ADBA
Engineering for Smart Agriculture
Cutting-Edge Scientific Solutions

e-ISSN:3150-0218
RESEARCH ARTICLE
Vol.1 / No.1 / 2026
pp. 30-35 / Article No.e005
https://doi.org/10.69882/adba.esa.2026071

Effectiveness of Handle Vibration Dampers in Reducing Operator Exposure in Single-Axle Tractors

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ABSTRACT There has been an unprecedented uptake of single-axle tractors due to their low price point and ability to maneuver within the smallholder farming system. Unfortunately, this tractor exposes farmers to high hand-transmitted vibrations that have been found to predispose them to Hand-Arm Vibration Syndrome (HAVS), a serious work-related condition caused by damage to the vascular, neurological, and musculoskeletal systems. This study aimed to examine the efficacy of a rubber handle vibration damper in minimizing the vibration exposure of operators while handling single-axle tractors. Experimental investigations were carried out during operation in a field experiment. The vibration tests were carried out on a 15 hp single axle tractor in second and third gears. Accelerations were measured using RMS values in three orthogonal directions (vertical, forward, and lateral) before and after damper application. A (8) and HAVS latency period were also calculated. The results indicated an effective reduction in vibrations in all directions by 29%-50%. The average reductions were 42% in the second gear and 46% in the third gear for vibrations. Accordingly, significant reductions in the A (8) values were recorded despite some exposures being higher than those required for optimal safety. Significantly, the latent period for HAVS was extended by approximately 89%-90%, suggesting a considerable delay in developing vibration-related conditions. Conclusively, the rubber vibration dampener is very effective in reducing hand-transmitted vibrations and ensuring improved occupational safety. Nonetheless, further measures should be implemented in conjunction with vibration damping.

KEYWORDS
Hand-arm vibration
Vibration damper
A (8)
HAVS
Agricultural ergonomics
Single-axle tractor

INTRODUCTION

Mechanization in agriculture is gaining momentum in developing countries, with the government and other organizations trying to enhance productivity and promote food security while at the same time minimizing reliance on labor-based agriculture (Yadav *et al.* 2025). This has been quite visible in small-scale agriculture, which is common in many developing countries like Ethiopia, where most of the farmers operate less than two hectares of agricultural land (Shitaye *et al.* 2024; Zerssa *et al.* 2021). The use of machines in this context becomes difficult owing to fragmented land and harsh geographical conditions. Thus, walking tractors, also called single-axle tractors or power tillers, have become an ideal choice of intermediate technology machinery (Khan and Rehman 2019). The fact that walking tractors are affordable compared to tractors on four wheels ensures that they are within reach of small farmers, and their size enables efficient performance on smaller and oddly-shaped fields. Moreover, walking tractors are versatile; a single tractor can perform several tasks in agriculture, such as tilling, planting, transport, and even water pumping (Daum *et al.* 2023).

Increased use of such machinery is also influenced by socio-economic factors, such as labor scarcity in rural areas, high labor costs, and the need to intensify cultivation (Tadele 2020; Wu *et al.* 2025). Mechanization with single-axle tractors ensures timely soil tillage and planting, which are essential for increasing productivity in the rain-fed agriculture system. Moreover, usage of such machines reduces the workload among farmers, especially among women, who make a considerable proportion of the agricultural labor force (Nam and Jang-Sub 2024).

Manuscript received: 02 June 2026,
Revised: 05 July 2026,
Accepted: 20 August 2026,
Accepted: 17 September 2026.

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Even though there are many positive features associated with this tractor type, its wide adoption poses some problems, especially in terms of operator safety and ergonomic design (Hota *et al.* 2023). In contrast to large tractors, such vehicles are operated by walking behind and holding handles, which means that hands are under substantial exposure to hand-transmitted vibration. Thus, it is crucial to combine technological improvements in machinery with proper health protection strategies (Oncescu *et al.* 2025).

