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EDITED BY

Giuseppe Petrone,
University of Naples Federico II, Italy

REVIEWED BY

Lorenzo Maccioni,
Free University of Bozen-Bolzano, Italy
Giovanni Carabin,
Free University of Bozen-Bolzano, Italy

*CORRESPONDENCE

Rajeev Kumar,
✉ rajeeviitkqp11@gmail.com

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Assessment of whole-body vibration and development of mitigation intervention for single-axle tractor-trailer combination

Rachamalla Naveen¹, Adarsh Kumar¹, Rajeev Kumar^{1*}, H. L. Kushwaha¹, Manoj Khanna¹, V. Ramasubramanian² and Sajja Poojith¹

¹Indian Agricultural Research Institute, Pusa, India, ²National Academy of Agricultural Research Management, Hyderabad, India

Introduction: Tractorization is synonymous with farm mechanization in India. Tractor-trailers are extensively used for the transportation of farm inputs and produce on and off-road, exposing drivers to excessive vibration.

Objectives: The study was undertaken to assess tractor drivers' vibration exposure while using trailers and to develop low-cost mitigation interventions.

Methodology: The whole-body vibrations were measured at the tractor seat during the transportation with a no, half (3715 kg soil) and full payload (5910 kg soil) trailer on two terrain conditions, namely, asphalt and farm terrains. The speeds recommended by ISO 5008-1979 of 10, 12 and 14 km/h on asphalt roads and 4, 5 and 7 km/h on farm roads, as well as actual working speeds preferred by the operator (18, 20 and 22 km/h on asphalt road and 8, 10 and 12 km/h on farm terrain), were selected for experiments. Two vibration reduction interventions, namely spring suspended single point hitch (I1) and polyurethane (PU) bush (I2), were developed and installed between the tractor and trailer. Whole-body vibration (WBV) was measured by repeating the experiments.

Results: The maximum vibration reduction on asphalt road at 22 km/h with I₁ was found as 14.3, 19.03 and 23.1%, whereas on-farm terrain at 12 km/h was found as 15.16, 22.43, and 25.56% for no, half and full payload. Similarly, with I₁ + I₂ interventions, the maximum total vibration reduction at 22 km/h was 16.86, 21.12 and 25.51% on asphalt roads, whereas on-farm terrain at 12 km/h was 17.07, 23.77 and 28.67%. The average value of lower health guidance caution zone (HGCZ) limits on asphalt roads increased by 1.11, 0.95 and 0.92 h and on-farm terrain 1.55, 1.14 and 0.83 h with no, half, and full payload. The average value of upper HGCZ limits on asphalt roads increased by 3.13, 3.21 and 3.68 h and on-farm terrain by 2.24, 2.94 and 3.31 h with intervention.

Conclusions: This infers that with developed interventions an operator can safely perform for a longer duration and at higher operational speeds because of the reduced vibration.

KEYWORDS

farm tractor-trailer, whole-body vibration, vibration reduction intervention, lower and upper health guidance caution zone limits, spring-suspended vibration absorber, polyurethane bush

1 Introduction

Tractors are the main prime mover on farms, and farm mechanization is a synonym for tractorization in India. The tractors are used for “on-the-farm and off-the-farm” operations. A tractor-trailer is a popular and cost-effective mode of transportation for commodities, agricultural produce, soils, etc., in rural India (Agro-Economic Policy Briefs, 2020). The total number of registered trailers in India is 2.27 million, and the tractors are approximately 9.42 million (Road Transport Yearbook, 2019-20). Singh (2001) also reported that the tractor-trailer is mostly used for transport activities and accounted for approximately 60% (600 h) of the average annual use. Almost every day of the year, during sowing and harvesting, tractors are operated for 12–14 h/day (Sorainen et al., 1998).

Operators of agricultural machinery are subjected to various hazards at work, including vibrations, which have a particularly damaging impact on human health (Kumar et al., 2001; Cvetanovic and Zlatkovic, 2013; Cutini et al., 2017; Benos et al., 2020; Chaturvedi et al., 2012). Tractor operators experience more vibration than other types of on-road vehicles (Mehta et al., 2000; Nupur et al., 2013). Tractor operators are generally subjected to whole-body vibrations (WBVs), transmitted through the driver seat and backrest, and segmental vibrations from the footrest and steering wheel (Singh et al., 2023) for a long duration. The magnitude of vibration is dependent on the type of terrain, travel speeds, amount of payload on the trailer, suspension systems, load distribution, and free play at the hitch point. These exposures have been reported beyond the recommended exposure action value (0.5 m/s^2) as per ISO 2631-1997 (Nupur et al., 2013; Kumar et al., 2001). Exposure to WBVs is one of the factors that most influence the performance, comfort, and long-term health risks of tractor operators' problems like back pain, spine degeneration, and spine disc disease on the 4–6-Hz resonance (Pope and Hansson, 1992; Pope et al., 1999; Hulshof and Veldhuijzen van Zanten, 1987; Bovenzi and Hulshof, 1999; Kumar et al., 2001; Khurmi and Gupta, 2005). Several epidemiological studies have demonstrated that mechanical vibrations cause musculoskeletal disorders (MSDs) in the driver workplace and that there is a relationship between WBV exposure and MSDs, especially for low back pain (LBP), associated with increased risk of injury (Bovenzi and Beta, 1994; Kumar et al., 1999). On the other hand, the level of WBV is affected by the type of operation and implementation coupled to the tractor, the speed of operation, and the terrain characteristics. Deo et al. (2021) conducted a study to measure the magnitude of WBV transmitted to the tractor's operator, where a fully loaded double-axle trailer was attached to the tractor. The magnitude of WBVs on the driver seat in the longitudinal direction on asphalt terrain varied from 0.257 to 0.376 m/s^2 and on farm terrain varied from 0.273 to 0.438 m/s^2 under the selected conditions, whereas the vertical direction vibration on asphalt varied from 0.373 to 0.552 m/s^2 and on farm terrain varied from 0.389 to 0.590 m/s^2 under the selected conditions.

