Vol. 19(7), pp. 716-726, July, 2023
DOI: 10.5897/AJAR2022.16283
Article Number: FAF00A970977
ISSN: 1991-637X

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African Journal of Agricultural Research

Full Length Research Paper

Evaluation of vibration reduction isolators for hand transmitted vibration of single-axle tractors

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Received 22 November, 2022; Accepted 2 June, 2023

The walk-behind control of single-axle tractors imposes a great workload on the operators which increases muscular fatigue. Experienced operators were involved during field experiments to investigate and establish the magnitudes of hand-transmitted vibration experienced by single-axle tractor operators with and without vibration reduction isolators during tillage operation. The results indicated that the magnitudes of vibration total values were 5.694 m/s^2 at approximately 1500 rpm on stationary mode, 6.972 and 7.985 m/s^2 at 1.5 and 2.7 km/h respectively during tillage operation. The use of rubber with metallic washers as vibration reduction isolators result in a significant reduction in magnitudes of vibration total values to 3.656 m/s^2 in stationary mode, 4.365 and 4.958 m/s^2 at 1.5 and 2.7 km/h respectively during tillage operation. The National standard TZS 1471 (2018) and ISO 5349-2 (2001) warns that, the exposure to higher magnitudes of vibration presumably carries increased health risk towards vibration-induced disorders and other occupational hazards associated with body fatigue. These call for collaborative efforts among design engineers, researchers, and the research and development organizations to further study the human-machine interaction behaviour of single-axle tractors and human engineering data to ensure human safety, satisfaction of the single-axle tractor operators and ensure safe and healthy working environments.

Key words: Single-axle tractor, hand transmitted vibration, vibration reduction isolators.

INTRODUCTION

Agriculture activities in Tanzania are the largest employment sector and are identified as a mainstay of the Tanzanian economy (URT, 2011). The agricultural performance has significant effect on the output and corresponding income and poverty levels of small-scale farmers, and the agricultural productions forms an important factor in assessing social-economic development (URT, 1995). According to NBS (2014) agricultural economic activities contributes 30.1% of the Gross Domestic Products (GDP) and 24% of the total

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merchandise export earnings and provide employment to about 66.7% of the active working populations. Therefore, growth in agricultural activities has an impact on the Nation’s overall socio-economic growth. “Agricultural First” literally means “Kilimo Kwanza” is a strategic agriculture transformation initiative introduced to optimize human and financial resources so as to speed up the modernization of agricultural management and practices. Also, promote the increased use of technology enhanced agricultural practices through farm mechanization (URT, 2009). It is anticipated that, food self-sufficient, security and transformation of agricultural operations can be achieved effectively through mechanization of agricultural operations (URT, 2006).

Single-axle tractors were introduced in large part of Tanzania through “Kilimo Kwanza” initiatives. The government considers the adoption and uses of single-axle tractors as a necessary dimension in realizing economic contribution of small and medium scale agriculture by-sector to GDP (URT, 2006). Single-axle tractors (also known as power tillers) are multipurpose, walk behind hand operated tractors in which the operators walk behind to control forward movement and guide the machine while turning or lifting the rear portion of the machine to manoeuvre at the headlands. Increases in the up-keep cost of draught animals and the scarcity of labourers for timely performance of various agricultural operations increase the demand for single-axle tractors. The single-axle tractor acts as the most representative agricultural machinery that plays a vital role in the process of mechanizing agriculture for small and medium land holding farmers. Sam and Kathirvel (2006) found that the use of single-axle tractors reduces the human-land ratio and increases the output-labour ratio. Salokhe et al. (1995) explained that due to compactness and versatility of single-axle tractors, they became suitable, attractive economically and operational alternative to majority of farmers.

