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THE IMPACT OF OPERATING PARAMETERS OF TRACTOR'S ENGINE ON EXHAUST EMISSIONS

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Abstract

At the beginning of the twenty-first century, one of the major challenges of humanity was to reduce the negative effects of civilization development. Besides the engines used in road vehicles there is a large group of engines for non-road applications. This group includes motor propelled vehicles not used on the road NRMM (Non-Road Mobile Machinery). Engines of these vehicles, among all of the non-road applications, are characterized by very specific working conditions that do not allow them to be qualified for propulsion engines. The main problem with these vehicles is the particulate matter and nitrogen oxides emission. The paper presents an analysis of the operating parameters of an engine and exhaust emissions of a tractor operating on a chassis dynamometer. Studies of the tractor involved measurements of engine operating parameters and the concentration of harmful substances in the exhaust gases. Information about the parameters of the engine and the intensity of emissions were obtained during the dynamometer test. The study included a comparative analysis of the operating parameters of the engine obtained from the diagnostic system and direct measurements on a chassis dynamometer and a correction of the torque obtained from the vehicle computer system was made. As a result, values of specific emission during engine tests under varying values of load were determined.

Keywords: *Non-Road Mobile Machinery, exhaust emission, operating parameters*

1. Introduction

Currently, Diesel engines must meet strict requirements for emissions of toxic compounds in exhaust gases. Offered non-road machinery must comply with the current standard Stage 4/Tier 4F (Tab. 1) [2-4]. Introducing this standard has posted completely new requirements for engine manufacturers. Mainly it comes to reducing emissions of particulates and nitrogen oxides. Changes in engines design have been introduced, such as modifications of the fuel injection system, which at the stage of preparing an air-fuel mixture to prevent the formation of excessive amounts of harmful compounds. Also extensive exhaust aftertreatment systems have been introduced, with an emphasis on reducing the concentration of nitrogen oxides and particulate matter.

Tab.1. The limit values of harmful compounds for the first and the last emission standard [3]

Exhaust compound	Tier 1 [g/kWh]	Tier 4 Final [g/kWh]	Decrease [%]
HC	1.0	0.14	86
NO_x	6.9	0.3	96
CO	8.5	2.2	74
PM	0.4	0.015	96

Capabilities of diagnostic systems in non-road vehicles (machines) are extensive and include control systems of the engine and the vehicle. In addition to purely diagnostic features the diagnostic systems can also be used to monitor the components which are e.g. the additional equipment of agricultural machinery.

Evaluation of the exhaust emissions can be carried out on a test bench, on which the operating parameters of the drive unit can be obtained, and at the same time, the measurement of the concentration of exhaust gas components can be done. Another possibility of evaluation of the operating parameters of the engine is the usage of the vehicle's diagnostic system, which provides engine's parameters, which are the basis for assessing the engine torque, and in the consequence the designated engine power.

The article describes a procedure for data use from the vehicle diagnostic system to designate the engine power, and in consequence the specific emissions of pollutants. However, this procedure requires a correction of the engine load read from diagnostic system, which is applied in newton meters and does not include its own engine resistance.

2. Methodology of the research

The object of the research was an agricultural tractor brand Fendt 828 equipped with Deutz engine TTCD 6.1 with a maximum torque of 1217 Nm at 1450 rpm and maximum power of 210 kW at 1700 rpm (Fig. 1). It meets the exhaust emissions standard Stage 4/Tier 4F. During the study a mobile dyno Egers Dynamometer PT301 [7] with a single axle was used. The dyno as the main element of the loading uses a retarder, which is air-cooled by two blowers. The dynamometer allows power measurements up to 600 kW (at a maximum speed of 3600 rpm) and torque to 7200 Nm with an accuracy of up to 1 kW/Nm.

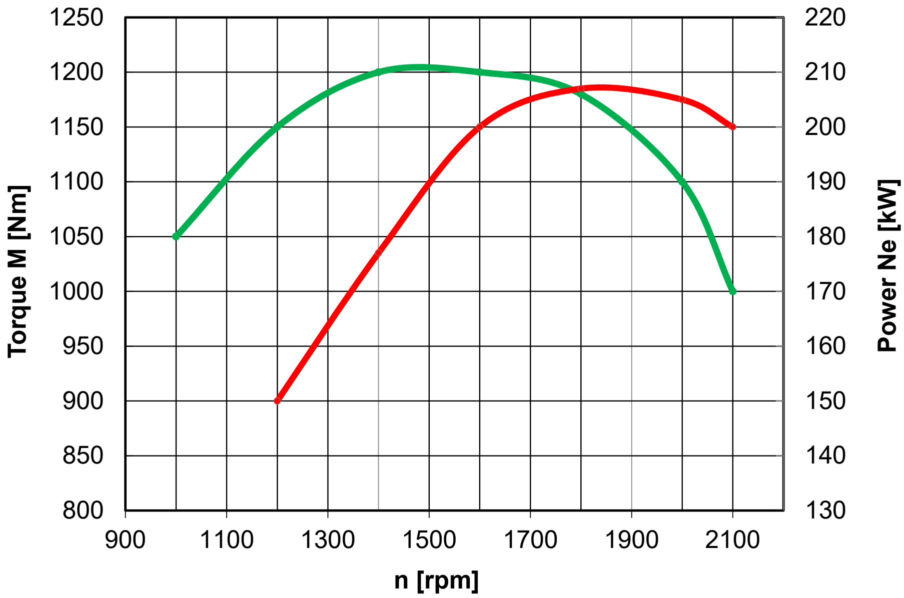

Fig. 1. Characteristics of the engine TCD 6.1 [8]

