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Preliminary communication

Noise Emission in the Cabs of Modern Farm Tractors

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Abstract: One of the most important parameters determining the operational quality of farm tractors and sales results is the noise level in the cab. In this study the level of noise to which the operator in the cab is exposed and which negatively affects their psychophysical condition was measured and analysed. Tractor manufacturers in Europe and on other continents have effectively reduced the noise level generated by their products. None of 385 models of 20 brands exceeded the noise limit of 115 dB(A) set by the Polish law. However, there were models where the daily 8 hour noise exposure level exceeded 85 dB(A). Our research showed that this parameter still needs to be improved.

Keywords: agriculture; farm tractor cab; mel scale; noise emissions and standards; Weber-Fechner law

1 INTRODUCTION

The sound level, also known as the noise level, determines the undesirable and bothersome vibrations of the elastic medium affecting the human hearing centre. According to the Polish Standard [1], noise is a sound of any acoustic characteristics, which is undesirable in specific conditions and for a particular person. Noise is generated by vibrations of liquids, gases or solids, which cause a change in pressure (disturb the balance of the medium). Atmospheric pressure is the reference pressure in the sound level test. Vibrations are transmitted by the structure of the medium and as a result, acoustic waves are emitted. The difference between the pressure in the medium when the acoustic wave passes through it and the reference (atmospheric) pressure is expressed in pascals (Pa). However, pressure is measured on a logarithmic scale of sound pressure, so sound level tests are based on the measurement of the sound pressure level L_p expressed in decibels (dB).

The relationship between the physical measure of a stimulus and the reaction of the senses, e.g. vision, hearing or smell, is expressed by the Weber-Fechner law one of basic psychophysical laws, discovered in 1849 [2]. This phenomenological law was the result of a number of practical observations and has a wide range of technical applications. It was formulated by Ernst Heinrich Weber and sounded as follows: If the sizes of stimuli are compared, our perception is not influenced by the arithmetic difference between them, but by the ratio of the quantities compared.

The dependence of the subjectively perceived pitch on the objectively measured frequency is measured on the mel scale (Fig. 1).

Stevens initiated the development of psychophysical measurements with scaling methods [3]. Mel is the unit of frequency in this scale (after the first three letters of melody). There is a non-linear relationship between the mel scale and Hz [4]. On the basis of measurements, a tone with a frequency of 1000 Hz at a sound pressure level of 40 dB above the threshold of audibility was assumed to be 1000 mel. The number of mels is proportional to the pitch of a sound at its specific frequency and loudness. When constructing the scale of sensory impressions (e.g. sound-relate impressions), the lowest value of a stimulus registered by human senses is assumed as the threshold value.

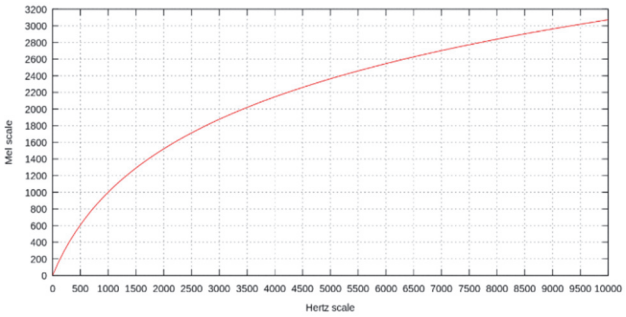

Figure 1 The relative mel scale defined by S. Stevens, J. Volkman, and E. Newman in 1937

This value has a conventional nature because people differ in their perception. One's assessment of loudness is proportional to the logarithm of the sound pressure at the eardrum. If the noise level changes by only 1 dB, this means its value has increased by 26%. On average, the noise level doubles every 3 dB. Therefore, it is important to reduce the noise reaching the human ear by each decibel, especially during tedious routine jobs requiring concentration, such as long-term operation of farming vehicles and machinery.

The following types of noise are distinguished depending on the frequency of vibrations of the medium:

- audible to humans 20 - 20000 Hz,
- inaudible to humans:
  - infrasound 1 - 20 Hz,
  - ultrasound 20000 - 100000 Hz.

The nuisance or harmfulness of noise depends on its intensity, exposure level, type of noise sources and the relation between humans and the noise source. The noise in the work environment is characterised by:

- the exposure level related to 8 h/day or a working week,
- the maximum sound level A,
- the peak sound level C.