Despite of the observed economic and social benefits that farmer realizes in the use of single-axle tractors; in practice, operators of single-axle tractors experiences psychological or physiological difficulties on the ergonomical interaction between the human hand-arm and the machine system. Verma et al. (2014) were in opinion that the use of improved mechanical technology increases workload on the operators as well as occupational hazards and diseases, which impair the performance of the operators. Kao (2003) observes that vibration induced disorders in a form of muscular fatigue has adverse ill-health effects to soft tissue, nerves, bones and joints, muscle tendons and can affect the nervous system. Nelson (2004) found that the prolonged exposure of hand-transmitted vibration for workers using vibrating hand-held power tools and equipment may cause microscopic damage to the hand-arm systems which starts as a pain and progressively develop into a complex occupational vibration-induced disorder collectively as Hand-Arm Vibration Syndrome’ (HAVS). Operators of single-axle tractor have to endure various environmental stresses (Tewari et al., 2004; Salokhe et al., 2009). Tiwari and Gite (2006) found that all efforts combined with exposure to varying degrees of solar radiation, noise and dusty environment cause a lot of stress on the operator resulting in physiological hazards or psychological fatigue.

Sanders and McCormick (1992) observed that human factors seek to change the way the human-machine system interacts to better match the capabilities, limitations and needs of people. Liljedahl et al. (1989) observed further that mechanical system design requires enhancing certain desirable human values that will ensure improved safety; reduced fatigue, greater user acceptance, increased job satisfaction and improved quality of life for operators. Ying et al. (1998); Jiao et al. (1989) found that investigating the intensities of hand-arm vibration experienced by operators of a single-axle tractor during operation has theoretical importance and practical value; due to the unbalanced inertia forces of the engine and the unevenness of the farm surface. Dong (1996) concluded that the engine was the main source of vibration and that handle vibration was strong and seriously affecting operator’s health.

Few studies of vibration transmission in the hand-arm system have been reported under actual field conditions (Dewangan and Tewari, 2008; Pelmear and Leong, 2001). Chaturvedi et al. (2012) explained that a major apprehension and safety concern of single-axle tractor operator is the adverse effect of exposure to high intensity of hand-arm vibration.

Tewari et al. (2004) observed that investigating the magnitude of hand-transmitted vibration in the actual working field is essential in order to understand any risk to musculoskeletal disorder development and determine reasonable workload in different work conditions.

Notwithstanding research studies and activities done on intervention development to reduce operator’s exposure to hand transmitted vibration, there are very small improvements in the vibration reduction in single-axle tractors design (Busse et al., 2019; Lu et al., 2018; Chaturvedi et al., 2016) since most of the reported studies were pathological or epidemiological studies involving industrial workers in efforts to prevent the occurrence of Hand-Arm Vibration Syndrome (HAVS) and mostly done under controlled laboratory conditions. Therefore, the study findings become difficult to be adapted to a normal agricultural environment (Lu et al., 2018). The current study were conducted in a actual farm field setting, involving experienced operators to investigate hand-transmitted vibration magnitudes from single-axle tractor with and without the use of vibration reduction isolator, compared them and evaluate vibration reduction caused by isolators on hand-transmitted vibration magnitudes experienced by single-axle tractor operators during tillage operations.

Figure 1. Disc plough setting for tillage operation.
Source: Author

MATERIALS AND METHODS

Materials

Description of the study area

The study was conducted at Chekereni Village of Mabogini ward, about 17 km South-East of Moshi Municipal in Kilimanjaro Region.

Single-Axle tractor

Diesel engine Dongfeng DF-18L (18 HP) (Figure 1) single-axle tractor; with an approximate total weight of the engine and tillage implement of about 520 kg was used during tillage operations.

A single-axle tractor with inflated pneumatic tyres was serviced and examined before the operation to ensure that there were no known mechanical defects that would distort or present unfair results. The specifications for the single-axle tractor are shown in Table 1.

Single-Axle tractor operators

The representative operators were healthy male operators with sound physical and mental fitness. Five operators were selected for tillage operation on the basis of their skills, knowledge and experience in the control and operation of single-axle tractors in a varying farm conditions. Operators were informed of the study limitations and experimental requirements so as to enlisting full attention and sensitize them such that they give their will and hearted cooperation.

Equipments and Instrumentations

The set-up of the single-axle tractor during field operation is shown in Figure 2 and include: Dongfeng DF-18L single-axle tractor; MTN/VM 110 accelerometer, mild steel adapter bracket with leather loop, stop watch, Note pad, digital camera and laptop computer.

