24th COBEM - 2017

24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-0166
EVALUATION OF THE FLOOR-SEAT TRANSMISSIBILITY (SEAT) IN RIDING VEHICLES AND VERIFICATION OF VIBRATION LEVELS REGARDING HEALTH AND COMFORT IN WBV

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Abstract. *The whole-body vibration (WBV) in passengers is one of the important factors in assessing the comfort of a vehicle. In this work, two seat-pads were used to measure the vibration in three axes on the floor and in the seat of an economy vehicle in normal use. The test campaign comprises a route that is composed of two types of track, one made of smooth asphalt, and another one, composed of cobbled stones. An algorithm in Matlab ™ was developed and implemented for field measurements as well as routines for data post-processing and vibration evaluation for comfort and health according to ISO 2631-1 (1997) and NR-15. For the performed measurements, floor-seat transmissibility is calculated for the three axes in order to evaluate the effectiveness of the seat. It was found that at 4.08 Hz frequency, the transmissibility for the vertical axis of the seat showed a resonance with a gain factor of 3.48, and that this value of transmissibility is greatly reduced at higher frequencies. These results show good agreement with similar studies available in the literature. The SEAT values for the three axes were calculated, obtaining a value of 70% in the vertical direction, and 118% in the horizontal direction corresponding to acceleration and braking of the vehicle. It was also possible to evaluate that for the measured case, vibration limits for exposure times of 8 hours are reached in the floor, but not at the seat of the vehicle.*

Keywords: *Transmissibility; WBV; SEAT value; Vibration in vehicles; Health.*

1. INTRODUCTION

In the automotive industry the comfort, safety, and conditions of use of the automobiles are increasingly being used as comparative purposes. The vibration which affects the occupant during daily use influence in these three items, being one of the main criteria in the choice of a car model (Griffin, 1990). Besides influencing in the comfort, studies suggest that prolonged exposure to whole body vibration may lead to fatigue and diseases (Bovenzi, 2005), being common in professional drivers the occurrence of back pain due to vibration.

Because most of the vibration experienced by a passenger is transmitted by the seat, this ends up being object of study of the industries, seeking to achieve a construction that allows most of the vibration suffered by the vehicle to be attenuated and not transmitted to the occupant (Griffin, 1990).

In the present study, the tri-axial transmissibility between the floor and the base of the passenger seat of a ride car under normal conditions of use is measured. In order to obtain a single index that evaluates the efficiency of the seat throughout the measured frequency range, the SEAT value was calculated and compared with similar works available in the literature. The evaluation was also carried out regarding comfort and health risk based on the standard ISO 2631-1 (1997).

2. ASSESSMENT OF HEALTH AND COMFORT DUE TO VIBRATION

The most common way of evaluating vibration magnitude is by the rms (root mean squared) value (Fernandes,2000). However, vibration signal with different spectral content may have identical intensities but have different effects on the human body (Griffin, 1990). To quantify this effect, standard ISO 2631-1 (1997) proposes weighting curves, which will assign different weights to the rms acceleration depending on their frequency and the corresponding parts of the human body. The result of the weighting process is the weighted rms acceleration a_w (m/s^2) which is calculated according to the Eq. (1):

$$a_w = [\sum (W_i a_i)^2]^{\frac{1}{2}} \ , \tag{1}$$

where W_i are the weighting factors indicated by the standard and a_i means the rms acceleration.

The standard ISO 2631-1 (1997) also indicates different weighting curves depending where the measurement is performed and the purpose of the assessment (health or comfort). The related curves used in this work are indicated in Tab.1:

Table 1. Weighting curves according to ISO 2631-1

Weighting curve	**Health**	**Comfort**
W_K	Z axis, seat surface measurement.	Z axis, seat surface measurement X, Y and Z axis, foot level measurement (floor)
W_d	X axis, seat surface measurement. Y axis, seat surface measurement.	X axis, seat surface measurement Y axis, seat surface measurement.