For the measurements of the concentration of toxic compounds in the exhaust gases, the Semtech DS analyser [6] and to the exhaust flow meter were used. The analyser allowed measuring the values of concentration of gaseous compounds and the connection with the vehicle's diagnostic system allowed reading the torque and rotary speed of the engine. During the measurements, was measured at the same time the torque on the dyno and read from the tractor diagnostic system [5]. Moreover, the measurements of emissions (gaseous and particulate) and the exhaust gas flow were performed (Fig. 2).

The study was divided into four range of engine speeds, during which gradually the engine load was increasing by dyno brake. The exact values are shown below in Tab. 2.

Fig. 2. Measuring station during the study (the dynamometer is directly behind the tractor)

Tab. 2. The list of measurement points during the test on the dyno

No.	Rotary speed of the engine [rpm]				Torque on the dyno [Nm]
	1000	1400	1800	2000	
1.	•	•	•	•	0
2.	•	•	•	•	100
3.	•	•	•	•	200
4.	•	•	•	•	300
5.	–	•	•	•	400
6.	–	•	•	•	500
7.	–	•	•	•	600
8.	–	–	•	•	700

At each measurement point, the engine was operating for 30 seconds, which allowed to stabilization of the exhaust flow and engine speed. As a result, the measurement results are affected by a smaller measurement uncertainty, which allows for analysis, which is more accurate and reflecting to reality. In the first stage (at a speed of 1000 rpm) in 5th point the measurement was stopped because the loading brake due to the low speed of power take-off shaft was characterized by a too high amplitude of vibrations which could cause damage to the element.

3. Analysis of the operating parameters of the engine

Engine torque values recorded by the analyser during testing are presented in Fig. 3. Specific steps in which measurements were carried out are shown in the speed range (1000, 1400, 1800 and 2000 rpm). All data in the graphs came from the diagnostic system of the tractor; they have been recorded and then processed.

The main measurement started about 1000 second (it was divided into 4 stages) and ended about 3500 second. The initial phase of heating and cooling the drive unit were not taken into account during results analysing. In a first stage, (1000-rpm) only four measuring points were conducted for the reasons described earlier. The engine was loaded gradually, from minimum load to a load equal to – depending on the rotary speed of the engine – about 70-85%. In the later part of the article, the graphics show only selected cases.

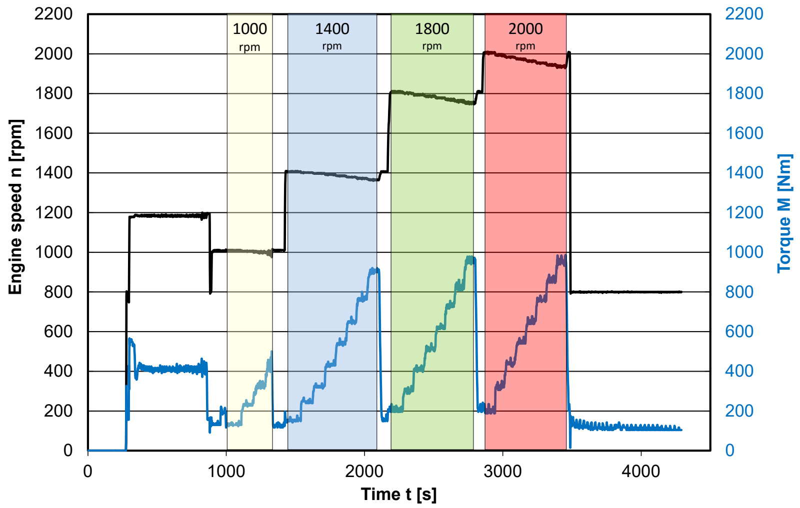

Fig. 3. The torque generated by the engine during the test against its rotational speed

For rotary speed of 1000 rpm – the minimum value of load (0 Nm on the dyno), the value of 130 Nm from diagnostic system was read. As the load increases, the deviation was reduced to ten percent. A similar situation was observed for an engine speed of 1400 rpm: for idling (0 Nm) the load value of 150 Nm was observed, and for maximum measuring point (700 Nm on the dyno) system diagnostic read value of 970 Nm (difference of 270 Nm and relative value more than 40%). Also in the case of an engine speed of 1800 rpm for idling (0 Nm) the load value of 200 Nm was observed, and for maximum measuring point (700 Nm on the dyno) system diagnostic read value of 950 Nm (difference of 250 Nm and relative values more than 30%). Similarly, in the case of an engine speed of 2000 rpm for idling (0 Nm) the load value of 200 Nm (relative difference tends to infinity), and for maximum measuring point (700 Nm on the dyno) system diagnostic read value of 950 Nm (a difference of 250 Nm and in relative value more than 30%).

