Occupational noise level exposures outside and inside agricultural tractor cabs

Exposição ao nível de ruído ocupacional fora e dentro de cabines de tratores agrícolas

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Cristiano Márcio Alves de Souza
Doctor of Agricultural Engineering
Institution: Universidade Federal da Grande Dourados (UFGD)
Address: Rod. Dourados-Itahum, Km 12, Cidade Universitaria, Dourados - MS
E-mail: csouza@ufgd.edu.br

Gilmar Martinelli Junior
Master of Science in Agricultural Systems Engineering
Institution: JOMA Acres
Address: 6945 Elm Sugar Rd, Scott, OH, United States, 45832
E-mail: gmartinelli.junior@gmail.com

Ricardo Rodrigues da Silva
Agricultural Engineer
Institution: Universidade Federal da Grande Dourados (UFGD)
Address: Rod. Dourados-Itahum, Km 12, Cidade Universitaria, Dourados - MS
E-mail: ricardo_petelin@hotmail.com

Leidy Zulys Leyva Rafull
Doctor of Agricultural Engineering
Institution: Universidade Federal da Grande Dourados (UFGD)
Address: Rod. Dourados-Itahum, Km 12, Cidade Universitaria, Dourados - MS
E-mail: leidyrafull@ufgd.edu.br

Roberto Carlos Orlando
Doctor of Agricultural Engineering
Institution: Universidade Federal da Grande Dourados (UFGD)
Address: Rod. Dourados-Itahum, Km 12, Cidade Universitaria, Dourados - MS
E-mail: robertoorlando@ufgd.edu.br
ABSTRACT
The farm tractor fleet in the Brazilian market has increased. They are machines known to emit much noise. Noise can cause severe damage and disturbance in people who work directly with and around these machines. Therefore, the work aimed to evaluate the noise levels emitted by two cab farm tractors of different engine power, analyzing the effect of engine speed and distance radius from the noise source on occupational health. The noise level outside and inside of the tractor cab, the attenuation index, and the noise level reduction provided by the cab sound insulation were determined. Attenuation indexes and noise reduction ratings were satisfactory in studying the noise levels inside and outside the tractor cab. The tractor with the most power in the engine has better sound insulation compared to those lowest power. The noise levels that operators are exposed to in the cab were lower than the limits established by Brazilian government laws. On the other hand, outside the cab, the noise levels emitted by the tractor of greater power are not safe for the workers' health if they are at a distance radius from the noise source of less than 7 m, requiring the use of an ear protector.

Keywords: farm machinery, ergonomics, workplace health.

RESUMO
A frota de tratores agrícolas no mercado brasileiro aumentou expressivamente, sendo máquinas conhecidas por emitirem altos níveis de ruído, que pode causar sérios danos e distúrbios auditivos aos trabalhadores. Assim, neste trabalho o objetivo foi determinar os níveis de ruídos emitidos por dois tratores agrícolas cabinados de duas potências do motor diferentes, e sua atenuação devido a proteção da cabine, analisando-se a rotação do motor e o raio de afastamento da fonte emissora sobre a saúde do trabalhador. Foram determinados o nível de ruído fora e dentro da cabine dos tratores, o índice de atenuação e o nível de redução de ruído proporcionado pelo isolamento acústico das cabines. O índice de atenuação e o nível de redução de ruído foram satisfatórios para analisar a proteção proporcionada pela cabine, demonstrando que o trator de maior potência possui melhor isolamento acústico comparado com o trator menor. Os níveis de ruído que os operadores estão expostos dentro da cabine foram inferiores aos limites estabelecidos pela legislação brasileira. Por outro lado, fora da cabine, os níveis de ruído emitido pelo trator de maior potência não são seguros para a saúde do trabalhado, se estes estiverem a uma distância da fonte emissora menor que 7 m, exigindo obrigatoriamente uso de protetor auricular.