Because measurement is performed on all three axes, the values a_{wx}, a_{wy} and a_{wz} are obtained, which represent the weighted acceleration values obtained in the x, y and z axes respectively. To ease subsequent comparison with limit values it is necessary to obtain a unique value of acceleration, called vibration total value a_v. According to the standard ISO 2631-1 (1997), Eq. (2) evaluates this value:

$$a_v = \sqrt{k_x{}^2 a_{wx}{}^2 + k_y{}^2 a_{wy}{}^2 + k_z{}^2 a_{wz}{}^2} \ , \tag{2}$$

where k_x, k_y and k_z are the multiplying factors of the measuring position, which depend on the axis on which the measurement occurs, and the purpose of the assessment (health or comfort). The used multiplying factors are as follows in Tab. 2:

Table 2. Multiplying factors according to ISO 2631-1(1997).

Multiplying factors	**Health**	**Comfort**
k_x	1.4 (floor and seat)	1.0 (seat); 0.25 (floor)
k_y	1.4 (floor and seat)	1.0 (seat); 0.25 (floor)
k_z	1.0 (floor and seat)	1.0 (seat); 0.4 (floor)

For cases where exposure to vibration occurs in two or more periods for different durations and magnitudes, the equivalent vibration magnitude a_{ve} corresponding to the total duration of exposure should be calculated as indicated by Eq. (3):

$$a_{ve} = \left[\frac{\sum (a_{vi}{}^2 T_i)}{\sum T_i} \right]^{\frac{1}{2}} , \tag{3}$$

where a_{vi} is the vibration magnitude in m/s^2 for a duration of T_i, and i is the corresponding period.

To set vibration limit values, the standard indicates the use of the daily exposure value A(8), given by-Eq. (4):

$$A(8) = a_{ve}\sqrt{\frac{T}{T_o}} \,, \quad (4)$$

where T_0 is a reference time duration of 8 hours. The value given by A(8) can be understood as the weighted total vibration that corresponds to a daily working exposure of 8 hours, as the average exposure over an 8-hour day, facilitating comparisons with pre-established limits.

Two limit values are indicated for A(8). One of these limits is the EAV (exposure action value), which when exceeded indicates the need for actions that result in decreasing the level of vibration, but without presenting a high risk to health.

The other limit value used is the ELV (exposure limit value), which represents the level of vibration that once exceeded presents a high risk to health, being necessary measures that eliminate the vibration, and that defines insalubrity due to vibration exposure. The standard presents the option of using two equations to evaluate limit values, and in this work, we assumed to use the equation that presents the smallest values, since it is a more conservative option. The limit values used are the limits present in ISO 2631-1 (1997) and in the regulatory standard number 15 (NR-15, 2014), which sets limits for assessing and characterizing unhealthy activities and operations. These limits are shown in the Tab.3:

Table 3. Vibration limit values according to ISO 2631-1(1997) and NR-15(2014).

	EAV	ELV
Limit values NR-15 (2014) $[m/s^2]$	0.55*	1.10
Limit values ISO 2631-1 (1997) $[m/s^2]$	0.43**	0.87**

*Value determined as half the limit value.

**Values obtained by interpolation of the graph of ISO 2631-1 (1997) for 8 hours of exposure.

In relation to comfort, the standard ISO 2631-1 (1997) provides a scale that uses the equivalent vibration magnitude as reference, which is shown in Tab. 4:

Table 4. Discomfort scale according to ISO 2631-1

Vibration range $[m/s^2]$	**Comfort index**
Less than 0.315	Comfortable
0.315-0.63	A little uncomfortable
0.5-1	Fairly uncomfortable
0.8-1.6	Uncomfortable
1.25-2.5	Very uncomfortable
Greater than 2.0	Extremely uncomfortable

3. TRANSMISSIBILITY

Many studies evaluating automotive seats are carried out based on the subjective opinion of test pilots (Zhen, 2014) but this procedure provides tendentious and widely dispersed measurements. A quantitative and reliable way to perform measurements of the effectiveness of a particular seat is by calculating the SEAT (seat effective amplitude transmissibility) value (Griffin, 1990). This technique allows to obtain the ratio between the acceleration of the output (seat) in relation to the acceleration of the input (floor) in a certain direction in the tested frequency band.

