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Comparative analysis of vibration transmissibility from floor to seat in diesel and electric self-propelled agricultural vehicles under real operating conditions

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Abstract. The transmissibility of vibrations from the floor to the operator's seat represents a fundamental indicator in assessing biomechanical comfort and the performance of suspension systems in self-propelled agricultural vehicles such as tractors. In the context of modern agriculture, prolonged exposure to vertical vibrations generated by uneven land necessitates a thorough analysis of the floor–seat system's ability to attenuate the dynamic loads transmitted to the operator.
This paper proposes a comparative analysis of vibration transmissibility for two types of agricultural vehicles—a diesel tractor (model TD 80 D) and an electric tractor (model TE-0)—under real operating conditions, on two types of agricultural land (flat and ploughed land), at constant speeds of 5 km/h and 8 km/h.
The study employs a rigorous experimental protocol, in which vibrations are simultaneously recorded at the cabin floor level and at the seat surface using strategically mounted triaxial accelerometer sensors, on the vertical axis (Z-axis), using the same reference operator, anthropometrically representative (75 kg). The transmissibility was determined by computing the spectral ratio of vibration amplitudes measured at the system's output (seat) relative to those recorded at the input (floor), over the frequency range [0–80 Hz], covering the critical domain for human health effects according to the ISO 2631-1 vibration exposure standard.
The comparative analysis of vibration transmissibility between the diesel and electric tractors, across various land types and speeds, enables a clear evaluation of the vibration

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behaviour specific to each technological configuration. In this context, two critical aspects were investigated: the maximum transmissibility value, as an indicator of the potential amplification of vibrations transmitted to the operator, and the isolation frequency, as a benchmark for the system's capacity to attenuate loads in critical exposure zones. The results indicate a significant increase in transmissibility on ploughed field, with direct implications for the operator's exposure to harmful vertical vibrations, which may lead to biomechanical discomfort, reduced concentration capacity, and increased risk of musculoskeletal disorders during prolonged operation.

Keywords: vibration transmissibility, seat-operator-tractor, diesel vs. electric, isolation frequency.

1. Introduction

In the context of agricultural engineering, which encompasses the analysis of vibration exposure in self-propelled agricultural machinery is a topic of major interest, with direct implications for the operator's health, comfort, and performance [1–2]. Self-propelled agricultural vehicles such as tractors, as essential components of agricultural mechanization, frequently operate on uneven land that generates constant vibrational loads—especially along the vertical axis (Z-axis)—transmitted through the vehicle's structure to the seat and, consequently, to the human body [3]. Prolonged exposure to such vibrations is associated with an increased risk of musculoskeletal disorders, spinal discomfort, and a decline in the operator's physical and cognitive abilities [4–5]. Tractors generate specific vibrations during agricultural operations, primarily due to whole-body vibrations caused by uneven road or field surfaces [6-11].

The vibrations generated during tractor operation can be attributed, among other factors, to the interaction between the engine and the transmission system [12]; however, the primary source of vehicle vibrations remains the uneven profile of the running surface. Therefore, the analysis of vertical vibrations induced by irregular land becomes essential for evaluating the dynamic behaviour of the vehicle and its impact on the operator [13].

Fundamental studies on the transmission of vibrations to the operator through the seat of agricultural vehicles [14–16] have highlighted the importance of vibration transmissibility in assessing the dynamic and ergonomic performance of self-propelled machinery. In dynamic system analysis, vibration transmissibility is commonly described as the ratio of the amplitude of vibrations transmitted to the system's output in comparison with the input source (e.g., seat surface) and those measured at the system's input (e.g., cabin floor), representing a key parameter for quantifying the system's vibration isolation capacity. This indicator directly influences the operator's biomechanical comfort, operational safety, and the structural integrity of the equipment, emphasizing the need for optimized design of seat suspension and damping systems. In particular, the vibration transmissibility from floor to seat in agricultural tractors must be analysed in the context of the operator's prolonged exposure to vibrations induced by travel over uneven land. Recent publications by the authors of studies [17–18] emphasize that frequencies in the range of 0.4–20 Hz are especially critical for operator health, having a major impact on the lumbar region and spinal column [19–21]. Vibration transmissibility, as defined in the study conducted by the authors [22], represents a reference indicator in evaluating the damping performance of a tractor seat subjected to dynamic loads. This parameter is established by comparing the acceleration magnitude recorded at the occupant–seat interface with the corresponding acceleration input detected at the structural base of cabin floor level, along the same axis of analysis (X, Y or Z), within a frequency range of 0.5 to 80 Hz. This method enables precise characterization of the vibrational behaviour of the seat suspension system, providing a clear picture of its effectiveness in reducing the vibrations transmitted to the operator—an essential aspect for maintaining biomechanical comfort and preventing harmful exposure, particularly in the context of operation on highly uneven agricultural land. The research conducted by the authors of study [23] highlighted the significant influence of land type on vibration transmissibility in self-propelled agricultural vehicles. The study shows that on uneven or unprocessed surfaces, the amplitude of vibrations transmitted to the operator can be two to three times greater compared to flat and well-levelled land. Vibration transmissibility is defined as the relative magnitude of the amplitude of vibrations at the system's output A_o (seat surface) and the amplitude of vibrations at the system's input A_i (seat base or vehicle floor). The calculation formula is described in Equation (1).