A significant relationship has been noted between long periods of exposure to vibrations and the occurrence of Hand-Arm Vibration Syndrome, which consists of vascular, neurological, and musculoskeletal problems (Dong *et al.* 2021). The extent of these impacts relies upon vibration intensity, frequency, time exposure, and operator-related variables like grip and posture (Gerhardsson *et al.* 2021). It is documented in scientific research that vibration intensities in farm machines tend to be higher than acceptable exposure limits, especially in walk-behind tractors, wherein operators are in constant contact with vibration-generating handles (Oncescu *et al.* 2025). Though vibration-isolating systems are suggested as engineering controls, there is not enough evidence of their efficacy in the field. While earlier studies conducted by Busse et al. (2021) have examined the dynamics of vibration in single-axle tractors and the effects of operational and soil factors, this study mainly deals with vibration assessment and modeling under controlled or semi-controlled conditions. This leads to a lack of sufficient evidence for the practical efficacy of vibration mitigation practices, especially in real field operations, reflective of small-scale farming operations.

Moreover, while the literature has extensively covered instantaneous vibration indices, relatively little research has been conducted on integrated exposure assessments via standardized measures such as A(8), let alone the implications for occupational health consequences like latency of Hand-Arm Vibration Syndrome (HAVS). The inability to relate the exposure indices directly to the health outcomes makes it difficult to draw direct correlations between the two. To bridge this gap, this paper presents a comprehensive study of a rubber vibration damper installed on the tractor handle, which considers (i) vibration monitoring on multiple axes, (ii) exposure quantification by applying the A(8) measure, and (iii) latency estimate of HAVS in a single experimental setup. Unlike other works, this study demonstrates a causal relationship between an engineering control measure and both exposure and latency mitigation.

MATERIALS AND METHODS

Study Area

Field trials were carried out at the Melkasa Agricultural Research Centre, situated in the semi-arid Rift Valley region of Ethiopia. This location represents smallholder farm environments characterized by sandy-loam soils, rainfall of 700-900mm per year, and temperature ranges of 18-28°C.

Experimental Design

A 15 hp diesel-engine-driven single-axle tractor (two-wheel), a popular choice among small-scale farmers in Ethiopia, was utilized in the experimental work. It was fitted with a moldboard plow to simulate primary tillage operations. The field experiment was carried out in different soil conditions to simulate practical agriculture settings. The amount of soil moisture and soil compaction, which affects the magnitude of vibrations experienced by operators, was assessed before each experiment. The study

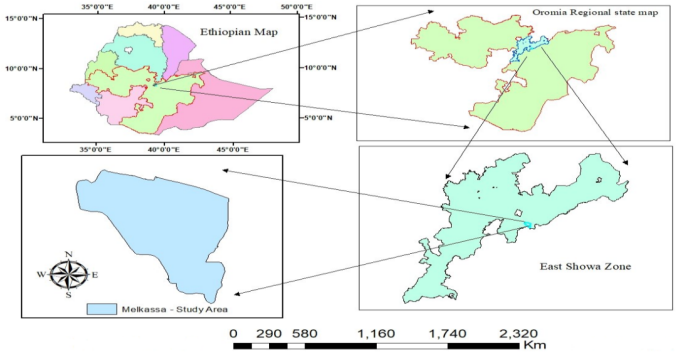


Figure 1 Location of experimental set

used a full factorial experimental design (2 × 2 × 2) to analyze the impacts of three independent factors on vibration:

- gear position (2nd and 3rd gear),
- soil condition (with different moisture contents),
- vibration condition (before and after damping with rubber dampers).

The number of replications of each factor combination was performed several times (specify), depending on the number of subjects and other conditions of the study. Hence, the total number of observations was calculated based on operators and number of replications.

The speed of the tractor varied within 2 to 5 km h^{-1} depending on field practice. The length and duration of all tests performed were kept constant. In order to avoid introducing any kind of variability because of differences among operators, whenever possible, the same operator was used, and also the order in which the various treatments were applied was randomized. The environmental factors, such as temperature, were also noted since the experiments were conducted in actual field conditions.

Study Participants

The number of participants involved in the experiment was seven operators (n = 7). The number of participants in this research has been arrived at by taking into consideration field logistical limitations, equipment limitations, and the rigors of conducting vibration exposure measurements that involve intensive instrumental observations. This is an example of a within-subjects experimental design where the participants act as controls in their own right during the experiment by virtue of being exposed to the same experimental treatment both before and after the test. Selection of participants was done under the criterion of inclusion to maintain uniformity and reliability of findings. All operators:

- were experienced in operating single-axle tractors,
- in good health,
- without any history of musculoskeletal diseases, and
- knowledgeable about field practices.