The following types of noise are distinguished depending on its intensity:

- fixed during observation the sound level A does not change by more than 5 dB(A),
- non-fixed during observation the sound level A changes by more than 5 dB(A),

- pulse one or more sound events lasting less than 1 second.

Modern technological devices (cars, household appliances, electronics, telephones, etc.) need to meet increasingly high quality requirements [5]. This also applies to agricultural machinery and vehicles, which should be highly reliable and durable [6-9]. Although farm tractors are classified as non-road mobile machinery (NRMM), they must also meet increasingly high standards set by environmentalists. This applies not only to exhaust gas emissions (the current standard is still Stage IV), biodegradability of operating fluids (oils), but also noise emissions to the atmosphere.

The noise level in agricultural machinery such as combine harvesters, sprayers, slope machinery, soil-shaping machinery, balers except tractors ranges from 85 to 117 dB(A) [10]. Tractors have a longer service life than other machinery (10 - 20 years to full depreciation). For this reason, the most important safety precaution is to ensure that the cab is as well insulated from noise and vibration as possible. Then the noise level decreases by 2 - 10 dB(A).

Broste et al. [11] tested 31 tractors to measure the noise level at a height of the driver's ears. They tested tractors without cabs and those with cabs but with open windows. Only in one tractor the noise level at full throttle was lower than 85 dB(A). According to the American OSHA (Occupational Safety and Health Administration) standards, the maximum daily exposure to continuous or intermittent noise is 8 h at 85 dB and 4 h at 95 dB.

Arin and Celen [12] measured the noise level in some machine units. The researchers used six different combinations of tractor and agricultural equipment. The results of the noise level measured in the tests are shown in Tab. 1.

Table 1 Noise levels measured in the tractor + equipment, *Ks* the noise level measured at the tractor operator's ear level, *Yo* the noise level measured in the tractor operator's surroundings (Arin and Celen, 1995)

Tractor + Equipment	Mean noise levels / dB (A)	
	Ks	*Yo*
Tractor + field sprayer	92.5	92.4
Tractor + chisel plough	94.7	80.9
Tractor + grain drills	95.4	84.3
Tractor + combicrum (farrow + roller)	96.1	90.7
Tractor + hoe	100.1	85.6
Tractor + rotary cultivator	99.1	88.2

The researchers also found that engine revolutions affected the noise level outside and around the tractor operator. The noise level in the open air was below the safe limit. In general, the noise level at 2000 rpm with gear amplification tended to increase. When the engine revolutions increased from 1000 to 2000 rpm, the noise level increased by 3 dB(A).

Noise emission has negative influence on the environment and reduces the comfort of people and animals exposed to it. Agricultural machinery operators and their assistants are at risk. In order to apply agrotechnical treatments at optimal times farm tractor operators need to spend several hours a day sitting in the cab, sometimes for many days. They are mostly exposed to mechanical noise, generated by mechanically, electrically, and pneumatically-powered machines and devices. Noise is also generated aerodynamically, hydraulically (cavitation), and technologically. Noise is emitted not only by the tractor's internal combustion engine and the hydraulic or pneumatic system, but also by agricultural machinery cooperating with it, e.g. combine harvesters, presses, trailed forage harvesters, mowers. Due to their low speeds (up to 50 km/h during road transport) the rolling resistance of tyres, which is so important in cars, should not affect noise emissions. This factor can also be neglected in field work. The durability and machine-hours of farming machinery as well as soil structure protection are more important factors. Most farm tractors (especially in Poland) have a cab as standard equipment. The noise level increases in open-station (non-cab) tractors, this system is popular in the American states with a friendly climate [13-15]. The World Health Organisation published a practical and detailed guide to the early diagnosis and treatment of occupational diseases, see [16] see textbook of the World Health Organisation.

In some countries, especially developed ones, noise levels in the general environment are increasing dangerously. For example, in the USA the noise level increases by 1 dB(A) per year. A study on noise levels in Ankara, the capital of Turkey, showed that between 1970 and 1979 they increased by 8 - 10 dB(A) [17]. Engineers work intensively to reduce the level of vibrations generated by agricultural machinery, which are transferred to the tractor operator' seat [18], whereas works on noise level reduction are marginalised. Only in the last 40 years serious measures have been taken to reduce excessive noise in workplaces [19]. The aim of this study was to determine the current noise emissions in farm tractors. Are modern tractors equipped with eco-friendly cabs in terms of the noise levels emitted into the atmosphere?

