Analysis of vibration levels in users of urban trains

Análise de níveis de vibração em usuários de trens urbanos

Mário Fedatto Neto[a], Herbert Martins Gomes[a]
mariofedatto@hotmail.com, herbert@mecanica.ufrgs.br

[a] Universidade Federal do Rio Grande do Sul – UFRGS

Abstract

Urban trains and subways are a Brazilian reality. One major aspect that is delegated to a second plan, concerns the quality transportation referred to availability, capacity and safety. Lately, vibration and noise produced by this means of transport have been affecting the life quality in neighborhoods as well as their users. In this paper, the whole body vibration levels in urban trains in Porto Alegre (Trensurb) are evaluated in some situations. Regarding the vibration and rms acceleration doses, the measured values were very low for the back, seat and floor in the vehicle which resulted below the action limit 0.5 m/s² thus, far from the exposure limit 1.1 m/s2 for an 8h exposure time. Generally speaking, the measured vibration levels are considered comfortable, according to values defined in standards, however in some positions and situation, they can be considered uncomfortable.

Keywords: Whole Body Vibration (WBV), Trains, Subways, ISO 2631.

Resumo

Os trens urbanos e metrôs são uma realidade brasileira. Um aspecto importante que é delegado a um segundo plano, diz respeito à qualidade do transporte quanto à disponibilidade, lotação e segurança. Ultimamente a vibração e o ruído produzido por estes meios de transporte têm afetado a qualidade de vida nas vizinhanças dos trajetos assim como dos seus usuários. Neste artigo, são avaliados os níveis de vibração de corpo inteiro nos usuários de trens urbanos de Porto Alegre (Trensurb) em situações usuais de utilização. Em relação às doses de vibração e de aceleração rms medidas, quando comparados com normas, essas se mostraram baixas, tendo sido verificados valores avaliados no encosto, assento e piso no veículo, abaixo do nível de ação 0,5 m/s² e portanto, longe do limite de exposição 1,1 m/s2 para exposição de 8h. Em geral, os níveis de vibração medidos foram considerados confortáveis, de acordo com valores definidos em normas, entretanto em algumas situações e posições de medição, mostraram-se desconfortáveis.

Palavras-chave: Vibração de Corpo Inteiro (VCI), Trens, Metrô, ISO 2631.

Introduction

As highlighted by Fedatto Neto (2016), “some activities may expose people to vibrations in a dangerous way”. The human organism has natural modes of vibration, and when this natural mode coincides with an externally received vibration, resonance may occur. This energy, if absorbed by the body, may cause changes in the tissues and organs. Bruel & Kjaer (1989) say that “the vibration received by the body can be classified into two main groups: Hand-Arm Vibration (HAV) and Whole-

Body Vibration (WBV)". Both forms can generate unnecessary risks (like lack of attention in dangerous or liable activities, dizziness, headache in reading, etc.) and even harm the human being depending on the frequency range, intensity and the period of exposure and may cause health problems. In other mild situations, this can be a source of discomfort.

> Griffin (1990) defines that the vibration felt by the human body is not expected to have a single, simple predictable consequence. Vibration can be an uncomfortable, nauseating, stimulating or unbearable, a source of pleasure or the cause of pain. An oscillatory movement can cause irritation, discomfort, interfere with normal daily activities, impair health or cause motion sickness, and depends on several factors - including characteristics of the movement, personal characteristics, concurrent performed activities and other environmental aspects (e.g., temperature, humidity, noise).

Trying to summarize with a single recommendation to avoid some intensity/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 human being.

Studies by Pope and Hansson (1992) indicate that vibrations in the low-frequency range could cause effects like abdominal pain, nausea, chest pain, loss of balance and muscle contractions. Complaints of fatigue, irritation, increased heart rate and even impotence in the male reproductive tract could be observed, from prolonged whole body exposure to vibration. Short-term occupational vibrations are also harmful, physiological effects such as increased heart rate, may also be caused by exposure to short-term vibration.

As reported by Fedatto Neto (2016), "trains and subways offer an environment with complex movements in all directions, generated by rails, vehicle, floor, seat and backrest". Passengers evaluate how comfortable their journey is, not only based on the movement in the wagon, but rather by the interaction of a number of factors such as noise, temperature, humidity, air quality, smells, general aspects of cleaning and seat type and padding.

In 2014, Trensurb (Company of Urban Trains of Porto Alegre) acquired a new train with 15 new wagons and affirmed that commuters might expect more comfort in the daily journeys. Due to complaints about comfort in the previous trains and praise for new trains, this motivated the investigation in this article in order to assess the current vibration levels in both vehicles. Academic studies on the evaluation of the vibration level for passenger's comfort in trains and subways in Brazil and worldwide are scarce. Few national authors have reported measurements in similar situations like such as Balbinot (2001), Anflor (2003), Becker (2006) and Walber (2009), Kaderli e Gomes (2011).

The international standard ISO 2631-4 seems to be the most appropriate standard in this context, although it is very dependent on ISO 2631-1 recommendations in general. This article is part of an attempt to evaluate and compare values of Whole Body Vibration related to comfort, checking measured values against a compilation of authors and regulations. This article also intends to check measured vibration values related to health effects against regulatory standard annex 1 of NR-9 (2014), following the procedures in NHO-09 (FUNDACENTRO, 2013) and NR-15 (2014).

The objective is to evaluate if the limits of exposure to vibration are respected for the users of the Trensurb trains in Porto Alegre and metropolitan region. The measured values regarding comfort are also compared and classified according to five references, as well as those included in ISO 2631-1 (1997).

Literature Review

Vibrations

When discussing vibration, it is critical to establish a definition on the subject in order to better understand the parameters and relationships that are involved. Thus, "vibration is any movement that a body performs around a fixed point, which can be described by its position, velocity or acceleration history, which is the usual way to measure it" (Rao, 2011). This movement, when periodic, is also characterized by the number of times the movement is repeated in a unit time interval and is called the vibration frequency developed by the body (Hertz [Hz]).

In this article, the reference is centered on the human body that is exposed to any vibration transmitted by the vehicle due to an external event, such as the interaction between rails and wheels, curves, acceleration and braking of the train or the relative movement of the propulsion wagon to the train composition. The main effects that are felt by passengers are listed as, but not limited to, the uncomfortable sensation of acceleration when passing in railroad junctions, shaking of the contact areas like feet, hands, back or breech, difficult in reading a newspaper or even the effect in speaking. For the vibration values analysis, it is possible to establish relations that allow a technical-scientific evaluation, the first one by means of the amplitude of vibration over the exposure time, and the second one, by the frequency and amplitude of vibration, known as a frequency spectrum. In this case, the spectrum represents the frequency content of the signals in time, and it is possible to identify which frequency components that are present in the signal, most contribute to the oscillatory movement. The amplitude of vibration may be evaluated by the rms (root mean square) acceleration value, also known as an effective value that allows quantifying the average energy contained in the oscillatory movement, related to the harmful potential of the vibration. "Not only due to the energy contained in the wave that the oscillatory movement causes damage to human tissues but also due to its frequency content" (Griffin, 1990). The rms value can be quantified for an acceleration signal $a(t)$, measured in the time interval $t_1 \leq t \leq t_2$, by:

$$a_{rms} = \sqrt{\frac{1}{t_2 - t_1}\int_{t_1}^{t_2}[a(t)]^2\,dt} \quad (1)$$

The consequence of vibration in human tissues is classified, according to their characteristics by ISO 2631-1 (1997). This classification is based on a simplification of the physical structure of the human body, resulting in a biomechanical system, modeled as a linear system, estimated by means of an equivalence to mass-spring-damped systems with defined natural frequencies. Figure 1, adapted of Brüel & Kjaer (1989), illustrates such simplification of body systems modeled by mass-spring systems. In ISO standard, frequency bands are presented for the main vibrational exposure, for HAV (Hand Arm Vibration) ranging from 6.3 to 1250 Hz and for WBV (Whole Body Vibration), that concerns this research, which ranges from 0.1 to 80 Hz. Accelerations with frequencies in that range affect the body as a whole (Griffin, 1990). The established range can be further divided into two intervals: the first, between 0.1 and 0.5 Hz, which are nausea-generating frequencies and the second interval between 0.5 and 80 Hz, the range for comfort evaluation, perception and health, which is of interest to this study.