Several researchers have pointed out that transportation with single-axle tractor-trailers involves significantly high vibration levels and risk to the driver's safety (Crolla and Dale, 1980; Scarlet et al., 2007; Deo et al., 2021). The free play at the existing ring and hook-type hitch attachment between the tractor and trailer



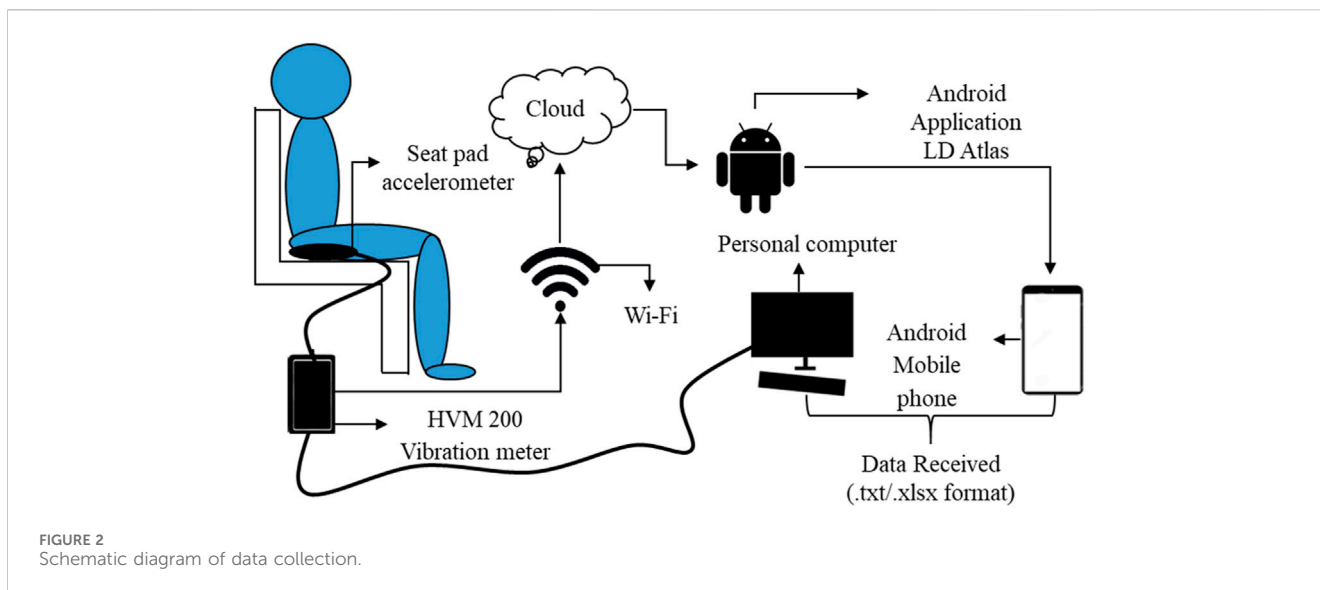
FIGURE 1
Fully loaded trailer on the weighing balance.

TABLE 1 Specifications of the vibration meter and seat pad accelerometer.

Particulars	Specifications
HVM200 vibration meter	
Input connector	¼ – 28 four-pin male
Excitation current	2 mA
Bandwidth	0.4–3,000 Hz
Measurement modes	Hand–arm, whole-body vibration
Whole body	RMS (x-, y-, and z-directions and total sum)
Frequency weightings	
Whole body	W_b , W_c , W_{di} , W_{cs} , W_f , W_j , W_k , and W_m
Measurement units	m/s^2
Seat pad accelerometer	
Voltage sensitivity	10.2 mV/(m/s^2)
Measurement range	$\pm 98 \text{ m/s}^2$ pk
Resonant frequency	$\geq 27 \text{ kHz}$
Temperature range (operating)	-23°C to $+50^\circ\text{C}$
Excitation voltage	6.5–30 VDC
Sensing element	Ceramic
Sensing geometry	Shear
Size (diameter × width)	200 mm × 12 mm
Weight	272 g

system is a key factor in contributing to the overall vibration of the tractor drivers (Crolla and Dale, 1980).

The vibration isolator is a preventive measure for vibration exposure, by which the mechanical energy is converted into heat energy and dissipated in a vibratory system. The vibration has to be attenuated before reaching the seat. The vibration exposure to drivers in tractors was reduced using seats provided with passive (Sankar and Afonso, 1993; Mehta and Tewari, 2010) or active suspensions (Stikeleather and Suggs, 1970) and by insulated cabs



(Hilton and Moran, 1975). A vibration isolator at the single-point hitch can reduce the vibration exerted by the existing ring and hook-hitching system. Significant vibration reduction in the tractor-trailer combination protects the driver. Considering the safety aspect of the operator, two interventions were developed in the present study and attached between the tractor and single-axle trailer. The WBVs were measured at the operator seats at “no, half, and full payload” at six levels of speeds as per ISO 5008 and normal working speeds of tractor-trailer combinations without and with interventions on two terrains. The reduction in WBVs, total vibration values, and lower and upper HGCZ limits and improvements in the working hours were computed from the measured WBV.

2 Materials and methods

The measurement of the WBV transmitted to the tractor driver during haulage operations under different operating conditions and the design and development of interventions for vibration reduction and evaluation were conducted at the Division of Agricultural Engineering, ICAR-Indian Agricultural Research Institute, New Delhi, India.

2.1 Selection of the tractor and trailer

A New Holland 3630 TX Plus 2WD Tractor was used for the experiments. The tractor’s fuel tank was completely filled, and it was operated without blasting by a 68-kg, 172-cm-tall driver with and without interventions. A 5-ton payload capacity trailer with 10 × 6 × 2-ft platform, 13-leaf suspension, 9–20-inch tires, and a ring-type hitch/tow eye of a single-axle/semi-trailer was used for the measurement of WBVs. The selected trailer used for the experiment during the weight measurement on the electronics weighing balance is shown in Figure 1.

A piezoelectric seat pad accelerometer (model: P364241) and an HVM200 Vibration Meter were used for the measurement of whole-body vibrations experienced by the tractor driver. The detailed specifications of the vibration meter and accelerometer are given in Table 1.

