



24th COBEM - 2017



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

COBEM-2017-0053

ANALYSIS OF VIBRATION IN URBAN TRAIN COMMUTERS IN PORTO ALEGRE AND METROPOLITAN REGION CONCERNING COMFORT AND HEALTH

Mário Fedatto Neto

Herbert Martins Gomes

Federal University of Rio Grande do Sul, 425 Sarmiento Leite St. – Porto Alegre/RS, Brasil

mariofedatto@hotmail.com

herbert@mecanica.ufrgs.br

Abstract. *Urban trains and subways are a Brazilian reality. One aspect that is delegated to the background, concerns the quality transportation referred to availability, capacity and safety. Lately, vibration and noise produced by this means of transport have been affecting life quality of surrounding areas as the comfort of the users. In this paper, the whole body vibration levels in urban trains in Porto Alegre (Trensurb) are evaluated in some situations. The vibration dose value and rms acceleration, when compared to standards, showed very low values. Those values were measured at the seatback, seat and floor of the train seats at some points inside the vehicle and it was found below the action limit (0.5 to 1.1 m/s²) and far from the exposure limit. Generally speaking, the measured vibration levels are considered comfortable, however, in some positions and situation they can be considered uncomfortable.*

Keywords WBV, trains, comfort, health, vibration.

1. INTRODUCTION

As stated in Fedatto Neto (2016) some daily activities expose people to vibrations. The human organism has natural vibration modes and when this vibration coincides with an externally received vibration, resonance may occur. This energy, when absorbed by the body, can cause changes in the tissues and organs. Bruel and Kajer (1989) says that the vibration received by the body can be classified into two major groups: Hand-Arm Vibration (HAV) and Whole-Body Vibration (WBV). The two forms can pose risks to the human being, depending on the range of intensity and the period of exposure to such vibrational modulations, which can be sources of discomfort and cause of health problems.

Griffin (1990) defines that the vibration felt by the human body is not expected to have a single, simple, or easily predictable consequence. Vibration can be an uncomfortable, nauseating, stimulating or unbearable, a source of pleasure or the cause of pain. An oscillatory movement may cause irritation, discomfort, interfere with normal daily activities, impair health or cause motion sickness, and depends on a variety of factors - including movement characteristics, personal characteristics, activities performed and other aspects of the environment (temperature, humidity, noise, etc.). Trying to summarize with a single recommendation to avoid some frequency of vibration, or by defining a single curve representing all responses to all frequencies of the human body, doesn't reflect a modern understanding of the effects of vibration on the body.

Trains and subways provide a place with complex movements in all directions, generated by rails, vehicle, floor, seat, and backrest. Passengers score how comfortable their journey is based not only on the movement offered by the wagon, but on the interaction of a number of factors such as noise, temperature, humidity, air quality, odors, and aspects of cleanliness and comfort of seat cushion.

The subway Trensurb, at Porto Alegre, announced in May 2014 the purchase of 15 new trains, and affirmed that the users might expect more comfort and an expansion in the locomotion offer. Due to complaints about previous trains, and praise of new trains, the theme of this work is chosen to assess the current vibration levels of these vehicles. Academic studies on vibration level evaluation for passenger comfort in trains and subways in Brazil. There is only ISO 2631-4 standard as the most appropriate standard, in this context, it is still very dependent on ISO 2631-1 recommendations regarding vibrations in general.

This work is part of an attempt to evaluate and compare values of whole-body vibration in three different positions on two distinct vehicles. These standards refer to health and comfort and allow to check if the vibration limits of exposure are preserved users of Trensurb Porto Alegre and metropolitan region. They also allow verifying comfort levels and here in this paper, a compilation of authors and standards are used to check comfort levels. These authors are

found in Harris et al. 2002 and Griffin, 1990, as Fothergrill, 1972; Osborne and Clark, 1974; Jones and Saunders, 1974; Fothergrill and Griffin, 1977; British Standard 6841, 1987; ISO 2631, 1997. This work also intends to check the results against the recent regulatory standard annex 1 of NR-9 (2014), following the measurement procedures depicted in NHO-09, 2013 and NR-15, 2014.

