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EXHAUST EMISSION FROM AGRICULTURAL FARM TRACTOR IN THE COURSE OF PLOUGHING

Summary

The amount of emitted harmful ingredients (CO_2, NO_x, HC, CO, PM) contained in agricultural farm tractor exhausts in the course of ploughing on the field which area is 26 ha, was determined by indirect method. The content of exhaust emitted in the course of direct soil cultivation and in the course of U-turning was expressed in relation to the time of work unit of the tractor ($g \cdot s^{-1}$) and also in relation to the unit of work done by the tractor ($g \cdot kWh^{-1}$). However the total exhaust emission content was presented in relation to area unit of the cultivated soil ($g \cdot ha^{-1}$). It was ascertained that the emission of each of the ingredients of exhaust was ca 35 $kg \cdot ha^{-1}$ CO_2, 0.4 $kg \cdot ha^{-1}$ NO_x and 0.04 $kg \cdot ha^{-1}$ HC, and emission of PM and CO was below the test sensitivity. It was also found that along the cultivation of soil most often the value of CO_2, NO_x and HC emission expressed in $g \cdot s^{-1}$ was by 13 to 15 times higher than on U-turns which can be connected to significantly higher use of fuel during the direct soil cultivation. However in the case of CO_2, NO_x and HC emission expressed in $g \cdot kWh^{-1}$, during the soil cultivation had only one, characteristic for each exhaust component, most often level of emission located in the range of small or medium values, as opposed to U-turns, during the performance of which the level of emission was more diverse.
***Key words**: agricultural farm tractor, fuel consumption, exhaust emission*

EMISJA SPALIN Z CIĄGNIKA ROLNICZEGO PODCZAS WYKONYWANIA ORKI

Streszczenie

Za pomocą metody pośredniej określono ilość wyemitowanych szkodliwych składników (CO_2, NO_x, HC, CO, PM) zawartych w spalinach ciągnika rolniczego podczas wykonywania orki na polu o powierzchni 26 ha. Składniki spalin wyemitowane w czasie bezpośredniego wykonywania uprawy gleby oraz w trakcie nawrotów wyrażono w odniesieniu do jednostki czasu pracy ciągnika ($g \cdot s^{-1}$), a także w stosunku do jednostki wykonanej przez ciągnik pracy ($g \cdot kWh^{-1}$). Natomiast łączną emisję składników spalin przedstawiono w odniesieniu do jednostki powierzchni uprawianego pola ($g \cdot ha^{-1}$). Stwierdzono, że emisja poszczególnych składników spalin wynosiła około 35 $kg \cdot ha^{-1}$ CO_2, 0,4 $kg \cdot ha^{-1}$ NO_x i 0,04 $kg \cdot ha^{-1}$ HC, a emisja PM i CO była poniżej czułości testu. Stwierdzono również, że przy uprawie gleby najczęściej występująca wartość emisji CO_2, NO_x i HC wyrażonej w $g \cdot s^{-1}$ była od 13 do 15 razy większa niż na uwrociach, co powiązać można ze znacznie większym zużyciem paliwa występującym w czasie bezpośredniej uprawy gleby. Natomiast w przypadku emisji CO_2, NO_x i HC wyrażonej w $g \cdot kWh^{-1}$, przy uprawie gleby występował jeden, charakterystyczny dla każdego składnika spalin, najczęstszy poziom emisji zlokalizowany w zakresie małych lub średnich wartości, w przeciwieństwie do uwroci, przy wykonywaniu których poziom emisji był bardziej zróżnicowany.
***Słowa kluczowe**: ciągnik rolniczy, zużycie paliwa, emisja spalin*

1. Introduction

Series of processes in agricultural production are characterized by big energy consumption. It concerns also field work. One of the following is ploughing in order to, among others, covering crop residues and soil management. It is connected to moving significant amount of soil. For example while ploughing to the depth of 20 cm in average conditions of humidity and soil compaction ca 3000 tons of soil is being moved in the course of cultivation of 1 ha of field. It is of course accompanied by high energy consumption in the form of liquid fuel thus the significant emission of exhaust into the air.

Exhaust from ignition engines contain harmful compounds for men and environment, such as carbon monoxide and dioxide, hydrocarbons (HC), nitrogen oxides (NO_x), Sulphur compounds and particulates (PM) [3]. Particulates (soot, hydrocarbons in condensed and crystalline form, nitrates, sulfates, water, metal pollens and traces of other chemical compounds) occur in the form of particles and for significant time stay in the air, from which they can be absorbed by respiratory system of men and animals [19]. Since 2012 the exhaust of ignition engines were classified by International Agency of Research on Cancer (IARC) being a Department of World Health Organization (WHO), as the factor causing cancerous illness [13].

Carbon dioxide is a natural compound emerging from burning organic substance with the participation of air. However in case of diesel oil of mineral origin burning, coal of mine origin is released, so such burning contributes to increase of the amount of carbon in circulation, which influences the increase in amount of greenhouse gases.

