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PRECISION DIAGNOSTICS OF A DIESEL ENGINE UNDER AGRICULTURAL TRACTOR OPERATING CONDITIONS

Summary. This paper presents a method for the precise diagnosis of a diesel engine in an agricultural tractor based on the analysis of efficiency changes and parameters characterizing the process of fuel-air mixture preparation. We proposed that the technical condition be identified based on available data from the engine controller, as this enables the implementation of precise online diagnostics of an agricultural tractor. The method was verified using the original cycle, during which we simulated several engine defects leading to a change in conditions and quality of the processes of creating and burning the fuel/air/flue gas mixture. In the paper, we justified the selection of the points at which the engine parameters were measured, as they provide the most information and allow for efficient identification of damage. These results indicate the possibility of damage identification without the use of the diagnostic cycle in the operation of operator-driven vehicles and autonomous vehicles.

1. INTRODUCTION

The operation of agricultural tractors for precision farming works, as well as the use of autonomous vehicles, necessitates several improvements in their design. This is becoming a major challenge because agricultural tractors of this type require a modern approach to online diagnostics. It is necessary to constantly monitor the operation of individual components, precisely identify changes in parameters, and quickly detect any types of unfitness. This prevents the damage from spreading and safety hazards from occurring. It will only prevent deterioration in the precision of agrotechnical procedures. This is particularly important during the operation of fully or partially autonomous vehicles.

Modern agricultural tractors exhibit advanced designs with many complex functional units. They meet increasing customer requirements, including, above all, increased work comfort and increased efficiency while minimizing operating costs. There is another challenge that vehicle manufacturers must face if they wish to operate on the market, namely, the need to comply with the latest emission standards. These standards are becoming increasingly stringent and, over the last 20 years, have forced manufacturers to make changes to the design of their combustion engines. These changes have been most significant for fuel, intake, and exhaust systems. Unfortunately, this has contributed to the complexity of engine design and, as a consequence, to the increased number of potential damage cases [1]. The correct operation of a tractor depends on the reliability of several mechatronic devices controlled by electronic and IT elements. Mechatronic technologies are used to manage the operation of the engine, drive system, gearbox, and functional parameters of machine aggregates [2]. Automatic

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control systems have also been introduced [3, 4] to ensure efficiency, reduce fuel consumption, and ensure the better use of torque and engine power. Owing to these systems, tractor control systems take over many management functions from the operator [5]. Modern agricultural tractor engines are equipped with the engine power supply system of the common rail type, as well as charging and exhaust gas discharge systems with modern designs and advanced algorithms controlling their operation [6]. Their proper functioning depends on the quality of fuel and the proper operation of precise mechatronic systems, which work well only within a small (micron) range of structural parameters [7]. Fuel consumption is one of the basic diagnostic parameters for identifying the technical condition of a vehicle [8]. The pressure values for fuel in the common rail system tank contribute to changing the fuel intensity, which flows out of the nozzle. It has a major impact on the increase in fuel expenditures [9].

Agricultural tractors exhibit numerous versatile functions. They are used for various types of work on farms and in forestry, construction, municipal services, and transport. The character of work, which is mainly performed in variable and difficult environmental conditions, contributes to a high risk of damage [10]. This results from operating at variable engine speeds, random load, and a high demand for changing torque [6]. Some operations are related to a schedule caused by potential losses, among others, in agrotechnical work [11]. Therefore, it is extremely important to quickly detect the damage to reduce the risk of decommissioning the vehicle or deterioration of the tractor operating parameters.

The current level of advancement of the electronic control systems enables the use of multi-level diagnostic systems providing the necessary information on the tractor's operating parameters. The first diagnostic level includes on-board diagnostics. It is the first source of information for the driver. The basic devices for the human-vehicle communication interface include multifunctional, programmable Human-Machine Interface terminals. On-board diagnostics are characterized by the automatic and quick detection of damage, thus preventing its expansion. [5]. Most often, the information obtained from the on-board diagnostics does not make the tractor come to a stop but only indicates the need to perform second-level diagnostics. In diagnostic tests, there are several ways of verifying whether an agricultural tractor engine is operating correctly. The test can be performed by comparing the current engine specifications and the OECD (Standard Codes for the Official Testing of Agricultural and Forestry Tractors) test for the same tractor make and model [12, 13]. The equipment for evaluation and diagnostic test monitors the engine performance, whereas a specialist diagnostic system [14] identifies default operating parameters or improper tuning of some engine parameters decisive for correct fuel combustion. It then compares the current performance with the OECD test results. The OECD tests are used to compare the tractor's performance before purchase [15] and allow a comparison between various driving modes [16]. In this paper [17], we propose using OECD tests for diagnostic purposes. On the other hand, a previous paper [1] describes the method of identification of operation parameters of a diesel engine. A detailed analysis of the current state of the engine is based on an analysis of the mixture formation and combustion processes obtained after installing additional sensors. The results of the operating tests of diesel engines also provide extremely important information about the most frequent types of damage occurring in their systems. An evaluation of the most frequent damage types (Fig. 1) was obtained from statistical tests of diesel engines, which were repaired in a year in a specialized workshop. Injectors, sensors, and fuel filters were repaired most often. Low-pressure pumps, controllers, and EGRs were repaired the least often.

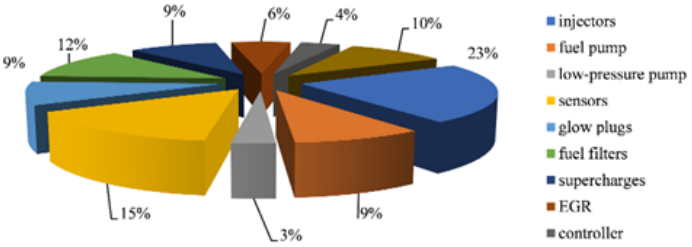

Fig. 1. Damage to diesel engines with an electronic control system that were repaired in a year in a specialized workshop

The most numerous group is electronic failures of the fuel supply system injector control (23%), followed by sensors (15%), filters (12%), and the engine air supply system (9%), including damage to the intake lines and turbocompressor.