A limited pool of test subjects was available since a skilled operator had to be able to control the tractor in a test environment.

Smaller sample sizes (usually ranging from 5 to 10 test subjects) are usually typical in hand-arm vibration and occupational biomechanics research due to the difficulty of using measuring equipment and performing repeated tests. Thus, the sample size used in this experiment is appropriate for this type of research.

Vibration Measurement

Handle vibration was measured using a tri-axial accelerometer mounted at the hand–handle interface.



Figure 2 Hand-arm vibration measurements

Data were sampled at 1000 Hz and processed using ISO 5349-1 frequency weighting. The total vibration value, expressed as the frequency-weighted root mean square (RMS) vibration value (a_{hv}) in m/s^2, was then determined using the following equation (Busse *et al.* 2021; Oncescu *et al.* 2025; Sinclair *et al.* 2021):

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

Where a_{hv} = Mean Square Acceleration, m/s^2
a_{hwx} = average measured vibration in x-direction, m/s^2
a_{hwy} = average measured vibration in y-direction, m/s^2
a_{hwz} = average measured vibration in z-direction, m/s^2

To simplify comparisons between daily vibration exposures of varying durations, the daily vibration exposures are expressed as an 8-hour energy-equivalent frequency-weighted vibration total value, a_{hv}(eq, 8h), as given in equation (2). For simplicity, a_{hv}(eq,8h) is abbreviated as A (8) (Kumar and Raja 2022; Sinclair *et al.* 2021):

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

T = the total daily duration of vibration exposure, often known as "trigger time."
T0 = the reference period of 8 hours.

Vibration Exposure Assessment

Vibration exposure daily was determined through the standardized metric of A(8), the equivalent continuous vibration exposure normalized for an 8-hour reference period based on the international standards for hand-transmitted vibrations. It is useful in allowing a comparison between the measured vibration exposure and the exposure limit values for risk evaluation purposes.

The value of A(8) was calculated using the frequency-weighted RMS accelerations in the three mutually perpendicular axes (i.e., vertical, longitudinal, and lateral) from the measurements made. The vibration exposure was then normalized for an 8-hour equivalent exposure period, taking into account the exposure time while operating the tractor.

In order to assess the success of the dampening treatment, observations were made using similar operational parameters before and after installing the vibration dampener. The variables controlled included the tractor speed, soil type, and operator handling. The analysis of the before and after intervention A(8) measurements helped in assessing the degree to which the vibration dampener reduced the level of exposure.

The A (8) calculations were further interpreted through comparison with existing workplace exposure limits, including the Exposure Action Value (EAV) and Exposure Limit Value (ELV). Such an interpretation helped determine the extent of risk reduction achieved by the installation of the dampener as well as the risk that remains.

Damper Design and Installation

A vibration isolator was designed and constructed using a composite natural rubber material. It was chosen due to several properties of natural rubbers that include high damping ability, high resilience, and high dissipation of mechanical energy when subjected to cyclic loading. Natural rubbers are often applied for vibration isolators due to their ability to combine elasticity and internal friction and absorb vibration converting it into heat energy.

The isolator was designed to be applied for the vibration reduction in a single axle tractor steering wheel assembly. The purpose of this device was to create an intermediate compliant contact layer in between the vibrating steering wheel assembly and the operator's hands so as to modify the dynamic stiffness of the entire assembly.

From the structural point of view, the device included a rubber-like damper with enhanced rigidity to preserve the ability to vibrate while remaining stable enough mechanically under normal loads. The shape and thickness of the rubber were chosen considering its durability and adequate damping efficiency.

The installation of the damper implied mounting it between the handle and the zone of grip using mechanical fastening to secure proper interaction without slippage. Particular attention was given to the preservation of handle ergonomic properties, meaning operator comfort was not disrupted by the installation procedure. This step was performed to position the damper directly in the path of vibrations and enable them to be damped efficiently.