The value of torque delivered by the diagnostic system is determined in relation to the cylinder and does not take any internal resistance when the engine is running. It also does not take into account the efficiency of transmission on the power take-off shaft of the tractor. Therefore, it is necessary to make the correction of torque. Load adjustment was carried out to:

– obtain load value of 0% (or torque 0 Nm) at idling – for a given engine speed,
– save the load of 100% as a maximum.

As a result of the correction (increase the area of obtained values of load), the minimum load value was a zero value and a maximum value is a value of 100% (a value of the torque was a maximum torque value for a given engine speed). Correction was carried out according to the formula:

$$\text{M corrected} = \frac{(\text{M read from CAN} - \text{M CAN min}) * \text{M CAN max}}{(\text{M CAN max} - \text{M CAN min})},$$

where:

M read from CAN – the current value of the load read from the diagnostic system for a given engine speed [%],

M CAN min – the minimum value of the load read from the diagnostic system for a given engine speed [%],

M CAN max – the maximum load value read from the diagnostic system for a given engine speed [%].

In Fig. 4 is shown that resistances of the engine and its own elements towards the power take-off shaft at 2000 rpm reach 22% (minimum load of 200 Nm at 2000 rpm). Failure to include the correction of torque value results in obtaining the incorrect values. Fig. 5 shows schematically the process of correcting selected points of operation of the engine – the range change of the load before and after the correction (in absolute values).

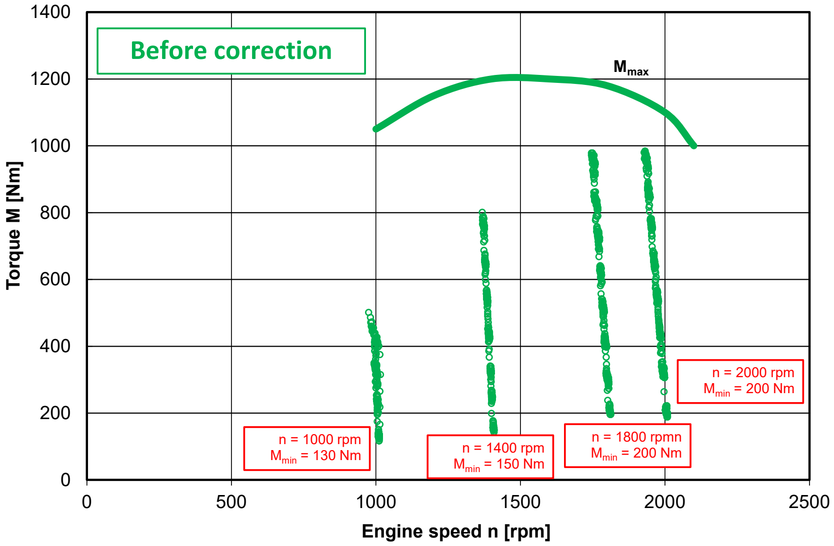

Fig. 4. Torque engine at idling before load correction

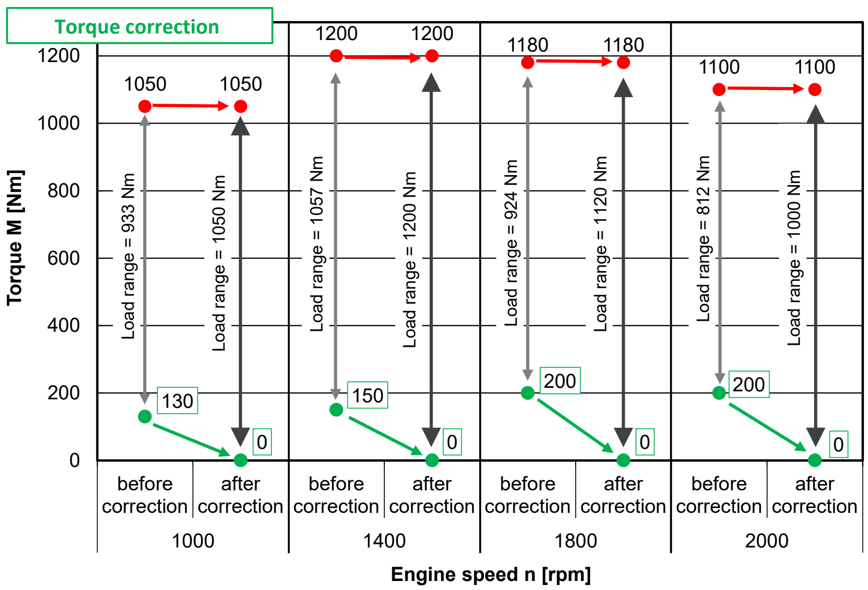

Fig. 5. The change of the torque range in the case of correction

Illustration of the effect of correction was made by referring to the absolute values – expressed in newton meters (Fig. 6). After correction of torque values corrected measurement points move towards zero on the chart, (minimum load values for a given speed are zero). Any other measured values of the load are proportionally adjusted to the maximum range, according to the procedure outlined above.

