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PRELIMINARY COMMUNICATIONS

Bus Drivers Whole-body Vibration Exposure, Evaluation Procedures, Prevention and Control

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Abstract: Public transport bus drivers are exposed to a wide range of hazards which can endanger their occupational safety and health. Risks of possible traffic accidents, stress (due to traffic jams, pace of work, conflicts with passengers and other road users, etc.), fatigue, long sitting hours, vibration, noise, exposure to air pollution, adverse microclimatic conditions are just some of the factors that can endanger a driver's health and are characterized by a different likelihood of occurrence and consequence severity. Whole-body vibration transferred to human over many years of exposure have the potential to endanger health with respect to the onset of musculoskeletal disorders, especially in synergy with prolonged sitting. In addition, whole-body vibration exposure is a possible source of discomfort, which, combined with other factors, can contribute to the negative effect on the general physical and mental state of the driver, and therefore the occurrence of fatigue and stress.

In order to manage the exposure of bus drivers to vibration, it is necessary to evaluate the exposure, using methodologies defined by international standards, based on expert analysis and measurements. The paper presents the dominant health risks arising from the whole-body vibration of professional bus drivers, the parameters of exposure evaluation, measurements and evaluation procedure in accordance with European Directive 2002/44/EC and ISO standards, as well as an overview of the precautions to be taken in to reduce the risk associated with bus drivers occupational whole-body vibration exposure.

Keywords: bus drivers, whole-body vibration, health risks, evaluation..

INTRODUCTION

Vibration in the work environment are physical agents that are divided into three basic categories from the point of view of human response: vibration transmitted by the hands and arms (HAV), vibration transmitted by the whole body (WBV) and vibration that cause motion sickness, which actually belong to the subset of whole-body vibration and occur when persons are exposed to very low frequencies, usually below 1 Hz.

Whole-body vibration occurs when the body is supported on a surface that is vibrating (e.g., sitting on a seat that vibrates, standing on a vibrating floor or lying on a vibrating surface). Whole-body vibration occurs in transport (e.g., road, off-road, rail, air and marine transport) and when near some machinery [1]. Bus drivers are included in the working population, who, due to the nature of their work, are exposed to whole-body vibration on a daily basis, and this exposure is usually long-term, that has multiannual and decade-long character. Whether it is bus drivers in urban, suburban or intercity bus services, exposure to WBV depends on a variety of variables related to the condition and performance of the vehicle, road characteristics and driving modes: age of bus, bus maintenance, position of the bus engine, bus suspension type, low-floor or high-floor bus, seat design and its suspension, road type (smooth freeway, rough freeway, city streets, speed humps, etc.), roads' conditions, moving speed [2-7]. On the other hand, the degree of manifestation of the negative effects of WBV is also influenced by factors related to the driver itself: age, body size and weight, body dynamic response, gender, experience, fitness [1] as well as vibration dose accumulated over a lifetime [8]. Due to the complexity and heterogeneity of the various effects on the exposure of whole-body vibration bus drivers, a systematic approach to exposure assessment is necessary in order to obtain the most relevant results. This is a prerequisite for later selection of the best whole-body vibration management strategies and programs in this workplace.

Basically, the effect of whole-body vibration on humans is considered from the aspect of positive and negative effects. Exposure to whole-body vibration for therapeutic purposes is present in medical practice for many age-related chronic conditions including balance and gait deficiencies, fibromyalgia, multiple sclerosis, cystic fibrosis, Parkinson's disease, and peripheral neuropathy [9]. On the other hand, exposure to vibration in the work environment is an undesirable phenomenon, since it can lead to lasting effects on the safety and health of professionally exposed persons and have a negative impact on work performance and comfort.

Numerous epidemiological studies have examined the relationship between exposure to WBV and their health effects. Although there are not yet fully proven doubts that WBV contributes to the development of a number of systemic diseases, studies to date have shown that exposure to WBV is primarily associated with an increase in lower back, neck and shoulder pain. Along with vibration, other exposure factors that may induce musculoskeletal pain in workers include maintaining statistical positions for a long period of time and twisting or torque while seated. These factors, along with the vibration from the vehicle and the impact from driving on rough roads, can result in compression of the disks and soft tissue strain, which both contribute to back pain [5,10].