2. MATERIALS AND METHODOLOGY

2.1 Proceedings and equipment

In order to determine the vibrational values effectively transmitted to the body, it was used accelerometers, strategically positioned in a contact plate compatible with the reading equipment. In this case, the equipment used to store the collected data is the portable Quest VI-400Pro vibration meter and analyzer (Quest-Technology, 2005). This apparatus can interpret the information presented by four different input channels, however, in the present experiment, only three of these channels were used for the stimuli received in the axis x, y and z.

To generate the input data required by the analyzer, a three-axis transducer accelerometer is used to convert the mechanical energy generated by the acceleration of the interface of body and vibration surface into proportional electrical signals, so that the mechanical excitation, perceived by the accelerometers is understood to the analyzer. The applied transducer is a seat pad, which is a disc with the outer edge made of a flexible material, to get the shape of the measurement interface site and with a rigid core that contains the encapsulated accelerometers, in a standardized way, to keep fixed at the user interface and surface allowing a readings of tri-axial vibration without relative displacements. The seat pad was properly positioned at the interface between the subject and seat, feet and floor, and backrest, where there is a vibration transfer from the train. The orientation follows ISO 2631-1, 1997, requirements as indicated in Figure 1; the alignment position between the seat pad core and the measurement place was also checked.

In order to acquire all the data required for a scientific analysis, the compatible software tool Quest Suite Professional II was used, which allows the calibration of the analyzer according to the weighting curves required for the desired analysis purpose and with the proper set of required multiplication factors. After preparing the measuring devices and storing the data it is necessary to check and set all the information. The same program that allows the calibration presents post-processing tools that produce graphs with all the necessary information for the vibration evaluation. Figure 1 shows the position of the seat pad on the seat and at backrest.

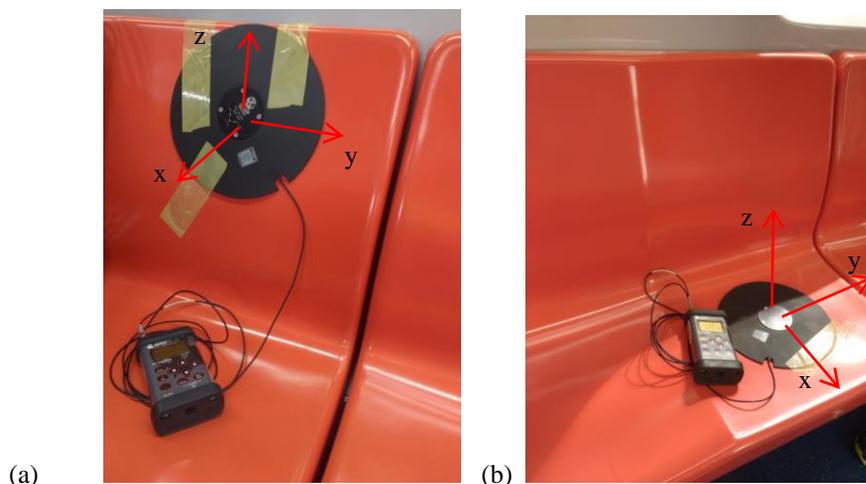


Figure 1. (a) Seatpad positioned at the backrest for vibration measurement. (b) Seatpad positioned on the seat. The coordinate system indicates the final orientation of the accelerometers.

2.2 Standard for WBV analysis

To analyze and quantify the effects of whole-body vibration on the human body it's necessary to pay attention to the standards that regulate and standardize measurements procedures and the analysis of vibrations that should be performed. There are international and national standards that deal with the theme, so for the present work, the recommendations and directions of ISO (International Organization for Standardization), European Directive (European Directive 2002/44 / CE) and Brazilian standards (NR - Regulatory Norms and NHO - Norms of Occupational Hygiene) are used. The ISO standards used were: ISO 2631-1, 1997, which deals with the appropriate methods for determining values related to vibration and comfort and human health; ISO 2631-4, 2001, which deals with guidelines for evaluating the effects of vibration and comfort on a rail transport system.