Figure 7 shows the torque values after the correction for the selected engine speed. The control unit determines the engine torque on the basis of several components, such as the amount of fuel injected into the cylinder, boost pressure, the rotational speed of the crankshaft and so on. The calculated torque, despite constant engine speed, is a value that changes. Values in the graph are mean values of 60-second measurement. For medium levels of the engine load, values of torque set on the dyno coincide with the values of a tractor OBD (a few percent deviation), but at a higher load measurements indicate that the deviation is about 15%. This is mainly caused by the fact that the corrected values of torque refer only to the engine, and does not take into account the loss of output to the power take-off shaft.

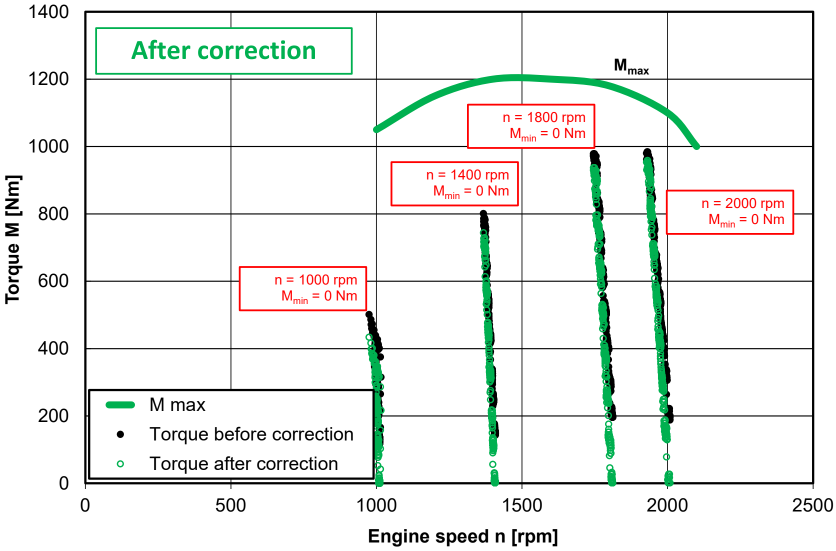

Fig. 6. The torque values after correction process

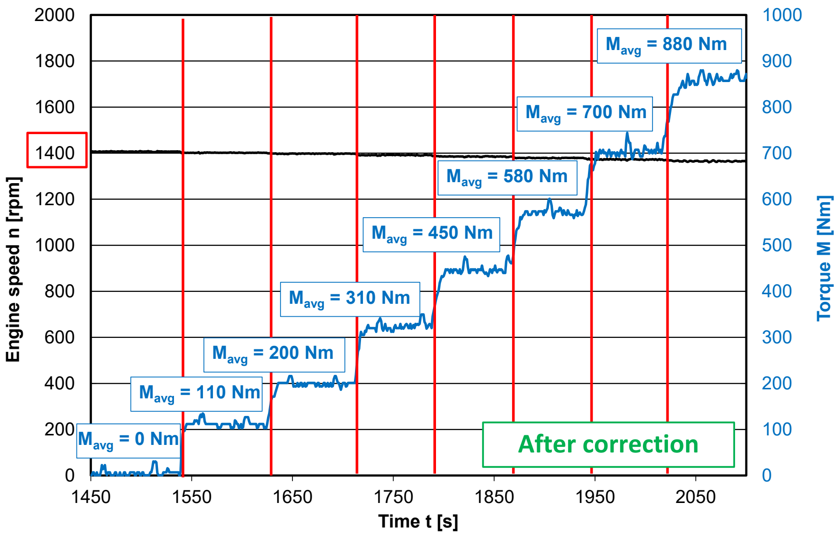

Fig. 7. Values of torque after load correction for engine speed of 1400 rpm

Analysis of differences in torque before and after the correction shows that the corrected values are always smaller than the value specified as "raw" from the diagnostic system. At an engine speed of 1400-rpm difference between the value before the correction and after the correction are 150 Nm (no load) to 20 Nm at the maximum value of load (Fig. 8). Relative differences in Fig. 9 indicate that the largest relative difference is obtained for the smallest load (150% load on the dyno equal to 100 Nm). Differences in relative terms for the load of 0 Nm read on the dyno were not determined because it would require a division by zero. At a rotary speed of 1800-rpm difference between the value before the correction and after the correction are from 200 Nm (no load) to 30 Nm with a maximum test load. The relative differences indicate that the largest relative difference is obtained for the smallest load (200% load on the dyno equal to 100 Nm). After torque correction, the relative differential was reduced to 20%. For the maximum value of load, relative difference was only 31-36%. At a speed of 2000 rpm, differences between the value before the correction and after the correction are from 200 Nm (no load) to 40 Nm for a maximum value of test load. After torque correction, the relative differential was reduced for 50%. For the maximum value of load, relative difference was only 30-36%.