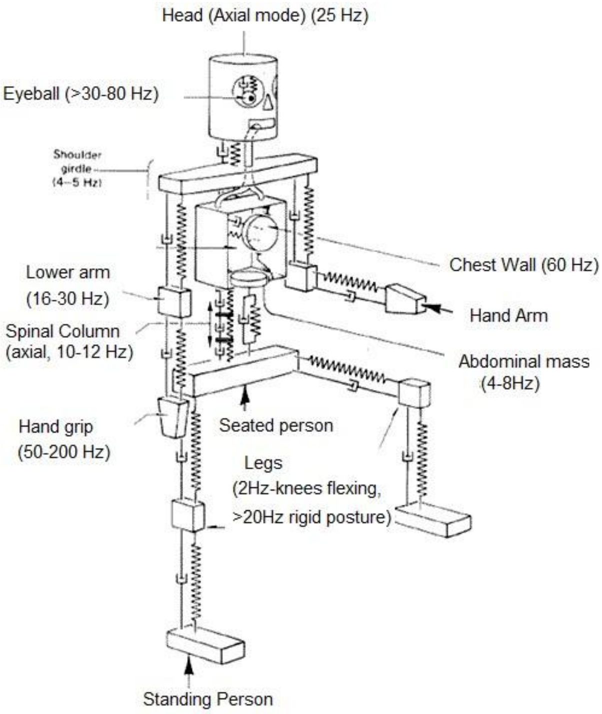

Figure 1. A simplified biomechanical system of the human body.

Effects of vibration in human body

> The movements and oscillations resulting from the application of mechanical forces in the human body have several possible effects: (1) movement can directly interfere with the physical activity of the body; (2) there may be damage or degradation of tissues; (3) there may be side effects (including subjective phenomena), operating through biological receptors and transfer mechanisms, which produce changes in the organism (Harris and Piersol, 2002).

Physiological responses in the cardiovascular, respiratory, skeletal, endocrine and metabolic systems and, in muscles and nerves can be induced by vibration. With the extremely low frequency of vibration, such as occurs in ships and transport vehicles, it can cause motion sickness. The action of the vibration on the human body and the effect on health occurs by the interaction of several circumstantial factors, related to the type of exposure to the oscillatory movement and the individual characteristics. Some of these relevant aspects include but not limited to, the amplitude and the frequency spectrum of vibration, the direction of vibration and the part of human body affected. “Other aspects are related to the form of exposure time in a daily period in which the body is susceptible to it as well as the pre-accumulated exposure” (Harris & Piersol, 2002). In addition to all the mentioned aspects, there are personal factors, such as physical and genetic condition, that can make some people more or less susceptible to diseases caused by the vibration than others in the same exposure situation.

For vertical vibration exposure, there are three frequency bands that affect specific areas in human tissue system under the effect of resonant frequencies. In the interval between 5 and 10 Hz the phenomenon of resonance can be perceived in the chest and abdominal region, in a higher frequency range of 20 to 30 Hz, the affected set is the head and the neck muscles that support head and shoulders, the last frequency range is between 30 and 60 Hz, with incidence of damage to the ocular system (Brüel and Kjaer, 1989, Chaffin and Anderson; Martin, 1999; Griffin, 1990).

Depending on the presence of resonance, problems related to the exposure range for whole body vibration can be detected in public transport commuters and workers. People who are subjected to daily vibrations, within the previously listed bands, are very prone to present problems in the spine, with pains and discomforts, especially in the lumbar region, a support for most of the body weight, when seated to drive. In addition, the literature still mentions the possibility of problems of visual fatigue and remarkable reduction of the sharpness of vision (Griffin, 1990).

The WBV theme is recurrent in the world literature but still incipient in the national literature. Recent literature surveys show this concern regarding user comfort on the effects of WBV vibration on vehicle seats, such as in the works of Zhang, Qiu and Griffin (2015) and Ji, Eger and Dickey (2017) and Nawayseh's work (2015), that investigates the effect of foam and air in seat cushions in the transmissibility of vibration in car and heavy vehicle passengers. The effect of discomfort on drivers, when exposed to long periods driving (Sammonds et al., 2017) and aircraft passenger discomfort assessment (Ciloglu et al., 2015) also indicate that there is a recent concern in the study of materials and solutions to mitigate passenger vibrations in such types of transportation. Unfortunately, from the literature review in the national literature, no studies were found related to the evaluation of the level of exposure to vibration in urban trains, which shows that this study is a pioneer in this type of evaluation.

As mentioned by Fedatto Neto (2016), in the case of urban trains and subways, "the main causes of the vibration transmitted to passengers and drivers are attributed to track irregularities, rail joint, engine, curves, braking and acceleration". Part of the vibrations coming from the track irregularities are partially absorbed and attenuated by the suspension system of the wagons, but impacts and low-frequency vibrations are rarely attenuated. Part of the vibrations is felt by standing users, directly supported on the floor of the wagon and another part on the handlebars and seats. Important aspects related to the positioning of the passengers and drivers in relation to the wagon can also affect the level of vibration, in addition to the direction of the seat in relation to the main direction of movement, the speed of the vehicle as well as padding or dissipative devices and vibration attenuators present in special seats (drivers).

Procedures for WBV evaluation

The rails, wheels, suspension, truck structure, interior accessories and vehicle speed all contribute to the passengers' vibrational experience. When the contribution of the seat to comfort is the first concern, it is vital to make measurements at the seat/body interface. This is the direct area of contact between the structure of the vehicle and the person whose function is to support the body and transmit its weight to the vehicle's own structure. In order to measure and interpret the collected data, there is a methodology and some procedures to be followed that are described in standards. In case of whole-body vibration (WBV), the usual international standards to be followed are ISO 2631-1 (1997), ISO 2631-4 (2001), ISO 2631-5 (2004) and for national standards, Annex 8 from NR-15 (2014) that refers to Annex 1 from NHO 09 (FUNDACENTRO, 2013) as a procedural guide.