The European Directive consulted was 2002/44 / EC (2002) which sets the exposure limit values for a worker in Europe, in the face of whole body vibrations and their respective level of daily exposure. Within the national standards, the regulatory standard NR-15, Annex 8 (2014) was used, which presents the limits of daily exposure to consider a work activity as unhealthy at Brazilian territory; and the Occupational Hygiene Standard, written by

FUNDACENTRO, NHO 09, 2013, that presents criteria and measurement procedures for the assessment of WBV on workers. Based on this standardization, the values for whole body vibration indicating an unhealthy condition are those that alternatively or concomitantly exceed the daily vibration exposure limit of 1.1 m/s² and a Vibration Dose Value (VDV) of 21.0 m/s^{1.75}.

3. RESULTS

3.1 Evaluation concerning health and comfort

The following are the measured values on the seat, backrest and floor of the Trensurb during an average transit day in two different situations: the first one, measured in the brand new vehicle, and the second one in the old model train, both at the normal track full trip, from the Public Market station - Porto Alegre, to Novo Hamburgo station - Novo Hamburgo.

For each proposed configuration, the respective weighted rms acceleration values were obtained for the three axes defined by ISO 2631-1, 1997 and NHO-09, 2013. These weighted rms accelerations have their readings obtained by the equipment that was set to use the correct weight curve. Total vibration is calculated with the use of the values measured in the field using these accelerations and the suitable multiplication factors for whole-body vibration health evaluation (NHO-09, 2013, the acceleration vector sum should be used).

Using the total vibration value, it's possible to calculate the acceleration resulting from the normalized exposure, where the daily exposure time the worker is exposed to vibration, is compared with the value of an 8-hour exposure. A summary of the measured values is shown in Tab. 1 below:

Table 1. Health and comfort vibration limits.

Health (NR-15, 2014)	
Exposure Action Value: EAV	0,5 m/s ²
Exposure Limit Value: ELV	1,1 m/s ²
Comfort (ISO 2361-1, 1997)	
Not uncomfortable	< 0,315 m/s ²
A little uncomfortable	0,63 m/s ²
Fairly uncomfortable	1,0 m/s ²
Uncomfortable	1,6 m/s ²
Very Uncomfortable	2,5 m/s ²
Extremely Uncomfortable	> 2,5 m/s ²

(Source: adapted from ISO 2631-1, 1997 e NR-15, 2014)

3.2 Results for seat

The first data reading refers to the seat in which the passenger travels. The choice position of the measured seat was random. Analyzing the data, it can be said that the indicated values for the new train seat present a safe exposure level to vibration for health. Furthermore, for the measured total rms acceleration value, there is a level of vibration that can be considered "comfortable" (sum rms of Table 2 compared to the comfort levels of ISO 2631, 1997). Figure 2 indicates the rms acceleration signal for each axis in this situation, where it is possible to observe the decrease in the level of acceleration at each station stop. Table 2 summarizes the statistical values for this measurement.

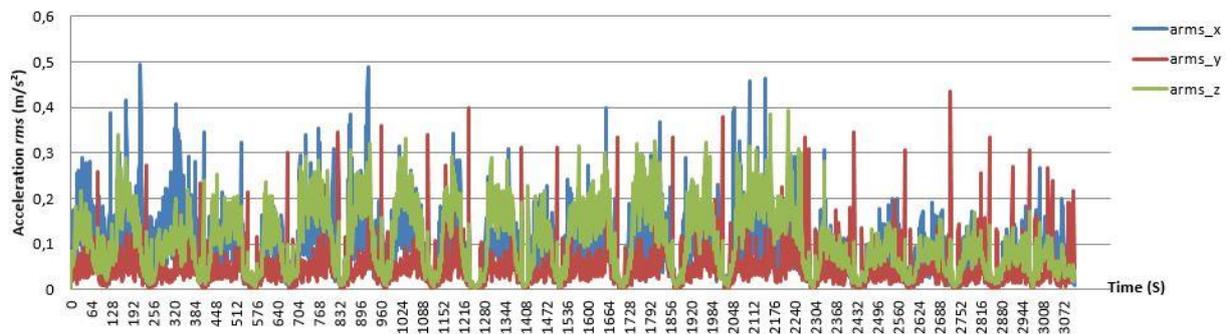


Figure 2. Graph of rms accelerations along train route: measurement performed on the new train.