Methods

Experimental design conditions

The single-axle tractor was set and operated at two lower gears (G_{1L} ≈ 1.5 km/h and G_{2L} ≈ 2.7 km/h) during the field experiment and the engine was running at about 75% of the rated engine speed; approximately 1500 rev/min. The average length of the plots during the experiment was 50 m. The magnitude of vibration was measured in the forward direction during each trial between two marked points at a distance of 40 m, using a hand-held vibration meter. In order to increase uniformity in observation time on each selected forward speed; the duration to run a field experiment was 15 min; in which, the vibration acceleration along x_h-, y_h- and z_h-axes were observed independently for five minute and changed to another axis for the same forward speed. Operators were to control the ploughing width of about 350 mm and ploughing depth of about 120 mm to 140 mm between operations.

Figure 2. Single-Axle tractor set-up during data collection.
Source: Author

The accelerometer (MTN/VM 110) used for data collection were a single axis instrument, selectable low-pass filter accelerometer with a frequency range between 5Hz to 5 kHz, and the measurement of vibration magnitudes were done sequentially by each randomly selected operator for each of the three translational axes. The mild steel adapter bracket was tightened in the operator's right hand using a leather loop, to stabilize positioning and increase the contact area of the accelerometer. A vibration magnitude of the selected axis was measured at the hand gripping the handle as in Figure 3.

Experimental field layout and data collection procedure

The split-split-plot experimental design techniques were used. The tillage operation was considered as the main plot, the forward speeds of operation as the sub-plot and locations of the three translational axes vibration direction as the sub-sub-plot. Pilot observations were taken with the unloaded single-axle tractor standing at a stationary position to approximate the representative directional vibration magnitude in each axis and the vibration total value during stationary position. Five randomized trials were conducted and the vibration acceleration direction to operator's hand was based on the root-sum-of-squares of the root-mean-square (r.m.s) magnitudes on three orthogonal directions in m/s² as shown in Figure 3 defined in Equation 2.1.

$$a_{hv} = \sqrt{(a_{hwx})^2 + \left(a_{hwy}\right)^2 + (a_{hwz})^2}.. \quad (1)$$

The mean value of these trials was taken as the representative vibration acceleration value for each operator in a particular field condition. The representative vibration total values expressed as energy-equivalent in eight hours (A8) were then calculated based on ISO (2001b) recommendations of the Equation 2:

$$a_{hv(eq.8h)} = A(8) = a_{hv}\sqrt{\frac{T}{T_0}} \quad (2)$$

Where a_{hv} is the vibration total value, T is the total daily duration of the exposure in s, and T_0 is the reference duration of 8 h (28800 s). The lifetime exposure (D_y) to hand transmitted vibration is estimated using Equation 3:

$$D_y = 31.8[A(8)]^{-1.06} \quad (3)$$

The statistical analysis, interpretation and presentation of observed data were done independently using MATLB® 2015a Software. Analysis of variance (ANOVA) table was used to compare the variations within a particular vibration direction and between vibration directions.

RESULTS AND DISCUSSION

The study area climatic and topographic conditions

The lowest and highest dry-bulb temperature (DBT) on average varied between 8-10 and 24-28°C, respectively and the relative humidity varied between 66.3 and 83.0%. Soil textural analysis of the dark light brownish organic soils was classified as silt loam soil, with the following percentage distributions: 0.6% gravel, 13.2% sand, 83.9% silt and 2.3% clay. Average soil moisture content on a dry basis was 4.62%, the bulk density of the soil was 1.253 g/cm^3 and the porosity of the soil was 0.54. Tillage

Table 1. Specifications for the Dongfeng DF-18L Single-Axle Tractor.