Palavras-chave: máquinas agrícolas, ergonomia, saúde ocupacional.
1 INTRODUCTION

The expansion of Brazilian agriculture over 45 years caused the tractor fleet to increase by more than 465%, where it was not accompanied by cab tractors until 2007; while in recent years, there has been growth in cab models, as reported in 2016 by the National Association of Automotive Vehicle Manufacturers (Anvafea). Besides having acoustic and thermal insulation, the cab can prevent the entry of dust particles, pesticides, and gases from the machine leakage, promoting workers’ health (Dul & Weerdmeester, 2012).

The high sound pressure or noise emitted combined with the long working day is one of the main problems affecting the tractor driver and those working around the machines. The cumulative effect of noise level exposure throughout the day can reduce the ear’s recovery capacity due to the reduced time before the next exposure time (Franklin et al., 2006). Newer tractors show reductions in noise emission values through technological evolution (Cunha et al., 2012; Crowder et al., 2016), and the study of official trials is an essential means to measure the noise levels of these machines.

Testing with farm equipment began in the 19th century. However, the maximum limits for machine noises were established only six decades ago. The Brazilian Association of Technical Standards has level and maximum noise emission testing standards. Parallelly, the standard regulatory NR-15 (Unhealthy Activities and Operations) of the Ministry of Labor and Employment of Brazil gives recommended noise exposure limits for the number of hours exposed.

In the NBR-10152 standard (Abnt, 2017a), there are noise level values for the worker to have acoustic comfort in various facilities, such as hospitals, schools, residences, offices, etc. However, Andrade (2017) remarked that there are no exposure limits for the interior noise of wheeled agricultural or forestry tractors regulated in Brazil. The interior noise of wheeled agricultural or forestry tractors is controlled by directive EC-76 of the European Council (EC, 2009), which prescribes conditions, methods, and procedures of measurements, as well as data processing and results validation (Harl & Lazović, 1999).
The NR-15 standard establishes that continuous or intermittent noise has a minimum tolerance limit of 85 dB(A) for eight exposed hours. Besides, there is still controversy about the noise level at which permanent hearing loss occurs, with some believing that the critical level may be closer to 80 dB(A) (Crowder et al., 2016). On the other hand, inside the cab, an acceptable noise level of up to 65 dB(A), like a comfortable condition established in NBR-10152, is a value that could also be adapted for interior noise.

Souza et al. (2001), Alves et al. (2011), and Baesso et al. (2017) evaluated the noise level of agricultural machinery, observing that high values (Carvalho et al., 2008) of noise were found above what is established by Brazilian legislation and the National Institute for Occupational Safety and Health (NIOSH) of U. S. Department of Health & Human Services. Thus, the tractor driver and workers must wear an earmuff during all or part of the operation time (Arcoverde et al., 2011; Oliveira Junior et al., 2011) because tractors without cabs frequently produce sound levels that allow less than 8 h of exposure before noise cause hearing loss is a problem.

Several factors have been studied to evaluate the noise produced by farm machinery, such as Santos et al. (2016), which observed increased noise levels with the tractor engine rotation and decreased as a function of the distance from the source (Yanagi Junior et al., 2012). Cunha et al. (2012) demonstrated the need to deepen acoustic studies in machine cabs, as it can attenuate the level of sound pressure to the point of reducing the unhealthiness of the work environment (Andrade, 2017).

The requirements regarding the interior noise level of a cab for wheeled agricultural or forestry tractors were evaluated by Harl and Lazović (1999), which reduced by 10 to 4% of interior noise level using a tractor cab when in a stationary condition and by 9 to 5% in a dynamic condition. These authors concluded that the interior noise level of the cab was moderated by using adequate absorbing and isolating materials for a defined frequency range, and lower interior noise levels were achieved by using elastic suspension between the tractor chassis and the cab. Analyzing the interior noise levels in cab tractors over three different manufactured years, Barač et al. (2018) showed that none produced a higher noise level than the permitted 90 dB.
Thus, this work aims to evaluate the attenuation of noise levels emitted by two cab agricultural tractors, with different engine powers, depending on the engine rotation and the distance of the noise source.