Table 2. Measured and calculated accelerations for seat on the new train.

MEASUREMENT TIME	0.86	hours			
AXIS	X	Y	Z	SUM ⁽¹⁾	
RMS	0.1169	0.0652	0.1264	0.1841	m/s ²
VDV	1.3813	0.9951	1.501	2.2694	m/s ^{1.75}
Max rms			0.1264		m/s ²
A(8), Max RMS			0.0604		m/s ²
Max VDV			1.5006		m/s ^{1.75}
VDV (8)			1.3004		
EXPOSURE TIME	8.00	hours			
	X	Y	Z	SUM	
Time to achieve EAV	146.3274	470.9387	125.2487	59.0266	hours
Time to achieve ELV	708.2247	2279.3432	606.2037	285.6886	hours
A(8) equivalent	0.1169	0.0652	0.1264	0.1841	m/s ²
EXPOSURE TIME	0.86	hours	= MEASUR. TIME		
	X	Y	Z	SUM	
Time to achieve EAV	169.6550	546.0158	145.2159	68.4366	hours
Time to achieve ELV	821.1301	2642.7167	702.8449	331.2332	hours

Hypotheses:

i) If the EXPOSURE TIME is equal to the MEASUREMENT TIME

To reach EAV 68.44 hours EAV not reached

To reach ELV 331.23 hours ELV not reached

ii) If EXPOSURE TIME is 8h and the MEASUREMENT TIME is representative of these 8h

To reach EAV 59.03 hours EAV not reached

To reach ELV 285.69 hours ELV not reached

Comfort rating (ISO 2631,1997)

Comfortable

(1) SUM indicates the vector weighted sum in the form: $a_v = \sqrt{k_x^2 \cdot a_{wx}^2 + k_y^2 \cdot a_{wy}^2 + k_z^2 \cdot a_{wz}^2}$

The graph shown in Figure 3 indicates the rms acceleration signal for each axis in this situation on the old train. Analyzing now the data and performing the relevant calculations to the values of the old train, it's observed, in this case, that the action limit value is reached in less than 8h in a representative time, thus making the exposure of a passenger in a workday susceptible to take some action to minimize this exposure. Furthermore, the comfort values in Table 3 from ISO are related to the measured rms, which in this condition indicates a situation slightly comfortable for the passenger. Compared to the new train, this figure is 2.5 times higher than the new train, which proved to be more comfortable than the old one.

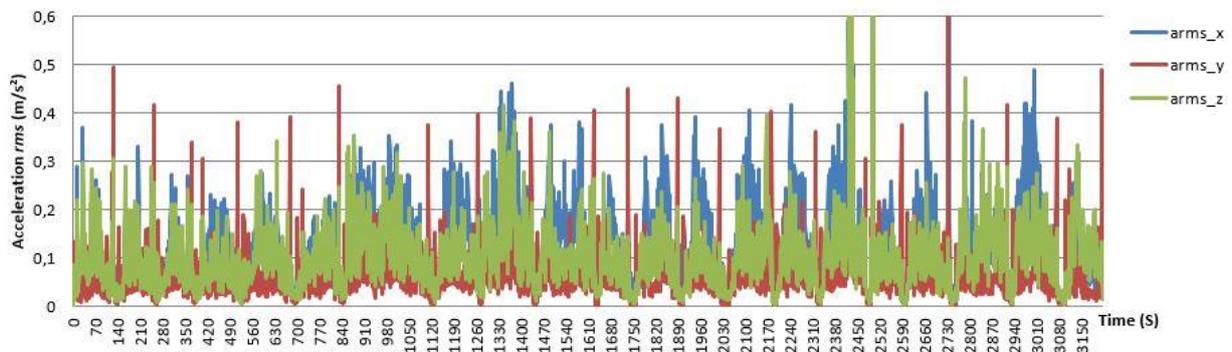


Figure 3. Graph of accelerations rms while the apparatus was installed in the seat: measurement performed in the old train.