According to Fedatto Neto (2016), standards use parameters to quantify and compare acceleration history values like the rms acceleration (root mean square), VDV (vibration dose values), MTVV (maximum vibration transient value), etc. The problem that arises from such an approach is the existence of possible frequency effects that can be neglected by the data acquisition models by use of rms acceleration alone since different frequency spectra can generate similar rms values for acceleration. Furthermore, the effect of the vibrations on these frequencies in each of the coordinate axes will be different since it will affect different parts of the body that may be more sensitive to different acceleration frequency spectra. Therefore, it is necessary to correct the acceleration readings with the application of compensation curves, which attributes weights on the effect of acceleration at some frequencies over others, according to the sensitivity of the human body, for different types and directions of the movement.

Using the weighting curves proposed by Standards, according to the type of exposure and the purposes of the evaluation (health or comfort assessment), this correction generates a new value, aw, the frequency-weighted acceleration. Equation (2) is used for the calculation of the rms weighted acceleration in m/s², where a_i represents the rms acceleration in a given frequency band and W_i is the recommended weighting factor for this band range, as defined in ISO 2631-1 (1997) Standard (Griffin, 1990; Harris and Piersol, 2000):

$$a_w = \sqrt{\sum_i (W_i a_i)^2} \qquad (2)$$

Figure 2 shows the plot of the required frequency weighting curves for the determination of whole-body vibration, the curves W_k and W_d are the only ones applied in the verification of the level of exposure related to WBV health. In view of the weighting curve and the vibration ranges defined by ISO 2631-1 (1997), weighting factors were established that corrects the rms acceleration reading on the longitudinal axis z, by the factor W_k and, on the transverse axes x and y, by the factor W_d, for WBV analysis on the contact surface of the seat. For comfort assessments, it is recommended to use the W_b curve for any axis. As highlighted by Fedatto Neto (2016), ISO 2631-1 (1997) recommends the use of a multiplier factor, k, which has predefined values and is related to the way different parts of the human body perceives the vibration in different directions. The weighting values are also distinguished by the vibration assessment mode, whether it is for health, comfort, perception or motion-sickness analysis.

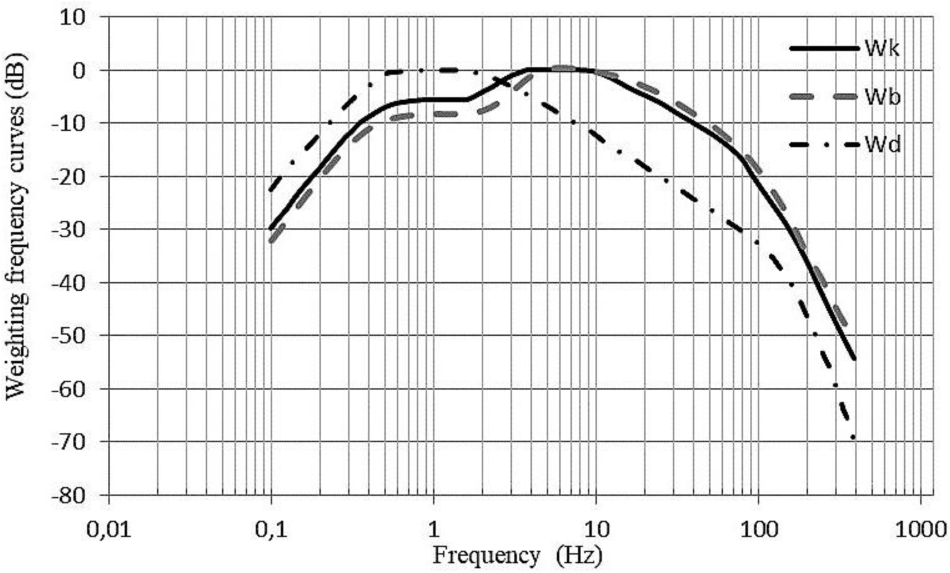

Figure 2. Frequency weighting curves W_k used for acceleration on the z-axis, and W_d, used to x and y-axes accelerations, for WBV. W_b frequency weighting curve used to evaluate comfort for any axis.

ISO 2631-1 (1997) presents values for the multiplication factors and the weights curves that must be applied in the vibration measurements. In this article, the parameters that define the corrections that should be applied are whole body vibration (for seat, backrest and floor) when assessing health and comfort. For each coordinate system axis, there are the corresponding weighting curves and multiplication factors listed in Table 1, adapted for ISO. The same values are recommended by NHO-09 (FUNDACENTRO, 2013) and by ISO 2631-4 (2001).

Table 1. Weighting curves and multiplicative factors for the measurements.

X-axis	Y-axis	Z-axis
Seat surface W_d and $k_x = 1.4$	Seat surface W_d and $k_y = 1.4$	Seat surface W_k and $k_z = 1.0$
Feat W_k and $k_x = 1.0$	Feat W_k and $k_y = 1.0$	Feat W_k and $k_z = 1.0$
Seatback W_c and $k_x = 1.0$	Seatback W_d and $k_y = 1.0$	Seatback W_d and $k_z = 1.0$

Thus, with the definition of the multiplication factors, it is possible to evaluate a total weighted acceleration value, Equation (3), in m/s²:

$$a_v = \sqrt{(k_x a_{wx})^2 + (k_y a_{wy})^2 + (k_z a_{wz})^2} \tag{3}$$

At this point, there is a difference between the recommendations of ISO 2631-1 (1997) and NR-15 (2014). The ISO says that the total acceleration can be used to evaluated vibrations concerning health and comfort if there is no dominant axis of vibration, i.e., the rms accelerations, in the three orthogonal directions have the same magnitude. Otherwise, one should take the main total weighted rms acceleration value to perform the assessment. In the NHO-09 procedure, the corresponding variable is the resulting rms acceleration as indicated by Equation (3).

Another situation that should be observed is the possibility of different exposure times to vibration, with periods that are not equal with different magnitudes. In these situations, the total equivalent acceleration must be determined, a_{ve}, based on the period of time of the exposure, symbolized in Equation (4) by T_i.

$$a_{ve} = \sqrt{\sum a_{vi}{}^2 . T_i / \sum T_i} \tag{4}$$

As the relevant assessment for the health is required to take into account the daily exposure time, as set out in Annex 8 of NR-15 (2014), it is necessary to check the exposure on daily basis in order to be able to compare with the values defined in Standards, compatible with 8-hour daily journey. Therefore, the resulting measured a_v may be representative of the whole exposure time and this value can be directly compared to the limit values. If the total exposure time is different to a work daily journey then using Equation (5) should be used, (Griffin, 1990; Harris and Piersol, 2002).

$$A(8) = a_{ve}\sqrt{T / T_0} \tag{5}$$

where T_0 represents an 8-hour daily working journey; T means a worker's effective journey and ave is the total weighted rms acceleration, when following NHO-09 precepts or the main dominant axis weighted rms acceleration value, when using ISO 2631-1 (2010) whenever one direction dominant vibration axis exists.