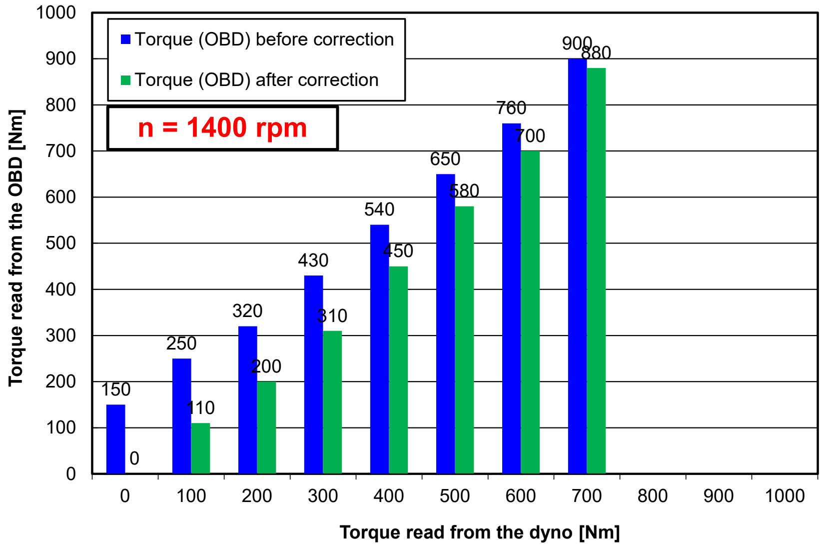

Fig. 8. Comparison of torque read from the dyno and diagnostic system (for 1400 rpm)

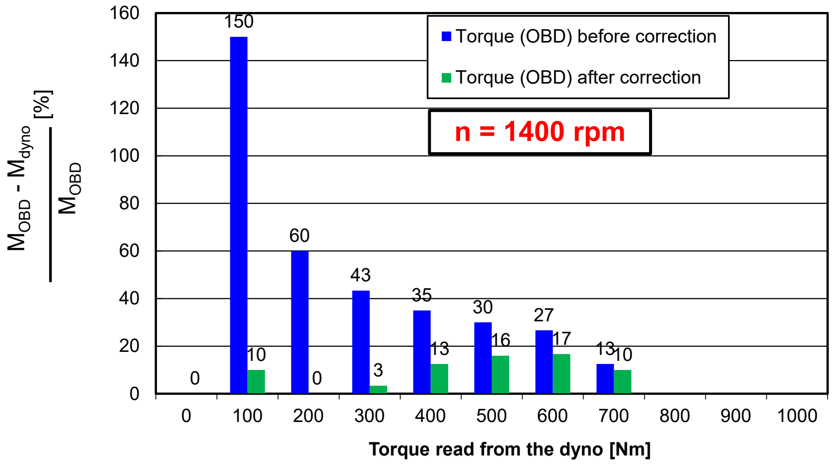

Fig. 9. The relative difference of torque before and after the correction (for 1400 rpm)

Determining the relative differences between the values of torque read from diagnostic system (before and after the correction) and values of torque on the dyno, it should be noted that the largest relative differences are for small load values (for the values of torque before correction). However, if one takes into account the torque values after the correction, the differences are much smaller (for small values of load) and tend to a minimum with increasing engine load.

4. The impact of the determined engine operation parameters on specific emissions

During the whole test, the measurements of harmful compounds emitted by the drive unit of the tractor were carried out. Fig. 10 illustrating the concentration of carbon dioxide expressed in percent. The values of the concentration of carbon dioxide in the exhaust gases provide a view on the air-fuel equivalence ratio. For small values of load, regardless of the rotary speed, these values are small what indicates on a high value of air-fuel equivalence ratio and in the areas of maximum load, the concentration of carbon dioxide tends to 8-10%, which translates into a value of air-fuel equivalence ratio of about 1.5.