2 MATERIAL AND METHODS

The test for noise level measurement on the larger cab tractor was carried out in an area attached to the Laboratory of Machine Design of the College of Agricultural Sciences of the Federal University of Grande Dourados, Dourados, Brazil. The New Holland TL85E cab tractor (TL85E tractor) has an engine, model MWM 229, of 64.7 kW (87 hp) at 2,400 rpm, four cylinders with 3,908.0 cm³ of capacity, maximum torque of 300 Nm at 1,400 rpm. At 540 rpm on the power take-off (PTO), the engine has 2,199 rpm, equivalent to the power of 56.7 kW in the PTO. The distance between the engine gas exhaust pipe and the cab is 420 mm.

The Massey Ferguson 265 cab tractor (MF265 tractor) test was performed at the Experimental Farm of the Federal University of Grande Dourados, Dourados, Brazil. It has a power of 47.8 kW (64 hp) at 2,000 rpm in its Perkins AD4203 engine, four cylinders with 3,335.9 cm³, and maximum torque of 249 Nm at 1,400 rpm. At 540 rpm on the PTO, the engine is 1,680 rpm and corresponds to the power of 36 kW. The PTO power is 39 kW at 627 rpm, equivalent to 2,000 rpm on the engine. The distance between the cab and the engine gas exhaust pipe is 825 mm.

The HM-852 sound level meter was used in the tests of the two tractors, ranging from 30 to 130 dB, with a resolution of 0.1 dB(A) and an RS-232-compatible port. It was programmed for A weighting and slow mode. The sound level meter met the specifications of IEC-60651 and IEC-60942, following the NBR-10151 standard. A 4500NV model weather meter was used to measure the ambient air's wind speed, temperature, and relative humidity.

The experiment was installed using a completely randomized design. The treatments were arranged according to a split-plot design, being that the plots were constituted by five engine rotations and the subplots by the four tractor sides and six distances radius
from the emission source, with three replications. In each experimental unit, noise level values were acquired to form composite samplings.

Using a 50 m tape measure, the markings of a distance radius at zero, 5, 10, 15, 20, and 25 m from the tractor noise source (exhaust pipe) were distributed along the front, rear, left and right sides (Figure 1). The crankshaft angular velocity (engine rotation) used were 1,500, 1,700, 1,900, 2,100, and 2,300 rpm, obtained by varying the engine fuel supply.

Figure 1. Schematic showing the data collection positions on each side of the tractors.

The tests were performed on sunny days, with winds with an intensity of less than 5.0 m s\(^{-1}\) and relative humidity of air less than 80\%. Measurements of noise levels were done with the decibel meter microphone placed 1.2 m from the ground surface, according to NBR-10151 (Abnt, 2019).
The microphone was used with a special protector (IEC 61672, Class 2), preventing the effect of winds. Ambient noises were collected before and during the tests. When data collection was done at the zero-point (noise emission source), the interior noise data was simultaneously performed inside the cab, near the height of the driver's ear (Marques Filho & Lanças, 2022), as established by the NR-15 (Andrade, 2017) and NBR-5131 standard (Abnt, 2017b).

Before each test began, the ambient noise levels, wind speeds, temperature, and relative humidity were measured. Noise level readings were acquired per 20 s for better accuracy of the measures, thus obtaining a sampling of 2 minutes, totaling 4,320 data automatically recorded in a serial port data logger. The data were collected in the morning and afternoon for approximately five hours. The tests were started after one hour of continuous operation of the tractors, keeping the PTO rotation at 540 rpm.

Noise reduction rating and the noise reduction coefficient were determined by comparing the sound pressure level obtained near the driver's ear inside the cab with those obtained on the outer perimeter of the central part of the cab.

The noise reduction rating (Equation 1) was determined according to the methodology adapted from the ANSI S12.6 Method B standard (ANSI, 1997) to represent a unit of measurement used to determine the effectiveness of hearing protection devices to decrease sound exposure within a given workplace, such as the tractor cab.

\[ N_{RR} = N_{RF} - N_{RC} \]  

Where,

- \( N_{RR} \) - noise reduction rating, dB(A);
- \( N_{RF} \) - noise level measured outside the cab (control value) dB(A);
- \( N_{RC} \) - noise level measured inside the cab, dB(A).