Table 3. Measured and calculated accelerations for the seat on the old train.

MEASUREMENT TIME	0.89	hours			
AXES	X	Y	Z	SUM	
RMS	0.2592	0.3419	0.2636	0.5035	m/s ²
VDV	15.6831	21.1541	14.848	23.5837	m/s ^{1.75}
Max rms			0.3419		m/s ²
A(8), Max RMS			0.1683		m/s ²
Max VDV			21.1541		m/s ^{1.75}
VDV (8)			13.6352		
EXPOSURE TIME	8.00	hours			
	X	Y	Z	SUM	
Time to achieve EAV	29.7713	17.1107	28.7921	7.8887	hours
Time to achieve ELV	144.0933	82.8158	139.3537	38.1812	hours
A(8) equivalent	0.2592	0.3419	0.2636	0.5035	m/s ²
EXPOSURE TIME	0.89	hours	= MEASUR. TIME		
	X	Y	Z	SUM	
Time to achieve EAV	33.3054	19.1419	32.2099	8.8251	hours
Time to achieve ELV	161.1982	92.6466	155.8960	42.7135	hours

Hypotheses:

i) If the EXPOSURE TIME is equal to the MEASUREMENT TIME

To reach EAV	8.83	hours	EAV not reached
To reach ELV	42.71	hours	ELV not reached

ii) If EXPOSURE TIME is 8h and the MEASUREMENT TIME is the representative of these 8h

To reach EAV	7.89	hours	EAV reached
To reach ELV	38.18	hours	ELV not reached

Comfort rating (ISO 2631,1997) Slightly comfortable

3.3 Results for backrest

Analyzing the data and calculating the values for the seat on the old train, one has a health condition and, compared to ISO comfort values, it is rated as a comfortable level of vibration exposure. For the new train values, the measured values show that there is also a comfortable level of exposure and a safe condition against vibration. Unlike for the seat, in the case of the backrest, both trains (new and old) have similar levels of acceleration, not having improvements in this aspect for the new train.

3.4 Results for train's floor

The third and last data reading refer to the floor that the user is in contact during the journey (Table 4 and Table 5). Figure 4 indicates the readings made for case pf the new train and in Figure 5, for the old train.

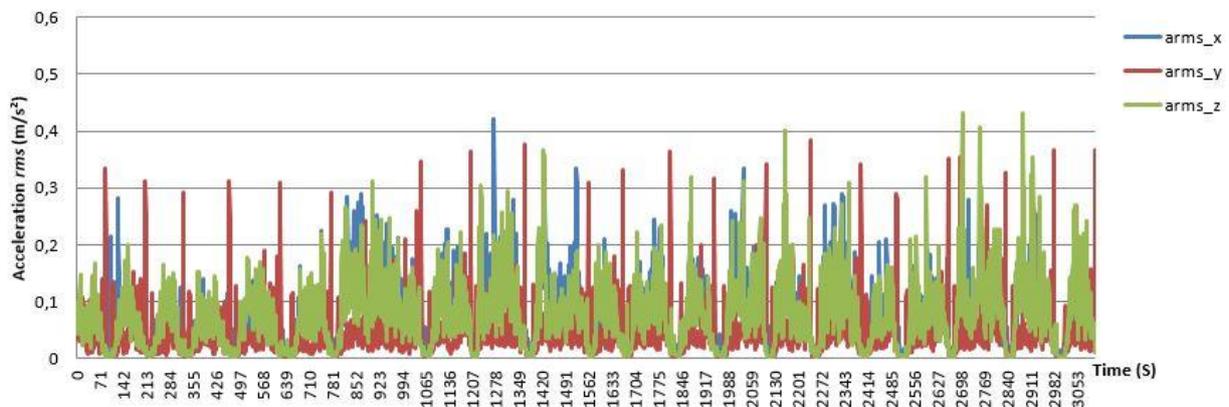


Figure 4. Graph of rms accelerations where the apparatus is installed on the train floor: measurement performed on the new train.