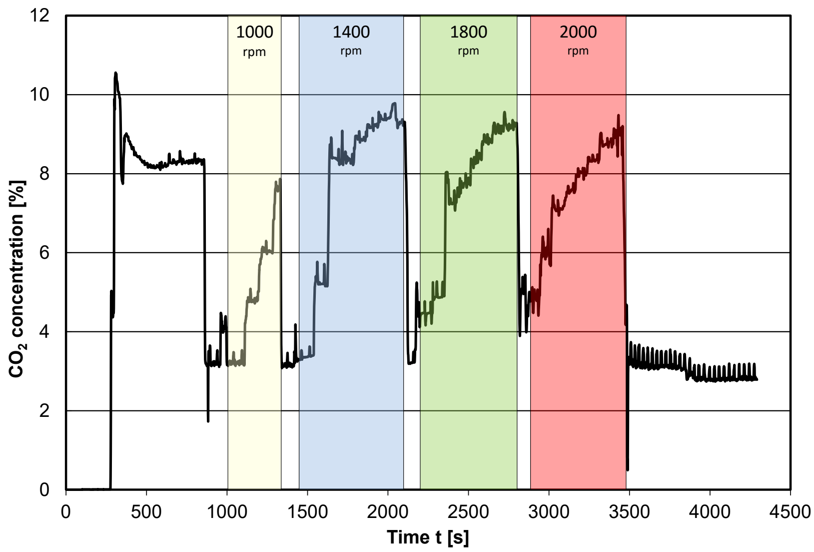

Fig. 10. The carbon dioxide concentration in the exhaust gases during the test

Although the tested agricultural tractor was equipped with a particulate filter, it was found that high combustion temperature contributes to minimize the mass of particulate matter formed during the combustion process (most of the particles were burned out). However, this assumption also has its drawbacks. The mass of particulate matter brought to the filter has decreased significantly which increases the lifetime of this element. It is possible to obtain the vehicle mileage reaching up to 15 000 mth without DPF (diesel particulate filter) replacement, but the drawback is the increased emissions of nitrogen oxides. Because of a higher combustion temperature, the concentration of nitrogen oxides increased, so that the SCR (selective catalytic reduction) system has to reduce the greater number of them. To meet this challenge a higher dose of AdBlue has to be used for the reaction of nitrogen oxides. This results in increased consumption of urea during operation in the field. The ratio of consumption of AdBlue to fuel is even 1:10. Despite this, the vehicle manufacturer protects the particulate filter at the expense of higher consumption of urea because of the high efficiency of the SCR system (Fig. 11). Initially, during the engine warm-up phase the concentration of nitrogen oxides did not exceed the standard of Stage 4 (50 ppm) because of the absence of engine load (lack of high temperature and pressure in the combustion chamber). However, during the first measuring point the concentration and the intensity of emissions of nitrogen oxides increased their value. After the increase of engine load – for rotary speed of 1400 rpm – was observed a sudden decrease in the intensity of emissions of nitrogen oxides (exhaust gas temperature increased to over 150°C at the end of the measuring system – 3 m behind the engine, it was a temperature of about 100°C lower than just behind the exhaust manifold). After reaching at the front of catalytic converter the temperature of 250°C (monitored by a temperature sensor) and AdBlue injection dose, the concentration of nitrogen oxides decreased to a level of about 5 times smaller than it is required by the standard (less than 10 ppm). Reduction took place in a continuous manner – there were no exceed of the allowable threshold established by standard (even when the engine load reached 85% of the maximum).

The next stage of the study was to determine the average values of the intensity of emissions for all values of rotary speed and engine load. In the graph 12 and 13, a comparison of the emissions intensity of carbon dioxide and oxides of nitrogen during all phases of the study is shown. A characteristic feature is that the emissions intensity of carbon dioxide increases as the load increases (increased fuel consumption). Another character is the course of changes in the level of nitrogen oxide emissions. In this case, the highest values were observed for the lowest speed (1000 rpm), and this was caused by insufficient temperature of the SCR system. After reaching operating temperature, the emissions intensity does not exceed 30 mg/s.

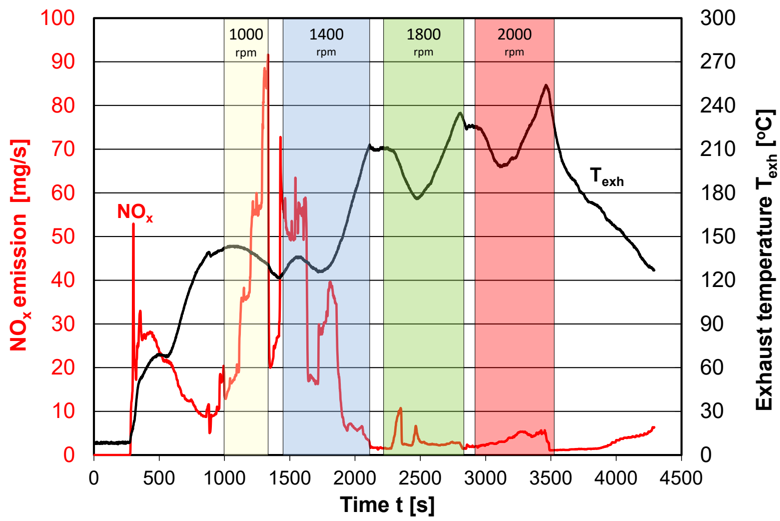

Fig. 11. The intensity of emissions of nitrogen oxides in exhaust gases during the test