The noise reduction coefficient measures the reduction in sound pressure intensity when it passes through part of the tractor cab, i.e., the level of sound insulation provided.
Equation 2 was obtained based on ISO 16283-1 and ASTM C423 standards, according to the methodology adapted from Granzotto et al. (2020) and Mimura et al. (2022).

\[ N_{RC} = 1 - 10^{-\frac{N_{RR}}{20}} \]  

(2)

Where,

- \( N_{RC} \) - noise reduction coefficient, decimal.

A decision-making structure was constructed to analyze the ambient noise and the noise from each side obtained at the two tractor test sites, according to Souza et al. (2022). This decision-making was based on the combination of the F test (\( F_{H0} \)) modified by Graybill (Vendruscolo et al., 2017), the t-test applied to the mean error (\( t_{\bar{e}} \)), and the analysis of the linear correlation coefficient (\( r_{YjY1} \)) (Ferreira et al., 2017). A p-value of 0.01 was considered significant.

Of all noise acquisitions obtained in the tests, 720 average values were used in the analysis. Using the software SAEG, version 9.1, the ANOVA and the regression analysis were done to evaluate the noise level, the noise reduction rating, and the attenuation index data. Those models that presented the highest determination coefficient and the significance of the regression coefficients by the t-test were selected. A P-value of 0.01 was considered significant.

### 3 RESULTS AND DISCUSSION

In each engine speed used in the tests of the TL85E tractor, the average ambient noise levels were 47.0 (1,500 rpm), 48.7 (1,700), 46.8 (1,900), 50.3 (2,100), and 46.5 dB(A) (2,300 rpm), and the relative humidity from 56.9 to 64.0%, and wind speeds from 1.5 to 4.0 m s\(^{-1}\) were obtained. The ambient noise levels measured using the MF265 tractor were 47.4 (1,500 rpm), 48.4 (1,700 rpm), 45.8 (1,900 rpm), 47.9 (2,100 rpm), and 48.1 dB(A) (2,300 rpm), and the air relative humidity from 53.4 to 76.0%, and wind speed was between 1.9 and 3.7 m s\(^{-1}\). Thus, the tractor tests were performed respecting all the...
requirements of the NBR-10151 and NR-17 standards so that their measured values can be considered valid.

The ambient noise levels obtained at the two sites of tractor tests were considered equal (Figure 2) for not presenting significance in the F-test and t-test, and still for $r_{YjY_1} > |1-\bar{e}|$. Thus, comparing noise level data obtained inside and outside the cab of two tractors might be safely performed.

![Figure 2. Comparison among the ambient noise levels (dB(A)) obtained during the tests of the two cab tractors in sites 1 (TL85E tractor) and 2 (MF265 tractor).](image)

According to ANOVA, the engine rotation, the distance radius from the exhaust pipe, and the tractor side where the data were collected influence (p<0.01) the noise levels emitted by the two cab tractors.

Thus, the noise level models have been adjusted as a function of engine rotation and distance radius from the exhaust pipe, obtained for the front (Equation 3), rear (Equation 4), left (Equation 5), and right (Equation 6) sides of the TL85E tractor, and the front (Equation 7), rear (Equation 8), left (Equation 9), and right (Equation 10) sides of the MF265 tractors tested.

\[
\text{dB} = 66.8868 - 2.0427^{**}x + 0.0465^{**}x^2 + 0.0126^{**}z \quad R^2=0.98 \quad (3)
\]

\[
\text{dB} = 62.3751 - 2.4346^{**}x + 0.0566^{**}x^2 + 0.0157^{**}z \quad R^2=0.95 \quad (4)
\]
\[
dB = 67.3981 - 2.2886^**x + 0.0505^**x^2 + 0.0129^**z \quad R^2=0.97 \quad (5)
\]
\[
dB = 66.7643 - 2.3119^**x + 0.0525^**x^2 + 0.0128^**z \quad R^2=0.99 \quad (6)
\]
\[
dB = 66.5316 + 0.8748^**x - 10.0575^**\sqrt{x} + 0.006451^**z \quad R^2=0.99 \quad (7)
\]
\[
dB = 70.2128 + 1.4132^**x - 12.9619^**\sqrt{x} + 0.004053^**z \quad R^2=0.99 \quad (8)
\]
\[
dB = 66.6797 + 0.8835^**x - 10.1736^**\sqrt{x} + 0.006437^**z \quad R^2=0.99 \quad (9)
\]
\[
dB = 67.6198 + 0.9095^**x - 10.3034^**\sqrt{x} + 0.006063^**z \quad R^2=0.99 \quad (10)
\]

Where,

- \(dB\) - noise level obtained around the engine exhaust pipe, \(dB(A)\);
- \(x\) - distance radius from the exhaust pipe of the engine, m;
- \(z\) - tractor engine rotation, rpm;
- ** - significant by t-test \((p<0.01)\).