The effectiveness of solving a problem related to damage repair depends on the selected diagnostic cycle algorithm. Ecological cycles were used for the engine on the test bench [12], engine operation with a load on an external loading device [17], and the definition of engine performance in real operating conditions [1]. The diagnostic cycle must be characterized by repeatability. At the same time, the requirements for the repeatability of diagnostic cycles can be reduced by using tools that record data from the controller in real-time. For this purpose, it is necessary to increase the importance of the quantitative component of diagnostics and focus on the analysis of how the parameters change over time. Currently, agricultural tractors are tested in stationary and dynamic tests. During the former, exhaust emissions are measured when the engine is running in a stable, steady state (constant torque and engine crankshaft speed). However, during the second test, exhaust emissions are measured when the engine operates in a transient state (with negative torque occurring) [13].

A literature review and analysis of information from agricultural tractor operation systems both indicate that, so far, no information is available on how damage to engine components affects its operation efficiency in emergency mode. This paper aims to identify the impact of damage to internal combustion engine components on the operation of an agricultural tractor.

We proposed an original diagnostic method consisting of identifying the damage based on efficiency analysis and excess air coefficient obtained without the need to apply a typical (complex) diagnostic cycle. The data from the engine control system were used to determine the efficiency and excess air coefficient.

Similar engines are used for other vehicles (e.g., cars, trucks, buses, and construction vehicles). This original diagnostic method can also be used to diagnose the listed vehicles.

2. RESEARCH METHODOLOGY

A new agricultural tractor from one of the world's leading manufacturers was the object of our research. The tractor's operation time counter was 10 h at the beginning of the test. The tractor was equipped with a diesel engine, a common rail fuel system, and a turbocompressor with variable geometry. Other basic technical data are presented in Table 1. The vehicle meets the STAGE IV exhaust gas pollution standard [12]. This was achieved by using a modern fuel system, modern elements of the intake system, and an extensive exhaust system which included, among other components, a diesel oxidation catalyst, a selective catalytic reduction system, and a CUC catalyst converting the remaining ammonia. The tractor was equipped with an automatic direct shift gearbox and 4x4 drive.

The tested agricultural tractor had a Bosch engine control and management module. It was an EDC17 CV41 controller equipped with two 96-pin connectors. The engine module received data from sensors, processed this data, and controlled the connected executive elements. Correct fuel dosage is one of the main functions of the controller. The fuel dose was adjusted based on signals from sensors such as temperature, air quantity and pressure, engine coolant temperature, oil temperature, accelerator pedal position, and engine crankshaft speed, as well as signals from devices reducing the amount of toxic compounds in exhaust gases.

Modern systems installed in tractors need complex devices to control their operation. This, in turn, necessitates the implementation of a new approach to operation, and especially to vehicle diagnosis.

The tractor's primary operating parameters were recorded with a Texa Navigator TXTs diagnostic scanner with a dedicated version of OFF-HIGHWAY software. Along with computer diagnostics of vehicles from various categories, including agricultural tractors, the device enabled the real-time recording of operation parameters of individual components, including the engine. The device supported the following communication protocols: flash codes, K, L, ISO9141-2, ISO14230, CAN ISO11898-2, ISO11898-3, SAE J1850 PWM, SAE J1850 VPW, and SAE J2534-1. Before the tests commenced, the device was configured using the Rec&Play function, which records changes in selected engine operation parameters over time. The technical parameters of the Texa TXTs were as follows: Hardware CORTEX

M3 STM32F103ZG 72 MHz, FLASH 1024 Kbytes, and SRAM 96 Kbytes. The devices were equipped with SRAM memory (8 Mbit- 512 Kb x 16 bits NAND) and flash memory (1 Gbit on an 8-bit bus).

Table 1

Technical specifications of the tractor's engine

Parameter	Value	Unit
Cubic capacity	4485	cm^3
Number of cylinders	4	
Maximum torque with power management at 1500 rpm	700	Nm
Maximum torque at 1500 rpm	605	Nm
Increase in torque with power management	42	%
Standard increase in torque	40	%
Maximum power according to ECE R120 with power management	124	kW
Maximum power according to ECE R120 at 1900 rpm	107	kW
Maximum power according to ECE R120 with power management in field mode	114	kW
Rated power according to ECE R120 with power management in road mode	123	kW
Rated power according to ECE R120 at 2200 rpm	99	kW
Tractor's weight (the analyzed version)	5240	kg
Tractor's length (the analyzed version)	5180	mm

The tests planned for this paper made it possible to identify the influence of frequently occurring engine damage types on the functional parameters of an agricultural tractor. The tests were performed during test runs with simulated engine damage. During the tests, for individual damage cases, we recorded various parameters, including fuel consumption, power, torque and engine efficiency, used air-to-fuel ratio, and supercharging pressure. The measured parameters were selected using an engine model developed in AMESim (Fig.2) to obtain a precise diagnosis. This process enabled the simulation of selected system malfunctions under various operating conditions (Fig. 2). In the presented model, the influence of the malfunctions on the functional parameters of the engine was examined by changing the cross-section geometry of the inlet system and the injector flow rate values. The modeling results and engine power measurements taken during the diagnostic cycle were used for model verification (Fig. 3).