The recorded data in a vibration meter were monitored remotely using Wi-Fi and Bluetooth protocol in an Android mobile and analyzed using G4 Utility software installed in a personal computer (PC). The seat pad accelerometer was positioned on the seat pad and connected to the vibration meter through a four-pin, three-channel sensor connector. Before the measurement, the vibration meter was configured with the installed LD Atlas Android application on mobile, and then a 1/3 octave bandwidth was selected with sensor sensitivity values in the app. The multiplying factor (k) of frequency weighting $W_d = 1.4$ for the x - and y -directions and $W_k = 1$ for the z -axis were also applied to the app. The data were collected for a time duration of 2 min. The acceleration values were recorded according to the ISO 2631-1:1997 standard. A schematic diagram of the complete data collection approach is shown in Figure 2.

2.2 Development of interventions for reducing the vibration transmitted to the tractor driver

While measuring vibrations, it became apparent that suitable remedial measures were needed to reduce vibrations within standardized limits. The free play at the hitch point in the tractor-trailer combination was observed to be one of the induced sources of vibration affecting the tractor driver. The method to reduce vibration exposure to the driver was considered by keeping the vibration isolator at the hitch point in this study. The vibration isolator consists of two interventions, namely, parallel spring-suspended single-point hitch (I_1) and polyurethane (PU) bush (I_2). The existing hitching unit of the tractor was replaced with developed intervention I_1 , which dampens the longitudinal linear forces acting between the tractor and trailer. The design of a retrofit-type single-point hitch with spring suspension, considering the existing rear arrangement of the tractor, ensures compatibility with the developed hitch. The development of interventions involved measuring the force at the hitch point, selecting appropriate materials, and designing interventions.

TABLE 2 Properties of the spring and polyurethane.

Spring		Polyurethane bush	
Property	Value	Property	Value
Material	Chrome vanadium	Density	1,125 kg/m ³
Ultimate strength	1,217 MPa	Tensile strength	18 MPa
Yield strength	621 MPa	Compressive strength	90–250 MPa
Shear endurance limit	243 MPa	Flexural strength	30 MPa
Density	7,850 kg/m ³	Shrinkage	0.004%–0.008%
Shear modulus of elasticity	80 GPa	Hardness	68–88 A
IIT Kharagpur (2014)		Natarajan et al. (2014)	

2.2.1 Measurement of force

Tensile and compressive forces were measured at the existing hitch point during the haulage operation for the development of the interventions. During the starting and stopping of the tractor–trailer, the tensile and compressive forces acting at the hitch point were measured. Therefore, a three-point hitch dynamometer (Kumar et al., 2020) was used to determine both the forces acting at the hitch point. The forces acting on the hitch point were measured at the maximum speed considered in the study (22 km/h) with a fully loaded tractor–trailer on asphalt terrain. The maximum compressive force acting at the hitch point was 2,746 N at 22 km/h in the longitudinal direction.

2.2.2 Selection of materials

Spring and PU materials were selected for developing vibration reduction interventions. Spring is used for creating shock isolators (Ahmed et al., 2020). Repetitive impact loading occurs between the tractor and trailer. Chrome vanadium is used for shock and impact loads. Therefore, a chrome vanadium spring is selected for the intervention. Polyurethane is a unique elastic material chosen for its versatile hardness range. This material can replace rubber, plastic, and metal due to its exceptional abrasion resistance and physical properties. It has a higher load-bearing capacity than conventional rubber, making it suitable for various applications. Polyurethane exhibits remarkable resistance to oxygen, sunlight, and weather conditions. Therefore, spring and polyurethane were selected for vibration reduction intervention (Chaturvedi et al., 2012). The properties of the selected spring and polyurethane are listed in Table 2.

2.2.3 Spring design

In the tractor–trailer combination, while the tractor is in the moving condition, the longitudinal compressive forces were observed to act at the hitch point. Therefore, a compressive spring with two ground ends was selected to absorb the forces acting at the hitch point. The measured compressive force varied from 294.3 to 2746.8 N. It was assumed that the force acting on both parallel springs was equally distributed to each spring because each spring was placed at an equal distance from the center (Figure 3A). The design of the spring was based on the study at IIT Kharagpur (2014). Different spring indexes and wire diameters were used for designing the spring. The optimum spring index (7) and spring wire diameter (12 mm) were selected. As per the space constraint, the deflection of the spring was considered 50 mm. The coil mean diameter, mean load, stress amplitude, shear stress

concentration factor, Wahl correction factor, mean shear stress, stress amplitude, ultimate strength, shear yield point, and shear endurance limit were calculated. The required calculated values were applied to the Soderberg equation, and the factor of safety was calculated as 1.298, which was greater than 1.2 (the desired factor of safety). Spring stiffness, number of turns, and spring length were also calculated. For optimizing the intervention design, a simple mass–spring system was simulated on MATLAB. It was observed that the frequency of the induced vibration was greater than the resonance point of the mass–spring system.

Therefore, a spring with a length of 310 mm, a wire diameter of 12 mm, a coil diameter of 84 mm, and a spring stiffness of 24,525 N/m was selected for intervention I₁. These springs were inserted into 60-mm-diameter, 400-mm-long shafts. The intervention (I₁) comprises two shafts, two compression springs, two mounting end plates for connecting to the tractor, and a mounting plate for connecting to the tow eye of a trailer. The dimensions and CAD drawings of these components are shown in Figure 3A. The entire arrangement of the spring-suspended single-point hitch unit was designed to slide freely on the center shafts, which absorb the longitudinal load from the trailer. The design considerations and obtained values for the selected spring are given in Table 3.

2.2.4 PU bush

The dimensions of the tow eye hook in the trailer were considered for the design of the PU bush for intervention (I₂). The reason for incorporating the PU bush along with intervention (I₁) in the existing hitch system of the trailer is to reduce movement because of the free space between the locking pin and tow eye. The metal contact results in impact transmission due to the undulation of roads, changes in speed, and inertial forces of the trailer. The polyurethane bush with a collar, placed into a tow eye of the trailer, provided isolation during the metal-to-metal contact. The CAD drawings of the developed PU bush and the dimensions for the tractor–trailer tow eye hook are shown in Figure 3B. The developed interventions I₁ and I₂ attached together to the tractor are shown in Figure 3C.