Engine model and type		DONGFENG DF-18L; ZS1110N: Single-cylinder, horizontal, four-stroke cycle diesel engine
Structural weight	Without tillage implement (kg)	390
	With tillage implement (kg)	495
Compression ratio		17:1
Rated power, kW (hp)/rpm		13. 5 (18)/2000
Travelling speed range in km/h		1.5, 2.7, 4.4, 5.70, 10.2, 16.50 Forward; 1.1, 4.10 Reverse
Ploughing speed/depth		First 3 speeds/150 mm
Specific fuel consumption (SFC) at continuous rated output, g/kW.hr		253.8

Source: Author

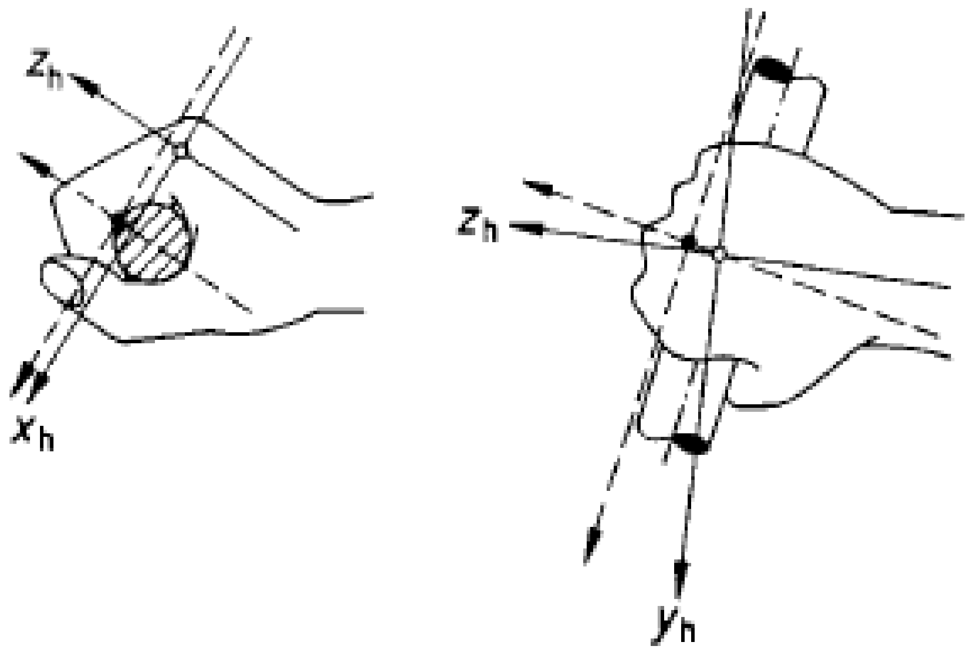

Figure 3. Orientation of the Axes.
Source: ISO 5349-1 (2001a) and ISO 5349-2 (2001b)

operation involves physical or mechanical manipulation of the soil to reduce bulk density or increasing soil porosity for the purpose of increasing soil aeration; destroy weeds and addition of soil fertility.

Hand transmitted vibration

Vibration direction acceleration magnitudes

Stationary mode

Table 2 presents the vibration magnitudes of different vibration directions at 1500 rev/min on the single-axle tractor at the stationary position. The magnitude of acceleration without isolators in the x_h-axis was 4.738 m/s^2 which are higher than 1.707 m/s^2 and 2.747 m/s^2 of the y_h-axis and z_h-axis respectively. Pictorially the reduction of magnitudes of direction acceleration is shown in Figure 4, where the use of isolators reduced magnitudes of direction acceleration in three translational axes to 3.039 m/s^2 in x_h-axis, 1.066 m/s^2 in y_h-axis and 1.696 m/s^2 in z_h-axis.

Incorporating the vibration isolators while the single-axle tractor is kept stationary, it was observed that vibration directional acceleration along x_h-axis were highest contributor to the vibration total value than y_h-axis and z_h-axis and were respectively lower by 64.9 and

Table 2. Vibration direction acceleration on stationary mode.

