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Assessment of the vibrational health risk in mining trucks operation: Driver's health and safety

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Abstract
Mining vehicles expose drivers to a significant level of vibration. If these vibrations exceed the standard levels, they can have an adverse musculoskeletal effect on the driver's health and safety. Among all mining vehicles, haul trucks transfer a significant amount of vibration to operators. This paper aims to assess the health risks caused by whole-body vibrations to the drivers of loading and hauling vehicles at the ShahVali Marlstone mine in Birjand, Iran. To achieve this, 13 dump trucks with capacities ranging from 20 to 35 tons were selected for data collection under normal operating conditions. Then, the whole-body vibration of the drivers was measured and analyzed according to the 2631-1 and -5 ISO. Regarding the results of this study, all vehicles have medium to high levels of vibrational health risk. The rigid truck had the highest level of harmful vibrations compared to articulated ones. According to ISO 2631-1, the average vibration magnitude for rigid truck drivers was 1.5 times greater than that of articulated truck drivers, while the vibrational health risk assessed by ISO 2631-5 was at higher levels. The mean seat isolation efficiency for rigid and articulated trucks was 84% and 72%, respectively. This indicated that seats with mechanical suspension systems transferred a higher level of harmful vibrations to the drivers compared to seats equipped with an air suspension system. Moreover, the mean acceptable truck operation time limit for articulated trucks is approximately 2.5 times shorter than that of rigid trucks.

Keywords
Earthmoving equipment, whole body vibration, dumper operator, ISO 2631-1, ISO 2631-5, Seat effective amplitude transmissibility

Introduction

Whole-body vibration (WBV) is one of the most significant occupational hazards in various industries. Drivers of mobile equipment, such as transport vehicles, heavy industrial vehicles, mining vehicles, excavators, and locomotives, are exposed to harmful levels of Whole-Body Vibration (WBV). The term WBV refers to the vibrations transmitted from a vehicle to the human body. According to past studies, daily exposure to WBV over several years can lead to work-related musculoskeletal disorders such as lower back pain or pain in the arm, neck, shoulder, and legs (Griffin, 2012). Moreover, these vibrations can cause a wide range of problems for drivers, including disorders of the joints, muscles, especially the spine, cardiovascular and respiratory issues, endocrine and changes, problems in the digestive system, impairment of vision, interference with activities, and discomfort. Among these issues, low back pain resulting from early degeneration of the lumbar system is reported as the most frequently encountered problem (McPhee et al., 2001). Mobile mining machines produce significant vibrations during their operations. Among these machines, mining trucks operate in various working cycles, which include loading, traveling from the loading area to the dumping area, unloading (or dumping), and returning to the loading area. They passed through harsh environmental mining with dirty haul roads of varying qualities. Therefore, these types of vehicles operate under significant amounts of mechanical vibrations for extended periods, which could pose a threat to the health and safety of drivers.

Up to now, the vibrational health risk levels have been widely analyzed for all mining mobile machines, shovels (Vanerkar et al., 2008; Marin et al., 2017), loaders (Eger et al., 2006; Mayton et al., 2014), dump trucks (Rahimdel and Mirzaei, 2020; 2021), LHD (Aye and Heyns, 2011), and drilling machines (Chaudhary et al., 2015). Marin et al. (2017) studied the whole-body vibration exposures in a set of vehicles operating in open-pit mines according to the ISO 2631-1 and ISO 2631-5 standards. The study considered hydraulic and electric shovels, dozers, loaders, water trucks, and dump trucks with capacities of 190, 240, and 320 tons for data collection and analysis. Results of the mentioned study showed that the vibration dose value for all studied trucks was above the action limits of ISO standards, which were consistent with previous studies (Smets et al., 2010; Limerick and Lynas, 2016). Moreover, the *z*-axis was identified as the predominant exposure axis for large haul trucks. It was also stated that at moderate to high-speed levels, the *z*-axis was the predominant exposure axis. Speed control may reduce the WBV exposures, and the truck seats should be selected to attenuate the vertical vibrations effectively. Lynas and Limerick (2020) measured the WBV of the shuttle car and LHD in an underground mine. The study's results indicate that shuttle cars exceed the recommended limit for whole-body vibration above the action limit of the health guidance caution zone. It was stated that roadway maintenance, decreased vehicle speed, and driver seat replacement significantly reduced the magnitude of vibrations. In another study by Rahimdel and Mirzaei (2020), the practical solutions were prioritized to reduce the whole-body vibration exposures of mining truck drivers by using multi-criteria decision-making techniques in fuzzy environment. In the mentioned research, a Komatsu HD785 dump truck with a 60-ton capacity was selected for tests and data collection. The weight of each decision criterion was determined by the Analytical Hierarchy Process method. Subsequently, the Technique for Order of Preference by Similarity to the Ideal Solution method was employed to select the best solution. Regarding the results of the reviewed study, seat suspension maintenance, vehicle suspension maintenance, driver training, and haul road maintenance were identified as the most effective methods for reducing vibrations and minimizing the injuries associated with WBV exposure.