$$T(f)=\frac{a_{chair}(f)}{a_{floor}(f)} \quad (1)$$

where: T(f) is the transmissibility; $a_{chair}(f)$ represents the acceleration at the seat surface at the frequency f and $a_{floor}(f)$ is the acceleration at the floor level at the frequency f.

Transmissibility indicates the efficiency of the system in terms of its dynamic response to vibrational inputs across a range of frequencies. This response is generally described by a transfer function, illustrating how both amplitude and phase components are altered throughout the transmission path.

The main objective of this research is to comparatively analyse the vibration transmissibility from the floor to the operator's seat in two types of self-propelled agricultural tractors—one diesel (model TD 80 D) and one electric (model TE-0)—under real operating conditions, without the influence of towed equipment. The study aims to characterize the vibrational behaviour specific to each technological configuration through tests conducted on two types of agricultural land (levelled and ploughed), at constant speeds of 5 km/h and 8 km/h. Through this approach, the article provides an objective evaluation of how structural design solutions and propulsion type influence the transmission of vibrations to the operator, thus contributing to a better understanding of the biomechanical risks associated with each type of agricultural vehicle.

1.1 Experimental protocol

The self-propelled agricultural vehicles used in the experimental tests on vibration transmissibility from the floor to the seat were a diesel agricultural tractor, model TD80D, manufactured by New Holland [24], and an electric prototype tractor, model TE-0 [25]. The technical specifications of the two vehicles are presented in Table 1, representing the baseline configurations analysed under real operating conditions.

Table 1. Technical specifications of the two tested tractors

Type	TD 80D	Electric Tractor TE-0
Manufacturer	New Holland	INMA Bucharest institute (Prototype model)
Engine Power	80 HP/59.2 [kW]	39.2 HP/28.8 [kW]
Distance Between Axles	2620 [mm]	2530 [mm]
Track Width	3510 (L)/2620 (h)/2000 (l) [mm]	3330 (L)/2530 (h)/1530 (l) [mm]
Suspension mechanism	Customizable suspension seat	Customizable suspension seat
Nominal Wheel Dimensions	front 1250 and back 1280	front 1250 and back 1280
Nominal Tire Pressure	1.7 [Bar]	1.7 [Bar]

Throughout the experimental trials, both agricultural tractor units were equipped with identical, height-adjustable suspension seat configurations, standardized at a setting of 10 cm. The seat utilized for vibration assessment was modular and interchangeable, being mounted successively on both tractor variants. It featured foam rubber padding engineered for vibration attenuation, along with polymer-based structural elements intended to enhance ergonomic comfort and operational functionality. The backrest inclination was set at a right angle of 90°. The tests were performed under standard operational conditions, employing two fixed travel velocities (5 km/h and 8 km/h) and two distinct configurations of driving surfaces: flat (levelled) land and ploughed (furrowed) land. The testing location was in Bucharest, at the National Institute for Research and Development INMA, at the geographical coordinates 44.5006742 N, 26.0724382 E, as shown in Figure 1.
The relevant operating conditions of the tractor-type vehicles were kept constant throughout the entire measurement period. The experimental measurements were conducted on four different types of driving surfaces: ploughed land, flat land, unprocessed land, and uneven land, under the same atmospheric conditions, characterized with ambient conditions characterized by a temperature of 23.1°C, a relative humidity of 45%, a wind velocity of 0.4 m/s, and an atmospheric pressure of 754.1 mmHg.
The methodology applied in the study on vibration transmissibility from the floor to the seat included the use of an advanced vibration acquisition and analysis system called the Vibration Analysis Toolkit (VATS), developed by NexGen Ergonomics (Pointe-Claire, Canada) [26].