Thus, the whole system can be regarded as a passive isolator, which acts on vibrations transmitted from the source (tractor) to the operator through the handle.

Data Analysis

Data analysis on vibration magnitude, physiological response, and grip strength measurements was conducted using both descriptive and inferential statistical analyses. Descriptive statistics, including mean, standard deviation, and percentage difference, were conducted to provide general statistics on the measured variables. On the other hand, paired samples t-test and ANOVA were conducted to establish whether there were significant differences in vibration characteristics, physiological responses, and grip strength measurements before and after installing the vibration dampers, as well as among different operational gears and vibration directions. Significance level was set at $p < 0.05$. Furthermore, vibration exposure time was assessed using the 8-hour energy equivalent frequency weighted acceleration A(8), which is based on international guidelines for assessing vibration exposure. Regression analysis was used to investigate the relationships between vibration exposure and some physiological effects, such as heart rate and the latency period of hand-arm vibration syndrome.

RESULTS AND DISCUSSIONS

Reduction in Vibration Magnitude

Results shown in Table 1 clearly indicate that application of the vibration damper has resulted in a considerable decrease of RMS accelerations at different vibration directions for all gear levels. Decrease of vibrations is not uniform as it is dependent on the direction of vibration and on the gear level, implying that the effectiveness of the damper depends on the properties of the dynamic system. For the second-gear level, there was a decrease of vibrations from 27.0 to 15.7 m/s^2 in vertical vibrations (decrease of 42%), from 21.5 to 13.3 m/s^2 in the forward direction (38% decrease), and from 24.2 to 13.1 m/s^2 in lateral vibrations (46% decrease). Thus, the damper is especially efficient at attenuating lateral and vertical vibrations, which can be associated with the dynamics of structural oscillations.

In the case of third-gear level, the reduction of vibrations is more pronounced; namely, vibrations are reduced by 46% in the vertical direction, by 50% in the lateral direction, and only by 29% in the forward direction. It can be assumed that longitudinal vibrations (due to the torque of the engine) cannot be effectively damped by the considered damper.

Table 1 Frequency-Weighted Handle Vibration Before and After Damper Installation

Gear	Direction	Before (m/s^2)	After (m/s^2)	Reduction (%)
2nd	Vertical	27.0	15.7	42
2nd	Forward	21.5	13.3	38
2nd	Lateral	24.2	13.1	46
3rd	Vertical	30.5	16.5	46
3rd	Forward	25.1	17.8	29
3rd	Lateral	28.0	14.0	50

Another important finding was the higher vibration dampening obtained when using the damper in third gear, especially for the lateral and vertical modes. It implies that the damper works more effectively with larger excitation amplitudes, because the energy level becomes higher and can be absorbed better by the rubber. The phenomenon reflects the basic damping principles according to which the absorber works most efficiently when the excitation amplitude becomes larger.

The significance of the findings from the ergonomic and occupational medicine standpoint is obvious. Since the vibration exposure is accumulated and depends on the direction of transmission, the reduction in vibration amplitudes can help reduce the risk of diseases caused by hand-transmitted vibrations, for example, Hand-Arm Vibration Syndrome.

On balance, the results prove that the vibration damper offers reliable vibration dampening (29-50%) depending on the axis and driving conditions. Nevertheless, the presence of fairly large post-damper vibration amplitudes means that further control measures are necessary to comply fully with occupational exposure standards.

Daily Vibration Exposure (A (8))

The effect of the vibration damper on the vibration total value (a_{hv}) and the normalized daily exposure A (8) in second and third gears is shown in Table 2. It can be seen clearly that there is a considerable lowering of vibration after the installation of the vibration damper.

Table 2 Vibration Total Value and Daily Exposure (A(8))

Gear	Condition	a_{hv} (m/s^2)	A(8) (m/s^2)	Reduction (%)
2nd	Before	27.0	19.1	—
2nd	After	15.7	11.2	42
3rd	Before	30.5	21.6	—
3rd	After	16.5	11.7	46

Under the condition of second gear operation, the vibration total value was lowered from 27.0 m/s^2 to 15.7 m/s^2, resulting in 42% reduction in vibration. In addition, A (8) was also significantly reduced from 19.1 m/s^2 to 11.2 m/s^2. On the other hand, during third gear operation, the vibration total value was considerably lowered from 30.5 m/s^2 to 16.5 m/s^2, which resulted in a 46% reduction in vibration; while A (8) was lowered from 21.6 m/s^2 to 11.7 m/s^2.