Chaudhary et al. (2022) studied the WBV exposure for operators of heavy earthmoving equipment (trucks) and non-transport equipment (drilling machines and shovels) at two surface coal mines in India. The vibrational data were obtained and analyzed according to the ISO 2631-1 standard. Moreover, the questionnaire survey was used to examine the association between musculoskeletal symptoms, such as pain in various body regions, and operators' personal information. The study's results showed that the risk of lower back pain in dump truck operators is more than four times higher than that of non-transport operators. The self-reported symptoms by operators indicated that knee pain is the main complaint among non-transport equipment operators. This pain is attributed to the prolonged sitting posture during work and repetitive, frequent leg movements. Moreover, lower back pain was reported to be highest among dump truck drivers due to the shocks from vibrations. Atal et al. (2022) predicted the risk factors of WBV of dumper operators in open-pit mines using the Bayesian network approach. In the mentioned study, the WBV measurements of dumpers in two open-pit coal mines in India were conducted following the ISO 2631-1 standard. Then, the relationships between vibration magnitude, age of the operator, and their years of exposure to lower back pain were studied. Results of the reviewed study revealed that the probability of a high-risk level was 69.1%, and the probability of lower back pain was 52.6%. In a more recent study, Rahimdel et al. (2022) developed a simultaneous integrated model to predict WBV exposure for mining truck drivers. This study conducted data collection and analysis on a haul truck with a 25-ton capacity at Zonuz Kaolin Mine in Iran. The truck's speed, payload, load geometry in the truck dump body, and the quality of the mine road were taken into consideration to identify the hazardous operating conditions that impact WBV exposure. The artificial neural network technique was then utilized to predict the level of vibrational health risk. Results of the study indicated that the risk to vibrational health ranged from medium to high levels. Haul road quality and the accumulation of material in the truck dump body significantly affected the WBV exposure, while the payload within the studied range did not significantly alter the vibration values. Furthermore, the quality of the haul road and load geometry significantly impacted the dynamic comfort of the seat. In the mentioned study, an artificial neural network was proposed as an efficient tool to predict the vibrational health risk level in conditions with no or missing data.

Regarding the past studies reviewed above, numerous attempts have been made in real work situations to determine WBV exposures to truck drivers in the mining environment. However, the effects of long-term exposure on mining truck drivers still need to be studied and clarified. Similar to other workplace hazards, the impact of vibrations on drivers' health must be recognized, addressed, and controlled as a physical work-related disorder. Most of the previous research has attempted to investigate the impact of various truck- or environmental-related conditions, such as truck speed and haul road conditions, on WBV exposure. Hence, it is crucial to study the vibrational health risk level for different types of trucks, such as rigid or articulated trucks, equipped with seats featuring various suspension systems. Different types of trucks are commonly utilized in both construction and mining operations. Therefore, this paper aims to study the WBV exposure of truck drivers by considering not only the operational conditions but also the type and age of the trucks. To achieve this, dump trucks at a Marlstone Mine are selected for testing and data collection. The vibration magnitude is obtained and analyzed in various working cycles, and the quality of haul roads is assessed based on the ISO 2631-1 and ISO 2631-5 standards. The dynamic confirmation of truck seats is analyzed and discussed as well. The results of this study are beneficial for mine managers and contractors in controlling and managing the risks to vibrational health. They are useful for researchers to study the effectiveness of various standards and measures in accurately predicting risk levels.
The paper is organized into three sections as follows. The research methodology is presented in Section 2. Section 3 is devoted to analyzing and discussing the WBV exposure of truck drivers in various operating conditions. The transmissibility amplitude for all studied trucks is obtained and discussed in Section 3, as well. Conclusions and recommendations are presented in Section 4.