a) Diesel tractor - TD80 D, flat land

b) Diesel tractor - TD80 D, ploughed land

c) Electric tractor - TE-0, flat land

d) Electric tractor - TE-0, ploughed land

Fig. 1.

The measurement setup was centred around the use of a Biometrics Systems MWX8 Data LOG data acquisition unit [27, 28], in combination with two additional MWX8 Units that facilitated the simultaneous and synchronized real-time acquisition of 15 biomechanical signal channels, corresponding to the three orthogonal axes (X, Y, and Z) of the accelerometers sensors. These sensors allow for a variable sampling rate on the analogue channel, ranging from 1 Hz to 20,000 Hz [27], providing flexibility and accuracy in recording vibrational signals across the entire frequency range of interest.

The Biometrics system is well-established in the field of advanced research, being applied in studies of biomechanics, functional assessment pertaining to the musculoskeletal system, physical rehabilitation, clinical practice, and robotic applications [29-32], and the assessment of routine functional activities. The recorded data were transmitted in real time to a dedicated computer, ensuring the high-precision transfer, display, and storage of the experimental information. For each tested vehicle, three tri-axial accelerometers of type Series 3 S3-1000G-HA (NexGen Ergonomics, Pointe-Claire, Canada) were mounted, as shown in the images illustrated in Figure 2. a)–d).

Mounting of the tri-axial accelerometer sensors:
a) at the floor level of the diesel tractor

b) at the floor level of the electric tractor

c) at the seat surface and backrest level on the diesel tractor

d) at the seat surface and backrest level on the electric tractor

Fig. 2.

2. Overview of method

In the detailed comparative study presented in this article, the experimental data collected for two distinct types of driving surfaces—flat land and ploughed land—were analysed at two travel speeds: 5 km/h and 8 km/h. The measurements focused on the vertical direction (Z-axis) for both the diesel tractor model TD 80 D and the electric tractor model TE-0, in order to comparatively evaluate the vibration transmissibility between the two types of propulsion. To ensure the consistency and comparability of the results, the tests were conducted using the same operator, selected to match the anthropometric average of a homogeneous sample of subjects, with a body mass of 75 kg. The centralization of essential data for the transmissibility analysis is presented in Table 2, highlighting the recorded values for each land–speed–vehicle combination.

Table 2. Centralisation of data for transmissibility analysis

Nr.	Type of Running Surface	Tractor Travel Speed[km/h]	Type of Agricultural Vehicle (Tractor Type)
1.	Flat land	5	Diesel / Electric
2.	Flat land	8	Diesel / Electric
3.	Ploughed land	5	Diesel / Electric
4.	Ploughed land	8	Diesel / Electric

The accelerations recorded using tri-axial accelerometer sensors, mounted both at the floor level of the tractor cabins and at the contact surfaces of the seat (cushion and backrest), were initially processed using the Biometrics software. The signals were segmented according to sensor type and mounting position to enable a differentiated analysis of vibration transmissibility at the relevant operator–vehicle contact zones.

Subsequently, the processed data were exported into the VATS (Vibration Analysis Toolkit) software, in which the transformation of signals from the time domain to the frequency domain was carried out using the Fast Fourier Transform (FFT) algorithm. This step allowed the identification of the dominant spectral components of the vibration signals, with the purpose of evaluating vibration transmissibility as a function of frequency. The Fourier Transform was applied to convert the discrete time signal X(n) into its corresponding frequency domain signal X(f), using the following equation, according to [33], as described in Equation (2):

$$X(f) = 1/N \sum_{n=0}^{N-1} \mathrm{x[n]}\, e^{-i2\pi\frac{f}{N}} \quad (2)$$

where: f = 0, 1, 2 … N-1 and defined by a memory length of N (where N = 1, 2, 3,…), expressing the discrete-time signal x[n] as an N-dimensional vector with complex-valued components, where f denotes the discrete frequency.