During the course of engine operation, parameters at idling, during acceleration from idle to nominal engine speed, and during tests using the NRTC cycle [12] were assessed in the diagnostic process (Fig. 4). The NRTC cycle has a high load factor and high dynamics. Such features of the NRTC cycle allow for a clear definition to be provided of the ecological engine operation range, as well as the identification of a wide range of engine system failures. At the same time, it is advisable to increase the proportion of points at low load for diagnostic purposes.

These possible diagnostic approaches will be identified by the mathematical and physical modeling of engine operation at an idle run and during acceleration from idle to nominal speed. It is advisable to present the results obtained in the form of a comparison of the efficiency coefficient for an engine in good operating condition and with simulated damage (Fig. 5). The efficiency value characteristic for an engine in good operating condition at idling is 0.2126 (computed value = -0.20017). The failure of one of the injectors during the engine's idling causes an increase in the efficiency of the working cylinders by 1.1. A reduction in the inlet system capacity (partial clogging of the air filter) at idling does not lead to a change in efficiency. On the other hand, if the inlet system is leaking, a decrease in efficiency is observed, which is connected to incorrect air-fuel proportions in the combustion process. Changes in engine efficiency can also be observed during free acceleration. If the efficiency of the working cylinders remains above the target value when one of the injectors is switched off, the other two failures lead to a drop in efficiency of 10% on average. Furthermore, it is difficult to identify the malfunction in this case. Due to the imperfections of the methods described, another diagnostic test had to be developed to identify the effect of damage on engine performance.

In this paper, we used the original diagnostic cycle, which consisted of a test run lasting 600 s. The sampling frequency of the analyzed parameters was 2 Hz. The diagnostic cycle was selected to simulate the operation of an agricultural tractor in transport conditions when used with a two-axle transport trailer. This type of operation was chosen because any damage to the tractor under these conditions has a direct impact on environmental pollution in densely populated areas. The test runs were performed under varying load conditions. During the diagnostic cycle, the rotational speed of the engine crankshaft varied over the entire range from idle run to maximum values (Figs. 3 and 4). At the same time, more than 90% of the engine operating points did not exceed 50% of the rated power, which is characteristic of the transport mode.

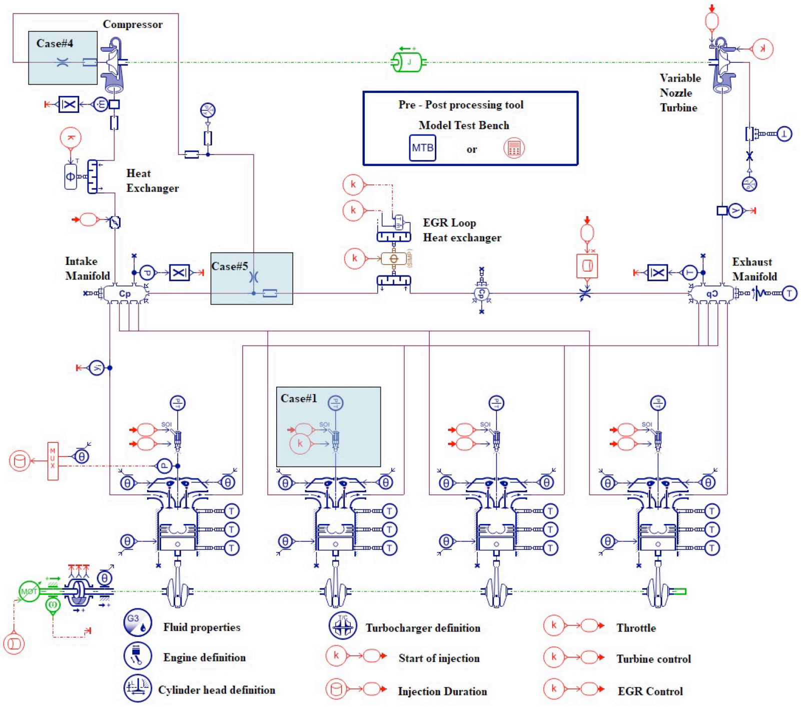

Fig. 2. Tractor engine model in AMESim software, which enabled the simulation of selected system malfunctions under various operating conditions

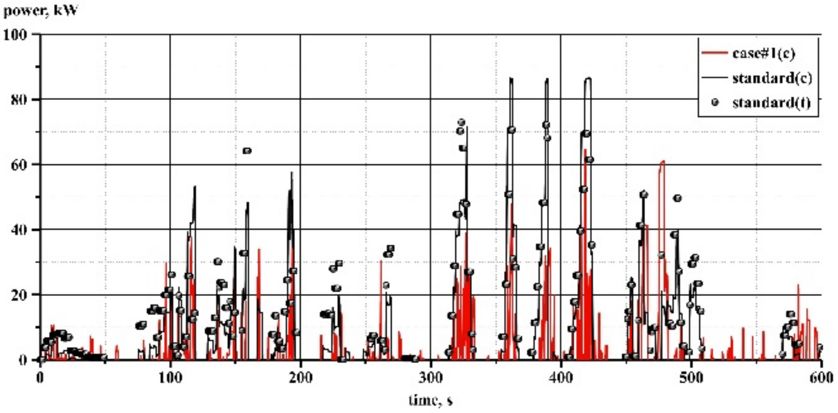

Fig. 3. Comparison of engine power measurements over the diagnostic cycle caused by a failure of one of the injectors under simulated and real conditions

First, we carried out the test with an engine in good operating conditions, and then we simulated five defects. Defects were selected based on the data given in Fig. 1 concerning the defects of a combustion engine with electronic control. The same test run was performed for each of these defects.

In this paper, we simulated the following engine defects:

Case #1 – Disconnected injector on the second cylinder. The fault consisted of disconnecting the electrical connector between the engine controller and the injector, which was intended to simulate one of the most frequent engine defects.