In accordance with current knowledge, Directive 2002/44/ EC in the definition of WBV lists the possible health risks, dwelling only on musculoskeletal disorders (MSDs): the mechanical vibration that, when transmitted to the whole body, entails risks to the health and safety of workers, in particular lower-back morbidity and trauma of the spine [11]. The risks are greatest when the vibration magnitudes are high, the exposure durations long, frequent, and regular, and the vibration involves severe shocks or jolts [12]. The inevitable prolonged sitting and possible other contributions to not applying ergonomics behavior are factors that are associated with whole-body vibration increasing the risk of musculoskeletal disorders.

In addition to possible work-related illness and traumas, whole-body vibration has a direct and indirect impact on occupational safety and health in terms of contributing to increased stress and fatigue, as well as reducing concentration. The appearance of such effects not only endangers the safety of bus drivers but also passengers. Of course, the effects of whole-body vibration on these phenomena should not be overestimated, but given their importance and possible consequences, they should be taken into account when designing a drivers vibration exposure management program.

Compared to other groups of professionally exposed persons (machine operators in the mining, construction, agriculture etc.), bus drivers are usually exposed to lower values of vibration magnitude. A review of the literature related to field studies of bus drivers whole-body vibration exposure [2,4-7] indicates that exposure values are generally below the limit but near or above the action and recommended values. Such results indicate the need for regular monitoring of WBV exposure, as well as monitoring bus drivers health status regarding the risk of WBV.

BASIC PARAMETERS OF EXPOSURE EVALUATION TO WBV

The influencing factors that determine how the vibration is transmitted and how they affect on humans are: vibration magnitude, vibration frequency, vibration direction and vibration exposure duration.

Vibration magnitude in the field of human vibrations is expressed by r.m.s (root-mean-square) value of acceletation (in m/s^2 for translational acceleration). This value is generally the most useful because it is directly related to the energy content of the vibration profile and thus the destructive capability of the vibration and also takes into account the time history of the wave form.

From the point of view of the adverse effect of vibration on health, not all frequencies have the same effect. Therefore, frequency weighting curves are introduced, which have the function of weighting the significance of frequency ranges in accordance with the harmfulness to the human body or in accordance with the sensitivity of the human body to them. They are defined by ISO 2631-1 [13]. As the vibration direction has an impact on the manifestation of the WBV effect, certain weighting curves for the vertical direction (z direction, frequency weighting curve W_k) and for horizontal directions (x and y directions, frequency weighting curve W_d) are determined. Frequency weighting curve for vertical direction gives utmost importance to frequencies between 4 Hz and 13 Hz, while frequency weighting curve for vertical direction gives utmost importance to frequencies between 0.5 Hz and 2 Hz. These curves are for principal frequency weightings, and there are also curves for additional weightings. There are specific additional multiplying factors for each of the directions (axes), which will be discussed in a later section of the paper.

In the European Union, the area of vibration occupational exposure management is governed by Directive 2002/44/EC [11], which defines the minimum requirements for safety and health at work caused by vibration. The daily exposure value depends on the frequency-weighted r.m.s (root mean square) value of the vibration acceleration and the actual time of the daily exposure. A supplementary parameter that can be used in assessing WBV exposure is the vibration dose value (VDV). The VDV calculation performs the duration weights as it is accumulated and automatically incorporates a method of giving more weight to occasional peaks (shocks) in the motion. The Directive relies on the ISO 2631-1 standard, both in terms of WBV exposure parameters and in the evaluation of exposure to WBV.

The daily exposure limit value of WBV and the daily action value of exposure to WBV, standardized to the eight-hour reference period, are respectively 1.15 m/s^2 and $0.5/s^2$. VDV limit and action values are 21 $m/s^{1.75}$ and 9.1 $m/s^{1.75}$, respectively. The exposure action value (EAV) is a daily amount of vibration exposure above which employers are required to take an action to control exposure, and the exposure limit value (ELV) is the maximum amount of vibration an employee may be exposed to on any single day.