The Eq. (5) shows how to calculate the SEAT value using the integral of the PSD (power spectral density) (Griffin, 1990):

$$SEAT\% = \sqrt{\frac{\int G_s(f)W_i^2(f)df}{\int G_f(f)W_i^2(f)df}}x100 \,, \quad (5)$$

where $G_s(f)$ is the seat PSD, $G_f(f)$ is the floor PSD and W_i are the weighting curves. The transmissibility, in turn, can be calculated in two equivalent ways (Maia *et al*, 1997). The first form uses the ratio between the input and output PSD:

$$H_{fs}(f)=\sqrt{\frac{G_s(f)}{G_f(f)}} \quad (6)$$

The second way of calculating the transmissibility is through the CSD (cross spectral density) between the output and the input:

$$H_{fs}(f)=\frac{G_{fs}(f)}{G_f(f)} \quad (7)$$

Since both equations must provide the same value, one can use the ratio between them as a measure of coherence γ between the input signal and the output signal, which is shown in the Eq. (8).

$$\gamma^2(f)=\frac{\left|G_{fs}(f)\right|^2}{G_f(f)G_s(f)} \quad (8)$$

The coherence value γ is value between 0 and 1. Values close to 1 indicates a good correlation between the two signals being analyzed. Near anti resonances, the values may vary since there are phase shifts between signals.

If the transmissibility can be reliably calculated, then the relation show in Eq. (9) to the SEAT value is valid:

$$SEAT\%=\sqrt{\frac{\int G_f(f)\left|H_{fs}(f)\right|^2 W_i(f)^2\,df}{\int G_f(f)W_i(f)^2\,df}} \quad (9)$$

4. METHODOLOGY

The measurements were performed on a 1000cc car, at passenger's seat and floor. The equipment used for measurement consisted of two accelerometers ADXL 335 with three axes, which has a nominal sensitivity of 300 $\frac{mV}{g}$ in each of its axes. Each accelerometer is inserted and fixed inside a seat-pad made of flexible silicone in disc format, according to the original design suggested by SAE. The seat-pad has the function to change as little as possible the dynamic properties of the interface between the passenger and the seat surface in order to maintain the measurement compatible with the condition of use. In Fig. 1 is show a cross-sectional photo of the seat-pad according to the SAE design:

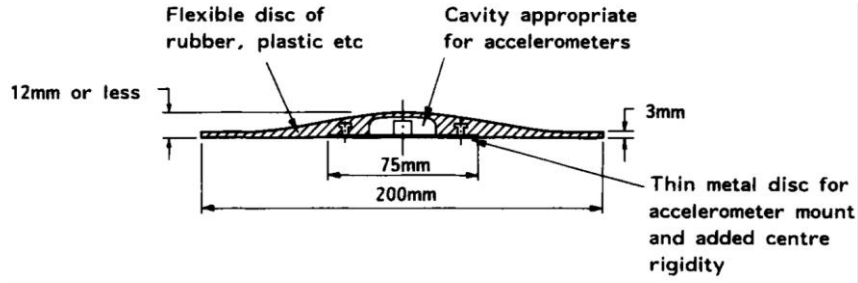

Figure 1. Cross section according to the design according to Society of Automotive Engineers (SAE) (Adapted from Griffin, 1990).

The seat-pads are positioned inside the car, one of them is arranged on the floor of the vehicle and the other on the base of the passenger seat, where a passenger weighing 90 kg will be sitting during the measurements. The position and direction of the axes of both accelerometers were arranged according to standard ISO 2631-1 (1997), depicted in Fig.2:

The data is acquired by an USB-1208 acquisition card from MCC and are transmitted in real time to a laptop through a script developed in Matlab™. According to ISO 2631-1 (1997) [3] the relevant frequency spectrum for human health and comfort is between 1Hz and 80Hz. Due to this an acquisition rate of 500Hz was imposed, in order to be above the Nyquist sampling frequency value. The measurement duration was 1200 seconds (20 minutes), comprising a distance of approximately 8.2 Km. The route was chosen to represent different surface conditions, one consisting of asphalt and the other of cobblestone, thus obtaining a more representative data of the use of the vehicle. Fig.3 shows the two road situations measured:

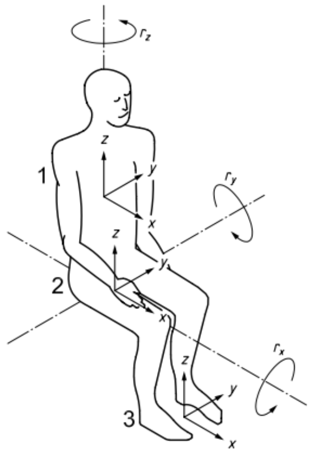

Figure 2. Basicentric axes for measuring vibration in the human body according to standard ISO 2631-1(1997), Amendment 1, 2010.

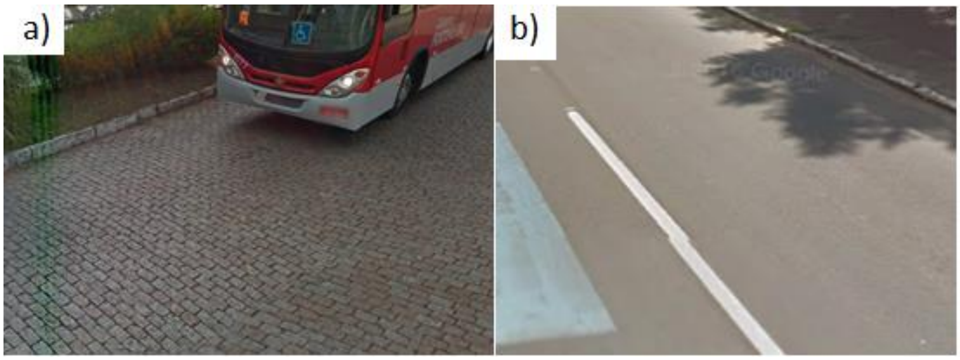

Figure 3. Measured road situations. (a) cobblestone, (b) asphalt.

5. RESULTS

The evaluation of vibration at the floor and seat in relation to the comfort provides the following results, shown in Tab.5, for the equivalent vibration magnitude (a_{ve}):

Table 5. Equivalent vibration magnitude for evaluation of comfort.

Measuring point	**Equivalent vibration magnitude**
Floor	0.256 m/s^2
Seat	0.497 m/s^2

Thus, it can be seen that the measures indicate values between comfortable and a little uncomfortable. The equivalent vibration on the floor is less than that of the seat because in the case of comfort evaluation the standard provides specific weighting curves for seat and floor.

For the evaluation of health risks with measurements at the floor the same weighting curves were used as those used for the measurement on the seat. Below in Tab.6, are the results for the daily exposure value A(8):

Table 6. Daily exposure value A(8).

Measuring point	A(8)
Floor	1.675 m/s^2
Seat	0.567 m/s^2

Comparing with the limit values shown in Table 3 we note that the vibration value for the floor measurement is well above the exposure limit value, while the value obtained in the seat is slightly above the exposure action value. This indicates a great attenuation effect due to the presence of the seat. In order to better investigate this attenuation, in the following a study of the transmissibility is performed.

The PSD of the acceleration in each direction and in both positions are shown in Fig.4 and in Fig.5:

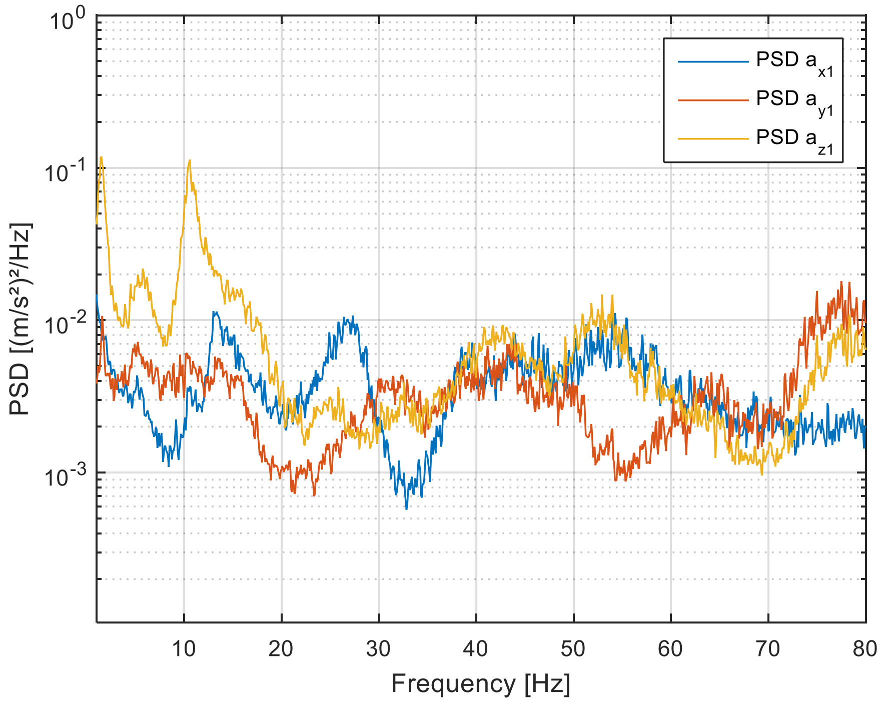

Figure 4. Measured PSD curves for car’s floor, in three directions.

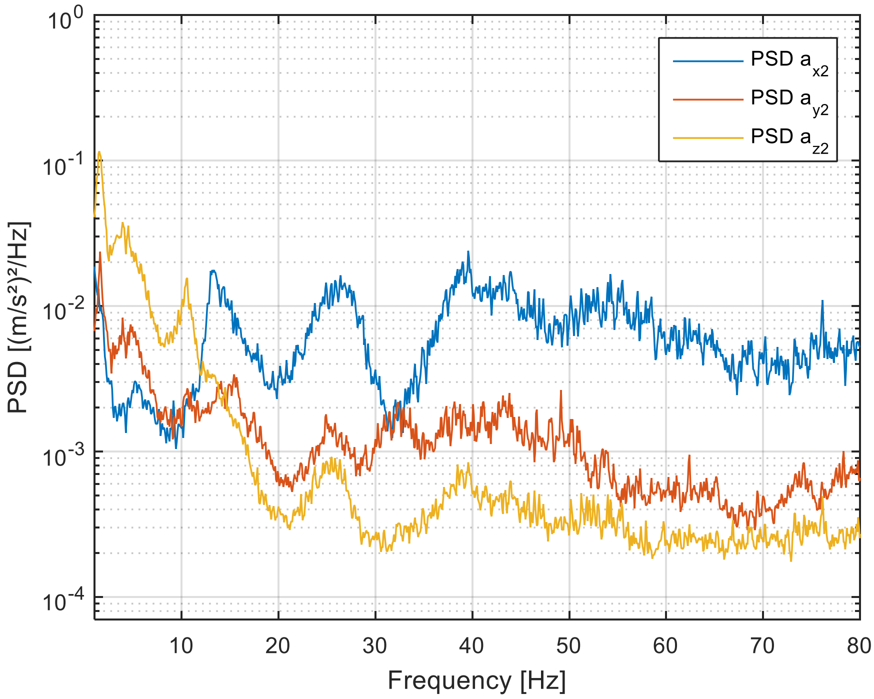

Figure 5. Measured PSD curves at car’s seat, in three directions.

Both graphs show that the most expressive values of vibration frequencies go up to 20Hz, consistent with the typical vibration in cars. It is also noted that the vibration on the vertical axis is at least one order of magnitude larger than on the other two axes, which is also expected. With the PSD values, the analysis of transmissibility and coherence can be performed, according to Eq. (6-8).