Table 4. Measured and calculated accelerations for the floor on the new train.

MEASUREMENT TIME	0.86	hours			
AXES	X	Y	Z	SUM	
RMS	0.0992	0.0654	0.0975	0.1537	m/s ²
VDV	1.2091	1.0198	1.185	1.5095	m/s ^{1.75}
Max rms			0.0992		m/s ²
A(8), Max RMS			0.0505		m/s ²
Max VDV			1.2091		m/s ^{1.75}
VDV (8)			0.8653		
EXPOSURE TIME	8.00	hours			
	X	Y	Z	SUM	
Time to achieve EAV	203.2198	468.0851	210.4561	84.6831	hours
Time to achieve ELV	983.5839	2265.5318	1018.6075	409.8663	hours
A(8) equivalent	0.0992	0.0654	0.0975	0.1537	m/s ²
EXPOSURE TIME	0.86	hours	= MEASUR. TIME		
	X	Y	Z	SUM	
Time to achieve EAV	235.3140	542.0091	243.6931	98.0570	hours
Time to achieve ELV	1138.9199	2623.3240	1179.4748	474.5959	hours

Hypotheses:

- i) If the EXPOSURE TIME is equal to the MEASUREMENT TIME
- | | | | |
|--------------|--------|-------|-----------------|
| To reach EAV | 98.06 | hours | EAV not reached |
| To reach ELV | 474.60 | hours | ELV not reached |
- ii) If EXPOSURE TIME is 8h and the MEASUREMENT TIME is the representative of these 8h
- | | | | |
|--------------|--------|-------|-----------------|
| To reach EAV | 84.68 | hours | EAV not reached |
| To reach ELV | 409.87 | hours | ELV not reached |

Comfort rating (ISO 2631,1997)

Comfortable

This means that, in comparison to regulatory limits, there will be no problems for the user exposed to vibration, in terms of health, if he/she only toured or even spent 8 hours inside the wagons.

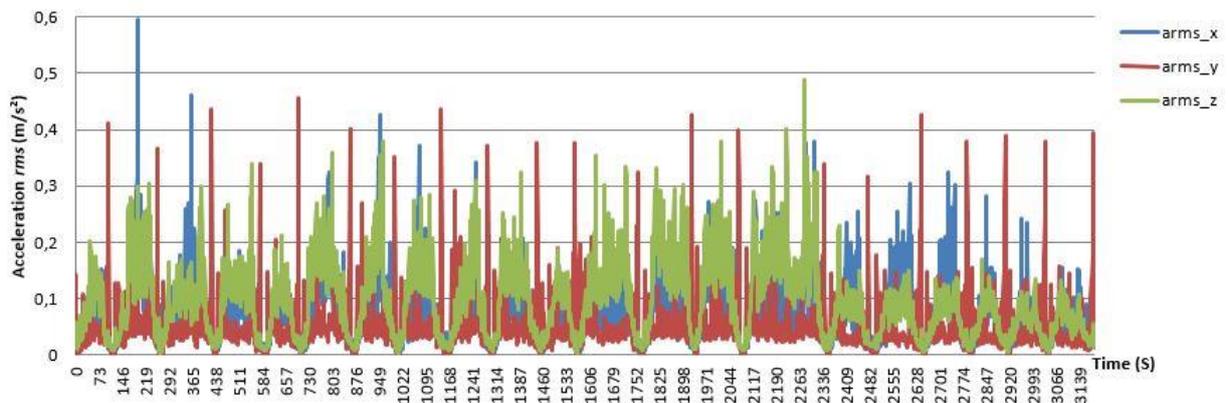


Figure 5. Graph of rms accelerations where the apparatus is installed on the train floor: measurement performed on the old train.

Table 5. Measured and calculated accelerations for the floor on the old train.