Another important aspect is to evaluate the resulting vibration dose value (VDV) that have limits defined by standards. The definition of VDV shows that it is recommended for cases where the values of acceleration have peaked variations, in relation to the usual steady rms values, since it emphasizes the occurrence of eventual peaks, which is not accounted with the rms definition. Equation (6) is applied to evaluate the VDV, where VDV_{total} represents the vibration dose value representative of the daily exposure for several exposure periods. NHO-01 defines the VDVR that represents the vibration dose value that accounts the three axes.

$$\begin{gathered} VDV = [\int_{t_1}^{t_2} [a_w(t)]^4 dt]^{1/4} \\ VDV_{total} = [\sum_j (VDV_j)^4]^{1/4} \ , VDVR = [\sum_j (VDV_{total\ j})^4]^{1/4}, \ j = x, y, z \end{gathered} \tag{6}$$

Concerning the analysis of the experimental data related to the oscillatory movement, it is not restricted to the equation of equivalent acceleration, ISO 2631 (1997) also prescribes the correct position of the vibration axes related to the body position. As shown in Figure 3, for vibrational analysis, the measuring equipment must be positioned so that the z-coordinate is taken on the vertical axis and, on the transverse axes, x and y. Such positioning comes from a basic orthogonal coordinate system, adopting the origin as the point of support of the body, where the vibration is transmitted to the body.

This axial orientation system remains the same for taking measurements transmitted from the seat and floor, altering for the backrest, due to its surface being 90º with the ground plane. Then the person's x-axis becomes the z-axis of the sensor, the y-axis of the person becomes the x-axis of the sensor, and the z-axis of the person becomes the y-axis of the sensor (Figure 3, adapted for 1997 ISO).

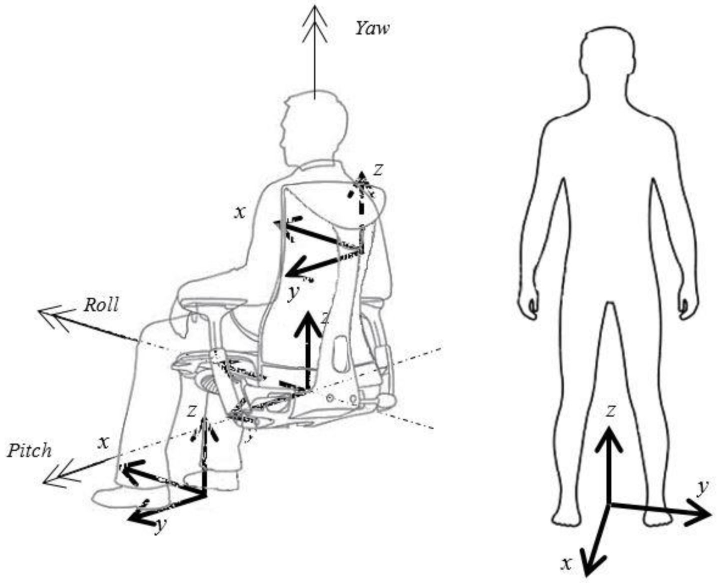

Figure 3. Axes and measurements guidelines for sitting and standing position.

Materials and Methods

Procedures and equipment used

The experimental procedure consisted in taking a full journey for the trains (new and old one) in usual conditions and measure the vibration levels at the seat, seatback and floor. The vibrations are originated by the train movement along the railroad, curves, acceleration and deceleration and then transmitted to wheels, suspension springs, truck and finally to the bodywork where the seats are attached. For the determination of the vibrational values effectively transmitted to the body, accelerometers were used, properly positioned in a contact pad (seat pad) compatible with the reading equipment. In this case, the software used to read and store the collected data is the Quest VI-400 Pro portable vibration meter and analyzer (QUEST TECHNOLOGIES, 2005). This apparatus has the ability to process the information presented by four different input channels, however, in the present experiment, only three of these channels were used for acquiring vibrations in x, y and z-axes.

To generate the input data required by the analyzer, a three axes transducer accelerometer is used to convert the mechanical energy generated by the acceleration measured at the interface into proportional electrical signals so that the mechanical excitation perceived by the accelerometers is processed by the analyzer. The applied transducer is a seat pad that is composed by a rubber disc with the outer edge made of a flexible material to fit the format of the measurement site and with a rigid core where the accelerometers are encapsulated in a standardized way to maintain fixed at the interface, allowing reading of tri-axial vibration without relative displacements. Position the seat pad may vary depending on the required evaluation: (i) at the interface between person and seat, (ii) feet and floor and (iii) passenger and backrest. These interfaces are the areas where transmission of vibration from the train occur, such as in the sitting and standing position, corresponding to the requirements of ISO

2631-1 (1997), as shown in the illustration of Figure 4. The alignment between the seat pad core and the vertical should also be observed.

In order to acquire all the data required for scientific analysis, it is necessary to configure the measuring equipment so that the signals received by the instruments can be interpreted in a coherent way. In this way, the compatible software, Quest Suite Professional II, is used, which allows the definition of sensor calibration constants, multiplicative factor values and definition of weighting curves according to the purpose of the analysis. Once the system has been properly prepared and the field data has been stored, all information has to be debugged. This is performed with the same program, which presents post-processing tools, producing graphs with all the information needed to evaluate the vibration exposure. Figure 4 indicates the position of the seat pad for seat and backrest. One can see that there is no cushion since the seat is molded in fiberglass. The seat pad was placed between foots and keep in this position by the dead-weight of passenger's legs, as shown in the illustration of Figure 4 (c).

(a)
(b)
(c)

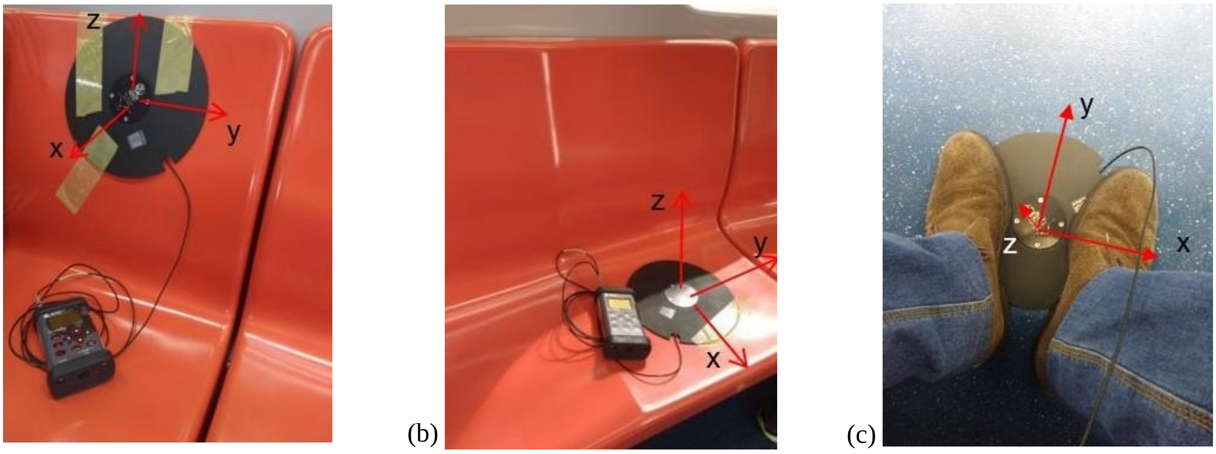

Figure 4. (a) Seat pad correctly positioned on the backrest for vibration measurement procedure; (b) Seat pad correctly positioned on the seat. (c) Seat pad correctly positioned on the train floor. Coordinate axes indicate the orientation of accelerometers.