2 MATERIALS AND METHOD

The research was based on the data published by top agrar polska in their catalogue [20] characterising more than 600 models of 27 brands of farm tractors. The tractors represent the most popular power range, i.e. from about 44.4 kW upwards. One of the parameters is the maximum noise level in the cab. Due to incomplete data 385 models of 20 brands were included in our analysis.

As the limits on the emission of harmful compounds applied only to engines with a power of 19 - 560 kW, our study was limited to these tractors. The data provided by tractor manufacturers were compared with the Polish standard [1], which specifies the maximum permissible noise levels in the work environment to protect workers' hearing and ensure that they can do basic tasks. The Polish standard also sets the following requirements for noise level measurements, based on international regulations and standards:

- $L_{ex,8h}$ (noise exposure level) < 85 dB (65 dB for pregnant women),
- $L_{A\max}$ (maximum sound level A) < 115 dB
- L_{Cpeak} (peak sound level C) < 135 dB.

Sounds over 85 dB(A) cause temporary or permanent hearing impairment. For this reason, the International Labour Organisation (ILO) adopted this value as the warning level.

3 RESULTS AND DISCUSSION

According to data from 2015 [20], Fendt 512 Vario tractors generate the lowest noise level, whereas Farmtrac 675 DTN tractors are the loudest Fig. 2.

Figure 2 The quietest (a) 64 dB(A) and the loudest (b) 89 dB(A) model among 385 farm tractors tested (factory photos: Fendt and Farmtrac)

The difference of as much as 25 dB(A) means that the Farmtrac is eight times noisier. It can be heard very well even when driving on asphalt (Author's remark). Farmtrac 690dt users also say that they can hear disturbing noises coming from the front axle. Thanks to farmers' good opinions about other parameters, for many years Fendt has topped the sales rankings not only in Germany and Switzerland but also in the United Kingdom, France, the Netherlands, Belgium, Austria, Sweden, Norway, Finland, Bulgaria, Spain, and Hungary. Between 2018 and 2020 Fendt was the third leading tractor manufacturer (after John Deere and New Holland) on the European market. Its share in the total sales volume amounts to 14 - 15% on average. The Fendt engineers are constantly trying to improve their products. This fact is evidenced by the title 'Tractor of the Year' awarded to Fendt 942 Vario in 2020.

Since the beginning of 2021 components manufactured by the Continental company have been used in the compact Fendt 200 Vario and Fendt 200 V/F/P Vario tractors to ensure high driving comfort. Fendt and Continental collaborated and developed a new transmission sleeve, which significantly reduces vibration and noise in the driver's cab and ensures the same comfort as in higher-class tractors. The new sleeves can also be used in the gearboxes of other Fendt tractors. Various support systems in Fendt tractors provide high comfort of operation to their users (Fig. 3).

Figure 3 Chassis-suspension systems reducing vibration and noise in Fendt tractors (source: Fendt)

Superior driving comfort, an intelligent combination of 5 systems for maximum driving and working comfort (source: Fendt):

1. Level-controlled front axle suspension. For consistent driving comfort, independent of the load due to level regulation.
2. Cab suspension mechanically or pneumatically suspended cab and spring-mounted driver's seat.
3. Active vibration-damping rear linkage. Compensation of rear implement vibrations prevents rocking. Front axle with even load full steerability.
4. Vibration-damped front linkage via nitrogen accumulator. Prevents rocking, protects the implement and guarantees driving safety and comfort with heavy loads.
5. Fendt Reaction steering system with return centre. Sensitively controllable Fendt Reaction steering system for safe directional stability.