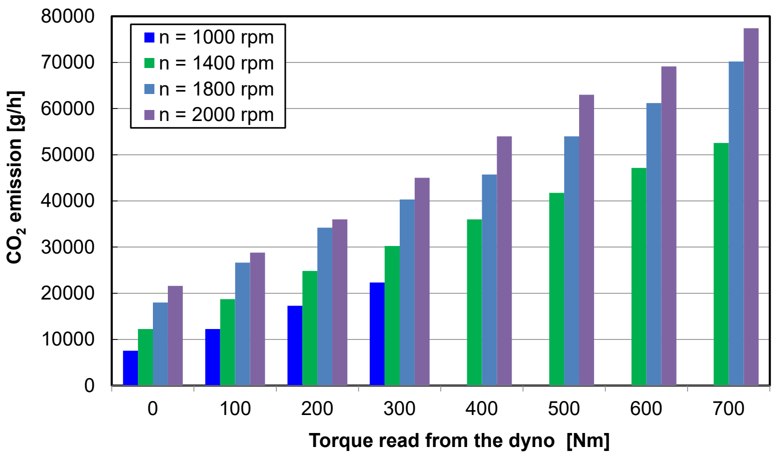

Fig. 12. Intensity of carbon dioxide emissions during all stages of the research

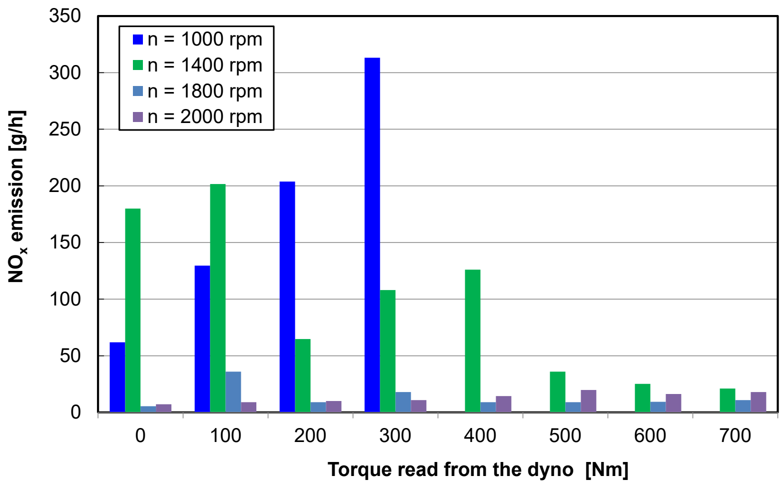

Fig. 13. Intensity of oxides of nitrogen emissions during all stages of the research

The determined values of the emissions intensity of individual components were used to determine the specific emissions of these pollutants. Values of the specific emissions of carbon dioxide, using the not corrected values of power, regardless of the engine load are in the range of about 400 to 600 g/kWh (Fig. 14). These values may raise some doubts, because the specific emissions of carbon dioxide during operation of the engine without load should have an infinitely large value. Therefore, in such cases it requires a correction of power with use of corrected values of torque.

Performed correction of the engine power for each engine speed was done due to carry out the correction of the engine torque. The results of specific emissions of carbon dioxide were used to compare these values. The determined values of the emissions intensity of individual components were used to determine the specific emission of these pollutants, but as engine power, the corrected output of the engine was substituted. The values of the specific emissions of carbon dioxide (Fig. 15) are different in Fig. 14: for a zero value of load, there are infinitely large values regardless of engine speed. The values of specific emissions of carbon dioxide for load of 100 Nm (as read from the dyno) are in the range of about 900 to 1200 g/kWh, and for the maximum load is about 400 g/kWh for all tested engine speed values.

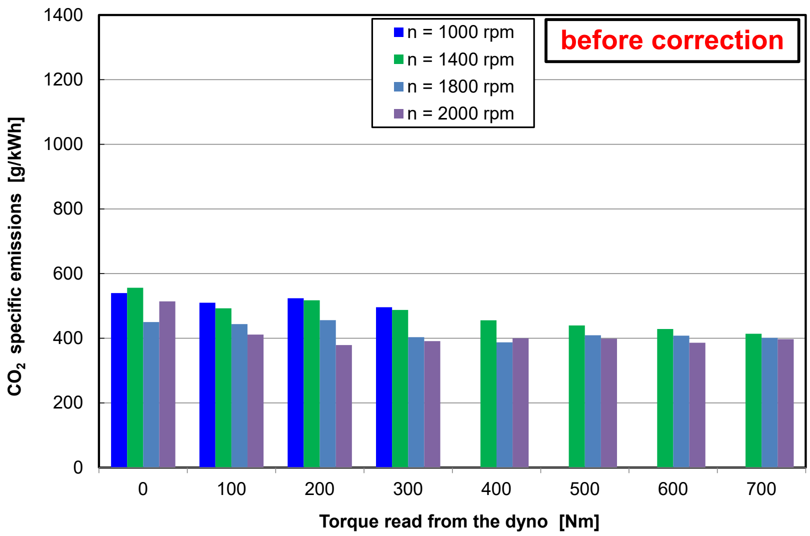

Fig. 14. Specific emissions of carbon dioxide during all stages of the research (for data before torque correction)