The calculation of transmissibility was performed using Microsoft Excel, based on the spectral data obtained from the conversion of vibration signals from the time domain to the frequency domain. These data, corresponding to the accelerations recorded at the floor and seat levels along the Z-axis, were used to determine the amplitude ratio at frequencies relevant for the vibration analysis.

3. Results

In this chapter, vibration transmissibility graphs were generated for each land–speed–vehicle combination, based on the values obtained from spectral processing. These graphs allow for the visual interpretation of the seat's vibrational behaviour in relation to the loads induced at the floor level, depending on frequency.

On the X-axis of each graph, the frequency (f) is represented in [Hz], while on the Y-axis, the vibration transmissibility is shown, calculated according to the formula presented in Equation (3). These graphical representations are essential for identifying the frequencies at which the seat–floor system exhibits amplification behaviour (transmissibility > 1) or attenuation behaviour (transmissibility < 1) of vibrations, depending on the type of vehicle and the driving conditions.

$$\text{Transmissibilty} = \left| \frac{A_0}{A_i} \right| = \sqrt{\frac{1+(2\varepsilon \frac{f_d}{f_n})^2}{\left[1-\left(\frac{f_d}{f_n}\right)^2\right]^2 + [2\varepsilon \frac{f_d}{f_n}]^2}} \quad (3)$$

where: A_0 = Amplitude of the vibrational response; A_i = Amplitude of the vibrational input; ε = Damping coefficient; f_d = Forcing frequency; f_n = Natural frequency.

For the calculation of transmissibility, the acceleration levels A_0 were divided by the acceleration levels A_i at the same frequency f [Hz] [34].

For all the resulting transmissibility values, the "Curve fitting" function was used, and a 6th-order polynomial curve was selected so that the coefficient of determination R^2 would be as close as possible to the value of 1. The transmissibility polynomial of the diesel tractor model TD 80 D is plotted in the graphs corresponding to cases 1–4 in Figures 3–6, in dark grey with a dashed line, while the transmissibility polynomial of the electric tractor model TE-0 is plotted in green with a dashed line. The green dashed horizontal line is referred to as the "unit transmissibility line" and represents the level at which vibrations reach isolation and are no longer transmitted (from the floor to the seat).

Case 1. Transmissibility graph for flat land, speed of 5 km/h

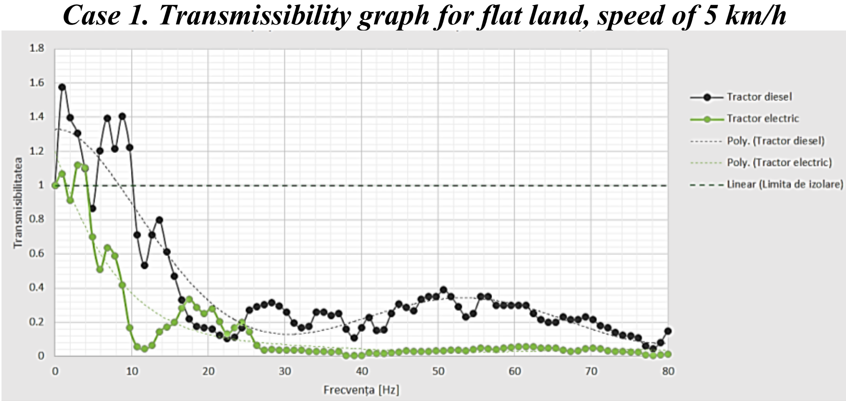

Fig. 3. Transmissibility graph, diesel tractor and electric tractor, frequency range [0–80] Hz	
Polynomial equation for the diesel tractor	Polynomial equation for the electric tractor
$y = -2E^{-10}x^6 + 7E^{-08}x^5 - 8E^{-06}x^4 + 0.0004x^3 - 0.0083x^2 + 0.0068x + 1.3281$	$y = 6E^{-11}x^6 - 2E^{-08}x^5 + 3E^{-06}x^4 - 0.0002x^3 + 0.0068x^2 - 0.1355x + 1.201$
Coefficient of determination R^2= 0.8896	Coefficient of determination R^2= 0.8918