Models of train under analysis

To determine the level of exposure to vibration, it is important to consider that there is a fleet of trains, divided into wagons of a new model and old ones (still operating), as shown in Figure 5. One can see, in this case, the seat is cushion with foam and leather. For this reason, it was choosing to take the measurements in each train model, new and old one, for the backrest, floor and seat. The measurements were performed during the normal operation of the train, with passenger transportation and at speeds according to usual day trip, from the first station, Public Market in Porto Alegre, to the last station, Novo Hamburgo, located in the city of Novo Hamburgo. Trensurb lane has 22 stations, totaling 43.8 km in length. It carries about 230 thousand people per day.

The fleet consists of 25 Series 100 Trains - old trains - of line 1, each with four cars, two Motor Wagons MA and MB, at the ends and two Race Wagons RA and RB, in the middle. The basic composition consists of MA-RA-RB-MB, which can be operated as a single unit, as well as up to three coupled units (12 cars). The train is made of stainless steel, with 4 doors on each side. The train has open wide gangway with 1600 mm wide and 1900 mm high each, meeting NBR 14021 (2005) and UIC 561 (Union international des Chamins de Fer, 1991) standards, with internal illumination, ventilation and exhaust system, provided by the Japanese consortium led by Mitsui & Co. and manufactured by Nippon Shario Seizo Kaisha Ltd, Hitachi Ltd, and Kawasaki Heavy Industries Ltd. The capacity of seated passengers is 228 and 853 standing, resulting 1081 passengers, at the rate of 5.4 people standing/m². Under regular conditions, the maximum service capacity is 21600 passengers/hour/direction.

(a)  (b) 

Figure 5. Interior view of (a) old and (b) new trains shows differences in seat orientation: new trains have seats oriented only orthogonal to the train movement.

The 15 TUEs of the 200 series - new trains - were delivered by the consortium FrotaPoa, formed by Alstom and CAF. They have energy expenditure of about 30%, lower than the 100 series, automated air conditioning system, multimedia communication system, indoor LED lighting, self-diagnosis and fault monitoring systems. Their basic composition is similar and is allowed to operate coupled. A differentiation of the new trains for the old ones is in the orientation of the seats, which in the new ones is orthogonal to the train movement, whereas in the old ones, they are positioned, in the lateral as well as in the longitudinal direction, only the common direction ware investigated. Regarding the total passenger capacity, it has a similar value per car to the old train, however admitting a greater number of standing people as result of seats' arrangement.

Train line construction commenced in 1980, linking the city center of Porto Alegre to the cities north of the metropolitan area (Canoas, Esteio, Sapucaia do Sul, São Leopoldo and recently Novo Hamburgo), the choice of this route was made in order to serve as a bypass for the BR-116 highway congested traffic, the only way before the train line. The average distance between stations is approximately 2100 meters and the minimum distance is 1500 meters. The nominal stop time at the stations is about 20s, with longer or shorter stops being possible.

The Trensurb train line was inaugurated on March 2, 1985, traveling from the Public Market station, Porto Alegre city, to Sapucaia do Sul city. On December 9, 1997, it was extended to Unisinos and, on November 20, 2000, it already had a station at São Leopoldo center. Finally, on January 30, 2014, the city of Novo Hamburgo was reached, and new four stations were opened, assisting commuters 40 km far from the city center.

The complete measured train line section from Porto Alegre to Novo Hamburgo is shown in Figure 6. This trip takes approximately 52 minutes.

Figure 6. Trensurb route of more than 40 km between the city of Porto Alegre and Novo Hamburgo.

Standards for WBV analysis

To analyze and quantify the effects of whole-body vibration on the human body, it is necessary to pay attention to standards that define the procedures for vibrations measurement and analysis. There are international and national standards that deal with the subject, so that for the present article, the rules from ISO (International Organization for Standardization), European Directive and Brazilian standards (NR-Regulatory Standards and NHO-Standards Occupational hygiene) are observed. The used ISO standards were: ISO 2631-1 (1997) which deals with appropriate methods for evaluating vibration levels for comfort and human health; ISO 2631-4 (2001) which deals with guidelines for assessing the effects of vibration and comfort on fixed-guideway transport systems.

The Directive 2002/44/EC (European Agency for Safety and Health at Work, 2002) presents limit values of exposure for workers in Europe facing whole body vibrations and the respective daily exposure level. Within the national regulations, the NR-15 regulation (Brazilian Association of

Technical Standards, 2014) is used. It presents vibration limits for daily exposure while the Occupational Hygiene Standard NHO 09 (FUNDACENTRO, 2013) shows criteria and procedures for the evaluation of WBV on workers. On the basis of the standardization, which is expressly set out in Annex 8 of the Occupational Hygiene Standard, the values related to the whole body vibration that indicate the existence of an unhealthy condition are those that exceed the daily exposure limits of 1.1 m/s^2 of acceleration, corresponding to a resulting Vibration Dose Value (VDV) of 21.0 $m/s^{1,75}$.

Results

Assessment of comfort and health risk

In the following, the measured values on the seat, backrest and floor of Trensurb trains during a regular day trip in two different situations are analyzed: (1) new model vehicle in its regular and complete trip; (2) old model train, following the same complete route from the Public Market station - Porto Alegre to Novo Hamburgo station.

For each proposed configuration, the respective rms weighted acceleration values were measured, in the three orthogonal axes, stipulated by ISO 2631-1 (1997) and also NHO-09 (FUNDACENTRO, 2013). These rms accelerations were obtained using accelerometers and are conventionally called by a_{wx}, a_{wy} and a_{wz}, indicating that they are weighted by their respective weighting curves. By means of these partial accelerations, the total vibration a_v is obtained by application of Equation (3) and with the multiplication factors adequate to evaluate the whole body vibration regarding health risk. NHO-09 (FUNDACENTRO, 2013) suggests that this vector sum should be used.

With the total vibration value, it becomes possible calculating the acceleration resulting from the normalized exposure by Equation (5), $A(8)$, where the daily exposure of the worker to the vibration is presented, and then confronted with the value relative to a daily exposure of 8-hours.

A summary of the values that will be evaluated is shown in Table 2. ELV is the exposure limit value for a daily vibration exposure and EAV means exposure action value. Where EAV as not defined in NR-15, but estimated in this study as half of the ELV, and the exposure limit value as same as ARNE (Acceleration Resulting from Normalized Exposure).

Table 2. Vibration limits for health and comfort.

Health (NR-15, 2014)	
Vibration Action Exposure: EAV	0,5 m/s²
Vibration Limit Exposure: ELV	1,1 m/s²
Comfort (ISO 2631-1, 1997)	
Comfortable	< 0,315 m/s²
A Little Uncomfortable	0,63 m/s²
Fairly Uncomfortable	1,0 m/s²
Uncomfortable	1,6 m/s²
Very Uncomfortable	2,5 m/s²
Extremely Uncomfortable	> 2,5 m/s²

For each trip and measured position (floor, backrest and seat) a table was generated by the commercial software Quest Pro. It contains summarized data regarding the 3 axis acceleration as well as statistical values like rms values, maximum acceleration values, vibration dose value and extrapolations for time to achieve exposure limit value and/or exposure action value.

