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EXPERIMENTAL INVESTIGATIONS OF SPECIAL VEHICLES VIBRATION WITH REGARD TO THEIR INFLUENCE ON HUMAN ORGANISM

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The paper presents investigations into the impact of vibration on drivers in selected vehicles Tatra 815 and Liaz. The investigations were carried out using the method of overall evaluation for constant rate of travel. It was found that the permissible limits of noxiousness, defined by the health protection regulations, were exceeded.

1. Introduction

Mechanical vibration encountered in the means of transport constitute the biggest threat in different areas of national economy. They are the basic factor that influences the comfort of passengers and the safety of those who operate the vehicles. What mainly affects the driver task and the passenger comfort are mechanical vibration of low frequency range which are the result of the dynamic interaction of vehicle and road system [1, 2, 3, 4, 5, 6, 7, 8]. The level of vibration depends on the construction of the vehicle (the construction of chassis and seat, masses and visco-elastic parameters of suspension of the vehicle), the construction and state of the road surface and the vehicle velocity. Experimental research into mechanical vibration in vehicles are carried out with regard to their general influence on a human organism and on the safety on the workstand.

When examining groups of bus, truck and special vehicle drivers, as well as agricultural tractor and road tractor drivers, some pathological changes, pains in the spine and lower part of the back were noted [9]. The experimental investigations into the vibration are carried out also in order to compare various vehicle constructions, and then to assign an indicator of the travel comfort [10, 11].

The investigations of the influence of vibration on human organism can be considered with regard to the following criteria:

• individual human features (age, sex, height, weight, psychological state, position);

• contact of the person with vibrating element in general and local sense (general vibration concern vibration transmitted to legs, back, pelvis, while local vibration refer to those transmitted through upper limbs);

• type of vibration; value of vibration parameters, frequency range, amplitude, velocity, acceleration, duration time, vibration directions.

As a result of prolonged influence of the vibration environment on a human organism, there can occur (depending on the characteristics of the vibration) a series of pathological changes in vascular, nervous and motor systems. For example, vibration of low frequency range influence the labyrinth of the ear [12]. Especially strong feelings may occur when organs are in the state of resonance.

The evaluation of the noxious influence of vibration is often based on the definition of biomechanical reactions of an organism, strong physiological reactions involving muscles activity, the conditions of blood circulation, reactions in the nervous system, slight deterioration in mental and physical abilities. A prolonged stay in vibration environment results in pathological response of an organism.

On the basis of experimental research it was found that the impact of vibration on a human organism is the reason for some functional changes [12].

2. Evaluation criteria of vibration influence on human organism

The process of developing the criteria and standards that refer to the estimation of the noxious influence of vibration on a human organism was based on experimental research as well as theoretical works among which the authors of the following papers need to be mentioned: G. Bekesy [13], G. Bobbert [14], R. Coerrmann [15], D. Dieckmann [16], M. Dupuis [17], D. E. Goldmann [18], M. J. Griffin [19], R. N. Janeway [20], T. Miwa [21], F. Pradko [22], Z. Engel [10], M. Nader [4].

The methods of evaluation of the vibration noxiousness are based on subjective feelings of the person exposed to vibration (psychological effects, pain, bad mood, ability of perception), during laboratory investigations or normal usage.

Normative acts released at the beginning of the eighties in many countries were not coherent in this sphere. The standards that are used most commonly in Europe are ISO-2631 [23], and VDI-2057 [24], BS 6841 [24].

The ISO 2631 recommendations of 1985 allowed to evaluate the vibration general influence on a human body in both the standing and sitting positions, the criterion being the root-mean-square (rms) values of acceleration of vertical and horizontal vibration.

The curves of permissible daily time of exposure were intended for the estimation of the vibration. There were assumed three levels of vibration perception: level of reduced comfort, level of noxiousness (reduced efficiency), and level of limiting permissible value with regard to harmful vibration influence on the organism.

An unequivocal determination of the exposure time was necessary to make use of the ISO criteria. The case of time evaluation for vibration of various sources was not clearly determined. According to the above standard, the rms acceleration value, the permissible values of which depend on the direction of vibration, their frequency and the exposure time, is the measure of noxiousness. The standard in question may be applied to periodic, non-periodic and random vibration in the frequency range of $1 \div 80$ Hz.

The rms acceleration values for non-periodic vibrations were determined as follows [25]:

$$a_s = \lim_{T \to \infty} \sqrt{\frac{1}{T} \cdot \int_0^T \left[a(t)^2\right]^2 dt}, \tag{2.1}$$

where T – exposure time, or for periodic vibration:

$$a_s = \sqrt{\frac{1}{T} \int_0^T [a(t)]^2 \, dt}, \tag{2.2}$$

where a_s — rms acceleration value [ms^{-2}], $a(t)$ – actual acceleration [ms^{-2}], T – vibration period [s].

The standard allows the evaluation of the vibration noxiousness using one number, the so-called corrected rms acceleration value, which is compared to the values that are permissible in frequency bands of the highest sensitivity.