Case #2 – Disconnected flowmeter. The fault consisted of disconnecting the electrical connector between the engine controller and the flowmeter identifying the amount and temperature of the air flowing through the engine intake system.

Case #3 – Disconnected temperature sensor. This sensor was located on the engine block and measured its temperature. The temperature value was transmitted from this sensor to the engine controller.

Case #4 – Reduced intake clearance by 50% (clogged). The fault simulated dirt on the air filter or a foreign object entering the intake system. The clearance was reduced at the intake to the air filter housing.

Case #5 – Loose intake system. The damage consisted of introducing a leak before the inlet to the intake manifold after the flowmeter and intercooler.

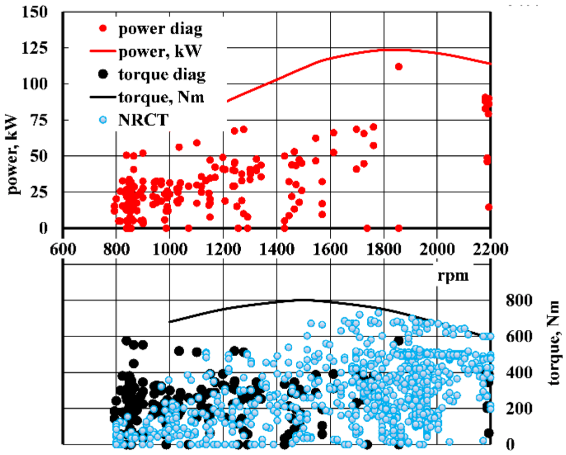

Fig. 4. Load field of the diesel engine during the diagnostic cycle (continuous lines correspond to the external characteristics of the engine) and the NRTC cycle

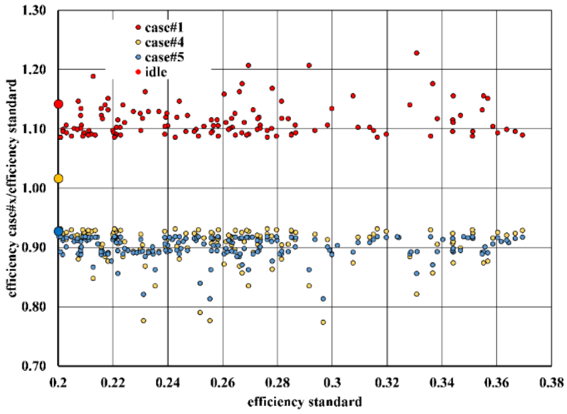

Fig. 5. Comparison of the efficiency coefficient for an engine in good operating condition and an engine with simulated damage

The tractor's engine was equipped with a control system allowing for precise diagnostics based not only on operation values but also on specialist measurements made during engine operation—namely, actual supercharging pressure and the fuel dose administered by the injector. The efficiency of diagnostic processes increased with the use of dependencies identified during the analysis in the form of the following basic engine operation parameters: power, torque, fuel consumption in relation to design parameters, and process quality indicators. The primary data recorded during diagnostic tests were processed, which provided rich data, allowing us to analyze the relations between them.

For example, when diagnosing engine power P, we could analyze its relations with the cylinder volume V_h, number of cylinders i, number of strokes τ, fuel properties (H_u, l_0), combustion process quality (η/λ), filling factor η_v, mechanical efficiency η_m, crankshaft speed n, and charged air density ρ_{air} [18]:

$$P = \frac{V_h \cdot i \cdot H_u}{\tau \cdot l_0} \cdot \frac{\eta}{\lambda} \cdot \eta_v \cdot \eta_m \cdot \rho_{air} \cdot n, \tag{1}$$

where: H_u – fuel calorific value, l_0 – theoretical air/fuel ratio, η – efficiency, λ – excess air coefficient.

During all six tests, we recorded the following engine parameters:

- fuel supply to one cylinder during the engine operating cycle (four-engine piston strokes) [mg/cycle]
- total weight of air taken by all four cylinders during the engine operating cycle (four-engine piston strokes) [mg/cycle]
- engine crankshaft speed [rpm]
- the required supercharging pressure determined by the controller at a given moment, taking into account, among other things, the engine load [Mpa]
- the resulting supercharging pressure, measured by a sensor in the intake manifold [Mpa]
- engine torque [Nm]
- engine load, measured as the ratio of required torque to maximum engine torque [%]

Based on the recorded data, we determined the following parameters:

- momentary power P generated by the engine [kW] from the following relationship:

$$P = M * \omega, \tag{2}$$

M – engine torque

ω – engine crankshaft angular speed

$$\omega = \frac{2 * \pi * n}{60}, \text{ where} \tag{3}$$

n – engine crankshaft speed

- G_{fuel} [kg/h] fuel consumption based on the following relationship:

$$G_{fuel} = \frac{q * n * i * 60}{2 * 1000 * 1000}, \tag{4}$$

q – fuel supply to one cylinder during the engine operating cycle [mg/cycle].

- the ratio between the obtained and the set supercharging pressure r based on the following relation:

$$r = \frac{p_{d\,uzys}}{p_{d\,wym}}, \tag{5}$$

$p_{d\,uzys}$ – supercharging pressure obtained, measured by the sensor in the intake manifold [Mpa]

$p_{d\,wym}$ – the required supercharging pressure determined by the controller at a given moment, taking into account, among other things, the engine load [Mpa]

- coefficient λ, which represents the ratio of the consumed air and fuel based on the below relationship:

$$\lambda = \frac{v_{pow}}{v_{pal} * i}, \tag{6}$$

v_{pow} – total weight of air taken by all four cylinders during one engine cycle [mg/cycle]

v_{pal} – weight of fuel dosed to one cylinder during one engine cycle [mg/cycle]

- engine efficiency

$$\eta = \frac{3600 \cdot 10^3}{Hu \cdot g_e}; \tag{7}$$

- fuel consumption per power unit

$$g_e = G_{fuel}/P \tag{8}$$

Fig. 6 presents our test plan. Simulated faults in the engine of the tested tractors are shown on the left. The parameters recorded during tests are shown on the right.