ISO 2631-1, on the other hand, defines the two health guidance zones (HGZ) shown in Figure 1 with respect to a combination of weighted r.m.s acceleration values and exposure duration, which almost coincide when the WBV exposure time is between 4 and 8 hours. For exposures below the zone, health effects have not been clearly documented and/or objectively observed; in the zone, caution with respect to potential health risks is indicated and above the zone health risks are likely [13]. From the foregoing, it is clear that the standard does not define safe whole-body vibration exposure values. It can be seen in Figure 1 that the vibration exposure values for a period of 8 hours are somewhat more rigorously set than in Directive 2002/44, since the upper limit of HGZ is lower than ELV. As stated by Griffin [14] while excessive magnitudes at short durations when using r.m.s. evaluation were avoided in ISO 2631, they are "allowed" in the Directive. In the Directive, these high magnitudes at short durations are controlled when using the VDV evaluation method (that is, 9.1 $m/s^{1.75}$ and 21 $m/s^{1.75}$) but not when using r.m.s. measures (that is 0.5 and m/s^2 and 1.15 m/s^2).

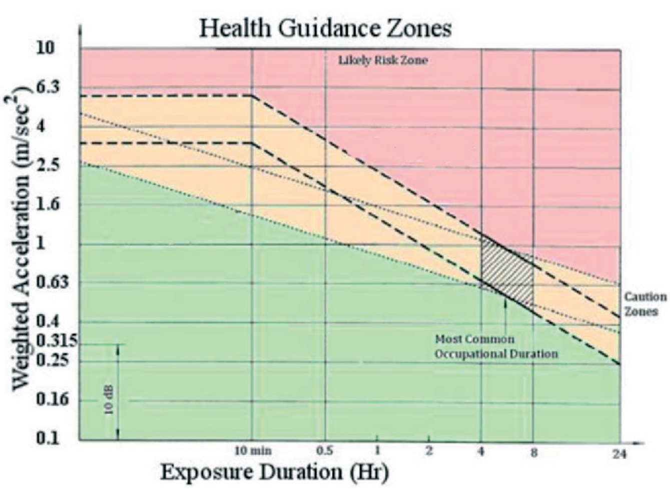

Figure 1. Health guidence zones according to ISO 2631-1 [15]

Apart from the health guidance zones, the standard provides ranges of daily exposure values relative to comfort (Table 1), noting that these values give approximate indications of likely reactions to various magnitudes of overall vibrations total values in public transportation [13]. Principal frequency weightings are applied to the seated persons and therefore the bus drivers, the same as when assessing the health effects of WBV, with the difference that each axis is considered equally influential.

Table 1. Comfort reactions to whole-body vibration environment according to ISO 2631-1

Daily WBV exposure value	Comfort experience
Less than 0,315 m/s^2	not uncomfortable
0,315 m/s^2 to 0,63 m/s^2	a little uncomfortable
0,5 m/s^2 to 1 m/s^2	fairly uncomfortable
0,8 m/s^2 to 1,6 m/s^2	uncomfortable
1,25 m/s^2 to 2,5 m/s^2	very uncomfortable
Greater than 2 m/s^2	extremely uncomfortable

WBV EXPOSURE EVALUATION PROCEDURE

The assesment of the level of exposure may be carried out on the basis of the information provided by the manufacturers regarding the emission level of the work equipment used, and based on the observation of specific work practices or measurement [11]. However, in the process of assessing the WBV exposure of a bus driver, the only justifiable procedure is based on field measurements, since vehicle vibration emission data (if any) do not represent a sufficient source of information. Other very important parameters (driving style, type and condition of the road, etc.) also influence the level of vibration magnitude, so only with the results obtained from the measurements can the WBV exposure assessment of the bus driver be considered relevant. Accordingly, as well as Directive 2002/44 and ISO 2631-1, the procedure should include the following basic methodological steps: bus driver whole-body vibration analysis, vibration measurement and daily vibration exposure calculations.

Exposure analysis should cover operations, sources and modes of vibration exposure, as well as typical actual exposure time. Also, depending on the mode of operation, the required measurement time will depend. Daily vibration exposure does not match daily working hours, as it should exclude all periods (breaks) when vibration exposure is absent. Certain job cycles (and their contribution to exposure time) need to be identified, such as driving between public bus terminals, driving to different intercity bus stops, etc. In this way, during the subsequent analysis of the results, it may be possible to identify characteristic exposures related to, for example, the type and condition of the road.