The corrected rms value can be calculated according to the following dependence:

$$a_k = \sqrt{\frac{1}{T} \int_0^T [W_f a(t)]^2 \, dt}, \tag{2.3}$$

where $W_f = W_f(f)$ – values of correction coefficient for middle frequencies f of tierced bands, T – analysis time.

The corrected rms value can be determined on the basis of the spectral analysis in the frequency range of $1 \div 80$ Hz in tierced bands:

$$a_k = \sqrt{\sum_{f=1}^{n} W_f^2 a_f^2}, \tag{2.4}$$

where a_f – rms value of vibration acceleration obtained as a result of spectroscopic analysis for tierced band of middle frequency f [ms^{-2}], n – number of octave or tierced bands.

In Poland, the presently binding standards concerning the evaluation of the vibration harmful influence on people are: PN-91/N-01352 [26], PN-91/N-01354 [27], PN-91/S-04100 [28], PN-90/K-11001 [29], PN-90/K-11003 [30]. The standard PN-91/N-01354 applies to general influence that occurs on workstands.

The estimate of the noxious impact of vibration in the case of general influence on the organism on workstands, is made depending on the vibration character using one of the three methods [27]:

- spectral method,
- weighted method,
- dosimetric method.

Rms values or weighted acceleration of vibration should not exceed fixed parameters in the permissible exposure time for a working shift, i.e. within 480 minutes.

On the basis of the research work carried out by the author [1, 4, 5, 6, 7, 31, 32, 33, 34, 35, 36], a modification of the domestic standards was suggested concerning the methods of investigations and evaluation of mechanical vibration of general influence, that occur on workstands in motor-cars, trucks, buses, trolley-buses, road tractors and special cars [28].

Three methods of evaluation of vibration in vehicles were developed:

- method of dosimetric evaluation,
- method of overall estimation for constant rate of travel v from 0 km/h to maximum velocity, every 20 km/h,
- method of spectral evaluation for constant rate of travel v from 0 km/h to maximum velocity, every 20 km/h.

The estimation of the vibration influence should be made with the use of the above methods.

The dosimetric method is applied to evaluate the influence of vibration met on workstands in vehicles within the whole working shift. The aim of the evaluation is to compare the equivalent corrected value of vibration acceleration a_w (in typical operating conditions within the whole working shift), that was determined in the dependence (2.5), and permissible corrected vibration acceleration $a_{w\mathrm{dop}}$ for the noxiousness limit according to the standard [28], remembering that

$$a_w = \sqrt{\frac{D}{T}}, \tag{2.5}$$

where D – vibration dose measured with dosimeter or calculated using the formula (2.6), T – time of vibration influence on the organism within one working shift,

$$D = \int_0^T a_w^2(t)dt, \tag{2.6}$$

where $a_w(t)$ – actual value of corrected vibration acceleration in time t measured by a device equipped with a correction filter in [m/s^2].

The aim of the overall evaluation method for constant rate of travel is to compare the equivalent corrected value of vibration acceleration $a_w(\nu)$, and the permissible corrected vibration acceleration $a_{w\text{dop}}$ for the noxiousness limit according to the standard [28], for every examined velocity ν.

Values of the corrected vibration acceleration $a_w(\nu)$ are measured by a device equipped with a correction filter made according to PN-91/N-01352, and they are averaged according to the following pattern:

$$a_w(\nu) = \sqrt{\frac{1}{n}\sum_{i=1}^{n} a_{wi}^2}, \tag{2.7}$$

where a_{wi} – value of corrected vibration acceleration measured in i-th time interval for rate of travel ν, n – number of read-outs at velocity ν, realised at equal time intervals (not longer than 5 seconds).

The spectral evaluation method for constant rate of travel ν involves an estimate of the corrected acceleration value or acceleration spectrum [28].

The aim of corrected acceleration evaluation of this method is to compare, for every examined rate of travel ν, the equivalent corrected value of vibration acceleration $a_w(\nu)$ calculated from the formula (2.8), with the permissible corrected values of vibration acceleration $a_{w\text{dop}}$ for the noxiousness limit given in the standard [28].

$$a_w(\nu) = \sqrt{\sum_{f=1}^{n} a_f^2 \cdot W_f^2}, \tag{2.8}$$

where a_f – rms value of vibration acceleration for tierced band of middle frequency f obtained as a result of spectral analysis, W_f – coefficient of correction for middle frequency of tierced bands, n – number of the realised tierced bands.

The objective of the spectral evaluation method for constant rate of travel ν in the case of acceleration spectrum is to compare, for every examined rate of travel, the spectra of rms values of vibration acceleration that were determined for individual tierced frequency bands, with the appropriate permissible values of acceleration of spectra vibration that correspond to the noxiousness limit (Table 2, standard [28]), or in the case of determining strong discomfort limit (in frequency range of $0.1 \div 0.63$ Hz), with the enclosure of the norm [28].