Measurements results for the seat

The first data analysis refers to the seats the passenger travels. The choice in the position of the measured seat was random according to the availability during the trip, most of the time, near the middle of the train. This makes the influence of vibration of the two support trucks of the wagon less sensitive but may result in a lower vibration level. By analyzing the data, it can be said that the values in terms of health risk, indicates that the seat of the new train presents a safe level for vibration exposure. In addition, there is a level of vibration that can be considered "comfortable" (sum rms of the third line of Table 3, compared to the comfort levels of ISO 2631-1, 1997) for the total rms acceleration value. Figure 7 shows the rms acceleration signal for each axis in this situation. It is possible to observe the decrease in the level of acceleration at the stop at each station for the three axes. Table 3 summarizes some statistical values in this measurement. Relevant data such as VDV, maximum rms for each axis and maximum VDV are also presented for each measurement. In this Table 3, SUM indicates the vector weighted sum as indicated by Equation (3).

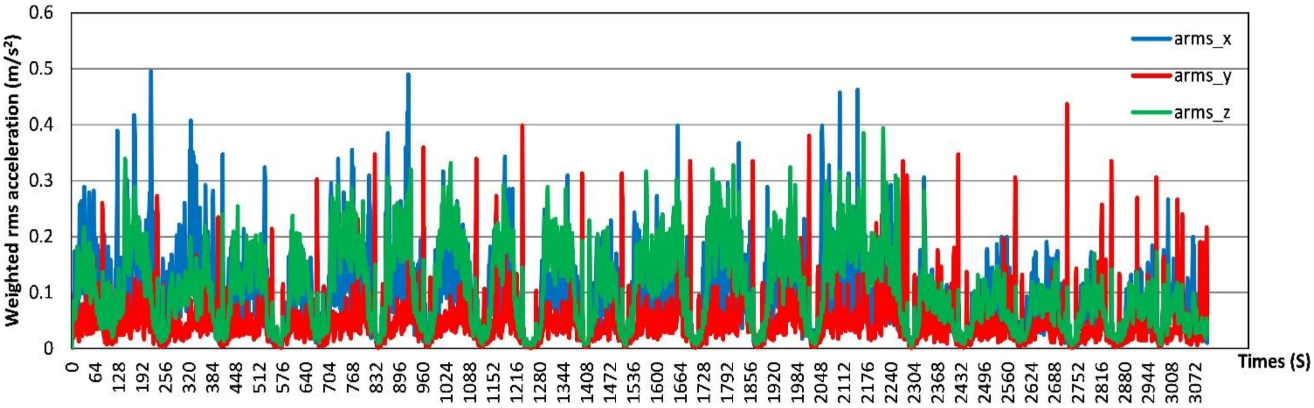

Figure 7. Rms acceleration values on the seat along the trip performed on the new train.

Table 3. Measured accelerations and calculated exposure times in a seat of the new train.

MEASUREMENT TIME	0,86 h			
	X	Y	Z	SUM
rms (m/s²)	0.12	0.07	0.13	0.18
VDV ($m/s^{1.75}$)	1.38	1.00	1.50	2.27
EXPOSURE TIME	8 h			
	X	Y	Z	SUM
Time to achieve EAV (h)	146.33	470.94	125.25	59.03
Time to achieve ELV (h)	708.22	2279.34	606.20	285.69
A(8) [m/s²]	0.12	0.07	0.13	0.18
EXPOSURE TIME	0,86 h			
	X	Y	Z	SUM
Time to achieve EAV (h)	169.66	546.02	145.22	68.44
Time to achieve ELV (h)	821.13	2642.72	702.84	331.23
Comfort rating (ISO 2631-1, 1997)			Comfortable	

The graph, shown in Figure 8, indicates the rms acceleration signal for each axis in the old train for the same previous situation and seat position. By now, analyzing the data and performing the relevant calculations for the old train, it is observed that, in this case, the limit action value is reached in less than 8-hours in a representative time, thus making the exposure in a working day of a passenger susceptible to taking action to minimize this exposure. One can say that regarding the comfort values defined by ISO 2631-1 (1997), the total rms acceleration (rms sum of Table 4) in this situation, is slightly comfortable for the passenger although when compared with the new train, this value is 2.5 times higher, which indicates the new train to be more comfortable than the old one.

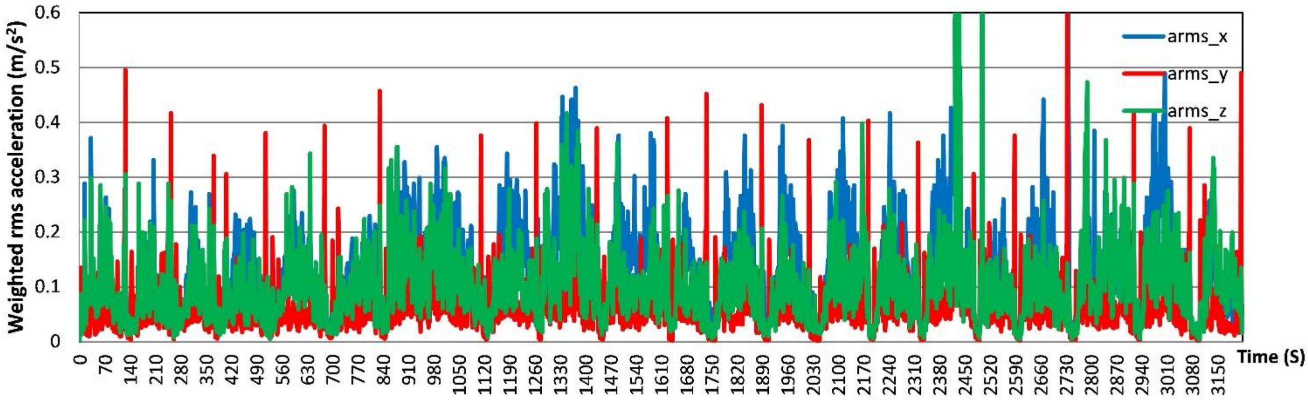

Figure 8. Rms acceleration values on the seat along the trip performed on the old train.

Table 4. Measured accelerations and calculated exposure times in a seat of the old train.

MEASUREMENT TIME	0,89 h			
	X	Y	Z	SUM
rms (m/s²)	0.26	0.34	0.26	0.50
VDV ($m/s^{1.75}$)	15.68	21.15	14.85	23.58
EXPOSURE TIME	8 h			
	X	Y	Z	SUM
Time to achieve EAV (h)	29.77	17.11	28.79	7.89
Time to achieve ELV (h)	144.09	82.82	139.35	38.18
A(8) [m/s²]	0.26	0.34	0.26	0.50
EXPOSURE TIME	0,89 h			
	X	Y	Z	SUM
Time to achieve EAV (h)	33.31	19.15	32.21	8.83
Time to achieve ELV (h)	161.20	92.65	155.90	42.71
Comfort rating (ISO 2631-1, 1997)			Slightly Comfortable	

In summary, by analyzing the data and calculating the exposure times for the old train seat, although with higher vibration levels than the new train, there is a health safety condition and the new train can be rated as a comfortable for vibration.

Measurements results for the backrest

For the new train values, the analysis of the measured values showed that, for the backrest, a comfortable level of acceleration is attained, as well as a safe condition against vibration. Unlike for the seat, in the case of the backrest, both trains (new and old) presented similar acceleration levels, and there were no improvements in this regard for the new train.