The small difference in reduction in third gear may be attributed to the fact that the damper works better in high excitation conditions, which means it dissipates more energy when there are large vibration amplitudes. The proportionate reduction in A(8) confirms the obvious correlation between the magnitude of instantaneous vibration and the accumulated exposure throughout the day.

In terms of occupational safety, the aforementioned reductions show that the vibration damper significantly improves the level of safety for the operators exposed to vibrations. Low A(8) values are less likely to cause vibration disorders, especially Hand-Arm Vibration Syndrome. That said, even though the damper was quite efficient in reducing the risk of harm to the workers, their remaining A(8) levels are considerably above the recommended safe exposure limit.

In conclusion, the presented analysis demonstrates that the vibration damper effectively reduces the amplitude of vibrations and exposure duration. At the same time, the fact that exposure remains quite high after the installation of the damper proves that other measures must also be taken in order to protect the operators.

Frequency-Domain Analysis

Frequency domain analysis offers further information about the dynamics of the system through the decomposition of the signal data into individual frequency components. While time domain results provide an understanding of the total vibration level, frequency domain analysis offers insights regarding how vibration energies are dispersed within various frequency intervals and how the effect of the damper affects certain dynamic behaviors of the system.

The findings demonstrate that there is a definite drop in the vibration amplitude levels close to resonance frequencies upon application of the rubber damper. This finding holds significance, especially since resonance zones constitute those regions in which

the hand-arm system and the tractor handle exhibit dynamic interactions and consequently amplify vibrations. In the case of no damper treatment, the resonance peaks play a significant role in vibration amplification and subsequent transfer of vibrations to the operator.

Furthermore, there were notable attenuations in the high-frequency vibration bands in the entire frequency spectrum range. High-frequency vibration bands usually carry a considerable percentage of the vibration energy transmitted from the vibration source (engine) and soil-tool interaction to the handle. Attenuation of these frequency levels shows that the rubber composite dampers are able to absorb vibrational energy within the internal structure through hysteresis and material damping effects, resulting in thermal energy dissipation.

Generally, the variations in the frequency responses show that there has been an improvement in the vibration isolation and transmissibility aspects of the system. The lowering of the spectral peaks and the attenuation of the energy levels at critical frequency bands indicate that, besides reducing vibration intensities, the dampers affect the vibration dynamic characteristics of the system to minimize the adverse frequencies.

Latency Period of HAVS

The latency period of Hand-Arm Vibration Syndrome development during operation before and after vibration damper application is presented in Table 3. The findings indicate a significant rise in the latency period in relation to the decline in vibration intensity.

When operating in second gear mode, vibration intensity was reduced from 27.0 m/s^2 to 16.0 m/s^2 after installing a vibration damper. This drop led to an increase in the latency period by 89%, from 2.55 years to 4.76 years. In addition, when operating in third gear mode, vibration intensity fell from 30.5 m/s^2 to 15.5 m/s^2, thus increasing the latency period by 90%, from 2.30 years to 4.40 years. It can be seen that there is a definite trend where a reduction in vibration intensity by about 40-50% results in almost double latency period.

This can be explained by the exposure-response relation that exists for the health effects resulting from vibration exposure. The lesser the vibration level, the lesser is the damage done physiologically to the tissues within the hand-arm system due to cumulative damage to the vasculature and nerves. Therefore, the duration within which symptoms can be detected is increased. These results imply that any reduction in vibration exposure levels can greatly benefit the delay of Hand-Arm Vibration Syndrome.

In terms of occupational health issues, there are consequences arising from this increase in latency periods. It means that the symptoms will take longer to show up among workers who expose themselves to vibrations continuously, thus making the time they can work in this manner longer without suffering from vibration-related illnesses such as white fingers, numbness, and weakened grip force. Even though this helps, it also indicates the significant risk of exposure to vibration after the four-to-five-year mark.