Case 2. Transmissibility graph for flat land, speed of 8 km/h

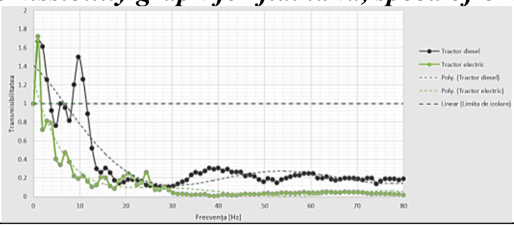

Fig. 4. Transmissibility graph, diesel tractor and electric tractor, frequency range [0–80] Hz	
Polynomial equation for the diesel tractor	Polynomial equation for the electric tractor
$y = -2E^{-10}x^6 + 5E^{-08}x^5 - 5E^{-06}x^4 + 0.0002x^3 - 0.0038x^2 - 0.0445x + 1.4068$	$y = 1E^{-10}x^6 - 4E^{-08}x^5 + 5E^{-06}x^4 - 0.0003x^3 + 0.0111x^2 - 0.1801x + 1.2465$
Coefficient of determination R^2	Coefficient of determination R^2
$R^2 = 0.8252$	$R^2 = 0.8604$

Case 3. Transmissibility graph for ploughed land, speed of 5 km/h

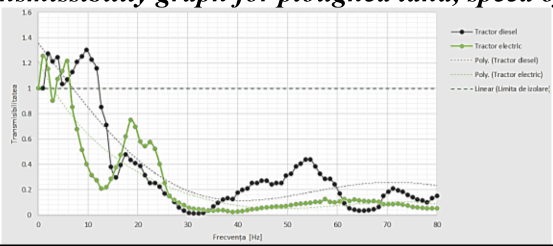

Fig. 5. Transmissibility graph, diesel tractor and electric tractor, frequency range [0–80] Hz	
Polynomial equation for the diesel tractor	Polynomial equation for the electric tractor
$y = 5E^{-07}x^6+2E^{-09}x^5 - 6E^{-07}x^4 + 4E^{-05}x^3 - 0.0004x^2 - 0.0505x + 1.3586$	$y = 5E^{-11}x^6 - 1E^{-08}x^5 + 1E^{-06}x^4 - 9E^{-05}x^3 + 0.0031x^2 - 0.0821x + 1.2173$
Coefficient of determination R^2	Coefficient of determination R^2
$R^2 = 0.7816$	$R^2 = 0.8298$

Case 4. Transmissibility graph for ploughed land, speed of 8 km/h

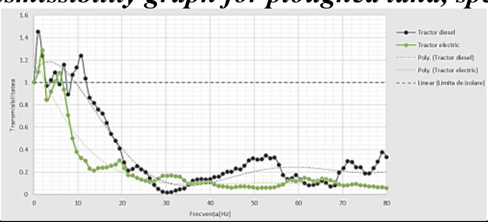

Fig. 6. Transmissibility graph, diesel tractor and electric tractor, frequency range [0–80] Hz	
Polynomial equation for the diesel tractor	Polynomial equation for the electric tractor
$y = -2E^{-10}x^6 + 7E^{-08}x^5 - 8E^{-06}x^4 + 0.0004x^3 - 0.011x^2 + 0.0606x + 1.0903$	$y = 1E^{-12}x^6 - 2E^{-09}x^5 + 5E^{-07}x^4 - 6E^{-05}x^3 + 0.0036x^2 - 0.1049x + 1.2531$
Coefficient of determination R^2	Coefficient of determination R^2
$R^2 = 0.8997$	$R^2 = 0.928$

Both in the specialized literature and in the present study, it has been highlighted that, in the context of the use and operation of agricultural tractor-type vehicles, the vibrations transmitted to the driver occur predominantly within the frequency range of [0–20 Hz]. Beyond this threshold, the vibration spectrum tends to stabilize, with higher frequencies being largely isolated and exhibiting significantly reduced amplitudes.

Based on this observation, two sets of transmissibility graphs were developed, corresponding to the intervals [0–20 Hz] and [0–80 Hz], in order to capture both the critical exposure range and the overall behaviour of the seat–floor system. These combined graphs are presented in Figures 7 and 8, facilitating a comparative analysis of transmissibility depending on the type of vehicle, land, and travel speed.