Type of tractor	Engine speed in rpm	Vibration acceleration (rms) in m/s^2						Vibration total values a_{hv} in m/s^2	
		x_h		y_h		z_h			
		Without	With	Without	With	Without	With	Without	With
DF-18L	1500	4.738	3.039	1.707	1.066	2.658	1.696	5.694	3.640

Source: Author

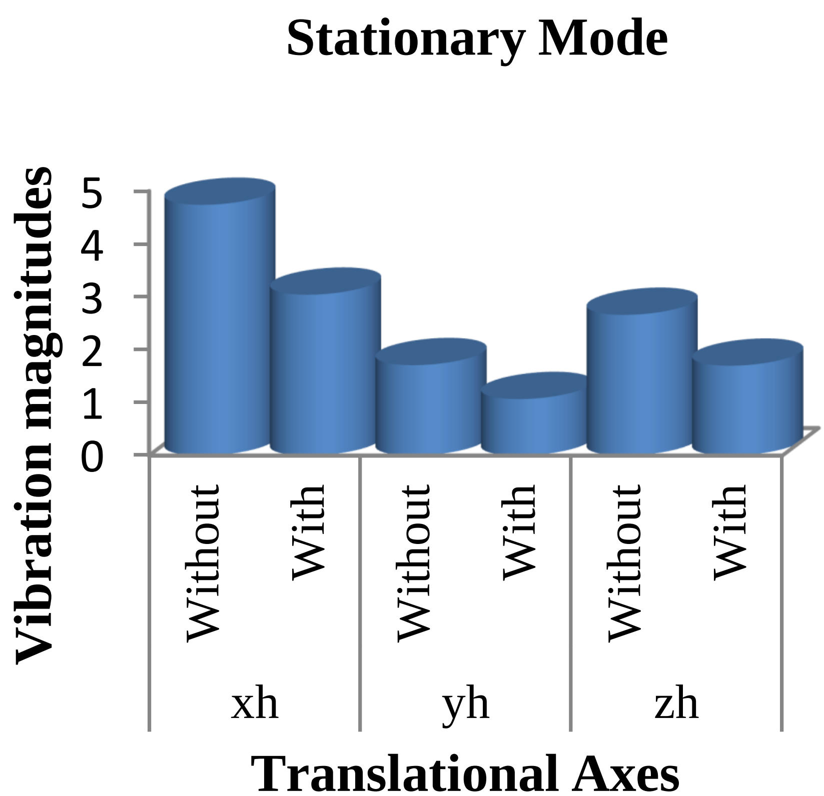

Figure 4. Vibration acceleration magnitude at stationary mode.
Source: Author

44.2% compared to x_h-axis at a selected engine speed. Since vibration of a single-axle tractor at a stationary position is influenced by the moving component of the tractor; therefore, it is evident that the vibration observed was due to the unbalanced forces caused by the reciprocating motion of the piston inside the cylinder of the diesel engine. The reductions in vibration direction vibration were observed at the interface between the engine seat and the chassis using rubber bushes with a metallic washer.

Vibration direction acceleration during tillage

The vibration magnitudes at different vibration directions in varying forward speeds during soil tillage are presented in Table 3. The magnitude of acceleration without isolators in x_h-axis varied from 5.576 to 6.561 m/s^2 which is higher than 2.415 to 2.602 m/s^2 and 3.418 to 3.734 m/s^2 for the y_h-axis and z_h-axis respectively, while the forward speed varied from 1.5 to 2.7 km/h; on average the x_h-axis was 56.7% and 38.7% higher than y_h-axis and z_h-axis respectivelUsing isolators between engine seat and the chassis, the direction vibration acceleration was observed to vary from 3.45 to 4.069 m/s^2 in x_h-axis, 1.502 to 1.613 m/s^2 in y_h-axis and 2.140 to 2.314 m/s^2 in z_h-axis while the forward speed varied from 1.5 to 2.7 km/h. On average x_h-axis was 53.5% and 37.9% higher than y_h-axis and z_h-axis respectively. In Figure 5; the study results show that the root-mean square (rms) vibration acceleration in the x_h direction was higher than in the y_h and z_h directions.

Table 3. Vibration direction acceleration during tillage operation.