Material and Method

This paper aims to analyze the level of vibrational health risk for haul trucks at Shahvali Marlstone Mine. This mine is from the Bagheran Cement Factory, located 150 km away from Birjand City in the Southern Khorasan Province of Iran. The geological resource of this mine is estimated at 120 million tons. The mining activities started in 2015 with an annual production of one million tons. The distance between the loading and dumping areas is 15 km. There are 16 three-axle rigid trucks with a capacity of 20 tons and 9 articulated trucks with a capacity ranging from 25 to 35 tons active in this mine. The loading operation is carried out using one Caterpillar 988G loader and one Hyundai HX330AL backhoe excavator. In this paper, 7 rigid trucks and 6 articulated trucks were selected for data collection and analysis. It should be noted that rigid-body trucks are equipped with mechanical seat suspension, while articulated trucks have pneumatic seats. Fig. 1 shows a truck selected during the loading operation. It is worth noting that such trucks have high maneuverability, stability, and controllability, making them ideal for use in mining, civil, and construction operations.

Fig. 1. The selected truck for data gathering and analysis

Data gathering and processing

The data collection is conducted in various operational cycles, which include loading, dumping, and traveling with and without payload. During the vibrational data gathering, the haul road quality was also considered. Haul roads were inspected and classified into two classes based on the road surface quality: gravel roads with surfaces containing smooth gravel and damaged asphalt roads with rough surfaces due to poor maintenance. In this study, two ADXL335 accelerometers (Devices, 2010), programmed in an AVR ATmega8A microcontroller (2023), were used to measure the vertical vibrations. These accelerometers require a supply voltage of 3.6V DC and operate with a full-scale range of ±3 g. One sensor was secured on the seat of the truck, beneath the driver's ischial tuberosities, and another was placed on the cabin floor near the seat base. The accelerometer device and its placement on the seat are shown in Fig. 2.

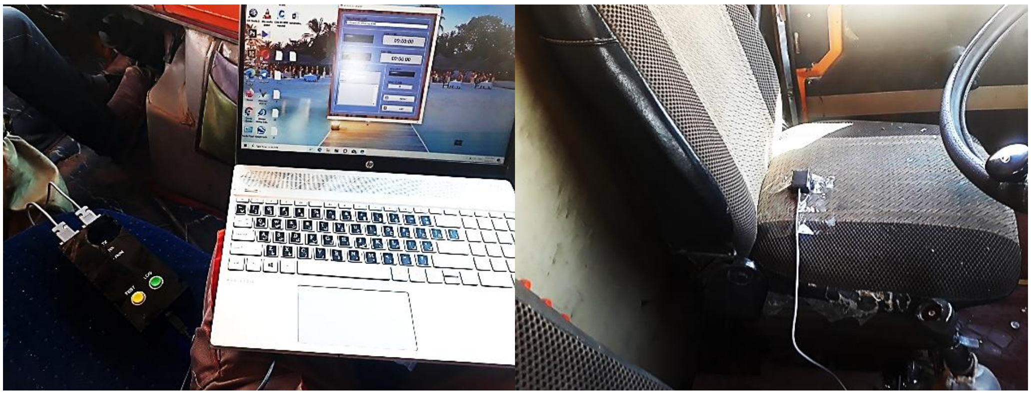

Fig. 2. Accelerometer and the placement of the sensor on the driver's seat

There are various standards for the WBV exposure analysis. Among them, ISO 2631-1 (1998) and ISO 2631-5 (2004) are the most widely used standards, which will be in this section.

Evaluation of WBV exposure based on ISO 2631-1 and ISO 2631-5 standards

According to ISO 2631-1 (1998), the frequency-weighted root mean square (*RMS*) of acceleration and the vibration dose value (*VDV*) are two measures used for evaluating the severity of vibrations.

$$a_{wrms} = \sqrt{\frac{1}{T}\int_0^T a_w^2(t)\, dt}\,, \tag{1}$$

$$VDV = \sqrt[4]{\int_0^T a_w^4(t)\, dt}\,, \tag{2}$$

Where, a_w is the frequency-weighted *rms* acceleration in m/s^2, $a_w(t)$ is the frequency-weighted *rms* acceleration at time t in m/s^2, and T is the measurement duration. The absence or presence of transient vibrations is evaluated by calculating peak accelerations, which provide the crest factor. The crest factor (*CF*) is the ratio of the maximum measured vibration to the *RMS* value of the measured vibration.

$$CF = \frac{\max\,(a_w(t))}{RMS\,(a_w)} \tag{3}$$

Regarding Eq. 3, the more impulsive a vibration is, the higher its crest factor. Therefore, the crest factor is used as a reliable indicator of the level of harmfulness of the vibration. The whole-body vibration exposure parameters are normalized to represent 8 hours of vehicle operation and are used for evaluating the vibrational health risk. The daily *rms* exposure, *A*(8), and the daily dose of vibration, *VDV*(8), for 8 hours in a working day, are calculated from the following equations:

$$A(8) = a_{wrms}\sqrt{\frac{T}{8}} \tag{4}$$

$$VDV(8) = VDV\sqrt{\frac{T}{8}} \tag{5}$$

Where T is the measurement duration.

Regarding ISO 2631-1, if the crest factor exceeds nine, the evaluation of vibration effects using the daily *rms* exposure may be underestimated. In such cases, the VDV is considered for evaluating the health risk level. ISO 2631-1 applies the "Health Guidance Caution Zone (HGCZ)" to evaluate exposure to whole-body vibration (WBV). The HGCZ can be explained graphically, as shown in Fig. 3. The relationship between vibrational health risk levels and the severity of vibrations is summarized in Tab. 1. In this paper, the exposures below, within, and above the HGCZ are considered as low, moderate, and high-risk levels of vibrations.

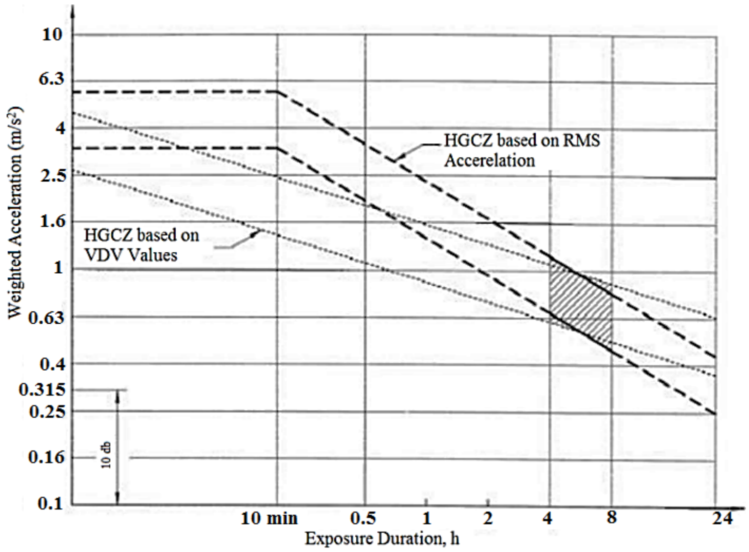

Fig. 3. Health guidance caution zones ISO 2631-1 (1998)

Tab. 1. WBV exposure limits and their HGCZ according to ISO 2631-1 (1998)

A(8) (m/s^2)	VDV(8) (m/s$^{1.75}$)	Predicted health risk	Exposure zone
< 0.45	< 8.5	Low	< HGCZ
0.45 - 0.90	8.5 – 17	Moderate	Within HGCZ
> 0.90	> 17	High	> HGCZ

The duration for which the vehicle can be operated before reaching the daily action limit values can be determined by utilizing WBV exposure limits as outlined by Limerick and Lynas (2016).

$$T_{RMS}(h) = 8 \times \left(\frac{0.45}{A(8)}\right)^2 \quad (6)$$

$$T_{VDV}(h) = 8 \times \left(\frac{8.5}{VDV(8)}\right)^4 \quad (7)$$

In the ISO 2631-5 standard, the equivalent static compressive stress (S_e) during the measurement period is calculated and considered for assessing the health risk level (Kim et al., 2018). In this standard, the acceleration dose in each direction (D_k) is defined as follows:

$$D_k = [\sum_i A_{ik}^6]^{1/6} \quad (8)$$

Where, A_{ik} is the *i*-th peak of the response acceleration in each axis.
Considering the acceleration dose, the average daily dose (D_{kd}) is calculated according to Eq. 9.

$$D_{kd} = D_k \left[\frac{t_d}{t_m}\right] \quad (9)$$

Where t_d is the duration of the daily exposure and t_m is the period over which D_k has been measured. The equivalent static compressive stress (S_e) during the measurement period is calculated using the average daily dose D_{kd} of each axis from the following equation:

$$S_{ed} = \left[\sum_{k=x,y,z}(m_k D_{kd})^6\right]^{1/6} \quad (10)$$

Where, m_k is the dose effect.

Regarding ISO 2536-5, the recommended values of dose-effect parameters for the *x*, *y*, and *z* axes are 0.015, 0.035, and 0.032, respectively. In fact, The S_{ed} is obtained by normalizing D_k to D_{kd} for the average daily exposure. The equivalent static compressive stress is normalized to represent 8 hours of vehicle operation and is used for evaluating the vibrational health risk. The daily equivalent static compressive stress for 8 hours in a working day (S_{ed} (8)) is calculated as follows:

$$S_{ed}\,(8) = S_{ed}\sqrt{\frac{T}{8}} \quad (11)$$

Where *T* is the measurement duration.

The daily equivalent static compression dose, S_{ed} (8), is used to conduct the health risk assessments. ISO 2536-5 defines the boundaries for probable health effects resulting from the multiple shocks of vibration exposure. In this regard, if S_{ed} (8) is less than 0.5 MPa, between 0.5 MPa and 0.8 MPa, and higher than 0.8 MPa, then the probability of adverse effects is considered low, moderate, and high, respectively.

Dynamic comfort of the vehicle seats

Seats are one of the most crucial components of vehicles as they provide support to the driver and passengers, significantly impacting the overall comfort of the ride. Dynamic comfort is associated with the level of vibrations felt by the occupant sitting on the seat (Zagorski et al., 2022). Seat Effective Amplitude Transmissibility (*SEAT*) is a well-known criterion used to evaluate the dynamic comfort of a seat. It provides a numerical assessment of the dynamic comfort of the seat. The *SEAT* indicator is calculated from vibrational data measured on the seat and floor of the truck cabin as follows:

$$SEAT = \frac{\text{Vibration of the seat}}{\text{Vibration of the floor}} \tag{12}$$

In this equation, the vibrations on the seat and floor can be represented by either *RMS* or *VDV* of the measured signals. A *SEAT* value of 100% indicates that there is neither overall improvement nor degradation in the vibration experienced on the seat. The lower values of the *SEAT* indicate that the seat provides effective isolation, while the higher *SEAT* values mean that the seat intensifies the imposed vibration (Rahimdel and Mirzaei, 2020).

Statistical analysis of the vibrational data

In this study, analysis of variance (ANOVA) was used to compare the differences in WBV exposure levels among vehicle operators. ANOVA is a well-known method for analyzing experimental data to determine if there are any statistically significant differences between the means of two or more independent data sets. There are two main types of ANOVA: one-way and two-way ANOVA. The one-way ANOVA is an extension of the *t*-test used to determine the significant difference between the means of more than two independent groups. The two-way ANOVA is employed to assess the impact of two independent variables on a continuous dependent variable (IBM, 2013). In this paper, vibration data classified based on the health risk level were taken as the dependent variable. The independent variables considered were the type and ages of trucks, the condition of the truck dump body (full or empty), and the quality of the haul road. In this approach, a null hypothesis is defined as the absence of a difference between the independent variable(s) and dependent variables. To achieve this, the calculated probability, known as the *p*-value, is used to reject the null hypothesis. In this paper, the *p*-value at a 95% confidence interval is computed using the logistic regression model to predict the most significant factors associated with WBV exposure. The data collected for this study during the fieldwork were analyzed using the IBM SPSS version 22 statistical package software (IBM, 2013).

Results

Characteristics of the drivers' factors for both rigid-body and articulated trucks are presented in Tab. 2. The average age of the rigid-body truck operators is 6.54 years less than that of articulated truck operators, while the average year of experience for all drivers ranges between 7 and 9. The mean weight of the rigid-body truck operators is 76.43 kg (with a standard deviation of 5.8). In comparison, it is 91.67 kg (*SD* = 22.5) for the operators of the articulated trucks. The mean body mass index (BMI) of the rigid truck drivers is 26.46 (*SD* = 1.74). Most drivers (84.6%) have a high BMI, while 15.4% have a normal BMI.

Tab. 2. Statistics index of the personal factors of the truck operators

Personal factor	Vehicle type	Min	Max	Mean	SD
Age (year)	Rigid truck	27	58	32.29	9.63
	Articulated truck	31	46	38.83	5.93
Weight (kg)	Rigid truck	65	85	76.43	5.80
	Articulated truck	60	125	90	19.14
Experience (year)	Rigid truck	3	20	9.14	4.97
	Articulated truck	5	10	8.50	1.89
BMI (kg/cm^2)	Rigid truck	23.88	29.30	26.46	1.74
	Articulated truck	23.44	34.63	30.31	4.19

The total number of measurement trials was 51. It is noted that the crest factor values in all measurements ranged from 2.11 to 7.26. Consequently, the frequency-weighted *RMS* values of vibrations were utilized for the health risk assessment. The mean values of vibration magnitude in different working cycles of the trucks, based on ISO 2631-1 and ISO 2631-4 standards, were obtained and are shown in Fig.s 4 and 5, respectively.

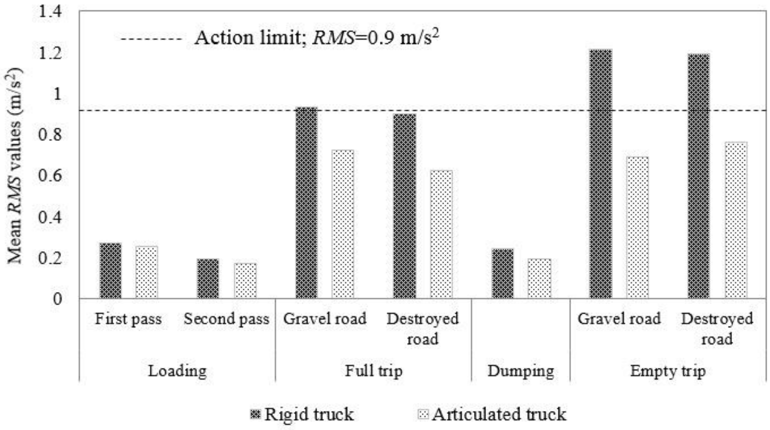

Fig. 4. Mean RMS values for trucks at different working cycles

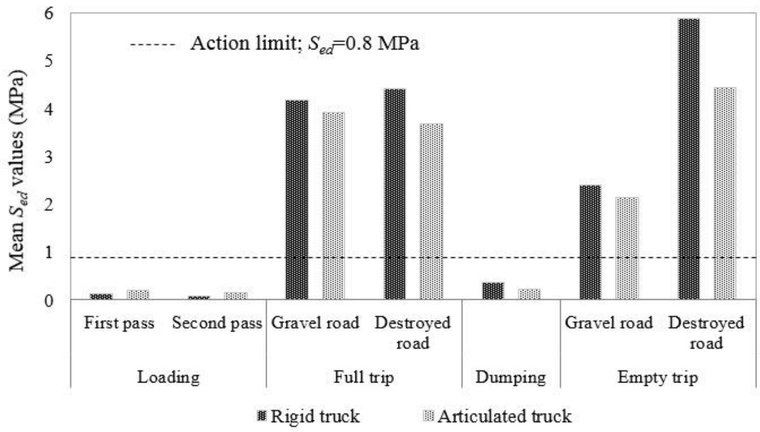

Fig 5. Mean S_{ed} values for trucks at different working cycles

Tab. 3 displays the statistical properties of *SEAT* values, including the mean and standard deviation at all operating cycles for both truck types.

Tab. 3. Mean SEAT values in different situations

Working cycle	Full trip		Empty trip	
Truck type	Gravel road	Destroyed road	Gravel road	Destroyed road
Rigid truck	0.79 ± 0.40	0.8 ± 0.49	0.89 ± 0.42	0.86 ± 0.36
Articulated truck	0.63 ± 0.18	0.76 ± 0.20	0.71 ± 0.16	0.78 ± 0.19

ANOVA is used to identify operational cycles and conditions that significantly impact the *RMS* and *SEAT* values. Results of ANOVA at a 95% confidence level are summarized in Tab. 4.

Tab. 4. Results of the ANOVA for RMS, S_{ed}, and SEAT values

Independent variable	Dependent variable	*df*	Mean square	*F*-value	Significant
Truck age	RMS	4	0.305	6.854	< 0.001
	S_{ed}	4	1.679	0.190	0.942
	SEAT	4	0.401	4.118	0.006
Truck type	RMS	1	1.188	26.662	0.001
	S_{ed}	1	4.476	0.508	0.480
	SEAT	1	0.013	0.13	0.721
Loading condition	RMS	1	0.66	14.816	< 0.001
	S_{ed}	1	0.174	0.020	0.889
	SEAT	1	0.052	0.531	0.470
Road	RMS	1	0.007	0.155	0.695
	S_{ed}	1	35.216	3.993	0.052
	SEAT	1	0.019	0.197	0.659

Moreover, to study the effect of truck ages on the *RMS* and *SEAT* values, Scheffe's Post Hoc Test (SPHT) is used. The SPHT is a mean comparison test used to identify the relationships between the subgroups based on the significant parameters (IBM, 2013). The results of the SPHT are summarized in Tab. 5. Note that in Tab. 5, there is no significant difference between subgroups of variables that share the same superscript letter in terms of the same superscript letter (or $p > 0.05$).

Tab. 5. The results of Scheffe's Post Hoc Test for the truck age subgroup

Truck ages (year)	1	16	13	11	20
Mean *RMS* values (m/s^2)	0.523^a	0.660^b	$0.729^{a,b}$	$1.041^{b,c}$	1.155^c
Mean *SEAT* values (m/s^2)	0.883^a	0.645^a	0.610^a	1.020^a	0.743^a

Discussion

Regarding the Mean *RMS* values (Fig. 4), all trucks are classified as low-risk during the loading and dumping cycles. However, the empty trucks on destroyed roads are categorized as being at the highest health risk level, surpassing the action limit of standards. The mean vibration magnitude for the rigid trucks is 1.5 times greater than that of the articulated trucks. The *RMS* values for both types of trucks during the loading cycle are the lowest compared to other working cycles. The vibrations in the second loading pass are lower than those in the first pass. It is worth noting that the cushioning effect of the material in the truck dump body dampens the vibrations imposed on the truck chassis during the second loading pass, which is consistent with past studies (Frimpong et al., 2011; Ali and Frimpong, 2021). The magnitude of the vibrations is highest when the truck is empty and lowest level during the dumping working cycles. Drivers tend to drive the truck at high speeds. Driving at high speed accentuates the roughness of the haul road, consequently producing the most intense vibrations. In such conditions, it is important to encourage drivers to decrease their speed, especially when the truck is empty.

Regarding the results of the S_{ed} values (Fig. 5), trucks in all working cycles except loading and dumping are at a high health risk level ($S_{ed} > 0.8$ MPa). Both the S_{ed} and *RMS* values for the rigid-body trucks are higher than those of the articulated trucks. The vibration magnitude is at its highest levels of WBV exposure during the empty and full trip, as well as during the loading and dumping cycles. It should be noted that the vibrational health risk assessed by ISO 2631-5 is higher, whereas these exposures may be underestimated when using the ISO 2631-1 method. These results are consistent with previous studies (Eger et al., 2008; Zhao and Schindler, 2014). Regarding previous studies, ISO 2631-1 fails to capture the peak of impulsive exposures, leading to an underestimation of the health risks associated with WBV exposure (Limerick and Lynas, 2016).

Regarding the dynamic performance analysis of truck seats, in most cases, the *SEAT* values are lower than one, indicating that the seats effectively isolate the vibrations transmitted to the driver's body. The mean seat isolation efficiency for rigid and articulated trucks is 84% and 72%, respectively. Moreover, the vibration isolation efficiency of the truck seats on both gravel and damaged asphalt roads is approximately the same.

A comparison of personal factors and *RMS* values in both rigid and articulated trucks was conducted using an analysis of variance. The results showed a significant difference between driving experience, BMI, and the frequency-weighted *RMS* of acceleration ($p < 0.001$). Regarding the ANOVA analysis, there is a significant difference between truck types and dump body conditions (loaded or unloaded truck) in *RMS* values ($p < 0.001$). Meanwhile, road conditions do not significantly affect vibration magnitude ($p > 0.05$). Furthermore, none of the working conditions alter the S_{ed} values. On the other hand, the S_{ed} values can be considered independent of all working conditions.

The results indicate that the age of the truck had a significant effect on both *RMS* and the isolation efficiency of the seats. SPHT results indicate a significant difference among the ages of the truck, vibration magnitudes, and the isolation efficiency of the truck seats. Older trucks are much rougher than newer ones due to their stiff suspensions. Therefore, the planned vehicle maintenance schedules and overhauls of the suspension systems should be considered to reduce vertical vibrations.

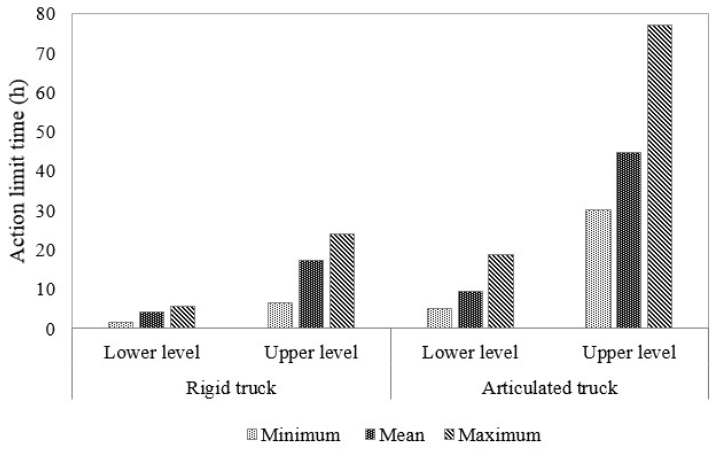

Fig. 6. The action limit times in hours for trucks

The acceptable truck operation times based on the WBV exposure limits were obtained using Eqs. (6) and (7), and are shown in Fig. 6. The mean acceptable time limit for articulated trucks is approximately 2.5 times less than that of rigid trucks, which is consistent with the previous results. Considering the minimum operation time, scheduling a break for the rigid trucks after 4 hours or halfway through each working shift is recommended. Moreover, these results indicate that articulated trucks can be operated until the end of the working shift.

Conclusions

In this paper, the whole-body exposure experienced by dump trucks was obtained and analyzed. Data collection and analysis were conducted for rigid and articulated dump trucks at Shahvali Marlstone Mine in Iran. The vibration magnitude for different types of trucks, haul road qualities, and truck dump body conditions were analyzed and discussed according to the ISO 2631-1 and 2631-5 standards. The findings from this study are summarized as follows:

- All trucks in the loading and dumping working cycles are at the lowest health risk level (below the action limit of standards). The highest amount of vibrations during the loading period occurs on the first loading pass when the truck is empty. The material in the dump body has an isolating effect that damps the impact of vibrations on the second pass.
- Analysis of the operators' personnel factor shows a significant difference between the driving experience, body mass index, and the magnitude of vibrations.
- The type and age of the trucks have a significant impact on WBV exposure. The vibration magnitude for rigid-body trucks is approximately 1.5 times greater than that of articulated trucks.
- Truck age has a notable effect on seat dynamic comfort. On average, the truck seats isolate 11 to 37 percent of the vibrations transmitted to the driver's body.
- ISO 2631-1 may underestimate the vibrational health risk level in comparison to ISO 2631-5, potentially due to uncertainties in considering peak impulsive exposures consistent with the previous studies.
- To adhere to acceptable operation time limits, it is recommended to allow a break for the rigid truck drivers after 4 hours or in the middle of the working shift.

The results of this study help identify and implement practical approaches and controls to reduce WBV exposures for earthmoving vehicles. They also provide valuable insights for future research to explore suitable standards and modeling techniques that can effectively predict the high-risk level of vibrations.

Conflict of interest: The authors declare that there is no conflict of interest.

Ethical approval: The paper was approved by the Ethics Committee of the University of Birjand.

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