Instrumentation that meets the requirements of *ISO 8041-1 Human response to vibration - Measuring instrumentation - Part 1: General purpose vibration meters* is used for measurements, since this instrumentation integrates all the necessary functions, such as r.m.s. averaging vibration magnitude and frequency weighting. Also, modern instruments equipped with triaxle accelerometers allow simultaneous measurements in all three directions.

Vibration magnitude is measured simultaneously in defined orthogonal directions (Figure 2), by placing accelerometers at the point where it is estimated that there are vibration transmission to a person. In order to evaluate the vibration exposure of the whole body of the sitting person, in Figure 2 the measurement axes are shown, i.e. the required orientation of the accelerometer.

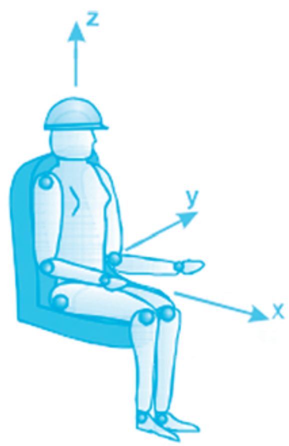

Figure 2. Direction of measurement [12]

The measurement point, or accelerometer position, can be on the seat pan, on the backrest or next to the seat, i.e. on the floor of the bus. The most reliable results of the vibration exposure of the bus driver are obtained by measurements on the seat pan. For this purpose, manufacturers provide specially designed accelerometers, which are built into the rubber pad. In order to determine seat transmissibility, measurements are made with two accelerometers simultaneously on the seat pan and on the floor of the bus near the driver's seat. This makes it possible to determine the SEAT (Seat Effective Amplitude Transmissibility) parameter. This value is the ratio of the frequency-weighted acceleration on the driver's seat and the frequency-weighted acceleration on the bus floor. SEAT value below 1 (or 100%) implies that the seat is attenuating vibration. The measurement duration may cover the entire working day, but from a previous adequate exposure analysis, this period can be minimized.

The calculation of daily exposure to whole-body vibration is based on the measurements results. According to the directions of vibration propagation, the daily exposure is calculated by the equation:

$$A_j(8) = k \times a_{w,j} \times \sqrt{\frac{T_{exp}}{T_0}} \quad (1)$$

where $A_j(8)$ is daily exposure in direction x, y or z, k is multiplying factor (for x-axis and y-axis: k = 1.4; for z-axis: k = 1.0), $a_{w,j}$ is frequency-weighted r.m.s. accelerations by axe x, y or z, T_{exp} is daily duration of exposure and T_0 is reference duration of eight hours.

When partial observation is made in the measurement against different conditions having different contribution to vibration exposure (e.g. different road type) during working hours, it is possible to determine partial daily vibration exposure $A_{x,i}(8)$, $A_{y,i}(8)$, $A_{z,i}(8)$ for each i task:

$$A_{j,i}(8) = k \times a_{w,j,i} \times \sqrt{\frac{T_{exp,i}}{T_0}} \quad (2)$$

where $a_{w,j,i}$ is frequency-weighted r.m.s. accelerations by axe x, y or z, $T_{exp,i}$ is daily duration of exposure for task i and T_0 is reference duration of eight hours. The multiplying factors are equal as in the equatation (1). Total vibration exposure by single axe j for tasks i to N is:

$$A_j(8) = \sqrt{A_{j,1}^2(8) + A_{j,2}^2(8) + \cdots + A_{j,N}^2} \quad (3)$$

Finally, daily whole-body vibration for bus operater is the highest value of daily exposures by each direction:

$$A(8) = \max\{A_x(8), A_y(8), A_z(8)\} \quad (4)$$

Vibration dose value (VDV) is a cumulative dose, based on the fourth root of the fourth power of the acceleration signal. VDV determination method is more sensitive to peaks than previously described A(8) method. It's value depends on measurement time:

$$VDV = \left\{ \int_0^T [a_w(t)]^4 dt \right\}^{1/4} \quad (5)$$

where $a_w(t)$ is instanteneous frequency-weighted acceleration, and T is duration of measurement. Sum of VDVs when there are i tasks (for example, task 1 driving on freeway, task 2 driving on city streets, etc. or some other criteria for tasks analyzes) is:

$$VDV_{total} = \sqrt[4]{\sum_i VDV_i^4} \quad (6)$$

The parameters described are necessary to evaluate the vibration exposure in accordance with the Directive 2002/44. For other additional daily exposure determination methods as well as vibration comfort evaluation see ISO 2631-1.