3. TEST RESULTS

Based on the data recorded during the tests representing the changes in engine operating parameters over time, we obtained a number of characteristics describing the impact of damage on engine operation. For this purpose, we employed multi-stage processing. Fig. 7 presents an example course of changes in supercharging pressure throughout the diagnostic test. Such a large amount of data can make it difficult to read the graph and interpret the presented information. Nevertheless, by analyzing the data recorded during the test runs, we can conclude that when the damage to the tractor's engine was simulated, significant differences between the values of the required and obtained supercharging pressure were often observed (Fig. 7). If the tractor was in the good operating condition, the difference between the two values was negligible. Basically, significant differences in the supercharging pressure were observed with each simulated failure. In some rotational speed and load ranges, the value of the required supercharging pressure was too small in comparison to the obtained one, while in other ranges, it was too high. Such variability is very unfavorable, as it directly affects the efficiency of the engine, and high demands for power and torque cannot be met. Moreover, such a difference between the required and the obtained supercharging pressure contributes to increased fuel consumption. During practically every test run with simulated engine damage, we observed frequent changes in the value of the obtained supercharging pressure despite the same load conditions. This may indicate a continuous attempt by the engine controller to correct its operational parameters. The primary data, such as the data presented in Fig. 4, were processed to obtain computed data.

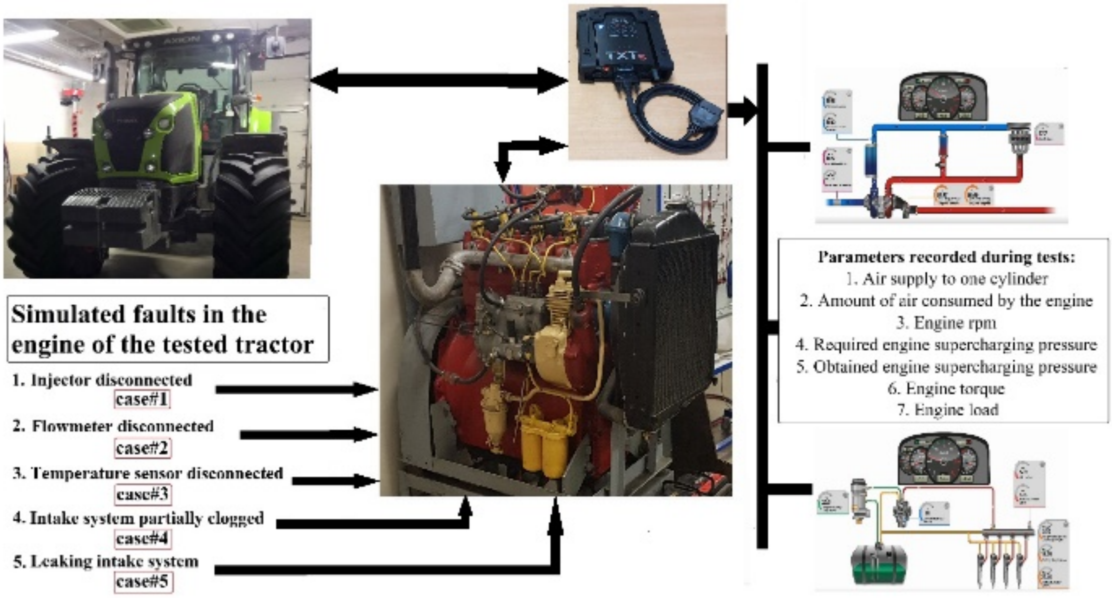

Fig. 6. Plan of the performed tests

After replacing the differential fuel consumption characteristics with an integrated one, we obtained a correlation that identified the impact of the simulated damage on engine operation. Fig. 8 shows the change in fuel consumption during the test runs. With most cases of engine damage, an increase in fuel consumption can be observed in relation to the operation of an engine in good operating condition (Fig. 8). The operation of the engine when one of the injectors is disconnected presents an exception. In this case, fuel consumption was reduced for the whole engine. In this case, we obtained an analogy to the well-known method of diagnosing fuel consumption reduction by switching off the cylinders in some engine operation modes [19, 20]. However, in this case, the fuel dose for individual cylinders increased. The remaining engine damage, both that related to the amount and conditions of air supply by the engine intake system and related to the temperature sensor, led to an increase in fuel consumption during the diagnostic cycle. This resulted from the fact that the engine operated in so-called emergency mode, in which the information missing to control the fuel dose was replaced by the most probable value [3, 4].

The repeatability of the conditions, together with an identical route during the diagnostic test for each case of simulated engine failure, can be confirmed through a comparison of the engine load fields (Fig. 9). Based on the comparison of the engine load points under the external engine characteristic, as shown in Fig. 9, during the diagnostic cycle, we can distinguish three characteristic engine operating areas. The first area was within the limits of the engine speed change from idling to 1,380 rpm. The second change range is from 1,400 to 1,800 rpm. The third area covers the change range from 1,800 to 2,200 rpm. The power and torque achieved at each load point were the same for each test series.