Measurements results for the floor

The third and last acquired data refer to the floor vibration where the passenger is leaning on during the trip (Table 5 summarizes the tests for the new train and Table 6 for the old one). Figure 9 shows the weighted rms acceleration values for the new train case and, in Figure 10, for the old train.

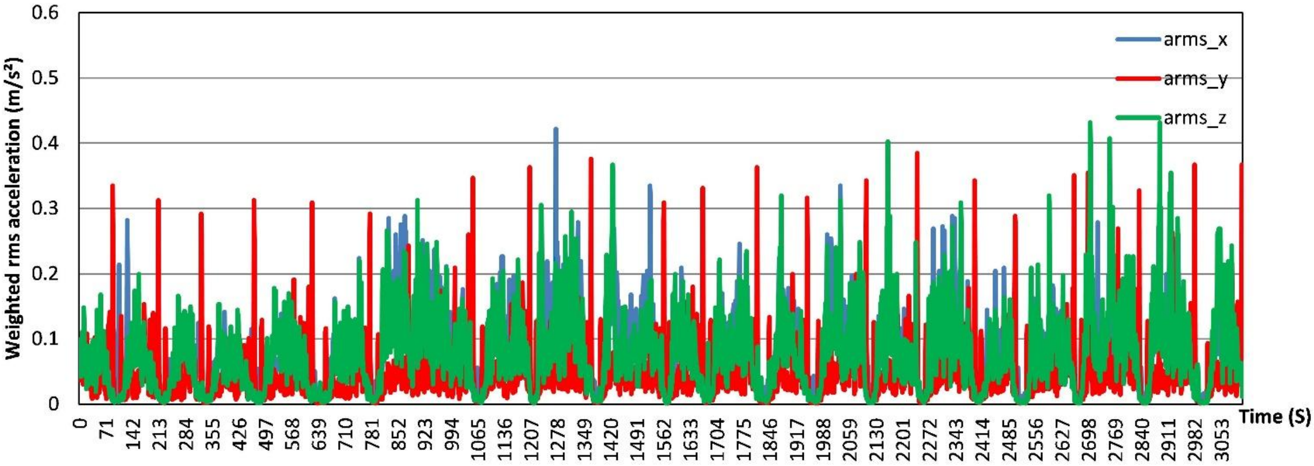

Figure 9. Rms acceleration values on the train's floor along the trip performed on the new train.

Table 5. Measured accelerations and calculated exposure times in the floor of the new train.

MEASUREMENT TIME	0,86 h			
	X	Y	Z	SUM
rms (m/s²)	0.10	0.07	0.10	0.50
VDV ($m/s^{1.75}$)	1.21	1.02	1.19	1.51
EXPOSURE TIME	8 h			
	X	Y	Z	SUM
Time to achieve EAV (h)	203.22	468.08	210.46	84.68
Time to achieve ELV (h)	983.58	2265.53	1018.6	409.87
A(8) [m/s²]	0.10	0.06	0.10	0.15
EXPOSURE TIME	0,86 h			
	X	Y	Z	SUM
Time to achieve EAV (h)	235.31	542.01	243.69	98.06
Time to achieve ELV (h)	1138.92	2623.32	1179.47	474.59
Comfort rating (ISO 2631-1, 1997)			Comfortable	

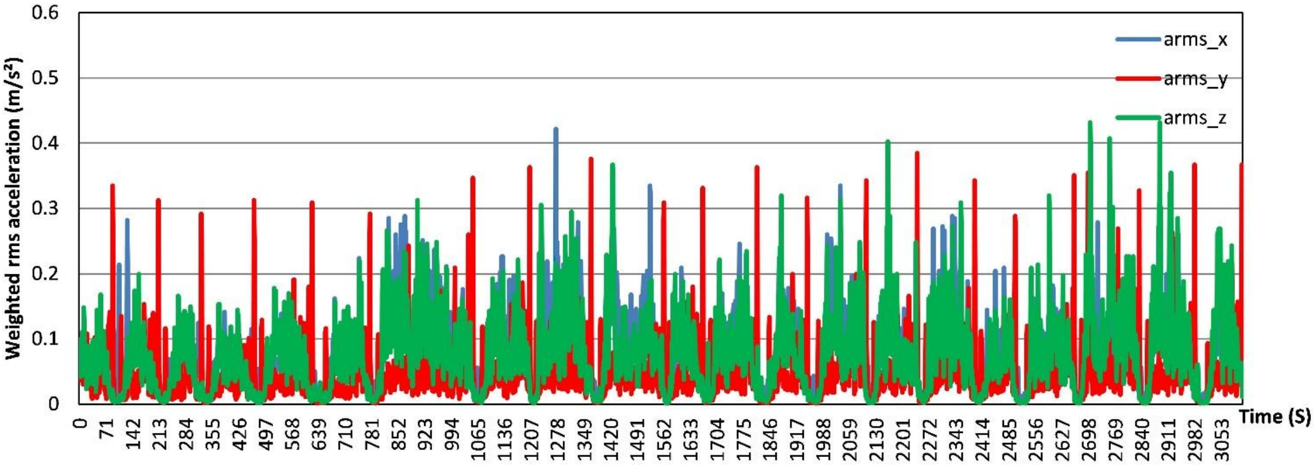

Figure 10. Rms acceleration values on the train's floor along the trip performed on the old train.

Table 6. Measured accelerations and calculated exposure times in the floor of the old train.

MEASUREMENT TIME	0,89 h			
	X	Y	Z	SUM
rms (m/s²)	0.10	0.07	0.12	0.17
VDV ($m/s^{1.75}$)	1.26	1.31	1.45	1.77
EXPOSURE TIME	8 h			
	X	Y	Z	SUM
Time to achieve EAV (h)	207.93	393.97	146.43	70.54
Time to achieve ELV (h)	1006.3	1906.83	708.71	341.40
A(8) [m/s²]	0.098	0.07	0.12	0.17
EXPOSURE TIME	0,89 h			
	X	Y	Z	SUM
Time to achieve EAV (h)	234.87	445.02	165.40	79.68
Time to achieve ELV (h)	1136.78	2153.93	800.56	385.64
Comfort rating (ISO 2631-1, 1997)			Comfortable	

This means that taking into account standard limits, there will be no exposure problems for the user of the new train related to health vibration if it only takes one trip or even stays 8-hours inside wagons. Also, by analyzing the data and performing the calculations for the acceleration values of the old train, it can be said that, in terms of health, there will be no problems for the user if he only makes one trip or passes 8h inside the wagons. Thus, as in the seat, in the case of vibration on the floor, as for comfort, both trains (new and old) have similar acceleration levels. The new train may be considered slightly better than the old one, although both trains present vibration levels that may be considered comfortable. Table 7 shows other acceleration values considered suitable for comfort by other authors in the literature. Comparing the obtained values with those indicated in Table 7 it is also concluded that the trains in the analyzed situations, may be classified as "comfortable".

Table 7. Limit values for assessing comfort level specified by other authors.

