation to the standard design. Two significant differences can be seen in comparison to the results registered with
regard to binary valve. The changes in concentration of nitrogen oxides and particulate matter is associated with the change in the valve positions for different exhaust gas recirculation system configurations (old/new). For the engine speed $n = 900$ rpm, the greatest changes in nitrogen oxide exhaust gas concentrations between new and old exhaust gas recirculation system configuration are noted for the closed valve, where an increase of nitrogen oxide exhaust gas concentrations was observed, however, for the full opening, a considerable reduction in exhaust gas concentrations (by more than 300%) follows for the full valve opening. Equally importantly, in terms of meeting emission norms, the change of particulate exhaust gas concentrations in the exhaust gas occurs due to the change in valve opening and the new outlet channel design. However, we noted an increase in particulate matter exhaust gas concentration. The purpose of meeting the new emission standard involves a need to apply a Diesel Particulate Filter with the ability of reducing particulate matter exhaust gas concentration by over 95%. In such a case, a reduction of both nitrogen oxides and particulate matter exhaust gas concentration is possible.

Figure 8. Influence of exhaust gas recirculation valve position (ON/OFF) on the exhaust gas concentration of: a) nitrogen oxides, b) particulate matter at new and old exhaust gas recirculation system configuration by engine rotational speed of 900 rpm and engine load of 100 N·m

The parameters including fuel consumption and accelerator pedal position as well as other parameters read from the engine electronic control unit were monitored for steady engine operating conditions during the experimental studies (Figures 9 and 10).
Figure 9. Accelerator pedal position vs. the position of the exhaust gas recirculation valve for engine load in the range of (10 ÷ 180) N·m

Figure 10. Fuel consumption vs. the position of the exhaust gas recirculation valve for engine load in the range of (10 ÷ 180) N·m

A change in fuel consumption can result from the correction change in accelerator pedal position controlled the engine electronic control unit (Figure 10).

5. Conclusions
It can be stated that the exhaust gas recirculation system has a significant influence on the ecological parameters of the operation of internal combustion engines used in off-road vehicles. The use binary exhaust gas recirculation valves is associated with particular limitations, as there is no possibility of indirect activation of the valve opening position. The use of a programmable valve provides not only the ability to regulate that opening but also provides the option of its selection due to the possibility of implementing preferred range control. For the system used in the study, the controllability of system scope was limited to 25% of the opening of the exhaust gas recirculation valve, which resulted from the application of the outlet tube with a small diameter. Such a reduced tube diameter also affects the distribution of velocity and pressure of exhaust gas through the exhaust gas recirculation valve making it turbulent.

Following are the findings of the experiments:
- Increase of the outlet diameter of the exhaust gas recirculation valve extends the scope of exhaust gas recirculation valve control but also has a significant impact on the emission of harmful substances in exhaust gases.
- There is possible of reducing nitrogen oxides concentration in exhaust gases up to 68% due to the use of a modified exhaust gas recirculation system (by comparison for the fully open exhaust gas recirculation valve also in old as in modified exhaust gas recirculation system).
- The extended scope of the control provides an option of a more extensive regulation of recirculated gas flow and results in the reduction of nitrogen oxides concentration between 7,2% and 68,2%.
- There is observed a relation between the exhaust gas concentration of harmful substances in the exhaust system and the opening of the exhaust gas recirculation valve. With the increase in the exhaust gas recirculation valve opening, the concentration of nitrogen oxides in the exhaust gas decreases, however, at the same time the particulates exhaust gas concentration increases, as its level is dependent on the engine load.
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