The noise levels obtained from the front, rear, left, and right sides (Figure 3) differed due to t-test significance, showing that their values varied according to the exposure side of the TL85E tractor. The differences in the comparison of noise levels were 2.9% (Figure 3A), 1.9% (Figure 3B), 2.4% (Figure 3C), and 1.6% (Figure 3D). As the gas exhaust pipe is further to the left and a distance of 420 mm from the tractor cab, it influenced the values of the radiated noise in the space to each side. The difference between the background and test measurements was always greater than 3.0 \(dB(A)\), so the background noise would not have been too high for accurate measurement (Crowder et al., 2016).

The noise levels obtained from the front, left, and right sides (Figure 4) were equal, while those noise levels from the rear side were 5.5% (Figure 4A) lower than the other sides of the MF265 tractor. Unlike the result of the noise generation of the TL85E tractor,
analyzing the noise levels of the MF265 tractor, which has a separation between the exhaust pipe and cab of 825 mm, had an influence only on the rear side.

Figure 3. Comparison between the average noise level emitted by TL85E tractor for all four sides, being front versus rear (A), front versus left (B), front versus right (C), and left versus right sides (D).

Alves et al. (2011) and Magalhães et al. (2012) verified different noise levels emitted by agricultural tractors when obtained on each side evaluated. This fact corroborates with the adjusted models and the behaviors observed in the estimating curves of the noise propagated on the four sides of the TL85E tractor (Figure 3) and MF265 tractor (Figure 4).

Figure 4. Comparison between the average noise emitted by MF265 tractor for all the sides, being front versus rear (A), front versus left (B), front versus right (C), and left versus right sides (D).
In a free field, the noise radiates into space from a source uniformly in all directions, but due to the obstacle provided by the cab, the sound pressure produced by the source is not the same on all sides.

Two different mathematical models were selected to represent the noise levels emitted by the two tractors as a function of the distance radius of the source. The noise levels of the TL85E tractor decrease in quadratic form as a function of the distance radius (Figure 5). On the other hand, using the MF265 tractor, there was a tendency for the noise level to decrease with the square root of the distance radius (Figure 6).

Figure 5. Noise level emitted by TL85E tractor as a function of the distance radius from the exhaust pipe (x, m) and motor rotation (z, rpm), obtained on the front (A) and rear (B), left (C), and right sides (D).
Figure 6. Noise level emitted by MF265 tractor as a function of the distance radius from the exhaust pipe (x, m) and the motor rotations (z, rpm) obtained on the front (A), rear (B), left (C), and right sides (D).
The noise levels emitted by the two tractors increased linearly with the engine rotation. Cunha et al. (2012) and Magalhães et al. (2012) verified a linear increase in noise level with the engine speed, corroborating the results obtained in this study.

The different behaviors of noise levels when their values decrease with the distance radius from the point source were also observed by Silvestrini et al. (2015). Baesso et al. (2015) observed a linear decrease with increased distance from the tractor. A reduction of noise levels with the distance radius, using linear models of the second and third degree, was observed by Alves et al. (2011). Pimenta Junior et al. (2012) observed a noise level decrease with the distance radius; however, their values were represented by the Gaussian model. Silva et al. (2014) observed spherical and Gaussian noise behavior with the distance radius.

The noise level was higher at the source of the TL85E tractor, reaching a value of 85.8 dB(A) in the lowest rotation (Figure 5), exceeding the limit for continuous or intermittent expositor noise of 85 dB(A) for a working day of 8 h, established by NR-15 standard.