Type of tractor	Speed	Vibration acceleration (rms) in m/s^2							
		x_h		y_h		z_h		Vibration total values a_{hv} in m/s^2	
		Without	With	Without	With	Without	With	Without	With
DF-18L	1.5	5.576	3.45	2.415	1.502	3.418	2.140	6.972	4.329
	2.7	6.561	4.069	2.602	1.613	3.734	2.314	7.985	4.951

Source: Author

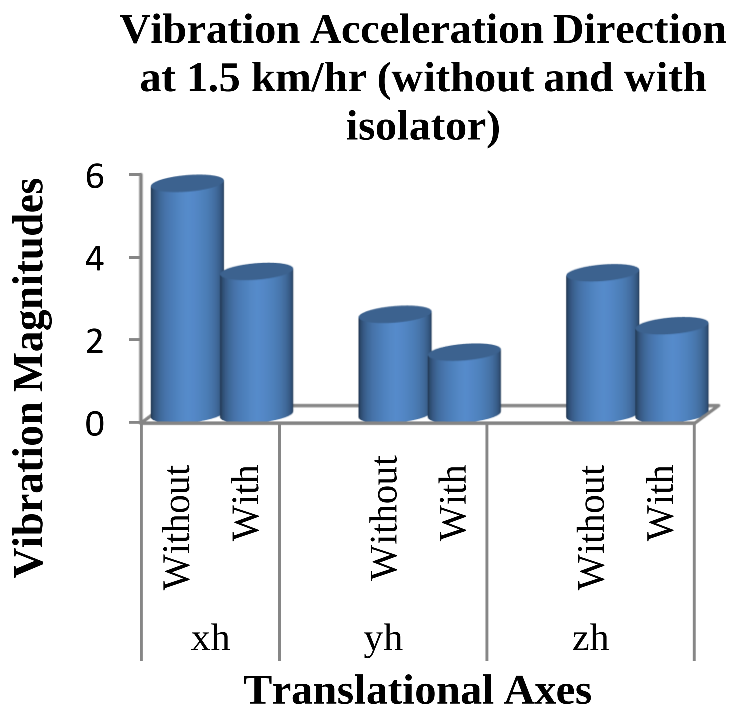

Figure 5. Vibration acceleration direction at 1.5 km/h.
Source: Author

In Figures 5 and 6, the study found that the increase in forward speed were also increases the vibration direction acceleration values and also vibration direction along x_h-axis were found to be the major contributor of the vibration total value experienced by operators. The multiple comparisons between the vibration magnitudes among vibration direction acceleration with and without isolators were done using the Bonferroni test based on student’s t statistics as shown in Table 4. The study further shows that there was a significant variation among the translational axes on the psychological fatigue experienced by operators and at large dominated by the vertical direction (x_h-axis). The vibration direction acceleration of single-axle tractor with or without isolator mechanism was observed to increase as forward speed increases at all speed settings. In both cases, the observed significant reductions in vibration magnitude along y_h and z_h direction or the reduced side movement of a single-axle tractor were caused by the downward force exerted on the tillage tool and the higher draft force resulted from interaction between the soil and the tillage tool.

Vibration total values

Stationary mode

On standing mode the single-axle tractor ran at 1500 rev/min engine speed with no tillage. The results show that the magnitude of vibration total value (a_{hv}) transmitted to the hand was 5.694 m/s^2. Since the single-axle tractor was in stationary mode there is no force interaction between tillage tool and the soil. Therefore, the vibration experienced by operators are primarily due to the engine excitation that is, caused by unbalanced