The International Standards Organization developed one more standard for the evaluation of WBV exposure and it offers a method for the evaluation of vibration containing multiple shocks (ISO 2631-5: 2018). New parameters are the daily compressive dose of the lumbar spine and risk factor. As Bovenzi states, "the derived metrics for the risk assessment of the lumbar spine are expressed in terms of daily compressive dose S_{ed} (MPa) and risk factor R (non-dimensional units) calculated from the static gravitational force acting on the vertebral endplates , the vibration related peaks of the dynamic compressive vertebral forces, and other factors such as the individual characteristics (age, body mass, body mass index, the size of the bony vertebral end-plates), the duration of vibration exposures and the postures of the drivers [16]. " These parameters take into account the cumulative exposure of WBV and its effect on the lumbar spine and allow estimation of the probability of low back disorders [16,17]. Frequent and intense multiple shocks are unlikely to be expected under normal bus driver working conditions. Previous studies on bus drivers WBV exposure therefore largely did not take into account these parameters, i.e. methods of determining them. Nevertheless, Lewis and Johnson [5] suggest that for a more comprehensive understanding of the vibration exposure of bus drivers, the methods of both ISO standards, 2631-1 and 2631-5, should be used.

MANAGING RISKS OF BUS DRIVERS WBV EXPOSURE

Considering all the limitations and specifics when it comes to the exposure of bus drivers, risk management methods should necessarily include the choice of seats that effectively reduce whole-body vibration, vehicle maintenance programs, providing relevant information and training for drivers, appropriate organization of work with the necessary rest time as well as health surveillance. Although limiting exposure time is one of the most effective measures when it comes to vibration exposure, its applicability in the workplace in question is difficult in practice. Of course, this measure would be necessary if exposure exceeded ELV, but no such cases were expected.

Adequate choice of seats is affected by vehicle suspension, road type [2], noting that poor maintenance and years of operation can reduce the degree of seat attenuation. The bus driver seats also have the primary function of supporting the occupant in a comfortable seated posture [4], which must be taken into account when selecting a seat, which should be adjustable. Drivers' awareness of the risks should be accompanied by appropriate training, which would primarily indicate ergonomic principles for reducing the risk of musculoskeletal disorders.

By Directive 2002/44 provisions all bus drivers found to have a daily WBV exposure level greater than EAV, must undergo medical examinations, which should be specific to the possible degenerative changes that are caused or contributed by WBV. When hiring new workers, particular attention should be paid to their possible exposure to WBV in an earlier period and/or the existence of another risk factor for low back disorders [16]. Periodic medical examinations are desirable, regardless of the intensity of the exposure, especially bearing in mind that bus drivers are at risk of musculoskeletal disorders due to the full range of factors, primarily the non-ergonomic position of the body.

CONCLUSION

Whole-body vibration which drivers in all forms of bus transport are exposed to require attention. Epidemiological studies imply that there is a wide range of adverse health effects, which development can occur due to WBV exposure. The possible development of musculoskeletal disorders is the most important aspect when it comes to preserving the health of the driver, but it is not the only topic that matters.

Achieving oscillatory comfort gives drivers the opportunity to reach full work productivity, with slow development of fatigue and concentration over long driving hours. For bus companies, it is vital not only the comfort of the drivers, but also of the users i.e. the passengers.

Previous studies has evolved in two basic, interconnected, directions. One is related to epidemiological studies that attempt to establish a dose-response relationship, i.e. the health outcome produced by whole-body vibration exposure. Another direction is finding the best technical, organizational and other ways for prevention and control of whole-body exposure risk.

The prospect of future research could move toward modeling the prediction of WBV bus driver exposure, based on a multi-criteria evaluation of the impact attributes of WBV exposure. In this way, bus companies could more easily manage vibration exposure through the selection of the most effective risk control methods. Certainly, like any other model, it would be necessary to perform the verification and possible modifications before the final application. The main activities are the establishment of the model, its iterations and verification supported by vibration measurements and evaluation in accordance with the international standards.

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