In 2021 the number of newly-registered tractors in all engine power categories increased considerably in Europe. According to CEMA (European Agricultural Machinery Industry Association), the number of newly-registered machines classified as farm tractors increased by 9%. According to Martin & Jacob Company, as many as 14074 new tractors were registered in Poland in 2021 (over 42% more than in 2020), which was the largest number in the last seven years. When the sales of farm tractors peaked in 2021, only 365 Fendt tractors were sold. This premium brand (it is expensive despite EU subsidies) came only twelfth in the sales ranking. This might mean that Polish farmers find other technical parameters of tractors (e.g. reliability and durability) more important than the noise level in the cab. Fendt tractors are not very popular in Croatia, either. In 2021 Croatian farmers purchased only 18 Fendt tractors (the total number of tractors sold in Croatia was 1062), but in 2006 as many as 54 tractors of this brand were sold in that country [21-23]. Interestingly, in 2022 the second most popular brand of tractors in Croatia was Lamborghini (99 tractors sold), which is a well-known manufacturer of luxurious sports cars. John Deere topped the ranking (146 tractors sold). Lamborghini tractors are mostly characterised by original and dynamic design. New shock-absorbing elements in the cab (hydraulic silent blocks) considerably reduce vibrations (up to 40% more than standard silent blocks) and noise coming from the outside. The cab sound level in the Lamborghini Strike HD 90.4/105.4/115.4/110/120 models is 76 dB(A), which is slightly higher than the average level in all other brands of tractors. This is much less than the cab noise level in the tractors manufactured in the 20th

century. In 1987 the field tests of the Lamborghini 674 70 ND 4WD tractor showed that the maximum cab noise level was as high as 85.5 dB(A).This made the farmer's work stressful, tiresome, and less productive.

The sales of quiet Fendt tractors is high in Germany (it was the second most popular brand in 2021 5765 tractors sold), Switzerland, France, the Netherlands, and Belgium.

In 2022 the results were no longer so good due to planning and production problems caused by disruptions in the supply chain and by new safety regulations introduced in July 2021. Although a large number of tractors was ordered, factories stopped manufacturing them, e.g. Fendt tractors in Germany (AGCO corporation). Factories in Italy and France stopped manufacturing farm tractors and machinery of brands such as Claas, Grégoire Besson, JCB, John Deere, Kramer, Kubota, Manitou, Massey Ferguson, New Holland, Sulky, and Weidemann. Farmers postpone their investment plans because very high inflation and a low value of financial instruments are expected. A low noise level inside the cab may be one of the arguments speaking in favour of a specific model/brand when a customer is choosing a farm tractor.

Table 2 The ranking of tractor models according to the noise level in the cab

No.	Brand and model	Noise in cab / dB(A)
1.	Fendt 512 Vario	64
2.	Fendt 513 Vario	64
3.	Fendt 514 Vario	64
4.	Fendt 516 Vario	64
5.	Fendt 716 Vario	68
6.	Fendt 718 Vario	68
7.	Fendt 720 Vario	68
8.	Fendt 722 Vario	68
9.	Fendt 724 Vario	68
10.	Fendt 822 Vario	68
11.	Fendt 824 Vario	68
12.	Fendt 826 Vario	68
13.	Fendt 828 Vario	68
14.	JCB Fastrac 8280	68
15.	JCB Fastrac 8310	68
16.	New Holland T8.320	68
…	…	…
369.	Case IH Farmall 105A	85
370.	Case IH Farmall 115A	85
371.	Case IH Farmall 85A	85
372.	Case IH Farmall 95A	85
373.	Farmtrac Europeline 670 DT 3B	85
374.	Farmtrac Europeline 675 DT	85
375.	Farmtrac Europeline 690 DT	85
376.	Kioti RX6020	85
377.	New Holland TD5.105	85
378.	New Holland TD5.115	85
379.	New Holland TD5.85	85
380.	New Holland TD5.95	85
381.	Ursus 9014H	85
382.	Farmtrac 675 DTN King	86
383.	John Deere 5055E	86
384.	Ursus 10014H	86
385.	Farmtrac 675 DTN	89

In the entire population of models tested the average noise level in the cab was 75 dB(A). This means that none of the models exceeded the limit of 115 dB(A) nor did any of them exceed the threshold of pain (120 dB for acoustic noise and 140 dB for sinusoidal sounds). However, the noise in over a dozen models (Tab. 2) exceeded the 8 hour exposure level of 85 dB(A), set in the Polish Standard.

The Fendt models topped the ranking. In none of them the noise level was a nuisance for humans. All these models have silent automatic transmission Vario. On the other hand, budget brands are the loudest, but some models of premium brands (John Deere, Case IH) are also relatively noisy. The average noise levels for 20 tractor brands are shown in Fig. 4.