MEASUREMENT TIME	0.89	hours			
AXES	X	Y	Z	SUM	
RMS	0.0981	0.0712	0.1169	0.1684	m/s ²
VDV	1.2576	1.3080	1.448	2.3213	m/s ^{1.75}
Max rms			0.1169		m/s ²
A(8), Max RMS			0.0560		m/s ²
Max VDV			1.4478		m/s ^{1.75}
VDV (8)			1.3388		
EXPOSURE TIME	8.00	hours			
	X	Y	Z	SUM	
Time to achieve EAV	207.9281	393.9730	146.4287	70.5375	hours
Time to achieve ELV	1006.3719	1906.8293	708.7150	341.4014	hours
A(8) equivalent	0.0981	0.0712	0.1169	0.1684	m/s ²
EXPOSURE TIME	0.89	hours	= MEASUR. TIME		
	X	Y	Z	SUM	
Time to achieve EAV	234.8733	445.0276	165.4043	79.6783	hours
Time to achieve ELV	1136.7866	2153.9334	800.5566	385.6432	hours

Hypotheses:

- i) If the EXPOSURE TIME is equal to the MEASUREMENT TIME
- | | | | |
|--------------|--------|-------|-----------------|
| To reach EAV | 79.68 | hours | EAV not reached |
| To reach ELV | 385.64 | hours | ELV not reached |
- ii) If EXPOSURE TIME is 8h and the MEASUREMENT TIME is the representative of these 8h
- | | | | |
|--------------|--------|-------|-----------------|
| To reach EAV | 70.54 | hours | EAV not reached |
| To reach ELV | 341.40 | hours | ELV not reached |

Comfort rating (ISO 2631,1997) Comfortable

Finally, analyzing the data and performing the calculations for the values of the old train, it can be said that there will be no problems for the user, in terms of health, if he/she only toured or even spent 8 hours inside the wagons. As for the seat, in the case of floor vibration and comfort, both trains (new and old) have similar acceleration levels, with the new one being slightly better than the old train, both considered as comfortable vibration levels.

Some other authors in the literature also define limits of acceleration values that are appropriate for comfort, and comparing the results with those limits, indicated in Table 6, this also leads to the conclusion that they are all, on average, classified as "comfortable" vibration levels.

Table 6. Limit values for assessing comfort level specified by other authors.

Fothergill, 1972	m/s²	British Standard 6841, 1987	m/s²
Very unpleasant	2.5	Extremely uncomfortable	2.50-3.50
Unpleasant	1.7	Very uncomfortable	1.25-2.50
Mildly unpleasant	1.1	Uncomfortable	0.80-1.60
Not unpleasant	0.7	Mildly uncomfortable	0.50-1.00
Noticeable	0.3	Noticeable	0.315-0.63
Fothergill e Griffin, 1977	m/s²	Not uncomfortable	0.25-0.315
Very uncomfortable	2.7	Oborne e Clarke,1974	m/s²
Uncomfortable	1.8	Very uncomfortable >	2.3
Mildly uncomfortable	1.1	Uncomfortable	2.3
Noticeable, but not uncomfortable	0.4	Fairly uncomfortable	1.2
Jones e Saunders, 1974	m/s²	Fairly comfortable	0.5
Very unpleasant	3.7	Comfortable	0.23

Very uncomfortable	2.2	Very comfortable <	0.23
Uncomfortable	1.2		
Mean threshold of discomfort	0.7		
Not uncomfortable	0.33		

(Source: adapted from Griffin, 1990; Harris *et al.*, 2002; ISO 2631-1, 1997 and Directive 2002/44/EC, 2002)

4. CONCLUSIONS

According to the data from whole-body vibration measurements in comfort assessment purposes, the urban train Trensurb has comfortable vibration levels, even when referring to the vehicle of the old model. There were only one of the ratings indicating "slightly comfortable" for the vehicle of the old model. In a situation of approximately 8 hours of exposure inside the wagon, a situation hardly attained by a passenger, this same passenger would be reaching the action limit value, with the indication that changes in the seat would be necessary to minimize this exposure.