The engine power and torque waveforms shown in the graphs for each of the diagnostic tests are indicative of a large number of small engine loads in the first speed range, mainly in the idling range. The differences obtained in the distribution of points during engine operation in this range signify the practical value of such tests. With an engine in good operating condition, a much smaller scatter between individual points was recorded, both for engine power and torque. On the other hand, in each of the simulated engine damage cases, a much greater scatter between individual points was found for power and torque. A large degree of similarity can be observed between the power and torque courses for each case of simulated damage. Particularly small differences were found between the simulated disconnection of the injector, flow meter, and temperature sensor. A slightly different pattern was found in the case of the simulated clogging and leakage in the intake system. In these cases, changes in higher engine crankshaft speed ranges were particularly noticeable.

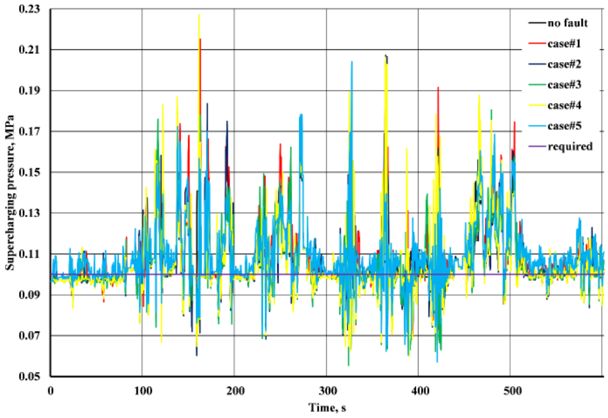

Fig. 7. Example course of changes in supercharging pressure during the whole diagnostic test and the difference between the obtained and required supercharging pressure

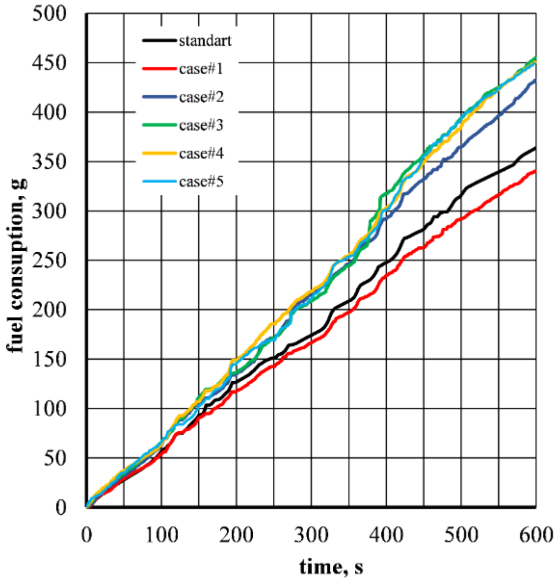

Fig. 8. Total fuel consumption characteristic for the tractor in the diagnostic cycle

4. ANALYSIS OF THE IMPACT OF SIMULATED AGRICULTURAL TRACTOR DAMAGE ON THE OPERATIONAL PARAMETERS OF A COMBUSTION ENGINE

An analysis of engine efficiency allowed us to increase the diagnostic accuracy and identify probable faults at an early stage before the tractor control system generated the fault codes. The data obtained from the controller allowed us to compare the efficiency of the undamaged engine to an engine with simulated damage. Of course, the accuracy of determining efficiency based on OBD data did not meet the requirements for testing processes in a combustion engine. At the same time, in diagnostic applications, the comparison proposed in this paper, based on the estimated efficiency values obtained by processing the recorded data, is considered sufficient.

For the engine with simulated damage and the undamaged engine, we performed a comparison of the distribution of engine load points in the efficiency space (Fig. 10). For the disconnected injector, an increase in efficiency can be observed in comparison with the value for an engine in good operating condition in the low load range (up to 20 kW). This is due to the improvements in fuel injection quality by the working injectors, which was caused by the compensation of idling gear by increasing cyclic fuel supply by the remaining working (efficient) injectors. In the case of defective sensors and faulty operation of the intake system, a decrease in engine efficiency was observed, which was confirmed by an increase in fuel consumption (Fig. 8).

Based on tests performed in the framework of this research, the following relationship describing engine efficiency was identified:

$$\eta_{case} = a + b \times \eta_{standart} + c \times \eta_{standart}^2, \tag{9}$$

where η_{case}, $\eta_{standart}$ are the efficiencies of the engine with simulated damage and an engine in good operating condition, respectively, and a, b, and c are the coefficients of a polynomial (Tab. 2).

A comparison of coefficients of Equation (11) allowed us to identify engine malfunctions.

Fig. 11 shows the relationship between the lambda coefficient for an engine in good operating conditions and the lambda coefficient for an engine with simulated damage. For each of the simulated failures, a non-linear relationship between the lambda coefficient for an efficient engine and the lambda coefficient for the simulated failures can be observed in the range of the characteristic values for idling (Fig. 11). The change in the air supply to the cylinder was analyzed in detail using the relationship between the ratio of the obtained supercharging pressure and the engine load values to the required values of these parameters (Fig. 12). For an engine in good operating condition practically across the entire load range, there is no difference between the obtained and the required supercharging pressure. Only with engine loads of more than 80% were greater differences between the two values observed. On the other hand, for each of the simulated defects, differences between the obtained and required supercharging pressure values were observed across practically the entire engine load range (Fig. 12). Particularly large differences are visible for the smallest and largest loads. With engine loads of up to 20%, the achieved pressure was too low in relation to the requirements. With high engine loads (over 70%), the obtained pressure was too high compared to the required pressure. Such discrepancies between the two supercharging pressure values are indicative of problems with controlling the amount of air supplied to the engine, which is also related to the air-to-fuel ratio.