Generally, the findings prove the efficiency of the vibration damper as far as promoting operator safety is concerned by ensuring that Hand Arm Vibration Syndrome does not occur until after several years of employment. The presence of risk in this context makes it important to employ additional approaches, such as reducing the exposure period.

Based on the data provided in Table 4, it can be concluded that there exist high statistical significance and structural consistency in the decrease in vibration levels when the dampers are applied to the equipment handles. The F-test statistic for the overall vibration equals 112.4 (with degrees of freedom equal to (1,6)), which indicates an extremely high significance level ($p < 0.0001$).

Table 4 Statistical Summary of Vibration Reduction

Variable	Test	Statistic	p-value	Interpretation
Vibration (overall)	ANOVA	F (1,6) = 112.4	<0.0001	Highly significant
Axis effect	ANOVA	F (2,12) = 36.7	<0.001	Significant

The results of the analysis show that the differences found are caused by the presence or absence of vibration damping, which is a powerful factor that determines vibration levels measured during equipment operation in the field environment. At the same time, the axis effect is found to be statistically significant as well (F-test statistic equal to 36.7, with degrees of freedom equal to (2,12); $p < 0.001$). The results suggest that vibration transmission depends on the direction of excitation. Therefore, the hand-arm system reacts differently to vibration in different directions, with some axes being particularly prone to vibration transmission.

CONCLUSION

In this experiment, the efficiency of a vibration dampener using rubber material to decrease the level of hand vibration in the operation of single-axle tractors was assessed under field conditions. The findings show that the designed vibration-damping mechanism effectively reduces vibration levels for all tested axes. Vibration levels were reduced by 29% to 50%, according to gear and direction of operation. In the second gear, vibration levels were reduced by 42%, while in the third gear, vibration levels were reduced by 46%.

The decrease in exposure to vibration also resulted in considerable improvement of health parameters among workers over time. The average latency period of Hand-Arm Vibration Syndrome became 89–90% larger than previously, suggesting that there was a noticeable increase in the time needed to develop vibration-related conditions due to vibration magnitude reduction. This finding demonstrates the connection between lowering vibration magnitude and improving the operator's biological response time to vibrations. Nevertheless, the obtained level of post-intervention vibrations still exceeded internationally acceptable recommendations in certain cases. It should be stated that, although the damper used as an engineering control is an effective means of reducing risks, its usage is insufficient in itself since occupational hazards cannot be fully avoided using this type of control alone. This suggests that additional actions are needed in order to completely secure farmers' safety. In general, the research proved that simple vibration-damping mechanisms may be efficiently used as a part of safety measures for small farms. Nevertheless, to ensure maximum occupational safety, it is necessary to combine engineering controls, exposure duration reduction, and ergonomic changes in machine-human interactions.

Ethical Approval The research used human participants (the tractor drivers) and followed the required ethics for carrying out research using human subjects. The study obtained ethical clearance from the Research Ethics Committee of Adama Science and Technology University.

Consent to Participate Participants were fully briefed on the objectives, methods, and possible dangers associated with the study. Informed written consent was sought from all participants before their participation in the research. All participants could exit the experiment at any point without facing any repercussions.

Experimental procedures were carefully planned to prevent any risk and ensure the safety of the participants during field work. Personal protective equipment was utilized by operators, and measurements were performed in a safe working environment.

Consent for Publication Informed consent was obtained from all participants regarding the usage of anonymous data for publishing their results. There is no personal identifying information in this paper.

Acknowledgments

The author acknowledges the support of the **Melkasa Agricultural Research Center** for providing experimental facilities and field support.

Ethical Standards

All procedures done on the subjects of this study were done according to the guidelines set forth by the institution's research committee and the Declaration of Helsinki.

Funding

This research received no external funding.

Data Availability Statement

Datasets produced/analyzed for the current study are available on request from the corresponding author. Sharing the datasets is subject to certain ethical considerations relating to participant privacy.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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How to cite this article: Busse, S. K. Effectiveness of Handle Vibration Dampers in Reducing Operator Exposure in Single-Axle Tractors. *Engineering for Smart Agriculture*, 1(1), 30-35, 2026.

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