The highest noise levels were obtained close to the exhaust pipe of the MF265 tractor, being that no other element contributed to the increase in the noise emitted by the machine. The observed values of noise level emitted by the source were lower than 81.0 dB(A), verified in the rotation of 2,300 rpm (Figure 6). In all the engine rotations and the four sides of the MF265 tractor, the noise levels were below the limit established in the NR-15 standard.

The noise levels determined close to the cab border were higher than those obtained in the interior of the TL85E tractor (Equation 11) and MF265 tractor cabs (Equation 12), with a tendency to increase their values with the crankshaft angular velocity. The engine rotation was increased by supplying more fuel, thus producing more power and consequently increasing the sound energy per unit of time.

\[
\text{dB} = 48.0053 + 0.0149^*z \quad R^2 = 0.88 \quad (11)
\]

\[
\text{dB} = 56.7667 + 0.0078^*z \quad R^2 = 0.97 \quad (12)
\]
Where,

** - significant by t-test (p<0.01).

Figure 7. Noise level emitted by TL85E tractor (A) and MF265 tractor (B) as a function of engine rotation, measured inside and outside the cab.

The difference between the noise level curves indicates a noise reduction provided by the cab sound insulation of both tractors. Analyzing this difference verified that the TL85E tractor cab was reduced by 16.2% and the MF265 tractor cab by 6.3%.

The ANSI standards state that any difference less than 3.0 dB(A) should be accepted as substantial because they are reliable (Crowder et al., 2016). Like this, the TL85E tractor cab showed a higher noise reduction rating than the MF265 tractor.

The higher noise reduction rating of the TL85E can be explained by the technological difference between the two tractors because they are of different generations and sizes, as verified by Cunha et al. (2012). MF265 tractor does not present high noise levels. Hence, the design of the tractor cab main objective is to protect against dust, sun, pesticide exposure, house air-conditioning, onboard computer, etc.

The noise reduction rating of the MF265 tractor cab decreased with the increase in engine rotation (Equation 12), reaching a critical value of only 3.4 dB(A) measured in the highest rotation (Figure 7B). This fact is problematic (Souza et al., 2001) because an agricultural machine couplet to the tractor may generate additional noise that can reach the cab's acoustic insulation limit.
The noise reduction coefficient determined for the TL85E tractor cab was not influenced by engine rotation (Figure 8), with the model coefficient not significant by the t-test (p<0.01). The average value of the noise reduction coefficient is 0.81. Thus, the cab can attenuate the high-energy sound waves, even for the highest engine angular velocities. On the other hand, the noise reduction coefficient of the MF265 tractor cab decreased when the engine rotation was increased (Equation 13)

\[ NRC = 0.9078 - 2.5679 \times 10^{-04} \times z \]  
\[ R^2 = 0.88 \]  
(13)

Where,

** - significant by t-test (p<0.01).

The sound levels inside the cabs of even well-maintained cab tractors positively correlated with age, and the tractor driver is not as protected against noise exposures in an older cab as he is in a new cab (Crowder et al., 2016).

Figure 8. Noise reduction coefficient (NRC) of the two tractor cabs as a function of the engine rotation.

The highest noise level is transmitted from the engine to the cab’s interior over the instrument panel housing, and there is a need for special care in noise protection (Harl & Lazovič, 1999).
Reducing the noise level should be given much importance to designing and constructing agricultural machinery. The tractor rollover protective structure dimensioning should be carried out to provide adequate comfort to the operator, generating information about the distances that must be maintained from the machines, minimum rotations of engines, and type of protection to protect all workers involved in agricultural operations.

4 CONCLUSIONS

The noise reduction coefficient was considered satisfactory for studying noise levels of cab tractors, showing that the TL85E tractor cab has better sound insulation than the MF265 tractor cab.

The noise reduction coefficient of the TL85E tractor cab is kept constant with the crankshaft angular velocity, while the reduction coefficient of the MF265 tractor cab decreases with the rise of engine acceleration.

The noise levels measured in the interior of the two tractor cabs are lower than the 85 dB(A) limits; however, those noises emitted by the TL85E tractor are suitable outside the cab to be 7-m away from the exhaust pipe.
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