For several years legally targeted activities are undertaken aiming at limiting emission of harmful compounds contained in exhaust of combustion engines, thus ignition engines. The aim of this action is to extort from engine constructors and producers a significant reduction of the emission of their products. In EU countries permissible emission of harmful substances contained in exhaust from the engines of the vehicles applied off road is contained in EURO

Stage standards. These standards limit, among others, the permissible content of nitrogen oxides (NO_x), hydrocarbons (HC), carbon monoxide (CO) and particulates (PM) in exhaust. According to the guidelines contained in standards exhaust emission tests are performed at specified cycles of engine load for steady or transient states of its work. Generally, the research conducted in laboratory conditions have to reproduce the work of engine in exploitation conditions, and fixed emission of harmful substances has to show if engine meets the imposed requirements or not. However, attention is paid increasingly to conducting exhaust emission measurements according to the tests characteristic to exploitation conditions of vehicles [9, 10, 12].

The amount and content of exhaust emitted by engine of farm tractor can be determined in direct way, which consists of constant flow measurement (with flow-meter) and content of exhaust (with analyzer). The method is accurate however it involves the necessity of assembling and maintenance of specialized apparatus directly on tractor [11]. Exhaust emission is related mainly to the amount of used fuel and torque which is the load of the engine and its rotational speed. Nowadays, working standard means equipping tractors in systems monitoring their work, which register several parameters (e.g. motion speed, rotational speed of engine shaft, fuel consumption and so on). Data are collected by the systems also enable to determine exhaust emission but in indirect way. It involves assigning the amounts and content of exhausts to determined states of engine load. In order to achieve this laboratory research on dynamometer bench using engine of determined type are being conducted. The effect of this research is so called engine ecological characteristics, which contains information about the level of emission of individual exhaust components depending on torque and rotational speed. It is a kind of pattern enabling the evaluation of amount and content of exhaust emitted by certain engine or engines of similar type used in field conditions.

The aim of this research was to determine, in indirect way, the amount of harmful contents in exhausts of farm tractor as well as their quantitative distribution on the field in the course of ploughing.

2. Experiment

The research was conducted on the grounds of agricultural enterprise in West Pomeranian Voivodeship in the course of ploughing for spring rape sowing. During the research the tractor John Deere 8330, power 230 kW was aggregated with revolving 7-furrow slice, semi-mounted plough EuroDiamant manufactured by Lemken, coupled with Cambell crushing-soil packing shaft. The field was cultivated after harvest with earlier re-made after crops cultivation. On Fig. 1 shape of the field and area of crops were shown, where the research was conducted (the area was cultivated during one shift). The area of research was characterized by small corrugation.

In Table 1 parameters characterizing condition of ploughing were presented. Measuring method of the numbers in Table 1 was described in work [8].

In order to achieve data concerning engine working state in the course of ploughing system EDM produced by Intex, which monitors engine work and tractor motion [5] was used. This system registers: time of starting and stopping and working time of the engine, rotational speed of engine crankshaft, volume of fuel consumption, geographical coordinates of tractor location, its speed and covered distance of the road.

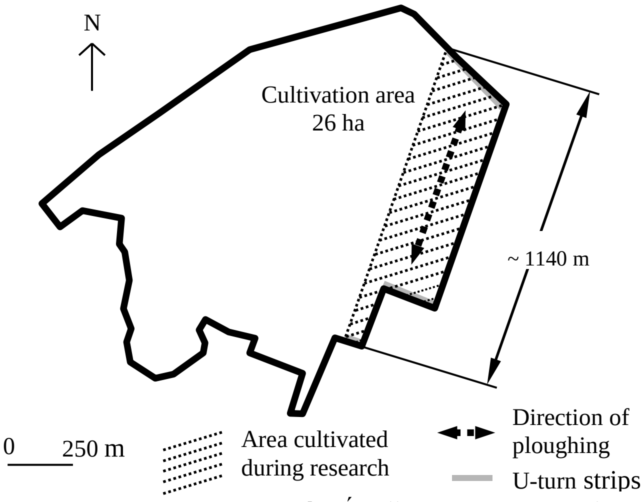

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Fig. 1. Area and shape of the field
Rys. 1. Wielkość i kształt uprawianego pola

The measurements of engine work parameters are registered with 1Hz frequency. This system however does not register one very important parameter of engine work that is torque, which influences significantly exhaust emission. In order to determine the torque of engine, various indirect methods are applied [4, 14, 16]. In the described in research indirect method presented in detail in work [7] was used. In this method the torque is evaluated on the base of volume fuel consumption and engine rotational speed and experimentally determined characteristics, including the dependence of torque and unitary fuel consumption in function of rotational speed of engine crankshaft. Finally, using the above method, map of engine power output distribution which is the product of its torque actual values and rotational speed illustrating distribution of power developed by engine in the course of ploughing in the geographical coordinates system was achieved.

The next step of research consisted in determination in laboratory conditions ecological characteristics of engine. Analyzer CAPELEC 3201 with accuracy class 0, adapted for measuring content of: CO_2, CO, NO_x, HC and exhaust fogging (exhaust blackening) [1] was used. The degree of exhaust fogging does not in full capture the emission image of particulates (PM), because it only shows the presence of soot in exhaust. However this popular method was applied in the research because it is characteristic for easy measuring and low costs [19].

Next, on the map, made in geographical coordinate's system, of the engine power distribution, the emission values of each ingredient of exhausts adequately to the state of load in the given field position was mapped. It has to be added that during describing the results similarities in characteristics of diesel engines with direct injection, proven in numerous research [6, 15, 17, 18] were used. It allowed to determine ecological characteristics of the engine under research based on measurements made on engine of the same type (1.3 MultiJet), but with lower power rating compared to the power of engine used in John Deere 8330 tractor.

Table 1. Conditions of ploughing

Tab. 1. Warunki wykonywania orki

Area			Soil layer	Value	
Soil graining [%] and granulometric group	fraction	2 ≥ d >1	*Ploughing layer*	2.7	Loamy fine-grained sand
		1 ≥ d > 0.5		7.9	
		0.5 ≥ d > 0.25		15.1	
		0.25 ≥ d > 0.1		33.2	
		0.1≥ d > 0.05		17.1	
		0.05 ≥ d > 0.02		8	
		0.02 ≥ d > 0.002		11	
		d ≤ 0.002		5	
Content of humus in soil, %				2.1	
Current gravimetrical soil moisture, %			*0 - 10 cm*	15.0 s=2,0	
			10 - 20 cm	15.0 s=2,3	
			20 - 30 cm	14.3 s=2,0	
Volumetric density of soil, $g \cdot cm^{-3}$			*0 - 10 cm*	1.35 s=0,10	
			10 - 20 cm	1.57 s=0,14	
			20 - 30 cm	1.57 s=0,10	
Firmness of soil, kPa			*0 - 10 cm*	538 s=258	
			10 - 20 cm	1183 s=463	
			20 - 30 cm	2212 s=588	
Shearing stress of soil, kPa			*0 - 10 cm*	24 s=10	
			10 - 20 cm	50 s=16	
			20 - 30 cm	56 s=11	
Ploughing speed, $m \cdot s^{-1}$				2.53 s=0,23	
Working depth of plough, cm				25 s=2	
Working width of plough, m				3.34 s=0,05	

s – standard aberration

Source: own work / Źródło: opracowanie własne

In the final effect the picture of emission of every exhaust component depending on geographical coordinates of the tractor in the field was achieved, without necessity of direct use of exhaust analyzer, which is sensitive to difficult conditions of field research.

Total emission of respective exhaust ingredients was evaluated by summing up the partial emissions used to making emission map.

The achieved distribution of exhaust emission is difficult to interpret (for example on Fig. 2 such distribution for CO_2 is presented), because the value of emission of particular exhaust ingredients depends on many factors. The most important are: time of tractor staying in particular place, engine load, the used gear ratio in drive system (influencing the working point of the engine in the area of its power supply) which influences the amount of consumed fuel.

Because analysis of previously mentioned distributions is difficult, thus from the engine power distribution occurring during the ploughing process on the field two states of its load were selected. One corresponded directly to soil cultivation, however the other one was connected with making U-turns of tractor with plough on so called U-turns. The accepted criterion in selection included speed of the tractor – $v \leq 5$ and $v > 5$ $km \cdot h^{-1}$. Correctness of the applied approach is confirmed by selected states corresponding to tractor speed $v \leq 5$ $km \cdot h^{-1}$, when the map of tractor power distribution is generated again, were extracted on U-turns (Fig. 3). It enabled selection of exhaust emission corresponding to tractor work directly in the course of soil cultivation and U-turns thus making analysis intended in the goal of research.

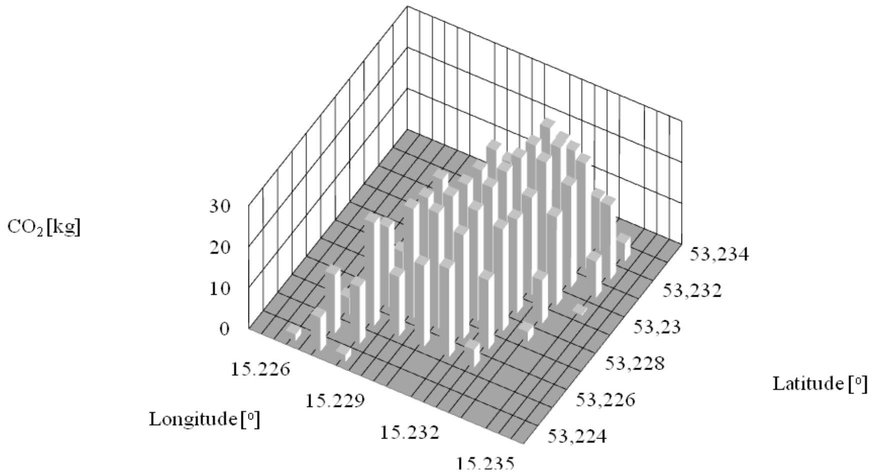

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Fig. 2. Distribution in the field of CO_2 emission contained in the exhaust of the tractor under research

Rys. 2. Rozkład na polu emisji CO_2 zawartego w spalinach badanego ciągnika

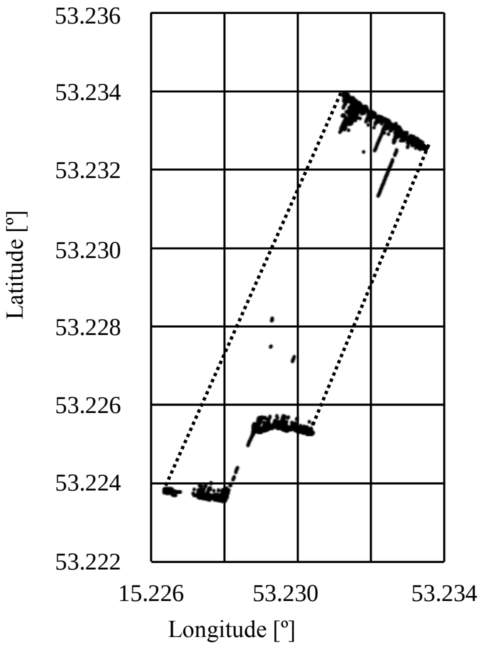

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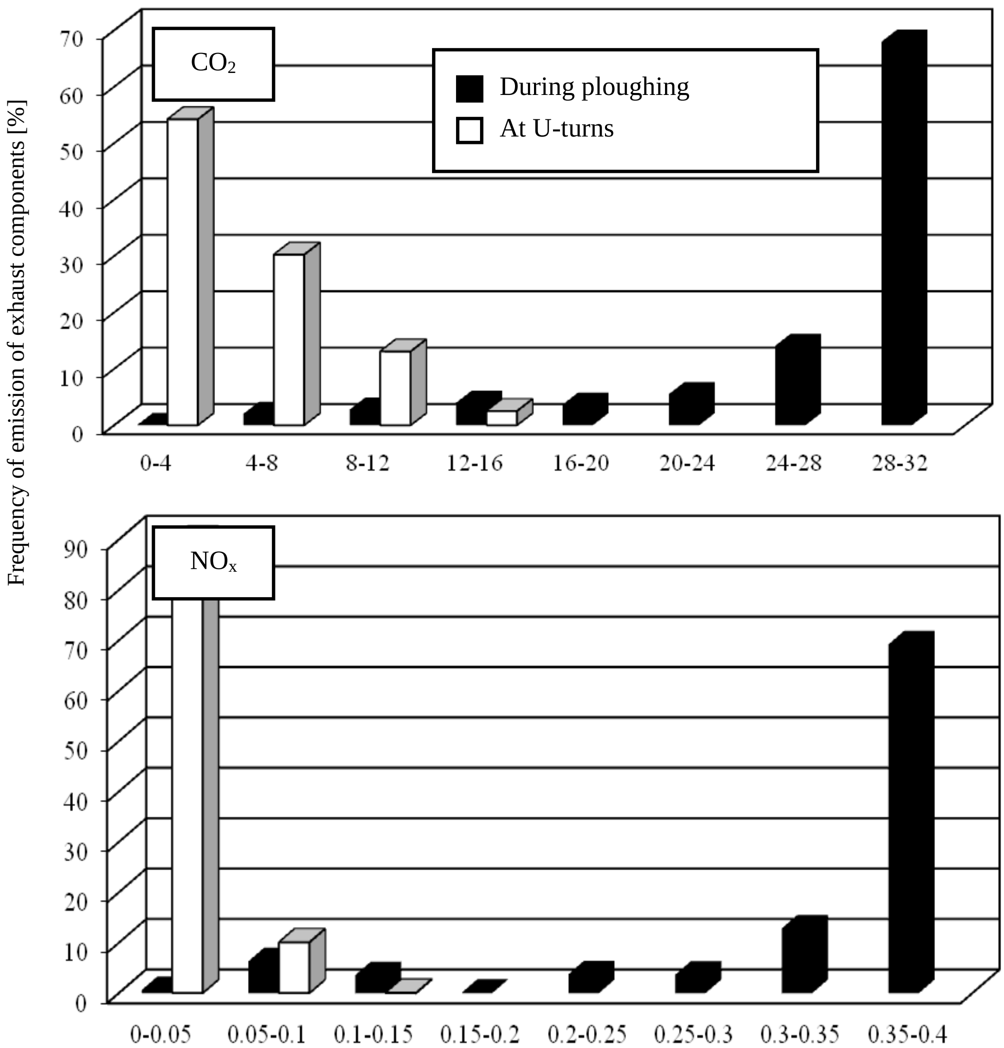
Fig. 3. Areas of U-turns on the field under research selected on the basis of tractor speed

Rys. 3. Wyselekcjonowane na podstawie predkości ruchu ciągnika obszary uwroci na badanym polu

3. Results and Discussion

It was ascertained that particulates (PM) did not occur in exhaust and CO emission was at the level of sensitivity of the device. It is confirmed property of diesel engines equipped in Common Rail injection system and turbocharge for example [2]. Thus later in the paper the analysis is limited only to the content of CO_2, NO_x, and HC in exhaust.

Fig. 4 presents distribution of frequency of emission occurrence of individual exhaust components as function of interval values of emission expressed in $g \cdot s^{-1}$. It was established that in the course of soil cultivation most often big values of individual exhaust emission ingredients occurred: 28-32 $g \cdot s^{-1}$ CO_2 at frequency 68%, 0.35-0.4 $g \cdot s^{-1}$ NO_x, at frequency 69% and 0.030-0.035 $g \cdot s^{-1}$ HC at frequency 85%. However at U-turns most often the values of emission were small: 0-4 $g \cdot s^{-1}$ CO_2 at frequency 54%, 0-0.05 $g \cdot s^{-1}$ NO_x at frequency 90% and 0-0.005 $g \cdot s^{-1}$ HC at frequency 80% (Fig. 4). It was ascertained, based on this that in the course of soil cultivation most often occurred emission (expressed in $g \cdot s^{-1}$) of individual ingredients of exhaust was by 13 to 15 times higher than at U-turns, which was the result of much higher power of tractor in the course of soil cultivation (Fig. 5) thus higher fuel consumption.



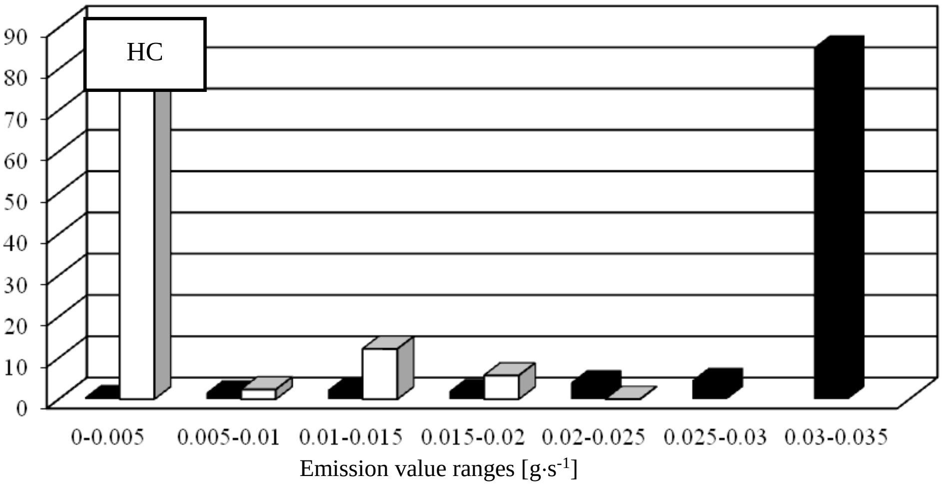


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Fig. 4. Frequency of CO_2, NO_x and HC emission of determined value expressed in [$g \cdot s^{-1}$]
Rys. 4. Częstości emisji CO_2, NO_x i HC o określonej wartości wyrażonej w $g \cdot s^{-1}$

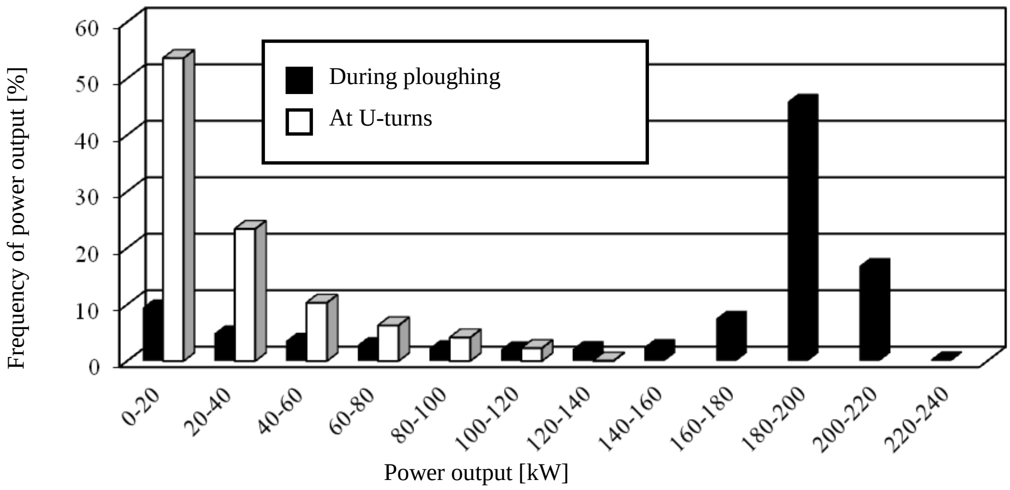

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Fig. 5. Distribution of power output of the tractor under research in the course of ploughing with separating states of engine load corresponding to soil cultivation and making U-turns
Rys. 5. Rozkład mocy użytecznej badanego ciągnika w czasie orki z wydzieleniem stanów obciążenia silnika odpowiadających uprawie gleby i wykonywaniu uwroci

However, on Fig. 6 the value of CO_2, NO_x and HC emission in the course of soil cultivation and on U-turns expressed in $g \cdot s^{-1}$ as function of developed power output was presented. The graphs were supplemented with lines and trend equations containing emission occurring at the time of soil cultivation and U-turns. Intensity of emission of all exhaust components was lower on U-turns than while soil cultivation. Directional factors of trend lines certify that relations exist between the intensity of exhaust components emission and developed power by engine. Especially big differences in value of directional factors of trend lines occur in case of NO_x emission. For emission of these exhaust components the value of directional factor of trend line describing the work of tractor on U-turn is 5.5 times lower than by trend line connected to soil cultivation. Based on this it can be assumed that NO_x emission does not only depend on engine load but also on several other parameters of its work, among others on pressure and temperature in the burning chamber, proportions of composition of fuel-air mixture and number of cycles and pressure of fuel injection.

In Table 2 the mass of emitted individual components of exhaust coming from the engine in the course of soil cultivation and U-turns and also their total emission were as well as values of other parameters characteristic for tractor work in the course of ploughing were presented in the Table 2.

Soil cultivation was accompanied by big engine loads, which shows significant value of developed power (Fig. 5, Table 2). It resulted in big demand for fuel. In the course of soil cultivation the average fuel consumption per hour was nearly 5 times higher than during U-turns.

To achieve proper parameters of the combustion process of fuel it is necessary to supply respectively big amount of air to the engine. In order to achieve total and complete combustion of an hourly dose of fuel given in Table 2 an amount of at least 490 and 105 kg of air should be supplied during one hour of tractor work respectively in the course of soil cultivating and making U-turns. Theoretically, with this amount of air the whole amount of carbon contained in diesel fuel is going to be emitted in the form of CO_2. Smaller amount of supplied air would cause incomplete combustion manifesting itself by presence of carbon monoxide and soot in exhaust.

No CO presence or fogging (blackening) was ascertained in exhaust in the course of conducted measurements, which indicates that total combustion takes place in the engine during soil cultivation and U-turn.

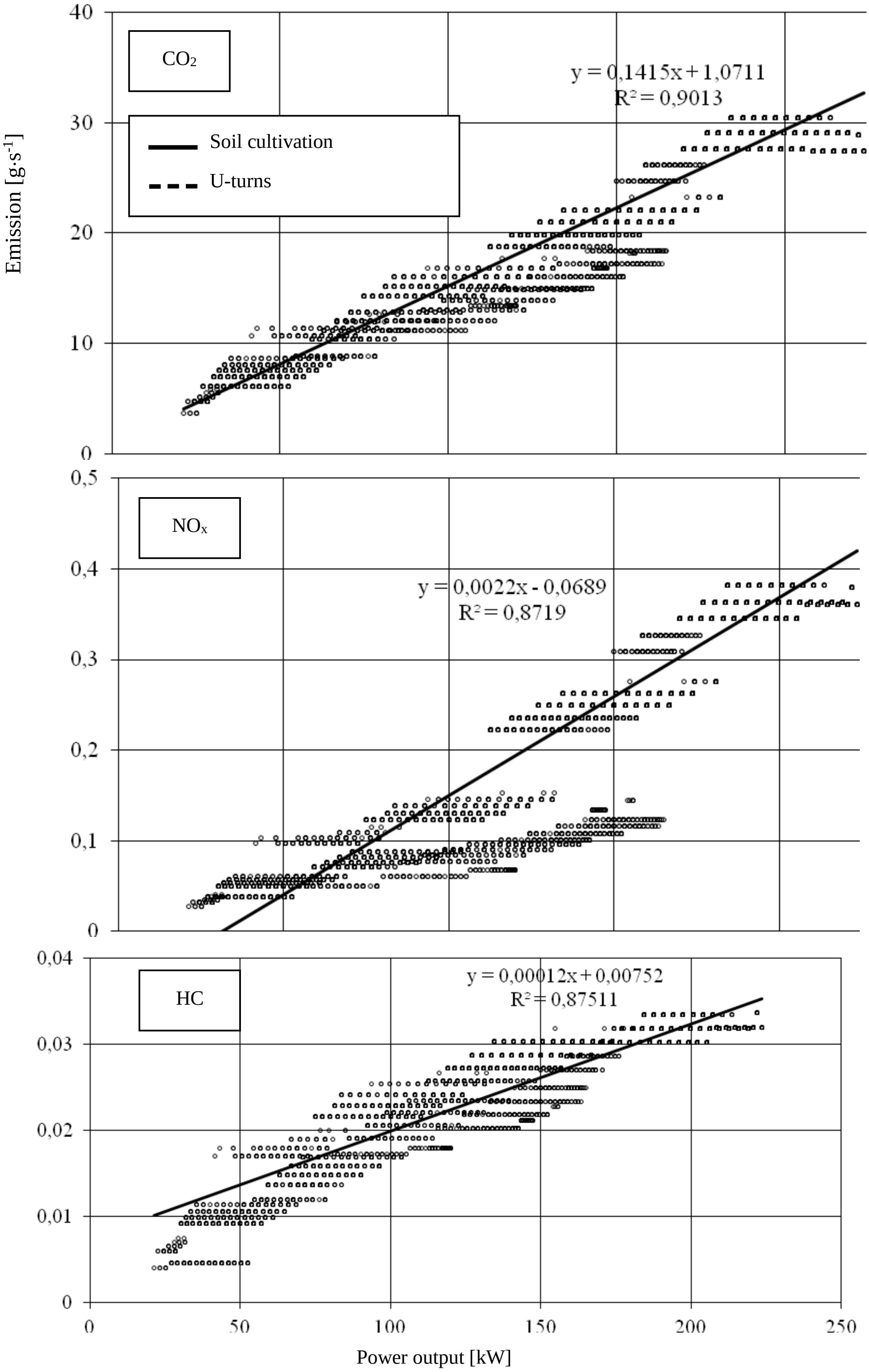

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Fig. 6. The dependence of CO_2, NO_x, and HC emission on engine development of power output
Rys. 6. Zależność emisji CO_2, NO_x i HC od rozwijanej przez ciągnik mocy użytecznej

Table. 2. The chosen parameters of tractor work and mass of emitted exhaust components in the course of ploughing on designated field

Tab. 2. Wybrane parametry pracy ciągnika i masa wyemitowanych składników spalin podczas orki na wytypowanym polu