In the case when the counted value of vibration acceleration calculated with the help of the overall evaluation method (Eq. (2.7)) or spectral evaluation method (Eq. (2.8)) exceeds the permissible values, the permissible time of vibration influence t_{dop} within the whole working shift should be calculated according to the following formula:

$$t_{\nu\text{dop}} = \left(\frac{a_{480}}{a_w(\nu)}\right)^2 \cdot 480, \tag{2.9}$$

where a_{480} – permissible value of vibration acceleration for time of influence $t = 480$ minutes, assumed for the noxiousness limit from Table 3 of standard PN-91/S-04100, $a_w(\nu)$ – vibration acceleration value determined by Eqs. (2.7) or (2.8) for constant rate of travel ν.

If the vibration evaluation is determined by the spectral method, the permissible time of vibration influence $t_{\nu\text{dop}}$ within a working shift is calculated using the Eq. (2.10):

$$t_{\nu\text{dop}} = \left(\frac{a_{f480}}{a_f}\right)^2 \cdot 480, \tag{2.10}$$

where a_{f480} – permissible rms value of vibration acceleration in the case of tierced frequency band f assumed from Table 2 of standard [27], a_f – measured value of vibration acceleration for tierced frequency band f, in which the strongest violation of noxiousness limit has occurred.

3. Experimental research

In order to evaluate the influence of vibration on drivers on working stands in the four selected cars used for concrete transport Tatra 815 and on Teka pump used for concrete feed on Liaz chassis, experimental research was carried out as well as evaluation of mechanical vibration of general influence in accordance with the standard PN-91/S-04100.

Vibration influence on people is evaluated on the basis of measurement of the corrected rms value on the level of frequency for the upper surface of the seat loaded by the mass of the driver. The following assumptions were made for the investigations:

• vibration that influence the drivers are of general character,

• measuring points were located on the upper surface of the seat in accordance with the standard PN-91/N-01352 on the basis of measurements for three directions of a rectangular fixed co-ordinate system (X, Y, Z),

• at least three constant velocities were established that are used most often in service conditions,

• all vehicles selected for the investigations satisfy technical requirements for traffic use.

The location of the detecting element with regard to the seat is shown in Fig. 1.

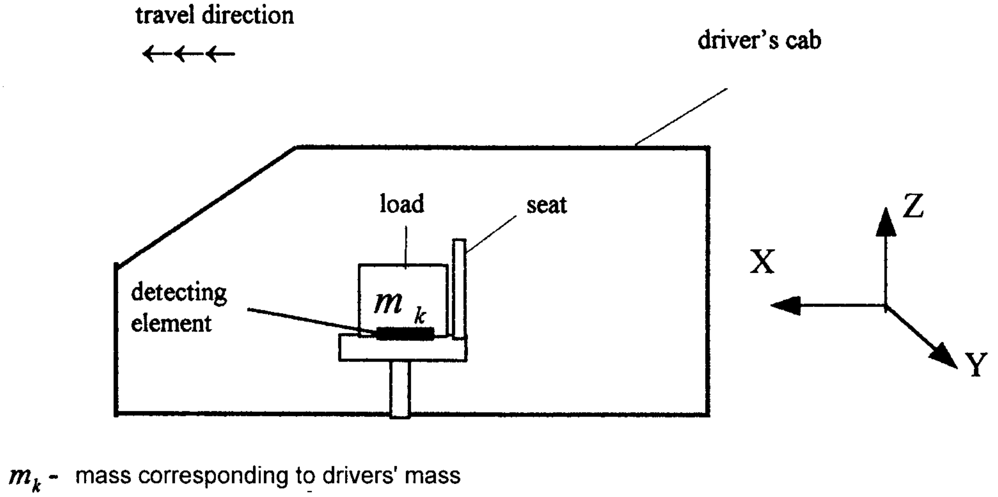

FIG. 1. Location of measuring system elements with regard to the seat.

When measuring the whole body vibrations that influence the driver, the measuring converter was placed on the seat making use of a measuring disk according to PN-91/N-01352.

The overall evaluation method was accepted in this work to estimate the influence of vibration.

The measurements of vibration in the driver cabs were taken for constant rate of travel from zero to the maximum value, every 20 km/h or every 10 km/h for normal usage.

The evaluation of vibration influence was made on the basis of measurement of the corrected values of vibration acceleration with the help of accelerometers placed in the measuring disk of the seat in the frequency range of $0.7 \div 100$ Hz.

The measurements of the level of vibration influencing the driver were made in various special vehicles, the list of which is presented in Table 1.

Table 1. List of examined vehicles and data concerning the drivers

Make of vehicle	Kind of vehicle	Driver	
		Mass [kg]	Height [cm]
Tatra 815 capacity 1	Special vehicle	63	170
Tatra 815 capacity 2	Special vehicle	85	177
Tatra 815 capacity 3	Special vehicle	80	172
Tatra 815 capacity 4	Special vehicle	79	170
Liaz - