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THE INFLUENCE OF SEAT DESIGN AND SURFACE TYPE ON THE LEVEL OF VIBRATIONS EXPERIENCED BY A TRUCK DRIVER

ABSTRACT: This paper presents an experimental analysis of the vibrations to which a heavy-duty vehicle driver is exposed when using different seat types and operating the vehicle on different road surfaces. The study was conducted to evaluate the influence of seat design and road surface characteristics on the driver's vibration exposure. Measurements were performed using accelerometers mounted at appropriate measurement locations, while both a mechanical seat and a pneumatic seat were evaluated during driving on asphalt and gravel roads. Based on the recorded signals, the root mean square (RMS) acceleration values and the peak acceleration values were determined. The obtained results were compared with each other and evaluated against the recommendations of ISO 2631 for whole-body vibration exposure. The results indicate that the type of road surface has a significant effect on the vibration levels experienced by the driver, with the highest values recorded during driving on gravel roads. Furthermore, the pneumatic seat demonstrated superior vibration isolation performance compared with the mechanical seat, resulting in reduced vibration exposure and improved driver comfort during vehicle operation.

KEYWORDS: whole-body vibration, heavy-duty vehicle, seat, root mean square (RMS) acceleration, driver comfort.

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UTICAJ KONSTRUKCIJE SEDIŠTA I VRSTE PODLOGE NA NIVO VIBRACIJA KOJIMA JE IZLOŽEN VOZAČ TERETNOG VOZILA

REZIME: Ovaj rad predstavlja eksperimentalnu analizu vibracija kojima je izložen vozač teretnog vozila pri korišćenju različitih tipova sedišta i upravljanju vozilom na različitim vrstama kolovoznih podloga. Istraživanje je sprovedeno sa ciljem procene uticaja konstrukcije sedišta i karakteristika kolovozne podloge na izloženost vozača vibracijama. Merenja su izvršena pomoću akcelerometara postavljenih na odgovarajućim mernim mestima, pri čemu su tokom vožnje na asfaltiranim i makadamskim putevima ispitivani mehaničko i pneumatsko sedište. Na osnovu registrovanih signala određene su efektivne (RMS) vrednosti ubrzanja, kao i maksimalne vrednosti ubrzanja. Dobijeni rezultati su međusobno upoređeni i procenjeni u skladu sa preporukama standarda ISO 2631 koje se odnose na izloženost vibracijama celog tela. Rezultati pokazuju da vrsta kolovozne podloge ima značajan uticaj na nivo vibracija kojima je vozač izložen, pri čemu su najviše vrednosti zabeležene tokom vožnje po makadamskim putevima. Pored toga, pneumatsko sedište pokazalo je bolje karakteristike izolacije vibracija u poređenju sa mehaničkim sedištem, što je rezultiralo smanjenom izloženošću vozača vibracijama i poboljšanim komforom tokom upravljanja vozilom.

KLJUČNE REČI: vibracije celog tela, teretno vozilo, sedište, efektivna (RMS) vrednost ubrzanja, komfor vozača.

INTRODUCTION

Vibrations experienced by heavy-duty vehicle drivers represent a significant factor affecting driving safety, work performance, and the long-term health of vehicle operators. During vehicle operation, vibrations are generated by the interaction between the tires and the road surface, the operation of the powertrain, and dynamic loads transmitted through the vehicle suspension system and the driver's seat to the human body. As emphasized by Dennerlein, J. T. et al. (2022), Kat, C.-J. et al. (2021), & Zhou, Z. and Griffin, M. J. (2014), prolonged exposure to whole-body vibration (WBV) may lead to fatigue, reduced concentration, driving discomfort, and various musculoskeletal disorders, particularly affecting the lumbar spine.

The intensity of the vibrations transmitted to the driver depends on several factors, including road surface characteristics, vehicle speed, suspension system design, tire condition, and seat design. Since the driver's seat represents the final element in the vibration transmission path between the vehicle and the driver, its characteristics play a crucial role in reducing vibration exposure and improving driving comfort. Consequently, modern heavy-duty vehicles increasingly employ pneumatic seat suspension systems to achieve more effective vibration isolation.

Whole-body vibration has been the subject of extensive research in the fields of ergonomics, transportation, and automotive engineering. Previous studies have focused on evaluating the effects of vibration on driver health and comfort, developing methods for vibration exposure assessment in accordance with the ISO 2631 standard (ISO, 1997), and investigating the effectiveness of different seat suspension systems in reducing vibration transmission. In their respective studies, Jovanović, B. S. & Djurić, S. A. (2009), Kia, K. et al. (2021), as well as Sekulić, D. et al. (2013, 2016) have devoted particular attention to the determination of root mean square (RMS) acceleration and vibration dose value (VDV), time-domain and frequency-domain vibration analyses, as well as the influence of road surface conditions, vehicle speed, and seat design on driver vibration exposure.

Although numerous studies have confirmed the importance of seat suspension systems in mitigating whole-body vibration, reported results vary depending on the vehicle type, operating conditions, and seat design characteristics. Therefore, there remains a need for experimental investigations comparing different seat types under realistic operating conditions in order to quantify their effectiveness in reducing driver vibration exposure.

In this study, an experimental investigation of whole-body vibration experienced by a heavy-duty vehicle driver was conducted using different seat types during operation on asphalt and gravel road surfaces. Vibration measurements were performed using a triaxial accelerometer mounted on the driver's seat, and the recorded signals were processed to determine the principal vibration parameters and to compare the vibration isolation performance of the investigated seats.

The objective of this study is to evaluate the influence of different seat suspension systems and operating conditions on the whole-body vibration exposure of a heavy-duty vehicle driver, and to identify the seat configuration that provides the most favorable vibration isolation performance under the investigated operating conditions.

MEASUREMENT METHODOLOGY

Theoretical background

Whole-body vibration (WBV) refers to mechanical oscillations transmitted to the driver's body through the seat, floor, or other contact surfaces during vehicle operation or machine use. In heavy-duty and off-road vehicles, these vibrations are primarily generated by road surface irregularities, powertrain operation, and dynamic loads occurring during vehicle operation. The level of vibration transmitted to the driver depends on several factors, including vehicle characteristics, operating conditions, suspension system performance, and seat design.

The assessment of whole-body vibration exposure is commonly performed in accordance with the requirements of the ISO 2631 standard (ISO, 1997), which specifies procedures for measuring, analyzing, and evaluating vibrations affecting the human body. The standard incorporates frequency weighting of vibration signals to account for the varying sensitivity of the human body to vibrations at different frequencies.

Within this regulatory framework, the primary parameter used for evaluating vibration exposure is the frequency-weighted root mean square (RMS) acceleration. This metric is defined as the square root of the mean value of the squared frequency-weighted acceleration over the observation period and is used to quantify the overall vibration exposure experienced by the driver. For translational vibrations, this parameter is expressed in m/s². The frequency-weighted RMS acceleration is calculated as follows:

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

where:

- a_w – frequency-weighted root mean square (RMS) acceleration (m/s²);
- a_w (t) – instantaneous value of the frequency-weighted acceleration;
- T – measurement duration (s).

The ISO 2631 standard (ISO, 1997) defines the root mean square (RMS) acceleration as the average energy level of vibration during the measurement period and one of the most important parameters for evaluating whole-body vibration exposure. Consequently, lower RMS values indicate more effective vibration isolation and more favorable operating conditions in terms of driver comfort and occupational health protection.

In addition to this frequency-weighted RMS acceleration, peak acceleration and the vibration dose value (VDV) are also commonly used in whole-body vibration analysis. While the former parameter describes the average energy content of vibration over the observation period, the VDV parameter is more suitable for assessing exposure under conditions where the vibration signal contains pronounced shocks or transient excitations.

To address these specific conditions, the standard outlines that the VDV method is more sensitive to short-duration, high-intensity vibration events because it is based on the fourth power of the frequency-weighted acceleration signal, whereas the RMS method relies on the second power of the same signal. Consequently, individual shock events have a substantially greater influence on the resulting VDV value, enabling a more accurate assessment of vibration exposure under operating conditions characterized by intermittent high-intensity vibrations.

For translational vibrations, the vibration dose value (VDV) is calculated as follows:

$$VDV = \left\{\int_0^T [a_w(t)]^4 dt\right\}^{\frac{1}{4}} \tag{2}$$

Compared with the RMS parameter, the vibration dose value (VDV) provides a more comprehensive assessment of vibration exposure in situations where the vibration signal contains short-duration, high-intensity events. Since the VDV places greater emphasis on high-amplitude components of the measured vibration signal, it is commonly used as a complementary parameter to the RMS analysis. As outlined in the ISO 2631 standard (ISO, 1997), this parameter is essential for evaluating operating conditions and the effects of vibration exposure on the driver.

Vibration signals can be analyzed in either the time domain or the frequency domain. Time-domain analysis provides the fundamental characteristics of the vibration signal, including the RMS acceleration, peak acceleration, and VDV, whereas frequency-domain analysis provides insight into the distribution of vibration energy across the frequency spectrum. This dual approach enables the identification of the dominant dynamic components of the vehicle–seat–driver system in accordance with the standard's analytical framework.

Under these guidelines, the RMS value serves as the primary parameter for assessing whole-body vibration exposure when the vibration signal does not contain significant shock components, i.e., when the crest factor is less than 9. When the signal contains pronounced peaks and the crest factor exceeds this threshold, the use of additional evaluation metrics, such as the VDV, is recommended to provide a more comprehensive assessment of vibration exposure.

Measurement conditions and data acquisition

The characteristics of the driver's seat have a significant influence on the level of vibrations transmitted from the vehicle to the driver. The effectiveness of the seat suspension system depends on its design, damping characteristics, and vehicle operating conditions. Therefore, experimental vibration analysis under different operating conditions represents an important basis for evaluating the influence of seat design on the driver's whole-body vibration exposure.

Vibration measurements were performed in accordance with the ISO 2631 standard (ISO, 1997), using the coordinate system defined at the point of vibration transmission to the human body. Vibration signals were recorded in three mutually orthogonal directions: the x-axis (longitudinal direction), the y-axis (lateral direction), and the z-axis (vertical direction). The measurement system orientation was adjusted according to these requirements to ensure reliable vibration acquisition and mutual comparison of the obtained results. When complete alignment of the measurement axes is not possible, the standard allows sensor orientation deviations of up to ±15°, while transducers positioned at the same measurement location must remain mutually orthogonal.

For the purposes of this study, vibration acceleration, expressed in m/s², was selected as the measured quantity. Measurements were conducted using the Maestro measurement system manufactured by 01 dB, equipped with a triaxial accelerometer integrated into a seat pad adapter designed to measure vibrations transmitted to the driver's body (Figure 1). The accelerometer was positioned on the driver's seat in the area of body contact, enabling simultaneous recording of vibrations in all three measurement directions.

After data acquisition, the acceleration time signals were processed using vibration analysis software. Based on the processed signals, the root mean square (RMS) acceleration values were determined and used for comparing vibration levels for different seat types and operating conditions.

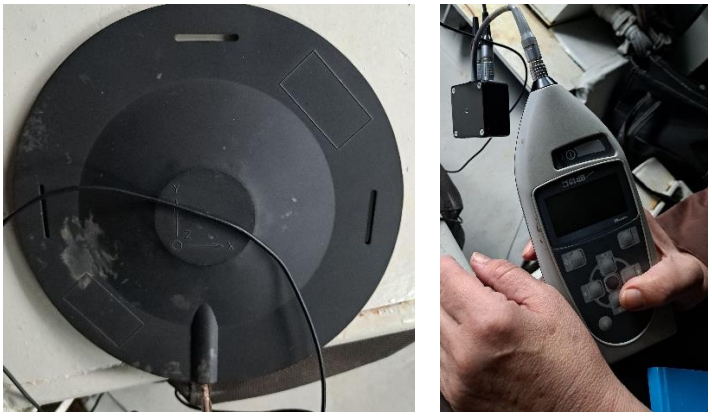


Figure 1 Elements of the measuring chain: Accelerometer (left) and Maestro vibration measurement device (right)

The experimental investigations were conducted on an unloaded heavy-duty vehicle, the main technical characteristics of which are presented in Table 1. The aim of the study was to evaluate the level of vibrations to which the driver is exposed under the previously described operating conditions.

Table 1 Technical characteristics of the test vehicle

Parameter	Specification
Drive configuration	6x6
Unladen vehicle mass	≈ 12 t
Engine power	205 kW
Suspension system type	Front axle: mechanical-hydraulic; second and third axles: mechanical
Tire dimensions	425/85 R21
Tire inflation pressure	4 bar

Within the experimental study, one mechanical seat and two pneumatic seats from different manufacturers were investigated. The mechanical seat is based on a conventional suspension system consisting of spring and damping elements, while the pneumatic seats utilize an air suspension system that provides more effective vibration attenuation and improved driver comfort.

The tests were performed on two types of surfaces: asphalt and gravel. The asphalt surface represented a relatively flat and uniform contact surface, whereas the gravel surface was selected to simulate more severe operating conditions with increased vibration excitation.

During the measurements, the vehicle was driven at an approximately constant speed. On the asphalt surface, the tests were conducted at a speed of 80 km/h, while on the gravel surface the vehicle speed was 20 km/h. Each measurement was repeated several times in order to reduce the influence of random deviations and improve the reliability of the obtained results.

Throughout all experiments, approximately constant test conditions were maintained, including vehicle loading conditions and tire inflation pressure. This minimized their influence on the measurement results and ensured the comparability of the experimental data.

EXPERIMENTAL RESULTS AND ANALYSIS

The measurement results (Table 2) were evaluated based on the comfort criteria defined in the ISO 2631 standard (ISO, 1997) and the health risk assessment criteria specified by Directive 2002/44/EC (European Parliament & Council, 2002) regarding occupational exposure to vibrations.

Table 2 Whole-Body Vibration results under different operating conditions

Road surface	Seat type	Speed (km/h)	Acceleration (m/s^2)			
			x	y	z	a_w
-	Mechanical	0	0.05	0.05	0.02	0.07
	Pneumatic – Manufacturer 1	0	0.05	0.05	0.05	0.09
	Pneumatic – Manufacturer 2	0	0.05	0.05	0.03	0.07
Gravel	Mechanical	20	0.47	0.6	1.18	1.41
	Pneumatic – Manufacturer 1	20	0.32	0.5	0.92	1.10
	Pneumatic – Manufacturer 2	20	0.44	0.6	0.83	1.11
Asphalt	Mechanical	80	0.27	0.15	0.59	0.67
	Pneumatic – Manufacturer 1	80	0.22	0.24	0.54	0.63
	Pneumatic – Manufacturer 2	80	0.23	0.14	0.63	0.68

The experimental results are presented in Figures 2–5, separately for each seat position, for an unloaded vehicle configuration, with a nominal tire inflation pressure of 4 bar, under different road surface conditions and vehicle speeds.

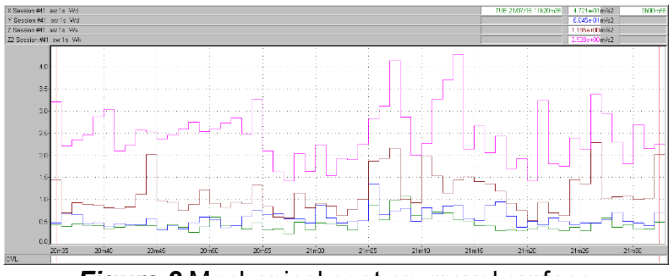


Figure 2 Mechanical seat on gravel surface

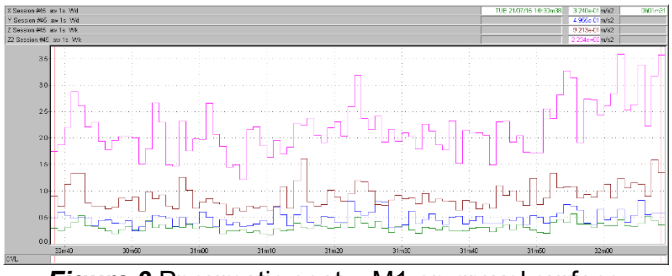


Figure 3 Pneumatic seat – M1 on gravel surface

Figures 2 and 3 show the time histories of acceleration signals recorded on the mechanical seat and the pneumatic seat from Manufacturer 1 (M1) during vehicle operation on a gravel surface at a speed of 20 km/h. The signals are presented using different colors and correspond to the acceleration components in the x, y, and z directions, as well as the calculated RMS acceleration value.

It can be observed that the pneumatic seat exhibits lower vibration amplitudes in all three measurement directions compared with the mechanical seat, indicating more effective vibration attenuation and lower RMS acceleration values.

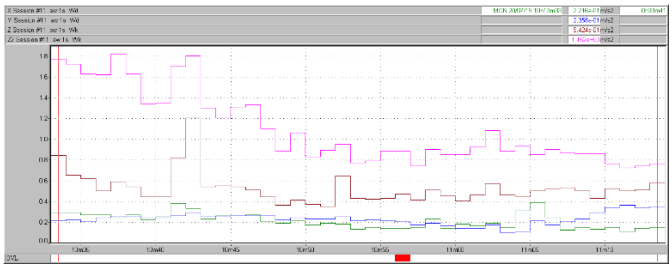


Figure 4 Pneumatic seat – M1 on asphalt surface

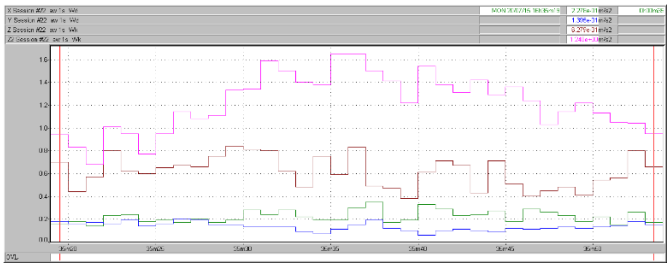


Figure 5 Pneumatic seat – M2 on asphalt surface

Figures 4 and 5 show the time histories of acceleration signals recorded on the pneumatic seat from Manufacturer 1 and the pneumatic seat from Manufacturer 2 (M2) during vehicle operation on an asphalt surface at a speed of 80 km/h. The signals are presented using different colors and correspond to the acceleration components in the x, y, and z directions, as well as the calculated RMS acceleration value.

A comparison of the presented signals reveals differences in the vibration levels between the investigated seats, indicating different vibration attenuation efficiencies of their suspension systems under driving conditions on an asphalt surface.

Comparison of RMS acceleration values for different seats

Figures 6 and 7 show the variation of RMS acceleration with respect to seat type under different road surface conditions (gravel and asphalt) and vehicle speeds.

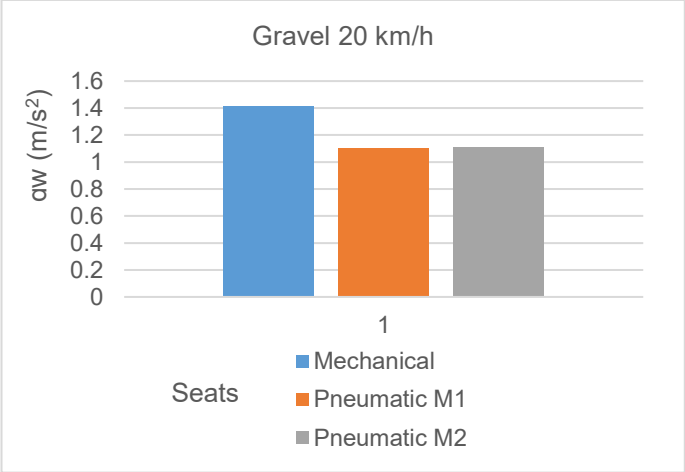


Figure 6 RMS acceleration for different seat types on a gravel surface

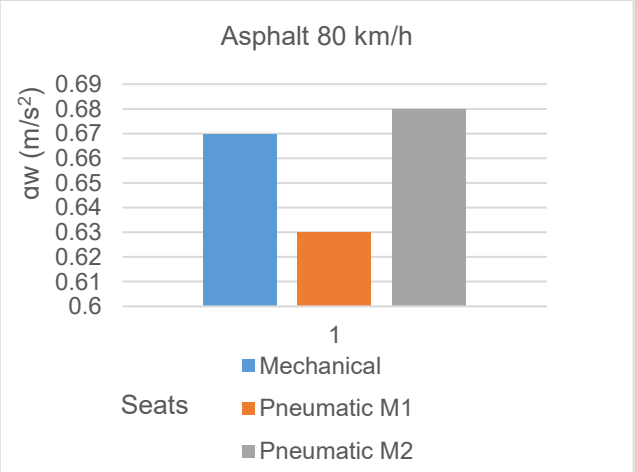


Figure 7 RMS acceleration for different seat types on an asphalt surface

It can be observed that, compared with the mechanical seat, the pneumatic seats generally achieved lower RMS acceleration values, indicating more effective attenuation of vibrations transmitted to the driver. The lowest RMS values were recorded for the pneumatic seat from Manufacturer 1 during vehicle operation on the gravel surface, indicating its highest effectiveness under conditions with pronounced surface irregularities. On the other hand, a deviation from this trend was observed for the seat from Manufacturer 2 on the asphalt surface. Namely, the pneumatic seat from Manufacturer 2 exhibited a higher RMS acceleration value compared with the mechanical seat, indicating that its advantages are not equally pronounced during driving on surfaces with lower vibration excitation levels.

These results indicate that the effectiveness of the seat suspension system depends not only on its design characteristics but also on the properties of the surface over which the vehicle is operated.

Effect of road surface conditions

Figure 8 presents the variation of RMS acceleration values for different road surface conditions and seat types.

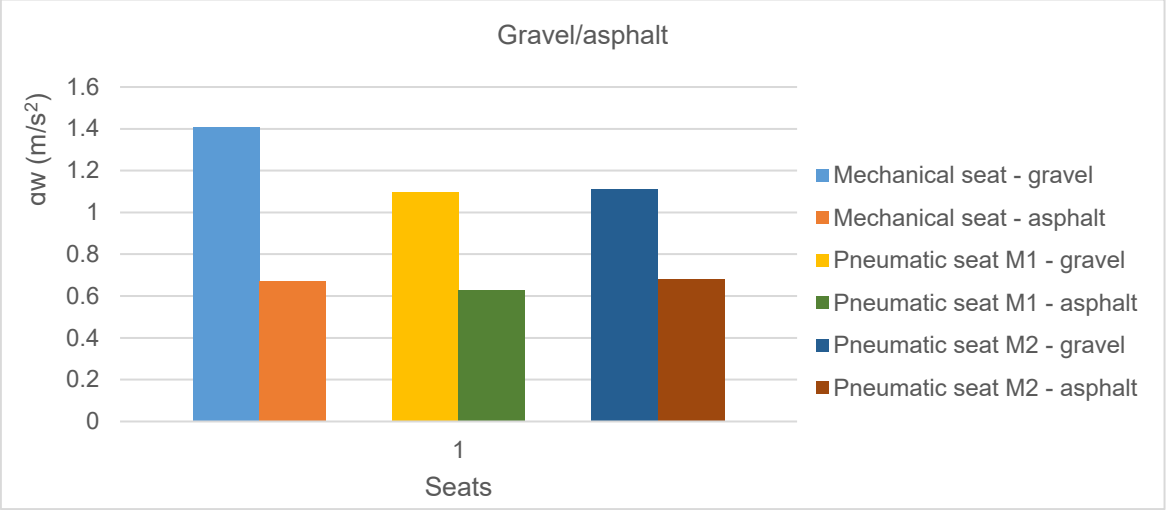


Figure 8 RMS acceleration for different seat types and road surface conditions

For each seat type, the RMS acceleration values obtained during driving on gravel and asphalt surfaces were compared. It can be observed that road surface characteristics have a significant influence on the level of vibrations transmitted to the seat. For all investigated seat types, the RMS values on the gravel surface were higher than those on the asphalt surface, which is an expected consequence of more pronounced surface irregularities and higher excitation generated by such a surface.

The mechanical seat exhibited the most pronounced difference between RMS values measured on gravel and asphalt surfaces, indicating a limited ability of this system to isolate vibrations caused by uneven road conditions. Both pneumatic seats achieved lower RMS values compared with the mechanical seat, particularly during driving on the gravel surface, where the vibration attenuation effect was most evident.

The pneumatic seat from Manufacturer 1 is particularly distinguished by achieving the lowest RMS value during driving on the gravel surface, indicating the highest vibration isolation capability under conditions of increased excitation. However, during driving on the asphalt surface, the differences between the seats were less pronounced, and the pneumatic seat from Manufacturer 2 exhibited a higher RMS value compared with the mechanical seat. This indicates that the characteristics of seat suspension systems affect vibration behavior differently under various operating conditions and that optimal performance depends on the combination of seat design and road surface type.

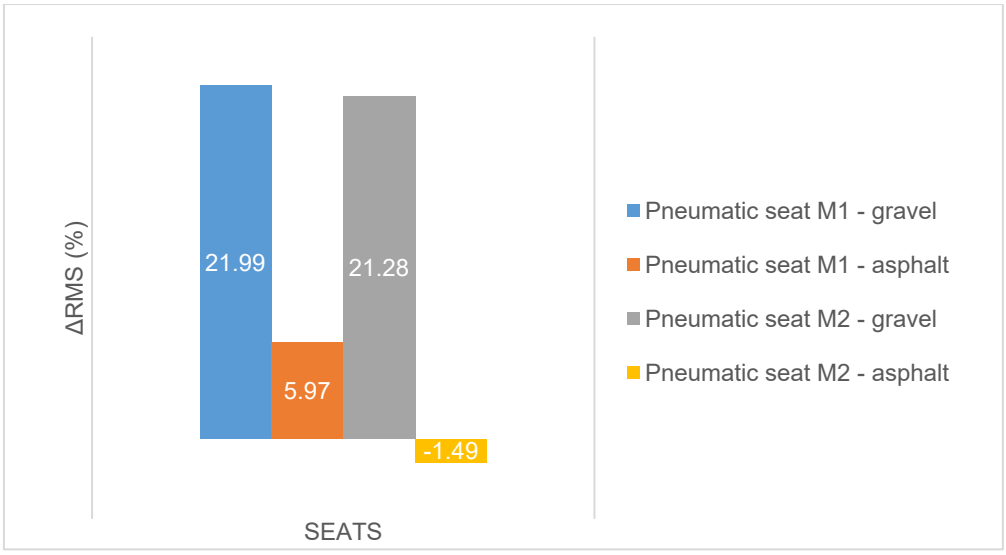


Figure 9 Percentage reduction of RMS acceleration for pneumatic seats compared with the mechanical seat on different road surfaces

Figure 9 presents the percentage differences in RMS acceleration values of the pneumatic seats compared with the mechanical seat. The negative value clearly indicates the case of the pneumatic seat from Manufacturer 2 on the asphalt surface, which exhibited a higher RMS acceleration value than the mechanical seat.

Evaluation of vibration exposure based on the ISO 2631 standard

The driver's vibration exposure level was assessed by comparing the obtained RMS values with the criteria specified in the ISO 2631 standard (Table 3).

Table 3 Comparison of RMS acceleration values with ISO 2631 comfort criteria

Condition	RMS (m/s^2)	ISO 2631 criteria	Reduction (%)
Gravel – Mechanical seat	1.41	Very uncomfortable	/
Gravel – Pneumatic seat M1	1.10	Uncomfortable	21,99
Gravel – Pneumatic seat M2	1.11	Uncomfortable	21.28
Asphalt – Mechanical seat	0.67	Fairly uncomfortable	/
Asphalt – Pneumatic seat M1	0.63	A little uncomfortable	5.97
Asphalt – Pneumatic seat M2	0.68	Fairly uncomfortable	-1.49

Under the guidelines of the ISO 2631 standard, an increase in RMS acceleration values indicates reduced comfort and heightened vibration exposure for the driver. The obtained results show that lower RMS values were recorded during driving on the asphalt surface compared with the gravel surface; however, all analyzed cases corresponded to the “fairly uncomfortable” level based on these criteria.

Significantly higher RMS values were recorded on the gravel surface, indicating a higher vibration load on the driver. The highest value was measured for the mechanical seat, while both pneumatic seats achieved lower RMS values, confirming their higher effectiveness in vibration attenuation under more demanding operating conditions.

During driving on the asphalt surface, the differences between the investigated seats were considerably less pronounced. The pneumatic seat from Manufacturer 1 achieved the lowest RMS value, while the RMS value recorded for the seat from Manufacturer 2 was approximately equal to, or slightly higher than, that of the mechanical seat. These results indicate that the effect of applying a pneumatic seat suspension system depends not only on the operating principle of the seat but also on its design characteristics and operating conditions.

CONCLUSIONS

This paper presents an experimental analysis of whole-body vibrations to which a truck driver is exposed when using different seat design solutions and under various operating conditions. The study included a comparison of a mechanical seat and pneumatic seats during vehicle operation on asphalt and gravel surfaces. Based on the measured acceleration signals, the main vibration parameters were determined and analyzed, with particular emphasis on RMS acceleration values.

The obtained results confirm that road surface characteristics represent one of the dominant factors influencing the level of vibrations transmitted to the driver. Driving on a gravel surface resulted in significantly higher vibration acceleration levels compared with asphalt, as a consequence of more pronounced surface irregularities, higher dynamic excitation, and less favorable vibration transmission conditions through the vehicle–seat–driver system.

The analysis of the influence of seat design showed that pneumatic seats generally demonstrated improved vibration attenuation performance compared with the conventional mechanical seat under the tested conditions. The lower RMS acceleration values recorded for pneumatic seats indicate a higher vibration isolation capability and a reduction in the vibration exposure transmitted to the driver. Compared with the mechanical seat, the pneumatic seat from Manufacturer 1 achieved an RMS acceleration reduction of approximately 22%, while the pneumatic seat from Manufacturer 2 achieved a reduction of approximately 21%. These differences were observed on the gravel surface, where the effect of the seat suspension system was most pronounced.

The comparison of different seat types indicates that the design characteristics of the suspension system have a significant influence on vibration transmission at the driver–vehicle contact interface. The application of pneumatic seat suspension systems can contribute to reducing whole-body vibration exposure and improving driver comfort, particularly in vehicles operating under variable and demanding conditions.

Based on the conducted research, it can be concluded that the selection of an appropriate seat suspension system represents an important factor in improving the driver's working environment in heavy-duty vehicles. The obtained results provide a basis for further investigations focused on detailed frequency-domain analysis of vibration signals, determination of transfer characteristics of the vehicle–seat–driver system, and development of advanced approaches for vibration exposure assessment under real operating conditions.

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