Parameter		Soil cultivation	U-turns	Total
Consumed fuel		365.7 dm^3 303.5 kg	16.9 dm^3 14.0 kg	382.6 dm^3 317.5 kg
Average hourly fuel consumption [$dm^3 \cdot h^{-1}$]		40.1	8.6	34.6
Average unitary fuel consumption [$g \cdot kWh^{-1}$]		185.0	255.8	187.7
Average power [kW]		179.9	27.9	153.0
Average speed [$m \cdot s^{-1}$]		2.45	0.59	2.12
Worktime [h]		9.1	2.0	11.1
Total emission of exhaust components [kg]	CO_2	869.7	33.1	902.8 (35 $kg \cdot ha^{-1}$)
	NO_x	10.6	0.2	10.8 (0.4 $kg \cdot ha^{-1}$)
	HC	0.98	0.04	1.02 (0.04 $kg \cdot ha^{-1}$)

Source: own work / Źródło: opracowanie własne

However slight amount of hydrocarbons emitted in exhaust, that is just 0.32 and 0.29% of consumed fuel mass respectively in the course of soil cultivation and U-turns, points to combustion near total. It should also be added that interchange of whole fuel into CO_2 has favorable influence on general efficiency of engine because complete and total combustion of the whole energy contained in fuel is used.

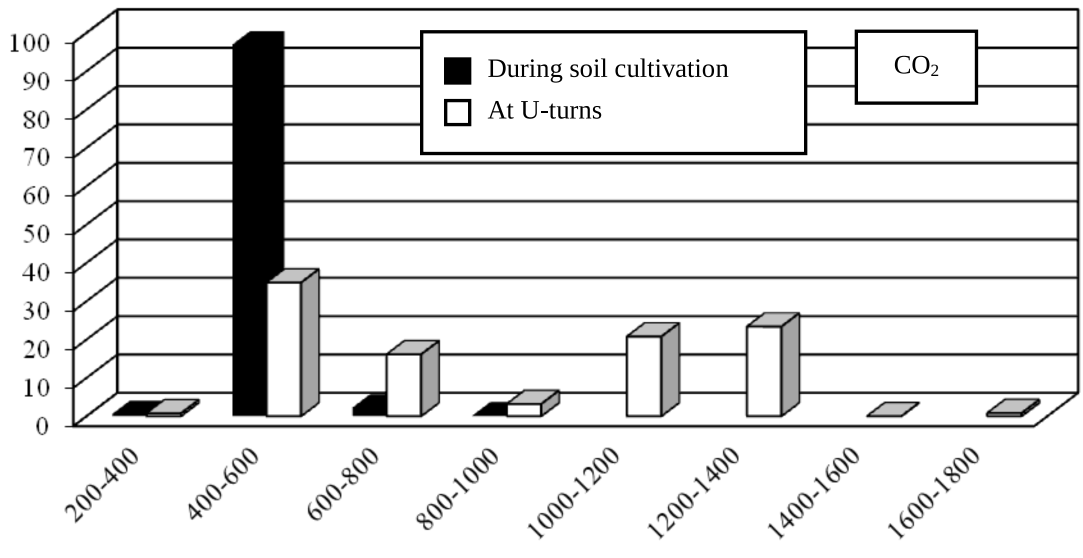
It is obvious that CO_2 has the largest share in exhausts emitted by tractor because it is the main product of the fuel combustion process (Table 2), which has been written about previously. Its mass emitted by the tractor under research was 2.8 times bigger than mass of the consumed fuel, which comes from binding carbon and oxygen in the combustion process. In the research conditions the amount of CO_2 emitted by tractor in the course of soil cultivation was 26 times larger than during U-turns.

Engines with self-ignition are not equipped with devices dosing air, so in reality its amount in the engine is larger in relation to the supplied dose of fuel. The excess of air containing nitrogen and high temperature accompanying combustion of fuel leads to formation, in exhaust, of nitrogen oxides, whose toxicity is very high. It was ascertained that the amount of emitted nitrogen oxides in exhaust of tractor under research was 10.8 kg on the field of 26 ha, of which 10.6 kg directly in the course of soil cultivation (Table 2).

Emission of the exhaust component originated from agricultural vehicles expressed in $g \cdot s^{-1}$ is the value directly informing about the amount of chemical compounds introduced to the environment. However this form of determining exhaust emission is not useful in case of comparing exhaust emission coming from various agricultural vehicles, where engines of various types and power rating were used. For such comparative purposes reference to mass emission of exhaust components to energy unit produced by engine seems more convenient. It should also be added that depending on the state of the load of engine related to the carried out task, during 1 second it can perform different work. In analysis of such cases also emission of exhaust components related to the unit producing energy may prove useful.

Fig. 7 presents distribution of components of exhaust emission expressed in $g \cdot kWh^{-1}$, so-called specific emission of exhaust components ascertained for ploughing done on selected field.

It was ascertained that at U-turns clearly dominant most often values of the measured emission of individual exhaust components did not appear. The reason was probably in different range of relatively small power developed by engine at U-turns (Fig. 5). However, in case of soil cultivation the most common dominant value of unitary emission can be assigned to individual components of exhaust. Nevertheless in case of soil cultivation and U-turns the most common ranges of exhaust emission were located in the area of small and medium specific values of exhaust components emission. It does not apply to CO_2 emission appearing on U-turns, which also is related to large values of emission range.