2.3 Experimental plan

The WBV was measured at the tractor seat during the transportation with an empty (no load), half-load (3,715 kg soil),

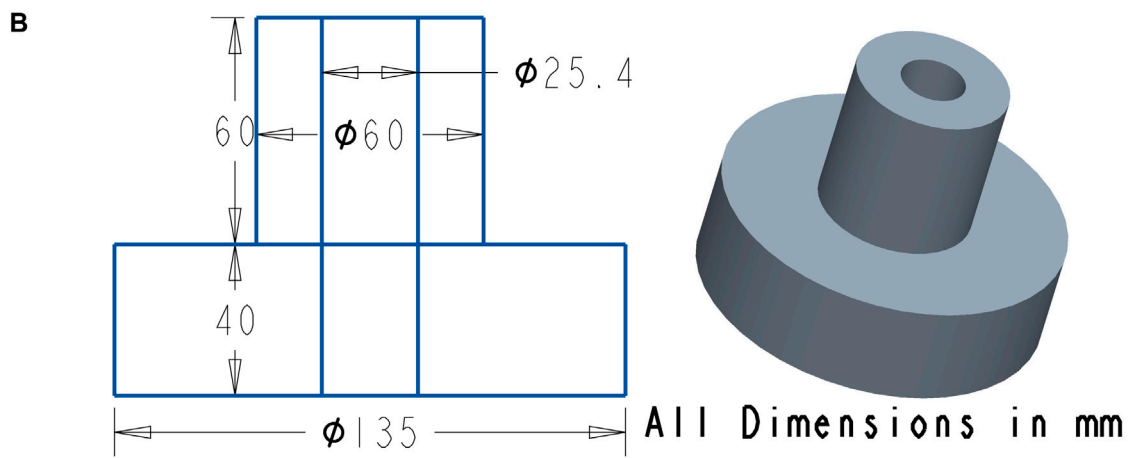
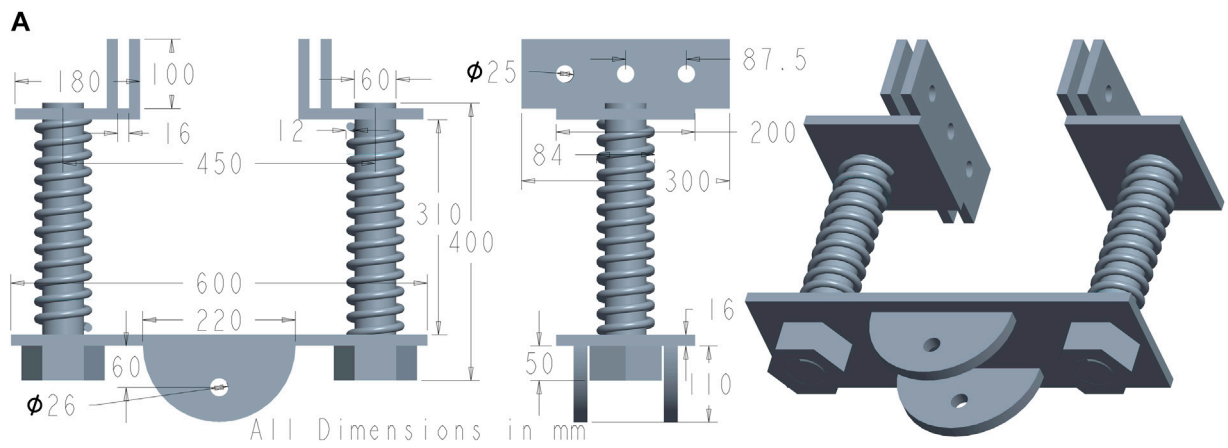


FIGURE 3 (A) CAD drawing of the spring-suspended tractor-trailer hitch (I₁); (B) PU bush (I₂); and (C) installed interventions I₁ + I₂.

TABLE 3 Design considerations and obtained values for the selected spring.

Parameter	Value
Force acting on the hitch point varied, N	294.3–2,746.8
Force acting on each spring, N	141.15–1,373.4
Deflection of the spring, mm	50
Spring index	7
Wire diameter, mm	12
Mean coil diameter, mm	84
Length of the spring, mm	310
Spring stiffness, N/m	24,525
Mass of the trailer and payload, kg	5,910
Active number of coils	14

and full-load (5,910 kg soil) trailer under two terrain conditions, namely, asphalt and farm terrains, respectively. The speeds recommended by ISO 5008-1979 of 10, 12, and 14 km/h on asphalt roads and 4, 5, and 7 km/h on farm roads, as well as actual working speeds preferred by the operator (18, 20, and 22 km/h on asphalt road and 8, 10, and 12 km/h on farm terrain), were selected for experiments. The speeds of the tractor were monitored and maintained using the rpm of the tractor and selected gear. The experiment was conducted in three replications for each treatment under all conditions. The conducted experiments are summarized in Table 4.

2.4 Determination of the lower and upper health guidance caution zone limits

IS 13276 (Part 1):2000/ISO 2631-1 (1997) was used for the evaluation of exposure risk. Health risk prediction primarily depends upon vibration magnitude and duration of exposure in a day. The HGCZ limit is the area between two parallel lines of lower and upper limits corresponding to working/exposure hours. The vibration exposure below, inside, and above the zone shows minimal, moderate, and high health risks, respectively. Exposure duration for upper and lower HGCZ limits was calculated from the formula given below, as discussed by Griffin (1998) and Kumar et al. (2001):

$$T_u = T_6 [6/a_w]^2 \text{ and } T_l = T_3 [3/a_w]^2,$$

where T_u and T_l are exposure durations at the upper and lower limits of the caution zone, respectively; T_6 and T_3 are exposure durations from 1–10 min at 6 m/s² and 3 m/s² rms acceleration for the health caution zone, respectively; and a_w is frequency-weighted acceleration.

3 Results and discussion

The magnitude of WBVs was measured on the driver seat in three directions (x -, y -, and z -directions), and the total vibration value was computed (IS-13276-Part 1:2000) under both terrain conditions. All 12 speeds and 3 loads on the trailer without and with interventions were computed under the same operational

TABLE 4 Experiment plan for vibration measurement.

Operational parameter	Level
Types of terrain	Asphalt road (T_1) Farm road (T_2)
Speed	Asphalt road: 18, 20, and 22 km/h (S_1 , S_2 , and S_3) 10, 12, and 14 km/h (S_4 , S_5 , and S_6) Farm road: 8, 10, and 12 km/h (S_7 , S_8 , and S_9) 4, 5, and 7 km/h (S_{10} , S_{11} , and S_{12})
Loading	No load (L_0) Half (L_h) Full (L_f)
Intervention	Without intervention and with intervention I_1 and interventions $I_1 + I_2$

conditions (Table 4). The upper and lower HGCZ durations were determined for predicting the health effect on the human body using the measured vibrations.

3.1 Asphalt terrain

3.1.1 Vibration in x -, y -, and z -directions

The WBV was measured on asphalt terrain at the selected speed ranges from 10 to 22 km/h.

Without intervention: The vibration values in x -, y -, and z -directions for an empty trailer at different speeds varied from 0.22 to 0.428, 0.126 to 0.264, and 0.378 to 0.698 m/s², respectively. For half-load conditions without intervention, vibrations varied from 0.248 to 0.551, 0.157 to 0.352, and 0.424 to 0.888 m/s² for three orthogonal directions, respectively. For full-load conditions, vibrations in three orthogonal directions varied from 0.293 to 0.612, 0.178 to 0.409, and 0.559 to 1.106 m/s², respectively.

With interventions I_1 and $I_1 + I_2$: The maximum reduction was achieved in the x -direction, followed by the z - and y -directions; moreover, the reduction was maximum in $I_1 + I_2$ for all operating conditions. The vibration reduction with $I_1 + I_2$ for no payload was 11.82%–25.0%, 5.48%–14.02%, and 6.08%–15.33%; for the half-load condition, it was 13.71%–28.13%, 6.37%–16.48%, and 8.02%–19.26%; for the full-load condition, it was 22.53%–37.25%, 9.55%–17.60%, and 10.2%–21.97% in x , y , and z -directions respectively.

3.1.2 Vibration total values (a_v)

The vibration total values (a_v) of weighted rms acceleration were computed from recorded vibrations and are given in Table 5. The total vibration values with three load conditions increased with operational speed. The vibration values obtained at normal operational speeds (18, 20, and 22 km/h) were relatively higher than the recommended speeds (10, 12, and 14 km/h) stated in ISO 5008: 2002, regardless of the load condition. The highest vibrations were observed when the vehicle was fully loaded and traveling at the highest speed of 22 km/h, while the minimum vibrations occurred at the lowest speed of 10 km/h under the no-load conditions. The total vibration value at the maximum recommended speed (14 km/h) and maximum working speed (22 km/h) at full load was reduced by 14.73% and 23.10% with I_1 intervention, whereas with $I_1 + I_2$ reductions, the values were 16.41% and 25.51%.

TABLE 5 Magnitude of total vibration values and daily exposure values (lower and upper HGCZ limits) on asphalt terrain with and without interventions.

Load	Speed, km/h	Without intervention			Spring-suspended hitch (I_1)			Spring-suspended hitch + PU bush ($I_1 + I_2$)		
		a_v , m/s^2	HGCZ limits, h		a_v , m/s^2	HGCZ limits, h		a_v , m/s^2	HGCZ limits, h	
			T_l	T_u		T_l	T_u		T_l	T_u
No load	10	0.461	7.06	>24	0.435	7.95	31.79	0.429	8.23	>24
	12	0.517	5.6	22.1	0.483	6.44	25.75	0.468	6.85	>24
	14	0.599	4.19	16.75	0.546	5.02	20.1	0.534	5.31	21.22
	18	0.662	3.39	13.57	0.593	4.27	17.08	0.577	4.47	17.9
	20	0.758	2.61	10.43	0.664	3.4	13.62	0.649	3.68	14.71
	22	0.86	2.01	8.11	0.737	2.76	11.03	0.715	2.98	11.91
Half load	10	0.516	5.63	22.53	0.477	6.6	26.41	0.470	6.83	>24
	12	0.638	3.68	14.73	0.576	4.52	18.08	0.571	4.62	18.47
	14	0.733	2.79	11.15	0.653	3.51	14.06	0.643	3.69	14.76
	18	0.827	2.19	8.77	0.711	2.97	11.86	0.688	3.18	12.71
	20	0.95	1.66	6.65	0.797	2.36	9.45	0.770	2.55	10.19
	22	1.103	1.23	4.94	0.893	1.88	7.52	0.870	1.98	7.92
Full load	10	0.656	3.49	13.95	0.586	4.37	17.48	0.574	4.56	18.22
	12	0.774	2.5	10.01	0.676	3.28	13.14	0.659	3.46	13.83
	14	0.835	2.15	8.6	0.712	2.96	11.83	0.698	3.08	12.33
	18	0.919	1.78	7.11	0.754	2.64	10.56	0.734	2.79	11.15
	20	1.084	1.28	5.11	0.856	2.05	8.19	0.836	2.15	8.59
	22	1.329	0.85	3.4	1.022	1.42	5.75	0.990	1.53	6.14

(a_v values exceeding 0.5 m/s^2 (within the caution zone) are shaded in gray; those exceeding 0.866 m/s^2 (above the caution zone) and T_u values lower than 8 h are shaded in red).

3.1.3 HGCZ exposure duration limits

The HGCZ exposure duration limits (T_u and T_l) were calculated from the total vibration value (Table 5) using HGCZ values [as per ISO 2631-1: 1997 IS 13276 (Part 1):2000; Figure B.1 and Equation B.1]. The upper and lower recommended weighted rms accelerations at 8 h exposure duration were 0.866 and 0.433 m/s^2 , respectively, as obtained using Equation B.1. The recommended weighted rms acceleration for 8 h exposure is compared with the estimated total acceleration value for the experimental conditions. Operating the tractor above the caution zone is likely to be a high health risk and also a potential health risk within the caution zone. Table 5 shows that under all operating conditions except at 10 km/h with no load conditions, the driver was at potential health risk and, under some operating conditions, even at high health risk. Based on the upper HGCZ limit without intervention, the total vibration values at speeds more than 20 km/h with half load and also more than 18 km/h at full load were above the caution zone because the total acceleration value (Table 5) exceeded the recommended value (0.866 m/s^2) for the 8-h exposure acceleration limit. At these operating conditions, T_u was less than 8 h under the same circumstances. Based on the upper HGCZ limit at the condition with interventions ($I_1, I_1 + I_2$), only a speed of 22 km/h with full load was above the caution zone as the total acceleration value (Table 5)

exceeded the recommended value of the 8-h exposure acceleration limit. Furthermore, T_u was less than 8 h under this operating condition (Table 5). For all other operating conditions (less than 22 km/h), T_u was more than 8 h, with the developed interventions indicating lesser severity of vibration magnitude. A graphical representation of change in T_u and T_l values of HGCZ without and with intervention at 22 km/h is shown in Figure 4A.

3.2 Farm terrain

3.2.1 Vibration in x-, y-, and z-directions

The WBV was also measured on farm terrain at the selected speeds from 4–10 km/h.

Without intervention: The vibration values in x-, y-, and z-directions for the no-load condition varied from 0.177 to 0.513, 0.112 to 0.35, and 0.260 to 0.779 m/s^2 , respectively. For the half-load condition, they varied from 0.213 to 0.602, 0.134 to 0.393, and 0.308 to 1.057 m/s^2 , respectively; similarly, for the full-load condition, they varied from 0.268 to 0.696, 0.181 to 0.448, and 0.437 to 1.305 m/s^2 , respectively.

With interventions I_1 and $I_1 + I_2$: The maximum reduction in vibration was found in the x-direction, followed by the z- and

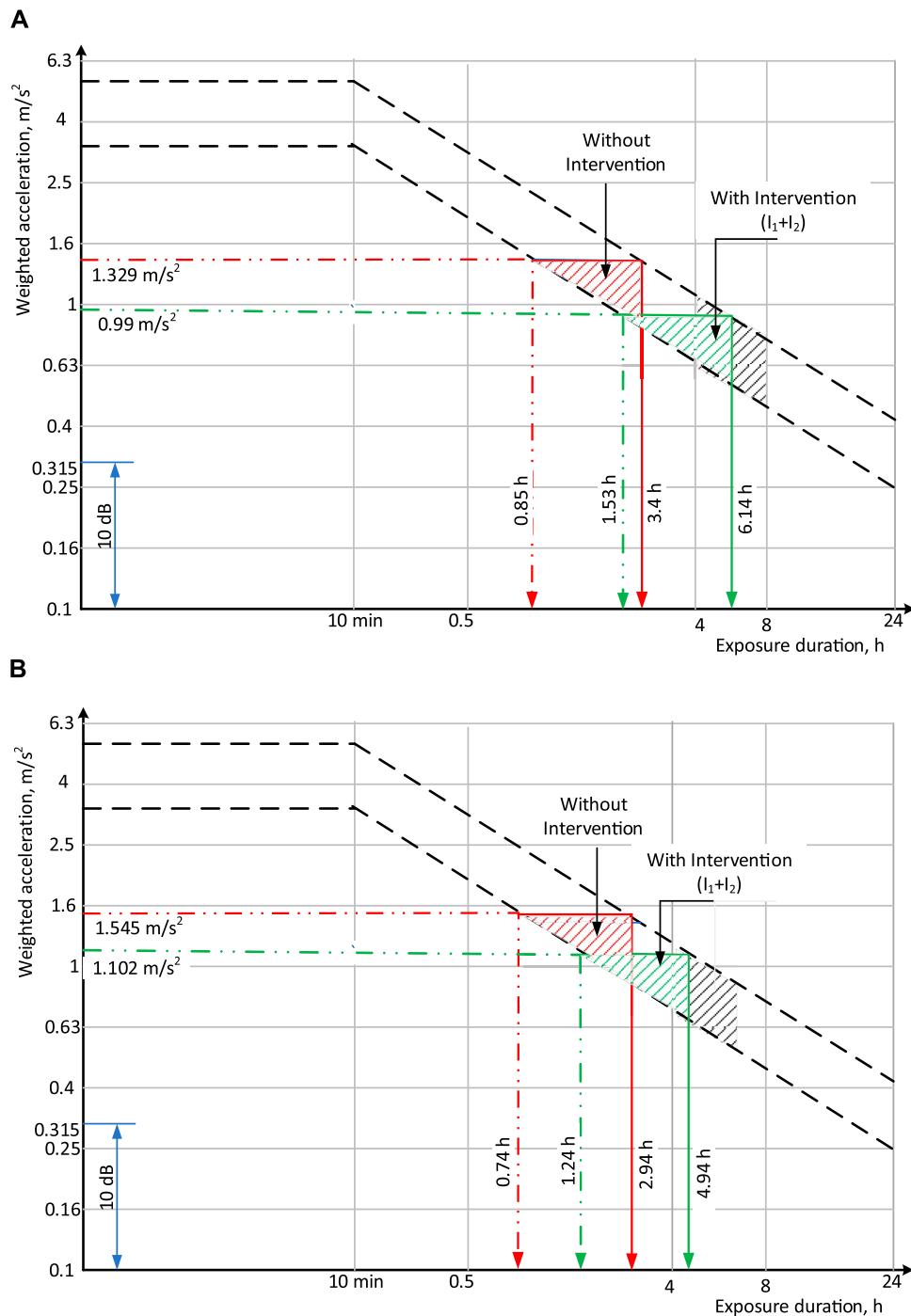


FIGURE 4 Graphical representation of lower and upper exposure limits with a fully loaded tractor-trailer (A) at 22 km/h on asphalt terrain and (B) at 12 km/h on farm terrain.

y-directions; furthermore, reduction was higher with $I_1 + I_2$ than with I_1 . The vibration reduction with the intervention $I_1 + I_2$ for the no-load condition was achieved as 13.56%–26.90%, 6.25%–10.57%, and 7.69%–14.51%; for the half-load condition, it was 15.96%–30.26%, 6.72%–16.28%, and 9.42%–22.80%; for the full-load condition, it was 18.66%–35.34%, 8.29%–17.41%, and 9.61%–28.35% in the x-, y-, and z-directions, respectively.