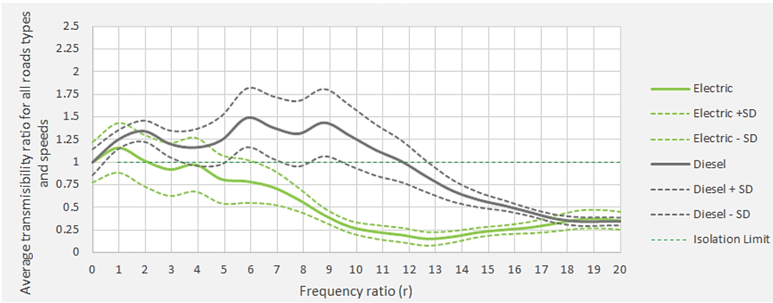

Fig. 7. Combined transmissibility [0–20] Hz for flat and ploughed land, speed 1 and speed 2, electric tractor model TE-0 and diesel tractor model TD80D.

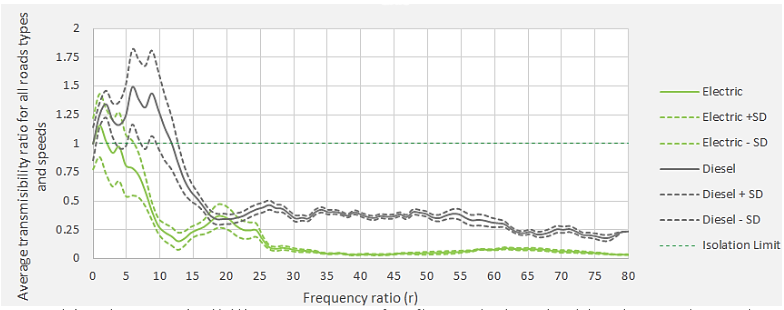

Fig. 8. Combined transmissibility [0–80] Hz for flat and ploughed land, speed 1 and speed 2, electric tractor model TE-0 and diesel tractor model TD80D.

For plotting the isolation efficiency graphs, the seats of the two analysed tractor types — diesel and electric — demonstrated a relatively effective capacity to isolate vibrations, particularly within the frequency range corresponding to the actual loads to which the operator is exposed during fieldwork. The exposure of the seat to vibrations generated at the floor level allows the evaluation of damping performance through an objective indicator: vibration transmissibility.

For this reason, plotting the transmissibility graphs is essential for understanding the efficiency of the seat suspension system across the entire frequency spectrum where vibration amplitudes are significant.

These graphs clearly highlight the frequencies at which the seat provides vibration attenuation (transmissibility < 1) and those where vibration amplification may occur (transmissibility > 1). Comparing the response of the two vehicle configurations (TD 80 D vs. TE-0) under different operating conditions allows for an in-depth evaluation of the efficiency of vertical vibration isolation and the identification of critical exposure zones.

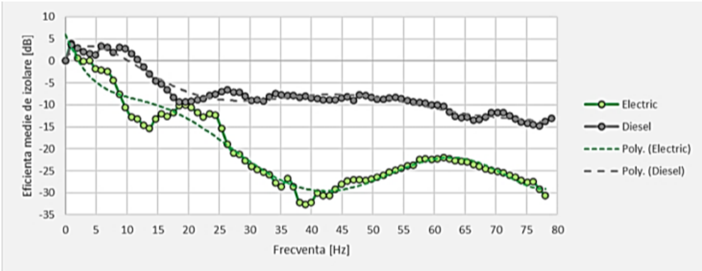

Fig. 9. Combined isolation efficiency [dB] in the range [0–80] Hz for flat and ploughed field, speed 1 and speed 2, electric tractor model TE-0 and diesel tractor model TD80D.

For the two types of driving surfaces analysed — flat land and ploughed land— at the predetermined travel speeds (5 km/h and 8 km/h), a graph representing the combined isolation efficiency [%] within the frequency range [0–80 Hz] was generated, as shown in Figure 10. This graph was developed for both tested agricultural vehicles: the electric tractor model TE-0 and the diesel tractor model TD 80 D.