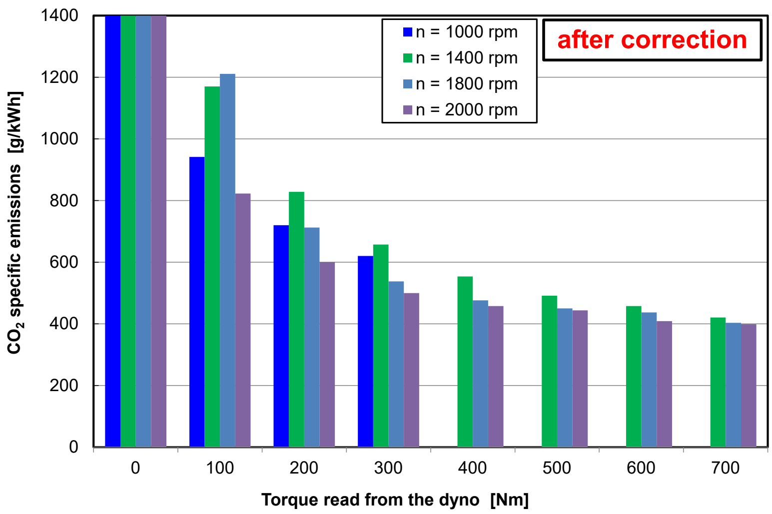

Fig. 15. Specific emissions of carbon dioxide during all stages of the research (after power output correction)

The values of the specific emissions of nitrogen oxides for minimum value of load is infinitely large, while for load of 100 Nm (as read from the dyno) are in the range of 0.2 to 10-12 g/kWh. Larger values of the specific emissions were obtained for a lower rotational speed, for which the temperature of the exhaust gas was low. In measurement point of maximum value of the engine load, reduction of specific emissions of nitrogen oxides was observed, to values close to zero (for all tested values of engine speed (Fig. 16)).

As a summary of the deliberations on taking into account dependency of power correction and the value of specific emissions, the relative differences in these values are shown in Fig. 17. Skipping the engine power correction causes a high error of designation of specific emissions.

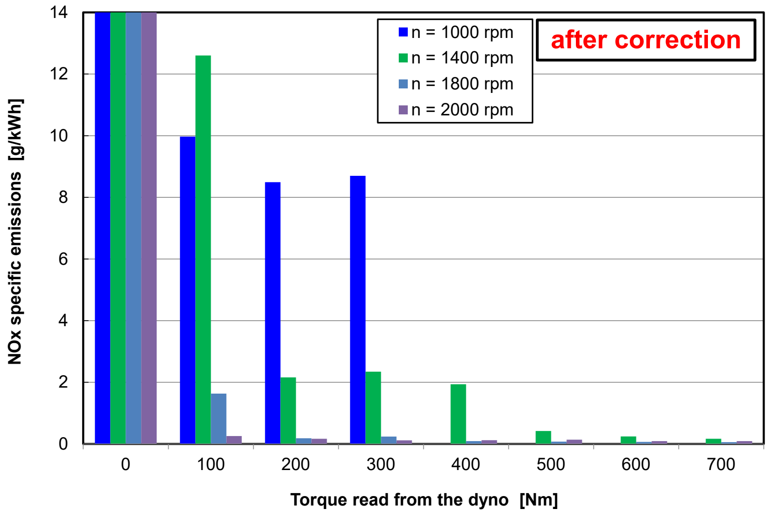

Fig. 16. Specific emissions of nitrogen oxides during all stages of the research (after power output correction)

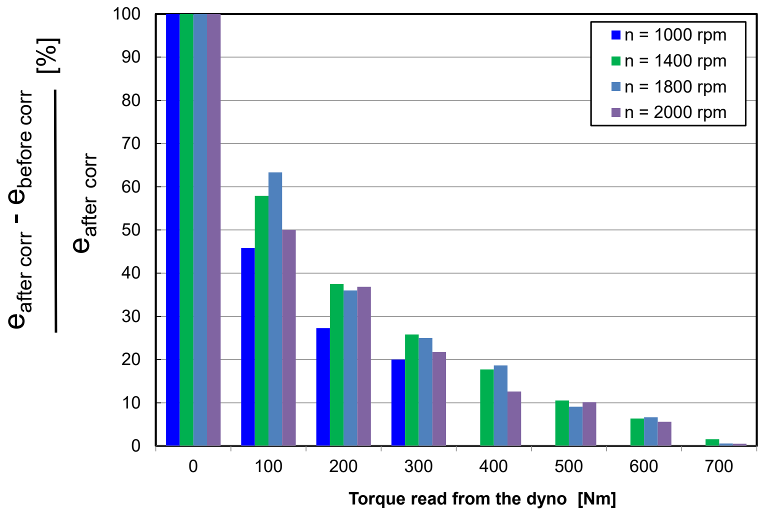

Fig. 17. Relative change of specific emissions of pollutants during all stages of research (for data before correction and after correction of engine output)

5. Summary

The presented analysis of the operating parameters of the engine and the results of emissions of the tractor during tests on the dynamometer resulting conclusions that can be summarized as follows: omitting engine power correction (correction of torque read directly from the diagnostic system of the engine) is associated with large inaccuracy of specific emissions. For zero load, the error is infinitely large, and for small values of load, it is approximately 50-60%. The values of this error decrease with increasing values of engine load: for medium load, it is about 10-20%. The smallest differences were found for maximum value of load – relative differences in values reach several percent. Taking into account that the engines of tractors do not always work using the maximum values of operating parameters, applying torque correction is necessary. Omitting this fact can in extreme cases lead to determining for e.g. specific fuel consumption, which will significantly deviate from the actual values.

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