3.2.2 Vibration total values (a_v)

Total vibration values, without and with intervention, for different operational conditions are given in Table 6. With the increase in speed, the total vibration values on farm terrain were observed to increase for all three selected load conditions. The vibration was higher when the vehicle was operating at normal working speeds (8, 10, and 12 km/h) than at the recommended

TABLE 6 Magnitude of total vibration values and daily exposure values (lower and upper HGCZ limits) on farm terrain with and without interventions.

Load	Speed, km/h	Without intervention			Spring-suspended hitch (I ₁)			Spring-suspended hitch + PU bush (I ₁ + I ₂)		
		a _v , m/s ²	HGCZ limits, h		a _v , m/s ²	HGCZ limits, h		a _v , m/s ²	HGCZ limits, h	
			T _l	T _u		T _l	T _u		T _l	T _u
No load	4	0.334	13.50	>24	0.310	15.73	62.92	0.307	16.07	64.28
	5	0.423	8.39	>24	0.385	10.1	40.41	0.379	10.5	42.01
	7	0.518	5.58	22.32	0.465	6.95	27.79	0.456	7.28	29.12
	8	0.655	3.49	13.97	0.576	4.52	18.07	0.562	4.74	18.97
	10	0.788	2.42	9.66	0.677	3.27	13.08	0.663	3.42	13.7
	12	0.996	1.51	6.05	0.845	2.1	8.4	0.826	2.2	8.79
Half load	4	0.398	9.50	>24	0.364	11.33	45.33	0.355	11.930	47.71
	5	0.534	5.26	21.06	0.480	6.51	26.03	0.469	6.82	27.26
	7	0.742	2.72	10.90	0.660	3.45	13.79	0.643	3.62	14.49
	8	0.974	1.76	7.04	0.794	2.38	9.52	0.771	2.52	10.09
	10	1.178	1.25	5.00	0.917	1.78	7.13	0.892	1.89	7.54
	12	1.279	1.02	4.09	0.992	1.52	6.1	0.975	1.58	6.32
Full load	4	0.544	5.07	20.30	0.491	6.25	25	0.481	6.5	26.01
	5	0.714	2.940	11.78	0.635	3.72	14.9	0.620	3.9	15.58
	7	1.040	1.990	7.94	0.751	2.66	10.65	0.727	2.83	11.34
	8	1.146	1.350	5.41	0.884	1.92	7.68	0.861	2.02	8.1
	10	1.350	0.970	3.87	1.028	1.42	5.68	0.987	1.54	6.16
	12	1.545	0.740	2.95	1.150	1.14	4.54	1.102	1.24	4.94

(a_v values exceeding 0.433 m/s² (within the caution zone) are shaded in gray; those exceeding 0.866 m/s² (above the caution zone) and T_u values lower than 8 h are shaded in red).

speeds (4, 5, and 7 km/h) stated in ISO 5008: 2002, regardless of the load condition. The highest vibrations were observed when the vehicle was fully loaded and traveling at 12 km/h, while the minimum vibrations occurred at no load and 4 km/h (Table 6). The total vibration value at the maximum recommended 7 km/h and full load on farm roads was reduced by 27.79% and 30.10%, respectively, with interventions. Similarly, the total vibration value at a maximum working speed of 12 km/h and full load were reduced by 25.57% and 28.67%, respectively, with intervention I₁ and I₁ + I₂.

3.2.3 HGCZ exposure duration limits

Table 6 shows that on farm roads without intervention under all operating conditions—except at 4 km/h with no-load and half-load conditions and 5 km/h at no-load conditions—the operator was at potential health risk as total vibration values exceeded the recommended lower HGCZ limit of 0.5 m/s². The driver operating the tractor at 12 km/h with no load, 8–10 km/h with half load, and 7–12 km/h with full load was at higher health risk as the total vibration values exceeded the recommended upper HGCZ limit of 0.866 m/s². With the application of intervention I₁, the total vibration values exceeded the upper HGCZ limits at 12, 10, and 7–8 km/h with no-, half-, and full-load conditions, respectively, below the upper HGCZ. With I₁ + I₂, the exceeded upper HGCZ

limits at 12, 8–10, and 7–8 km/h with no-, half-load, and full-load conditions, respectively, were below the upper HGCZ limits. Operating the tractor at 12 and 10–12 km/h with half-load and full-load conditions causes high health risks, so the driver should not work for 8 h. Graphical representation of change in T_u and T_l values of HGCZ without and with intervention at 12 km/h is shown in Figure 4B.

3.3 Enhancement of operational hours with developed interventions

Enhancement of working hours in the lower and upper HGCZs on both asphalt and farm terrains with interventions I₁ and I₁ + I₂ at the maximum recommended and normal working speed is shown in Figures 5A, B.

On asphalt roads, with interventions, WBVs reduced; consequently, the working hours of tractors increased even at high speed and also from above the HGCZ to within the HGCZ. The increased working duration was computed by subtracting the lower limit from the lower HGCZ values and the upper limit from the upper HGCZ values, comparing conditions without intervention to those with interventions I₁ and I₁ + I₂. The maximum duration at