The results obtained for the transmissibility and coherence for the three axes are shown in Fig.6 and Fig.7:

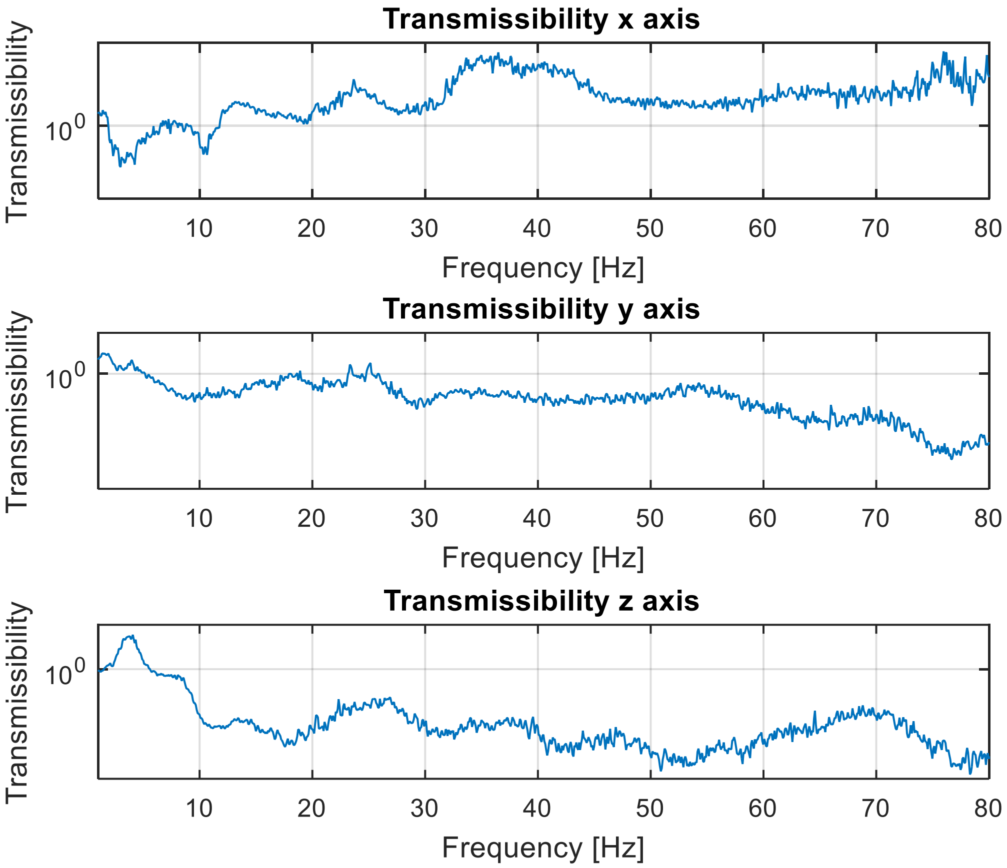

Figure 6. Results of the calculation of transmissibility for the three axes.

The results show for the vertical vibration that a peak in the value of vertical transmissibility occurs around 4.08 Hz, with a gain of 3.4 times. This is due to the fact that the natural frequency of the seat is close to this value. Similar studies available in the literature show that a peak of transmissibility close to 4 Hz is common in seats of ride vehicle (Mansfield, 2005; Van Niekerk *et al*, 2003; Kumar *et al*, 2016). In contrast, for frequencies greater than 10Hz the seat acts effectively in the vibration attenuation, providing transmissibility values lower than 0.35 in the remaining spectrum.

Using the Eq. 9 the calculation of the SEAT value for the X, Y and Z directions is performed. The result obtained is show in the Tab.7 below:

Table 7. SEAT values for each direction

Direction	**SEAT value (%)**
X	118.9
Y	73.8
Z	70.2

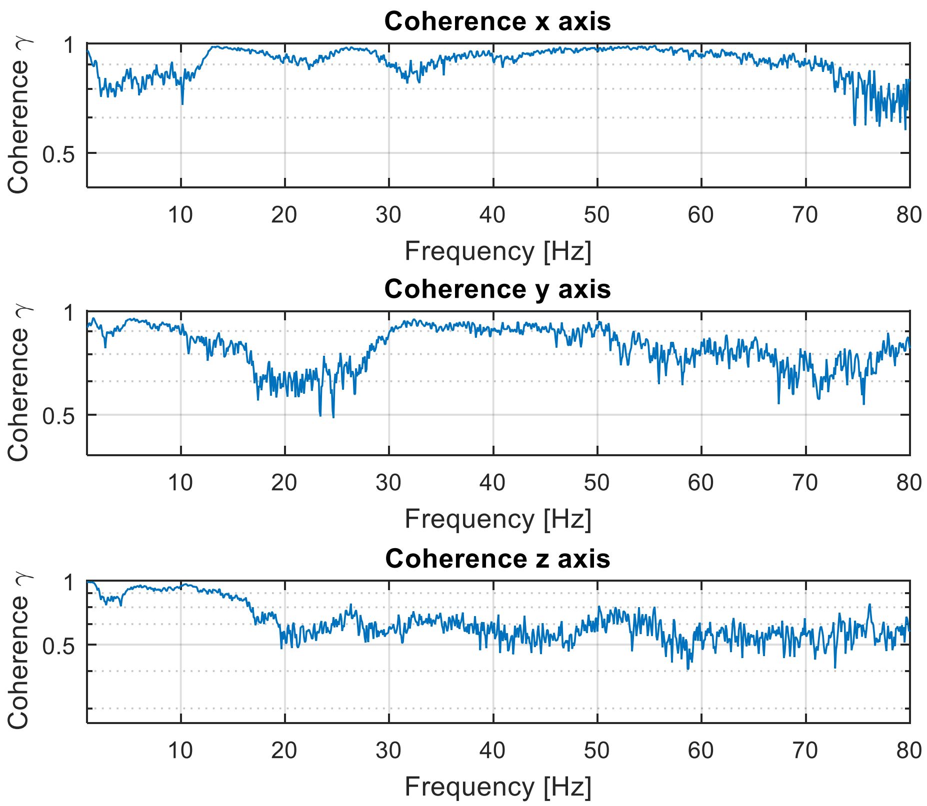

Figure 7. Results of the calculation of coherence for the three axes.

This result shows an efficacy of about 30% in the attenuation of the vibration in the main direction of stimulation, the vertical direction (Z). The value obtained for the SEAT value in this direction is close to that found in recent works (Van Niekerk *et al*, 2003; Paddan *et al*, 2001). However, in the horizontal direction, corresponding to the X axis in Fig.2, a 19% amplification occurs in the vibration. This shows that while the seat is able to attenuate the vertical vibrations for which it is designed, it is ineffective in the attenuation of vibrations due to accelerations and braking of the vehicle(in fact for direction x, there is an amplification), causing discomfort in the passenger. For SEAT values in the horizontal directions, no values were found in the literature for comparison.

In order to obtain statistical information on the result, the measurement was divided into 6 sections, comprising about 3 minutes and 40 seconds each. The SEAT value was calculated for each section using the student's t-distribution, and for a confidence level of 95%, the confidence interval was calculated. The results are shown in Tab.8. The confidence intervals shows that the SEAT values (mainly for the z direction) does not vary significantly during the trip, despite the diverse types of road roughness. This is a good indicative of the linear behavior of the seat.

Table 8. 95% Confidence intervals for SEAT values.

	Mean (%)	**CI (95%)**
SEAT in X direction	117.0	$\pm$ 46.8
SEAT in Y direction	81.8	$\pm$ 25.5
SEAT in Z direction	71.1	$\pm$ 4.28

6. CONCLUSIONS

The instrumentation applied to the vehicle allowed to obtain the PSD curves related to the acceleration in the floor and seat of the vehicle. The corresponding transmissibility curves were obtained, which indicated seat resonance for vertical vibration around 4.08 Hz with a gain that reaches a value around 3.4. For higher vibration frequencies, the seat acts as expected, efficiently attenuating the vibration. In order to obtain a single index that evaluates the efficiency of the seat throughout the measured frequency range, the SEAT value was calculated. As expected, the index reported that it was obtained an attenuation of about 30 % in the vertical vibration, although in the direction corresponding to acceleration and braking of the vehicle, the seat acts not efficiently attenuating the vibration, promoting an amplification, e.g., for the x direction of about 19%.

In terms of health, the vibration levels on the floor significantly exceeds the recommend ELV value reported in standards ISO 2631-1 (1997) and NR-15 (2014), while the seat vibration is slightly above the EAV value. Concerning comfort, the measured levels indicate values that can be classified as comfortable (floor) to a little uncomfortable (seat).

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