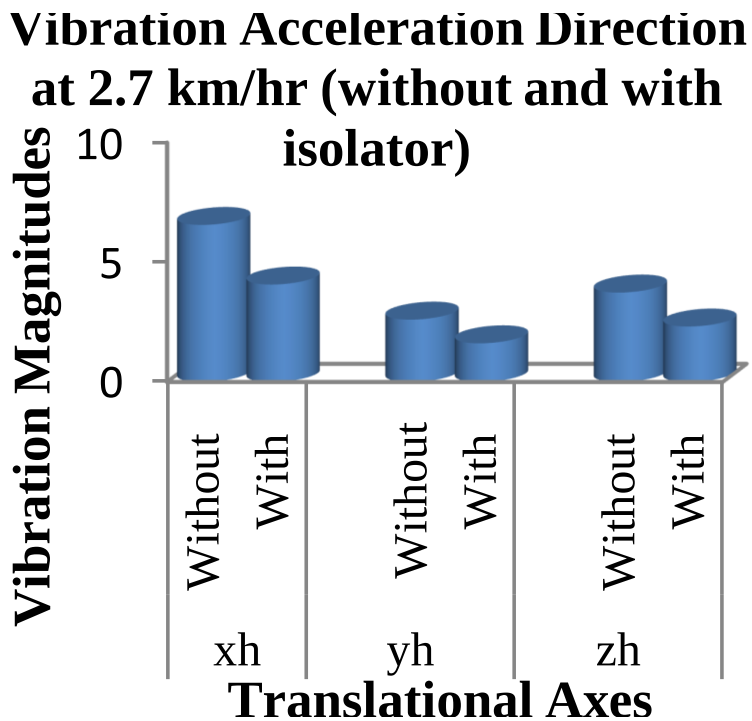

Figure 6. Vibration acceleration direction at 2.7 km/h.
Source: Author

Table 4. Bonferroni multiple comparisons.

Type of tractor	Operation mode	Speed (km/h)	Vibration total value in m/s^2	Bonferroni multiple comparison between vibration directions		
				x_h vs y_h*	x_h vs z_h*	y_h vs z_h*
Dongfeng	Tillage	1.5	4.329	1.948	1.310	- 0.638
		2.7	4.951	2.456	1.755	- 0.701

*The mean difference is significant at the 0.01 level.
Source: Author

inertia forces of moving parts, gas pressure inside the engine of the tractor and the deflections of the cantilever-like handle of the single-axle tractor.

Tillage operation

In Table 3 the magnitude of vibration total values (a_{hv}) transmitted to the hand were 4.329 and 4.951 m/s^2 at two forward speeds 1.5 and 2.7 km/h respectively. In Figure 7, the study further observes that the increase in forward speed increases the vibration total values at each selected speed combination due to the absence of cushioning mechanism to damp-out or absorb the vibration.

The study found that, with the same field layout and exposure time; a significant variation results in the vibration total values transmitted to the hand between operators at any selected forward speed. The variations in vibration acceleration among operators during operation are found to be caused by many factors among which include operator's individual posture, perception and the pairing between human hand-arm system and the vibrating tractor handles. The study further observes that the operator's hand acts as a vibration envelope. Therefore, long exposure to high vibration magnitudes subjects single-axle tractor operators to the susceptibility of physical or psychological fatigue that would cause harmful occupational health effects. The study found that many factors contribute to the high magnitudes of vibration felt at the single-axle tractor operator's hand, and achieving ergonomic satisfaction in single-axle tractor operations is a fairly challenging process as it requires collective efforts to establish acceptable levels of