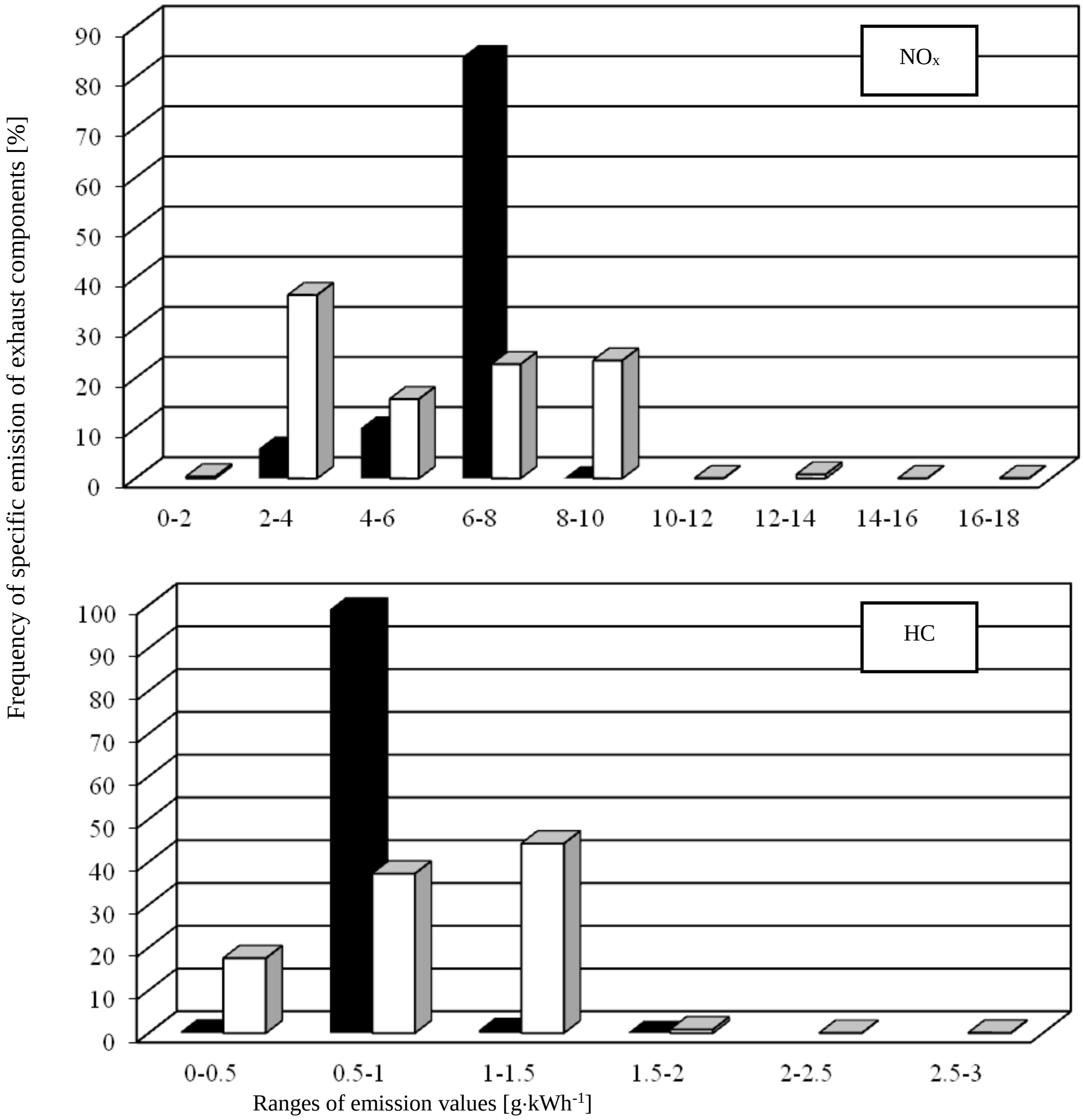


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Fig. 7. Frequency of specific exhaust emission
Rys. 7. Częstość jednostkowej emisji spalin

4. Conclusions

The applied method enables quantitative (mass and unitary) assessment of exhaust emission from agricultural tractors without the necessity of mounting specialized measuring devices on vehicles. Using fleet management systems, which are most common standard equipment of tractors, we can assess the amount of emitted into the air exhaust components. It is necessary to know ecological characteristics of engine of given type.

In the conditions of conducted research the emission of individual exhaust components in relation to 1 hectare of cultivated field was ca 35 $kg \cdot ha^{-1}$ CO_2, 0.4 $kg \cdot ha^{-1}$ NO_x and 0.04 $kg \cdot ha^{-1}$ HC. Fuel consumption was 12.2 $kg \cdot ha^{-1}$.

Emission of PM and CO by self-ignition engines with Common Rail ignition system and turbocharger is negligible, which is the evidence of proper fuel combustion process and achievement of general high efficiency of the engine. Small emission of HC, being only ca 0.3% of mass of consumed fuel also proves it.

In the course of soil cultivation most common appearing value of CO_2, NO_x and HC emission expressed in $g \cdot s^{-1}$ was from 13 to 15 times higher than at U-turns. Such differentiation in level of emission results from big tractor load during soil cultivation thus higher fuel consumption.

In case of CO_2, NO_x and HC expressed in $g \cdot kWh^{-1}$ during soil cultivation most common emission level located in the range of small and medium values also occurs, characteristic for each exhaust component, opposed to U-turns for which the emission level is more varied. This results from different states of engine work at U-turns.

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