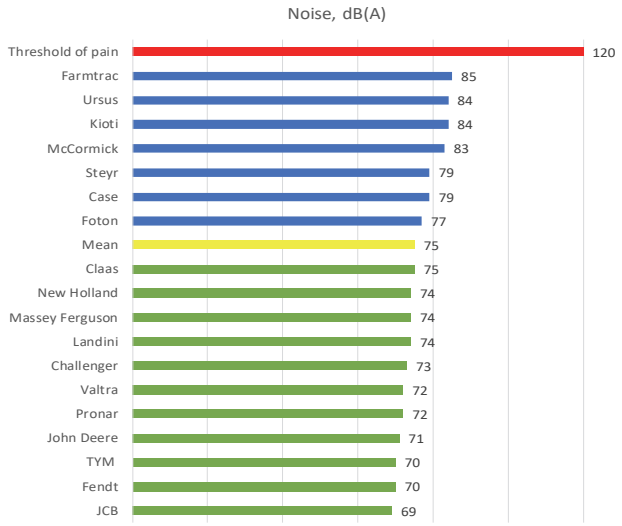

Figure 4 The average noise level in the tractor cab

Only the tractors made by JCB, a well-known manufacturer of heavy machinery and telescopic handlers, were better than the Fendt tractors. Polish farmers may also take the noise level in the cab into account when they make purchase decisions about new tractors. According to Martin & Jacob Group, in 2021 over 14000 tractors were purchased. The top ten best-selling brands included: John Deere (the average noise level in various models 71 dB(A)), New Holland 74 dB(A), Massey Ferguson 74 dB(A) and Claas 75 dB(A). Only Case IH 79 dB(A)) and Farmtrac (85 dB(A)), the models which are well-ranked in purchase decisions, exceeded the average noise level.

The charts below show the dependence between the noise level in the tractor cab and the rated engine power, displacement, torque, and the number of cylinders (Fig. 5).

The comparison showed that the parameters were negatively correlated with each other. This means that the greater the engine power, displacement, torque and the number of cylinders were, the lower the noise level in the cab was. The last chart (Fig. 5d) shows that the downsizing of tractor engines, which is a popular trend nowadays in order to reduce the emissions of harmful chemical compounds to the atmosphere, stands in opposition to the noise emissions generated by the engine. The negative correlation is the greatest here. For example, the 12 cylinder Challenger MT engine generates 72 dB(A), whereas the 3 cylinder John Deere 5055E engine generates 86 dB(A). However, there are also quieter 3 cylinder engines, such as those in Massey Ferguson models 5608, 5609, and 5610, where the noise level is only 69 dB(A).