Similar relationships can be observed when analyzing the graph in Fig. 13, which shows the change in the value of the obtained supercharging pressure. Throughout the diagnostic test, significant differences were observed between the supercharging pressure obtained in an engine in good operating condition and the supercharging pressure for each simulated failure. With engine loads of up to 10%, the supercharging pressure for each simulated failure was too low in relation to the supercharging pressure obtained in an engine in good operating condition. With high engine loads of over 70%, the supercharging pressure for each simulated failure was too high compared to the supercharging pressure obtained in an engine in good operating condition. With engine loads of 10% to 70%, the supercharging pressure for the simulated failure of a leaking intake system was too high compared to the supercharging pressure obtained in an engine in good operating condition.

Based on the performed tests and their results, three characteristic intervals related to engine load were identified. Therefore, it is no longer necessary to perform complete test runs. It is only possible to run tests in selected points related to load, power and torque defined with the proposed measurement methodology. Thus, the measurement points indicated provide important information.

5. CONCLUSIONS

The method proposed in this paper for diagnosing diesel engines in agricultural tractors under operating conditions consisted of recording data using a system for the collection and conversion of data from the control system during the original diagnostic test. The collected information was used to determine the efficiency of the engine based on the ratio of the amount of air supplied to the amount of fuel set by the controller managing engine operation. Such a method can be used for monitoring and diagnosing the condition of partially or fully autonomous agricultural tractors, where a modern approach to online diagnostics is necessary.

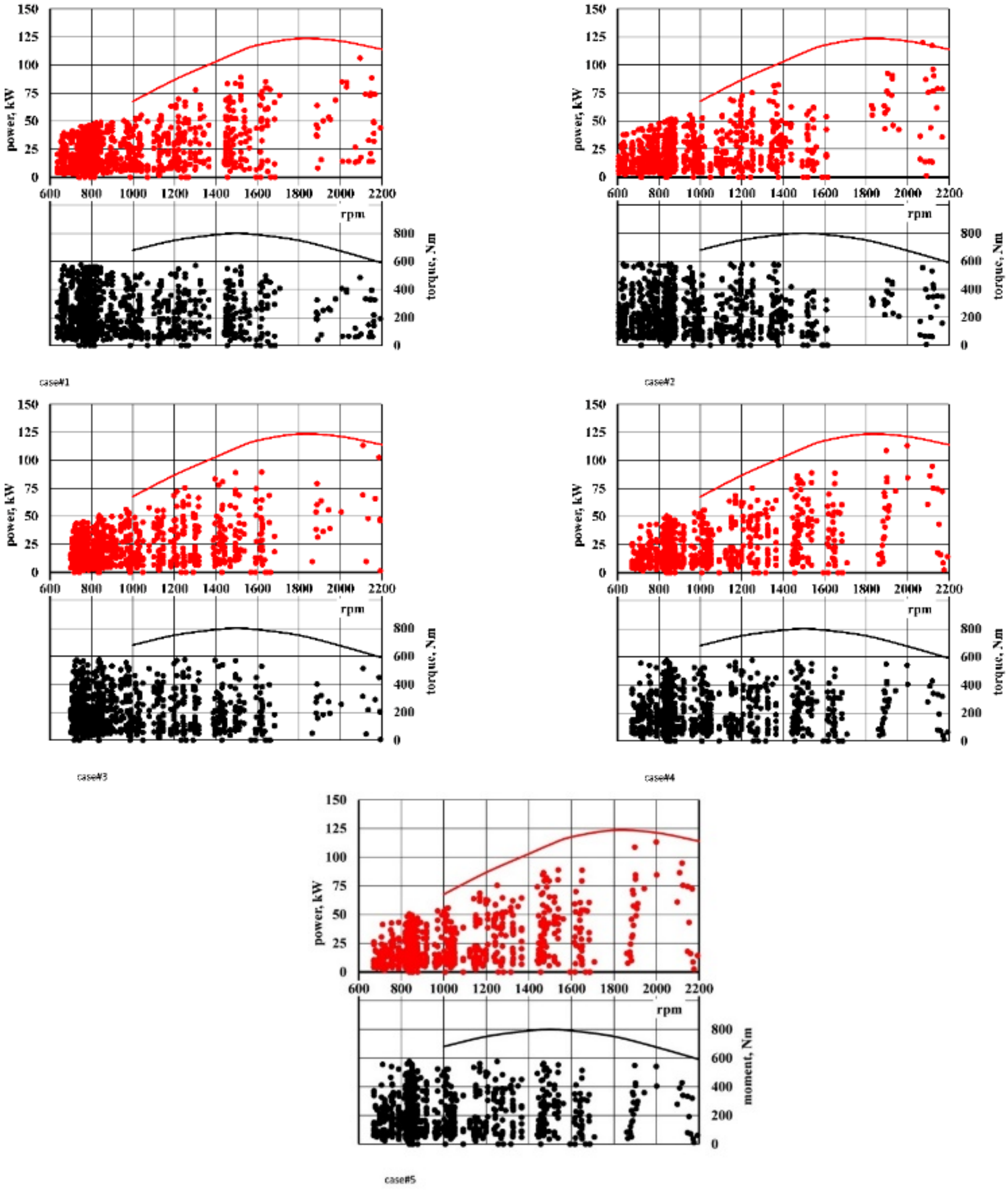

Fig. 9. Engine load area during the diagnostic cycle with an identical route for each simulated engine failure (external speed characteristics - continuous lines)

In vehicles of this type—owing to the continuous monitoring of the operation of individual components, the precise identification of changes in parameters, and the rapid detection of any type of failure—it is possible to prevent the damage from expanding and posing a safety hazard, as well as to reduce the performance precision for agrotechnical procedures.