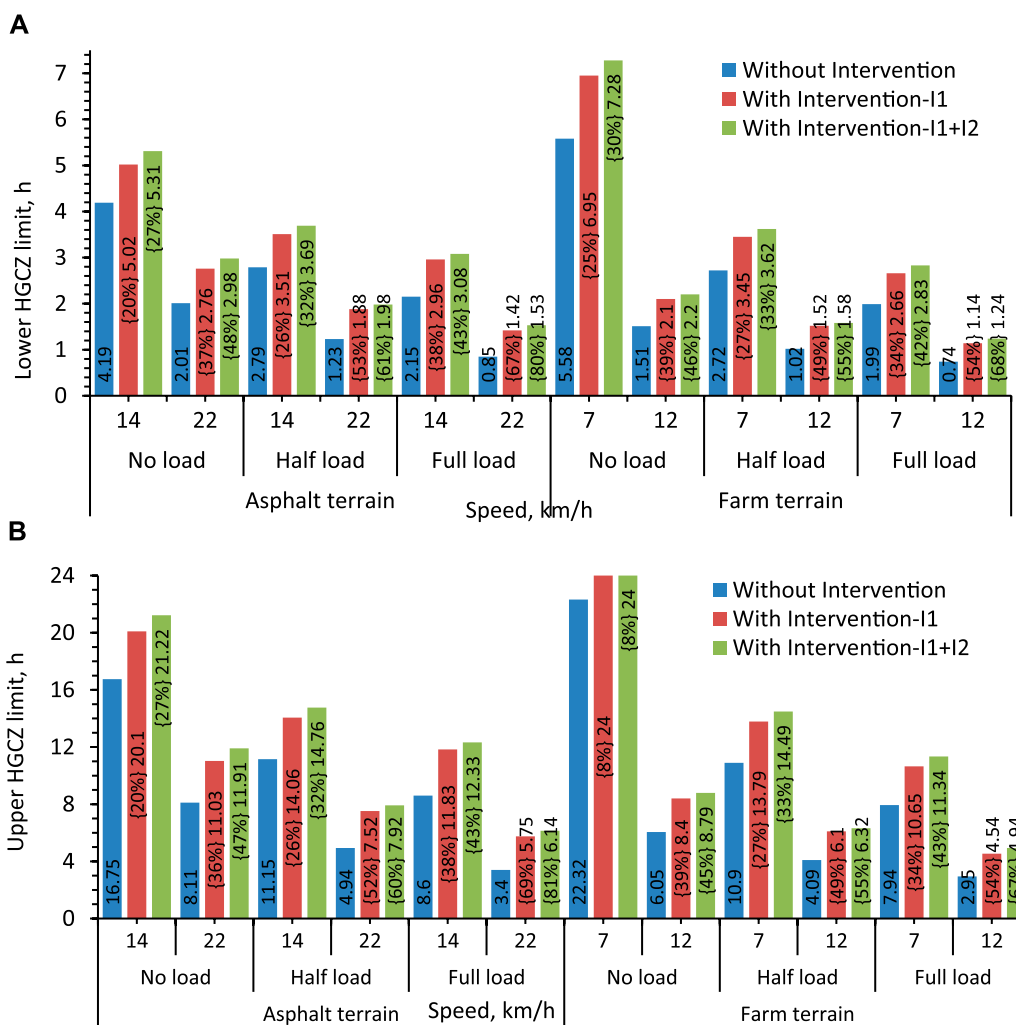


FIGURE 5 Working hours and its improvement (%) in the HGZ limit after the incorporation of interventions for asphalt and farm terrain. (A) Lower HGZ limit. (B) Upper HGZ limit.

22 km/h increased by 45, 39, and 34 min for lower HGZ limits and 2.92, 2.58, and 2.35 h for upper HGZ limits with an empty, half-loaded, and fully loaded tractor-trailer, respectively, by attaching the intervention I₁. Similarly, by attaching both the intervention I₁ + I₂ at 22 km/h, the maximum duration increased by 58, 45, and 40.8 min for lower HGZ limits and 3.8, 3, and 2.74 h for upper HGZ limits with an empty, half-loaded, and fully loaded tractor-trailer.

On farm roads, increased duration was also observed with interventions. The maximum duration was increased at 12 km/h by 35.4, 30, and 24 min for lower HGZ limits and 2.35, 2.01, and 1.59 h for upper HGZ limits with an empty, half-loaded, and fully loaded tractor-trailer, respectively, with intervention I₁. Similarly, with intervention I₁ + I₂ at 12 km/h, the maximum duration was increased by 41.4, 33.6, and 30 min for lower HGZ limits and 2.74, 2.23, and 2 h for upper HGZ limits with an empty, half-loaded, and fully loaded tractor-trailer.

The spring intervention I₁ absorbed the longitudinal direction forces, reducing the vibration magnitude. Polyurethane intervention

restricted the vertical movement of the hitch, reducing the vertical impact on the tractor and resulting in reduced vibrations in the vertical direction. The combination of both interventions reduced the total vibration value, enhancing the safe operational time for operators.

4 Conclusion

The measured vibration in the x-, y-, and z-directions increased with increasing speed and load on a trailer on both asphalt and farm terrains. The vibration with interventions in all three directions and total vibration reduced at all selected speeds and loads. The total vibration values on asphalt terrain varied from 0.441 to 0.860, 0.516 to 1.103, and 0.656 to 1.329 m/s², whereas on farm road, they varied from 0.334 to 0.996, 0.398 to 1.279, and 0.544 to 1.545 m/s² under no, half-, and full-load trailer conditions, respectively. The percentage vibration reduction by attaching the developed intervention in the x-direction was higher in all operating

conditions, followed by the z -direction and y -direction. The maximum total vibration at 22 km/h on asphalt roads was reduced by 16.86%, 21.12%, and 25.51% under empty, half, and full-load tractor-trailer conditions, respectively, by attaching the intervention. Similarly, the reduction on farm terrain was 17.07%, 23.77%, and 28.67%. On asphalt roads, the average value of lower HGCZ limits increased by 1.11, 0.95, and 0.92 h under empty, half-, and full-load tractor-trailer conditions, respectively, by attaching the intervention. On farm terrain, the average value of lower HGCZ limits increased by 1.55, 1.14, and 0.83 h. On asphalt roads, the average value of upper HGCZ limits increased by 3.13, 3.21, and 3.68 h and also increased in farm terrain by 2.24, 2.94, and 3.31 h under no-, half-, and full-load tractor-trailer conditions, respectively, with the incorporation of interventions. This infers that an operator can safely perform 2–3 h more with the developed simple interventions. The operational speed with intervention for full load increased from 18 to less than 22 km/h and 7 to 10 km/h for asphalt and farm terrain, respectively, considering the T_u limit of 8 h.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

RN: investigation, methodology, writing—original draft and writing—review and editing. AK: funding acquisition, supervision, writing—original draft, and writing—review and editing. RK: data curation, software, supervision, validation, writing—original draft, and writing—review and editing. HK: conceptualization, supervision, and writing—review and editing. MK: supervision and writing—review and editing. VR: supervision and writing—review and editing.

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