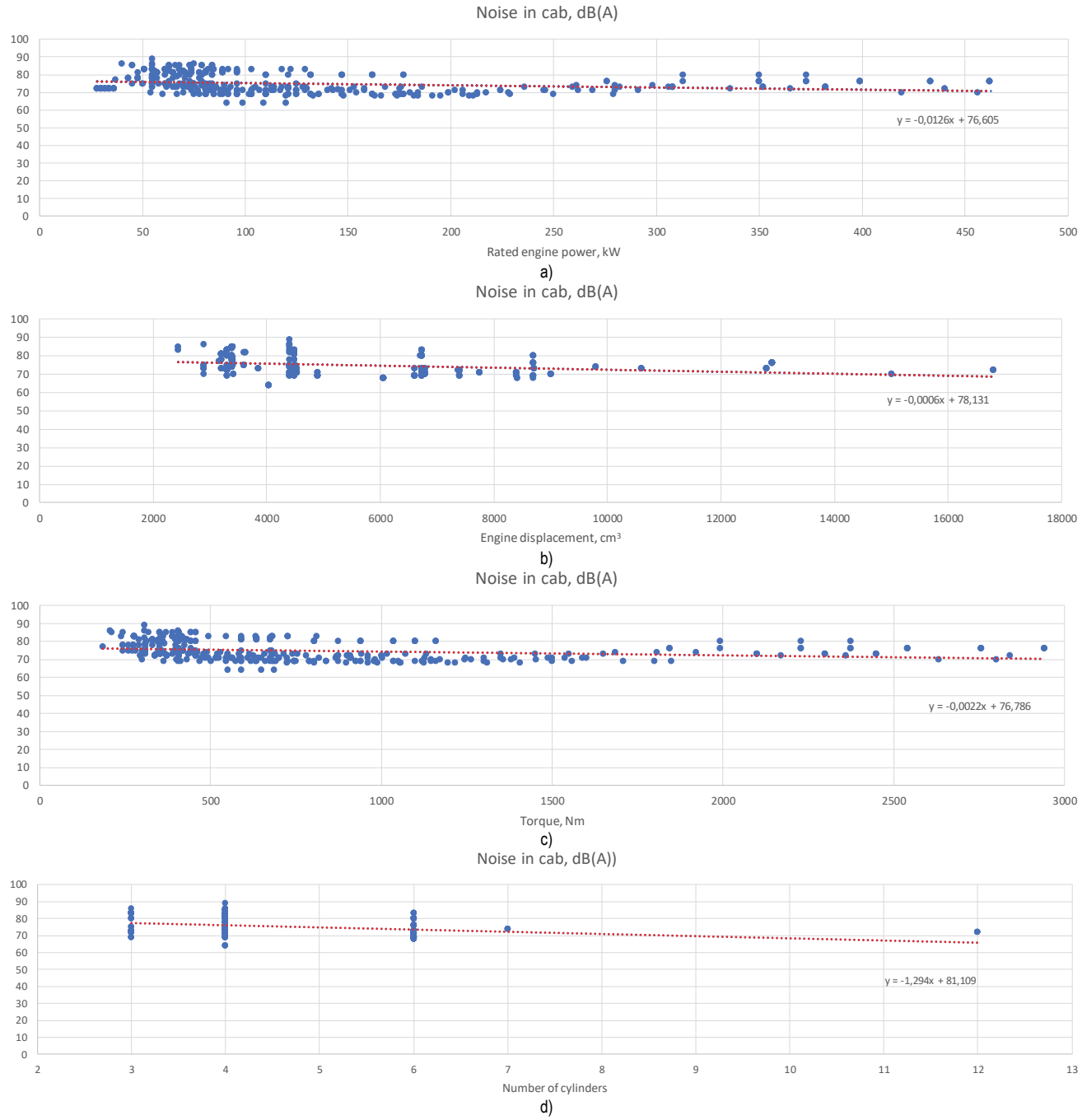

Figure 5 The influence of the rated engine power (a), engine displacement (b), torque (c), and the number of cylinders (d) on the noise level in the cabs of 385 tractor models

Over the years the situation has improved. For example, today the average noise emitted by NH tractors is 74 dB(A). Twenty years ago [12] used an SL 4001 digital sound meter to measure the noise level in the vicinity of the tractor operator. The lowest noise level, i.e. 79.7 dB(A), was noted in the NH L95 tractor. The highest noise level, i.e. as much as 91.7 dB(A), was measured near the exhaust pipe (in the exhaust gases). The engine of the NH L95 tractor manufactured between 1996 and 1998 had 4 cylinders and a power of 70 kW.

Durgut and Huseyin [4] measured similar noise levels in the same tractor model Tab. 3.

The maximum noise level, i.e. 96.6 dB(A), was measured in the vicinity of the tractor operator, whereas the minimum noise level in open space was only 67.7 dB(A). When the engine speed increased from 1000 to 2000 rpm, the noise increased by 6 dB(A). The manufacturer's methods of reducing noise emission to the tractor cab do not meet the operator's expectations. There was not much difference in the noise levels measured inside and outside the cab.

Table 3 The noise level in dB(A) when the tractor was out of gear

Front		Back		Tractor surroundings			
				Operator		Exhaust	
min.	max.	min.	max.	min.	max.	min.	max.
80.6	81.8	80.3	80.6	79.7	80.4	90.7	91.7

4 CONCLUSION

Noise is a disorganised mixture of various sounds. It is obvious that a high noise level is harmful, so it is desirable to reduce it. Noise negatively affects hearing and the

central nervous system. It impairs hearing, causes fatigue, noise-related disorders such as: decreased readiness to work, gastrointestinal disorders, increased sweating, headaches, dizziness, sleep disorders, and increased nervous excitability [24].

Unfortunately, it is difficult to reduce the noise level in a large group of farm tractors (there are over 1.5 million tractors registered in Poland, including about 700000 Ursus tractors a Polish brand). All of them have diesel engines, which make a characteristic noise. Unlike in cars, there are slim chances for electric motors in tractors. The new strict Stage V emission standards, which have been announced, will not solve the problem of noise in the cab, either. By monitoring disturbing sounds the operator can react quickly and avoid damage to the tractor, which involves expensive and time-consuming repairs.