The proposed diagnostic method was verified by simulating the most probable malfunctioning instances with subsequent analyses of both primary and computed data. The results obtained in this study confirmed the usefulness of the proposed method in identifying damage to agricultural tractor engines. Similar engines are used for other vehicles (e.g., for cars, trucks, buses, and construction vehicles). This original diagnostic method can also be used to diagnose the listed vehicles.

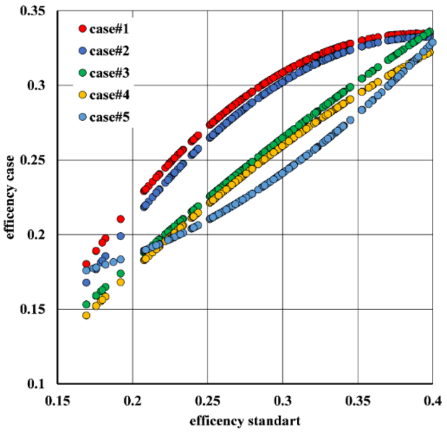

Fig. 10. Correlation between engine efficiency with simulated damage and a standard engine and a comparison of the distribution of engine load points in the efficiency space

Table 2

Value of coefficients of Equation (9) for individual simulated damage cases

	a	b	c
Case #1	0.1450894	2.4529727	-3.1350516
Case #2	-0.1663508	2.5071258	-3.1502456
Case #3	-0.0196680	1.1149152	-0.5553999
Case #4	-0.0528670	1.3446887	-1.0112574
Case #5	0.1746917	-0.2699040	1.6393644

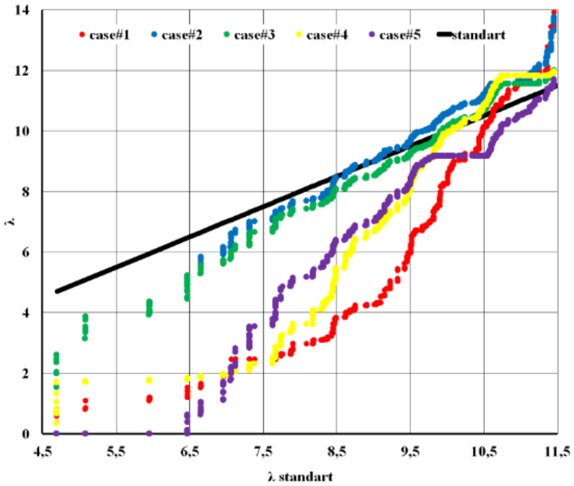

Fig. 11. Relationship between the λ coefficient for an engine in good operating conditions and the λ coefficient for an engine with simulated damage

Using the principles of the theory of combustion engines, we analyzed the influence of the frequently occurring defects discussed in this paper on the efficiency and the ratio of air amount to fuel supply cycles determined by the controller. The use of these parameters for diagnosis to increase the reliability of diagnostic results was justified. For example, when using directly defined fuel consumption as the decisive parameter, it is difficult to quickly identify instances of failure.

The data analysis employing statistical methods shows that:

- The quality of the mixture formation process and the combustion process with an idling engine can be improved when the injectors are not working properly. This relationship can be explained by an increase in the ECU supply to the working injectors, which improves the mixing and combustion process.
- For a similar reason, a flow meter malfunction leads to an increase in efficiency during idling and similar loads.

- In most engine damage cases, fuel consumption increases.
- Together with an increase in load, the efficiency of the engine decreases for all simulated failures. Taking into account adopted simplifications, the recorded decrease in values certainly exceeds the precision margin for determining this thermal parameter.
- A comparison of the air/fuel ratio for an engine in good operating condition and with simulated damage in the proposed diagnostic test determines the cause of the malfunction. In all simulated modes, this ratio was higher than the reference data.

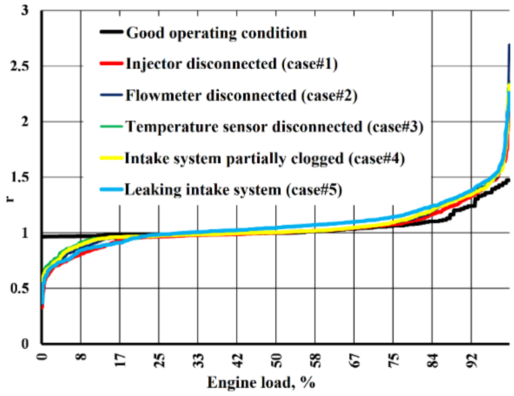

Fig. 12. Relationship between the ratio of the obtained values to the required values of supercharging pressure and the engine load during the diagnostic cycles with simulated damage and a standard engine

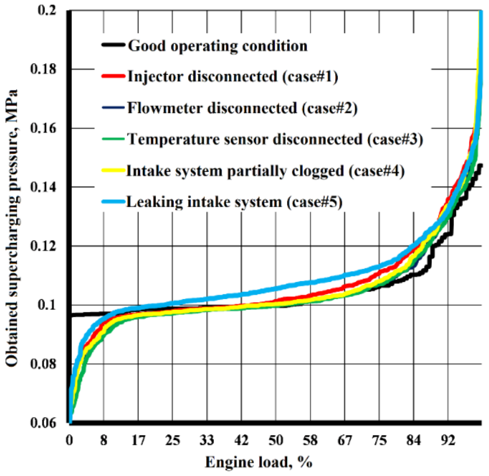

Fig. 13. The change in the value of the obtained supercharging pressure during the diagnostic cycles with simulated damage and a standard engine

Based on the performed tests and their results, three characteristic intervals related to engine load were identified. For this reason, it is possible to only diagnose engines in selected points related to load, power, and torque defined with the proposed measurement methodology.

The results of our work can be further used for developing precise online diagnostics for the operation of autonomous vehicles.

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