Fothergill & Griffin (1977)	m/s²
Very uncomfortable	2.7
Uncomfortable	1.8
Mildly uncomfortable	1.1
Noticeable, but not uncomfortable	0.4
Jones & Saunders (1974)	m/s²
Very unpleasant	3.7
Very uncomfortable	2.2
Uncomfortable	1.2
Mean threshold of discomfort	0.7
Not uncomfortable	0.33
Oborne & Clarke (1974)	m/s²
Very uncomfortable	> 2.3
Uncomfortable	2.3
Fairly uncomfortable	1.2
Fairly comfortable	0.5
Comfortable	0.23
Very comfortable	> 0.23

Conclusion

According to data obtained from whole body vibration measurements for comfort assessment purposes, the Trensurb urban train has comfortable vibration levels, even when referring to the vehicle of the old model. There was only one assessment, 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 reached by a passenger. In this condition, he would be reaching the limit of action, with the indication that changes in the seat would be necessary to minimize this exposure.

According to the NR-15 (2014), the values of vibration assessed in terms of the Vibration Dose Value (VDV) were shown to be low and acceptable, in relation to the ranges established as dangerous or unhealthy by health norms. Regarding the daily exposure vibration $A(8)$, the observed values were low, all of them being below the range of 0.5 to 1.1 m/s², and far below the exposure limit of 1.1 m/s². As indicated in Table 7 above, the measured vibration readings (seat and backrest) for comfort are in the category of "comfortable" classification, according to several other authors and international standards.

During the literature review, conducted in this study, no specific reference sources on comfort and health level were found for passengers on urban trains in Brazil, suggesting a topic that may be more deeply researched, in addition to making this article pioneer in Brazil. Since urban trains are broadly used ways of transportation in big cities, surveys and bibliographical reviews for authors outside the country can generate good comparisons and will certainly result in an improvement in the quality and comfort of transport for frequent users of this mode of transportation.

Finally, the work accomplished could verify that currently, the passengers of the Company of Urban Trains of Porto Alegre S.A. are in a situation of comfort for vibration in their trip, not representing any health risk in a usual daily exposure.

References

ANFLOR, C. T. M. 2003. *Estudo da transmissibilidade da vibração no corpo humano na direção vertical e desenvolvimento de um modelo biodinâmico de quatro graus de liberdade*. Porto Alegre, RS. Ph.D. Thesis. Universidade Federal do Rio Grande do Sul (UFRGS), 105 p. http://hdl.handle.net/10183/3207

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. 2005. NBR 14021: transporte - acessibilidade no sistema de trem urbano ou metropolitano. Rio de Janeiro, RJ.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. 2014. NR 9: programa de prevenções de riscos ambientais: Anexo nº 1 - Vibrações. Rio de Janeiro, RJ.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. 2014. NR 15: atividades e operações insalubres: Anexo nº 8 - Vibrações. Rio de Janeiro, RJ.

BRÜEL & KJAER. 1989. *Primer: human vibration, booklet*. Naerum, K. Larsen & Son, 31 p.

BALBINOT, A. 2001. *Caracterização dos níveis de vibração em motoristas de ônibus : um enfoque no conforto e na saúde.* Porto Alegre, RS. Ph.D. Thesis. Universidade Federal do Rio Grande do Sul (UFRGS), 281 p. http://hdl.handle.net/10183/2482

BECKER, T. 2006. *Desenvolvimento de uma mesa vibratória para estudos sobre vibração no corpo humano, medições em um grupo de motoristas e ajuste de um modelo biodinâmico.* Porto Alegre, RS. Ph.D. Thesis. Universidade Federal do Rio Grande do Sul, 179 p. http://hdl.handle.net/10183/5717

CHAFFIN, D. B.; ANDERSON, G. B. J.; MARTIN, B. J. 1999. *Occupational biomechanics.* New York, John Wiley & Sons, 376 p.

CILOGLU, H. *et al*. 2015. Assessment of the whole body vibration exposure and the dynamic seat comfort in passenger aircraft. *International Journal of Industrial Ergonomics.* **45**:116-123. https://doi.org/10.1016/j.ergon.2014.12.011

EUROPEAN AGENCY FOR SAFETY AND HEALTH AT WORK (EU-OSHA). 2002. Directive 2002/44/EC - Vibration. Bilbao, Spain.

FEDATTO NETO, M. 2016. *Avaliação dos níveis de vibração de corpo inteiro (VCI) em usuários de trens urbanos em Porto Alegre e região metropolitana.* Porto Alegre, RS. Monography (Bachelor of Mechanical Engineering). Universidade Federal do Rio Grande do Sul, 20 p. http://hdl.handle.net/10183/148032

FUNDACENTRO. 2013. Normas de Higiene Ocupacional - NHO 09: avaliação da exposição ocupacional a vibrações de corpo inteiro. São Paulo, SP.

GRIFFIN, M. J. 1990. *Handbook of human vibration*. London, Academic Press, 1008 p.

HARRIS, C. M.; PIERSOL, A. G. 2002. *Harris' shock and vibration handbook*. New York, McGraw-Hill, 1456 p.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. 1997. ISO 2631-1 mechanical vibration and shock: evaluation of human exposure to whole-body vibration – part 1: general requirements. Geneva, Switzerland.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. 2010. AMD-ISO 2631-1 mechanical vibration and shock: evaluation of human exposure to whole-body vibration – part 1: general requirements. Amendment 1. Geneva, Switzerland.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. 2001. ISO 2631-4 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. Geneva, Switzerland.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION. 2004. ISO 2631-5 mechanical vibration and shock: evaluation of human exposure to whole-body vibration – part 5: method for evaluation of vibration containing multiple shocks. Geneva, Switzerland.

JI, X.; EGER, T. R.; DICKEY, J. P. 2017. Evaluation of the vibration attenuation properties of an air-inflated cushion with two different heavy machinery seats in multi-axis vibration environments including jolts. *Applied Ergonomics.* **59**:293-301. https://doi.org/10.1016/j.apergo.2016.06.011

NAWAYSEH, N. 2015. Effect of the seating condition on the transmission of vibration through the seat pan and backrest. *International Journal of Industrial Ergonomics*. **45**:82-90. https://doi.org/10.1016/j.ergon.2014.12.005

POPE, M. H.; HANSSON, T. H. 1992. Vibration of the spine and low back pain. *Clinical Orthopaedics and Related Research.* **279**:49-59. https://doi.org/10.1097/00003086-199206000-00007

QUEST TECHNOLOGIES. 2005. VI-400PRO: real-time vibration analyzers, preliminary owner's manual. Oconomowoc, Wisconsin.

RAO, S. S. 2011. *Mechanical Vibrations*. Upper Saddle River, Prentice Hall, 1084 p.

SAMMONDS, G. M. *et al.* 2017. Effect of long-term driving on driver discomfort and its relationship with seat fidgets and movements (SFMs). *Applied Ergonomics*. **58**:119-127. https://doi.org/10.1016/j.apergo.2016.05.009

UNION INTERNATIONALE DES CHAMINS DE FER. 1991. UIC Leaflet 561: means of intercommunication for coaches. Paris, France.

WALBER, M. 2009. *Avaliação dos níveis de vibração existentes em passageiros de ônibus rodoviários intermunicipais, análise e modificação projetual.* Porto Alegre, RS. Ph.D. Thesis. Universidade Federal do Rio Grande do Sul, 199 p. http://hdl.handle.net/10183/16304

Submetido: 18/07/2017
Aceito: 11/09/2018