On the other hand, the characteristic sounds of the engine indicate its performance. Thus, this is an ambivalent problem. Rolls-Royce Motor Cars Ltd is famous for manufacturing the quietest cars in the world. However, the company needed to artificially (electronically) increase the noise level generated by the engine of Phantom (eighth generation) the flagship model, because drivers complained about it being too quiet. They could not hear the engine, which made safe driving difficult. The model has 6 mm thick laminated glass and 130 kg of noise suppressing materials hidden in its body. Inside 22 inch silent-seal tyres there is special foam, which has reduced rolling noise by 9 dB. This is a considerable decrease, because as small a change as 3 dB means a double increase or decrease in the noise level. Engineers have also made attempts to make use of excessive noise. The Boeing Company is trying to produce energy from the noise generated by their aeroplanes.

Besides, sometimes the cabs in modern tractors resemble the cockpit of a luxury car or aeroplane. However, new technical solutions, original design, and offered equipment do not always guarantee the farmer's comfort of work.

In recent years agricultural equipment manufacturers have been focusing on reducing noise levels in the tractor cab. Many manufacturers have designed tractor operator stations where noise does not exceed the safe level of 85 dB(A) and no hearing loss will occur after 16 hours of exposure. Designers are already thinking about new technical solutions in this area. For example, Zetor a Czech manufacturer, which is well-known in Poland and Croatia, is planning to install a new exhaust system in all Proxima tractors by the end of the year. The new system will reduce the noise level coming from engine, whereas the cab will receive even better acoustic insulation. However, noise levels in the operator's seat on various farm tractors are still high enough to pose a chronic health risk [25].

The detailed analysis of the results of the research on the noise level in the farm tractors available on the Polish market led to the following conclusions:

1. The noise level in the cab is an important parameter determining the assessment of the global quality of agricultural vehicles. Farm tractors with internal combustion engines generate noise which may be a nuisance to the operator, assistants, farm and forest animals, and the environment.
2. Some manufacturers of farm tractors do not seem to notice the problem and do not try to reduce the engine noise. Electric vehicles are still a vision of distant future. The noise generated by some of the currently manufactured models exceeds the permissible limit, and thus reduces the comfort of operation during field work.
3. The number of engine cylinders considerably influences the noise level in the cab. Downsizing does not reduce the engine noise level and does not result in greater work comfort of the tractor operator. The introduction of electric motors in farm tractors (the solution applied in cars) might reduce the noise generated by their engines. Due to the fact that electric vehicles are very quiet, tractors with electric motors could be used for farm work at night. However, there are similar problems to those with electric cars: the range on a single battery charge, high load at work, which will result in quick discharge, as well as the availability of fast charging stations.
4. The noise generated by the engine should be a canonical criterion taken into account both in the set of measurable (customer's choice) and non-measurable (user's assessment) features. This approach will be used in the methodology of the farm tractor purchase decision support system (AGRORANKING.pl), which is being developed, verified and validated at the moment.
5. It is not only the noise level inside the cab but also outside that matters because it affects livestock, residents, NATURA 2000 areas, etc. Therefore, soundproof side panels and the cab roof, or the use of sound-absorbing glass may not be enough for environmentalists.
6. The results of this study should be sent to farm tractor manufacturers (there are over 50 brands worldwide more than the number of car manufacturers). Farm tractor designers and engineers should take care of the operator's comfort and reduce the noise level. On the one hand, there are various exhaust gas treatment systems, systems protecting the tractor operator from the vehicle rollover (ROPS Rollover Protection Structures) and falling objects (FOPS Falling Object Protective Structures) [26]. On the other hand, there are no silencers on exhaust pipes. During operation the user has limited (or no) chance to reduce the noise level and usually can do nothing about it, assuming that this is the way it should be. Tractor operators can use ear protectors, but in this situation a radio in the cab does not make sense. The results of this study indicate that it is necessary to introduce noise reduction solutions in farm tractors.
7. Robotisation and telematics are the trends in future-oriented precision and digital Agriculture 4.0 and 5.0 (as well as the automotive industry), which will make use of autonomous systems. Specific environmental conditions need to be ensured for the driver to voice-operate farming machinery. Speech recognition systems (systems recognising voice commands) need clear sound, undisturbed by noise and vibrations to correctly identify commands given to the machine. If traditional methods and the use of new better damping materials fail to provide the right acoustic insulation, psychoacoustics can be applied. This is an interdisciplinary field of study which combines not only acoustics and psychology but also anatomy, neuropsychology, and physiology. The knowledge of the structure and physiology of the ear can also be used to create new automatic speech recognition systems.

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