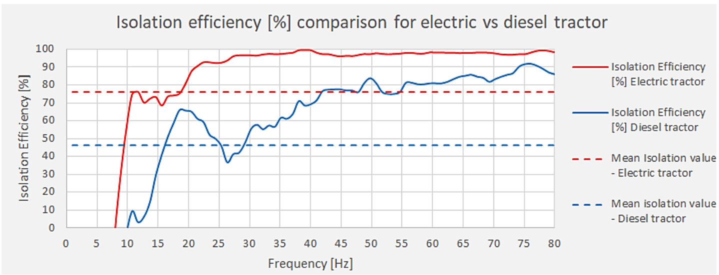

Fig. 10. Combined isolation efficiency [%] in the range [0–80] Hz for flat and ploughed land, speed 1 and speed 2, electric tractor model TE-0 and diesel tractor model TD80D.

4. Discussions

The graphical analysis presented in Figure 10, regarding the combined isolation efficiency in the frequency range [0–80 Hz], for the electric tractor TE-0 and the diesel tractor TD 80 D, at the two operating speeds (5 km/h and 8 km/h), provides a clear perspective on the suspension behaviour and on each vehicle's ability to attenuate the vibrations transmitted to the operator.

The results indicate that the electric tractor TE-0 exhibits superior isolation efficiency across the entire analysed frequency range (red curve), compared to the diesel tractor TD 80 D (blue curve). This enhanced performance suggests a better ability of the electric seat suspension system to reduce the transmission of vertical vibrations, thereby contributing to increased operator comfort and safety. Specifically, the average isolation efficiency of the electric tractor consistently exceeds 90%, reflecting very effective vibration attenuation under all tested conditions. In contrast, the diesel tractor's average efficiency is around 80%, indicating weaker performance in protecting against vibrational stress.

For the low-frequency range (0–20 Hz), which is critical in terms of its impact on the operator's biomechanical comfort, the electric tractor TE-0 achieves an isolation efficiency of 90% at 20 Hz, with a rapid increase in performance. This behaviour highlights an excellent ability to dampen vibrations that pose a high risk to the spine and lumbar region.

In comparison, the diesel tractor TD 80 D records an efficiency of approximately 65% at 20 Hz, indicating lower isolation of low-frequency vibrations. In the high-frequency range, the electric tractor TE-0 maintains its performance at a high level, keeping isolation efficiency above 90%, which is essential for reducing the transmission of high-frequency vibrations that can become harmful with repeated or prolonged exposure. The diesel tractor, although it improves its efficiency in this range, fails to reach the same level of performance, recording an average efficiency of approximately 80%.

5. Conclusions

Following the comparative analysis of vertical vibration transmissibility from the floor to the operator's seat for two types of self-propelled agricultural vehicles — a diesel tractor (TD 80 D) and an electric tractor (TE-0) — the study highlighted the significant influence of technological configuration on vibration isolation performance. Conducted under real operating conditions on four types of land (flat, ploughed, uneven, and uncultivated) at constant speeds of 5 km/h and 8 km/h, the study revealed that the dominant vibrations perceived by the operator are concentrated within the critical frequency range of [0–80 Hz], which is associated with increased risks to musculoskeletal health and biomechanical comfort. The results obtained indicate a clear superiority of the electric tractor TE-0 in terms of vibration isolation efficiency, recording values exceeding 90% across the entire analysed frequency range, in contrast to the average values of approximately 80% recorded by the diesel tractor. Specifically, at 20 Hz — a frequency relevant for human exposure — the suspension system efficiency of the electric seat reached 90%, compared to only 65% in the case of the diesel vehicle, highlighting an increased capacity to attenuate low-frequency vibrations.

The comparative analysis of isolation frequencies highlights the superior performance of the electric tractor TE-0 compared to the diesel tractor TD 80 D. While the diesel tractor only begins to isolate vibrations after 10 Hz, the electric model enters the isolation zone at 7.5 Hz, indicating a better capacity to attenuate low-frequency vibrations — which are critical for operator health. The average isolation efficiency is significantly higher in the case of the electric tractor, with a value of 79.80%, compared to just 45.56% for the diesel tractor. Across the entire frequency range [0–80 Hz], the electric tractor's seat maintains isolation values above 80%, while the diesel tractor rarely exceeds 50%. Additionally, the higher transmissibility values recorded for the diesel tractor, especially on rough land and at higher speeds, reflect an increased risk of discomfort and fatigue. On all types of land, the electric tractor consistently demonstrates a better ability to manage vibrations, making it a technologically efficient solution for reducing operator exposure and improving working conditions in agricultural operations.

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