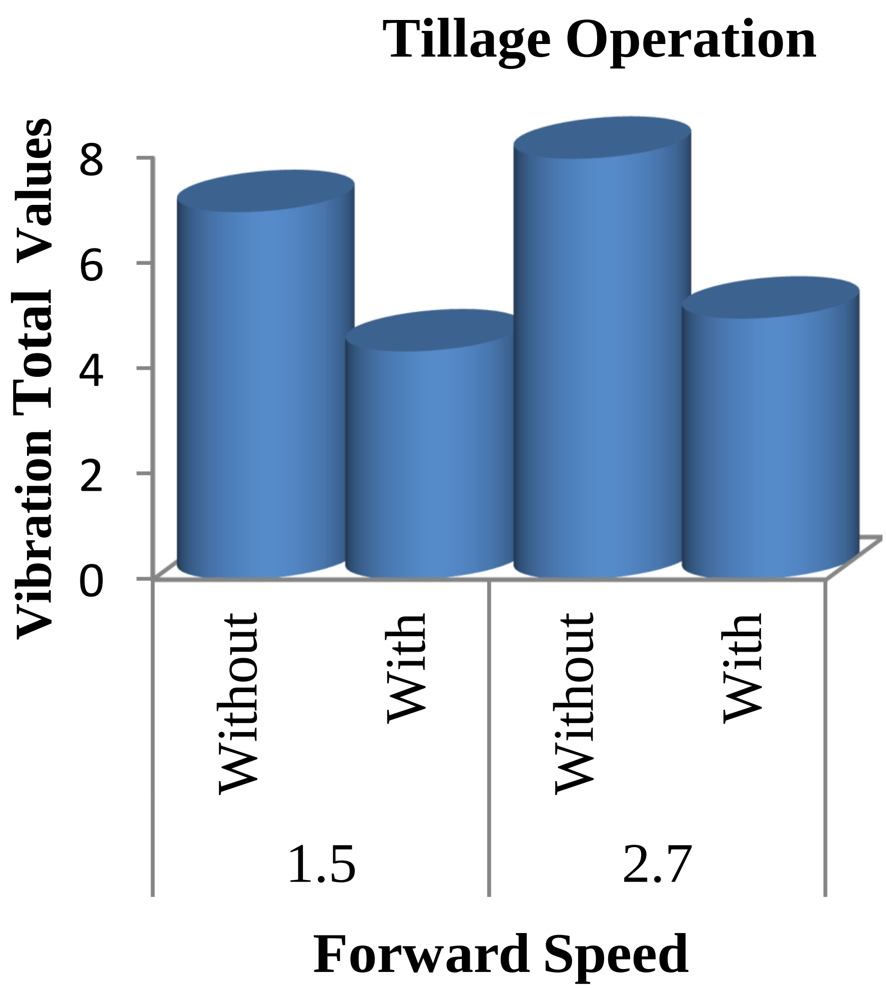

Figure 7. Vibration total value during tillage.
Source: Author

product safety due to various gaps that exist in human engineering data.

Vibration exposure duration

The significant differences in vibration total values among operators depict that there are differences also in operator's susceptibility to the onset of vibration-induced disorders. In practice, during the peak period of farm preparation, the on-field operation of a single-axle tractor exceed the assumed 8-hours operation which is taken as a basis for determining the latency period for operators to show symptoms of vibration induced disorders (Table 5).

Operator's vibration exposure versus existing standards and guidelines

Although there is a significant reduction in vibration direction acceleration in all forward speeds when the interfaces are separated by isolators, the study generally shows that the vibration total value obtained exceeds the recommended Exposure Action Value (EAV) of 2.5 m/s^2 and Exposure Limit Value (ELV) of 5 m/s^2 of exposure to a physical agent (Vibration).

The National and International standards and guidelines have cautiously pointed out that higher exposures to hand transmitted vibration presumably carry increased health risk towards vibration-induced disorders and therefore further development on single axle tractors design is needed to reduce vibration felt by operators on the tractor handles.

Operators exposure to environmental factors

Operators of single-axle tractor endure various environmental stresses such as noise, solar radiation, humidity and direct exposure to hand transmitted vibration

Table 5. Latency period for 10% prevalence of vascular induced disorder.

Type of tractor	Operation mode	Forward speeds (km/h)	Vibration total values (m/s^2)		Latency period in years	
			Without	With	Without	With
DF - 18L	Tillage	1.5	6.972	4.329	4.06	6.73
		2.7	7.985	4.951	3.52	5.84

Source: Author

caused by the variations in farm field conditions. The effect to these factors depends on individual operator's physical fitness, age, gender, clothing, alcohol and metabolic rate.

Conclusion

The uses of isolator mechanisms experience a significant reduction in vibration direction acceleration at all forward speeds. The study generally shows that the vibration total value obtained exceeds the safe margin recommended. The vibration total values (a_{hv}) lie between the suggested Exposure Action Value (EAV) of 2.5 m/s^2, (A(8) > 2.5 m/s^2) and Exposure Limit Value (ELV) of 5 m/s^2, (A(8) > 5 m/s^2). As cautioned above, higher exposures to vibration presumably carry increased health risks towards vibration-induced disorders. These call for collaborative efforts among design engineers, researchers, and the research and development organisations to further study the ergonomics of the human-machine interaction behaviour of single-axle tractors and best match with the human engineering data to ensure human safety and satisfaction of single-axle tractor operators.

CONFLICT OF INTERESTS

The authors declare that the study way purely academic and there was no potential conflicts of interest intended with respect to the research, authorships and/ or publication of this article.

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