Using NR-15 (2014), the vibration values obtained in terms of the Vibration Dose Value (VDV) have been found to be low and acceptable in the ranges established as dangerous or unhealthy. Regarding the daily exposure to vibration, the values verified were low, all of them being below the range of action, between 0.5 m/s² and very far from the exposure limit of 1.1 m/s². As indicated above, readings for measured vibration (seat and backrest) for comfort are in the classification category "comfortable" according to several other authors and international standards.

During the literature review carried out in this study, it was not found specific reference sources on the level of comfort and health for passengers on urban trains in Brazil, which suggests a theme that can be researched more deeply and that makes this paper a pioneering work on the theme in Brazil. As urban trains are a worldwide means of transportation, research and bibliographic reviews for authors outside the country can generate good comparisons and will certainly result in an improvement in the quality and comfort of transportation for frequent users of this mode of transportation.

Finally, the accomplished work could verify that currently, passengers of the Urban Trains Company in Porto Alegre S.A. are in a comfortable situation in their travels concerning the vibration, with no risk to their health in the usual daily exposure to this transport system.

5. REFERENCES

- Bruel and Kjaer, "Primer: Human Vibration. Booklet". Ed. Bruel & Kjaer, Denmark, 31p.1989.
- Directive 2002/44/EC. "On the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration)". The European Parliament and the Council of the European Union. Official Journal of the European Communities, L177/13-19, 2002.
- Griffin, M. J. "Handbook of Human Vibration". Academic Press, London, 1990. ISBN: 0-12-303040-4.
- Harris, C. M., Piersol, A. G. "Shock and Vibration Handbook". 5th Ed. McGraw-Hill, 1456p. 2002. ISBN: 0-07-137081-1.
- ISO 2631-1:1997. "Mechanical vibration and shock – Evaluation of human exposure to whole body vibration – Part 1: General requirements". International Organization for Standardization, 2007.
- ISO 2631-4:2001. "Mechanical vibration and shock – Evaluation of human exposure to whole body vibration – Part 4: Guidelines for the evaluation of the effects of vibration and rotational motion on passenger and crew comfort in fixed-guideway transport systems". International Organization for Standardization, 2007.
- NHO-09. "Occupational Hygiene Standards. Technical Procedure - Evaluation of Occupational Exposure to Whole Body Vibration" (In Portuguese). Fundacentro. 64p. 2013. [http://www.fundacentro.gov.br/biblioteca/normas-de-higiene-ocupacional/publicacao /detalhe/2013/4/nho-09-procedimento-tecnico-avaliacao-da-exposicao-ocupacional-a-vibracao-de-corpo-inteiro](http://www.fundacentro.gov.br/biblioteca/normas-de-higiene-ocupacional/publicacao/detalhe/2013/4/nho-09-procedimento-tecnico-avaliacao-da-exposicao-ocupacional-a-vibracao-de-corpo-inteiro). Accessed in 30/04/2016.
- NR-09. "Regulatory Standard No.09. Program of prevention of environmental risks - Annex N°1 Vibrations" (In Portuguese). 2014. <http://www.guiatrabalhista.com.br/legislacao/nr/nr9.htm>. Accessed in 26/04/2016.
- NR-15. "Regulatory Standard No.15. Unhealthy Activities and Operations - Annex N°8 Vibrations" (In Portuguese). 2014. [http://www.guiatrabalhista.com.br /legislacao/nr/nr15.htm](http://www.guiatrabalhista.com.br/legislacao/nr/nr15.htm). Accessed on 24/04/2016.
- Quest-Technology. "Real-time vibration Analyzers", VI-400PRO, Preliminary owner's manual. 2005.
- FEDATTO NETO, M. "Whole body vibration levels of evaluation in commuter rail users in Porto Alegre and the metropolitan area". (In Portuguese). 2016. 15f. Monografia (Trabalho de Conclusão do Curso em Engenharia Mecânica) - Departamento de Engenharia Mecânica, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2016.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.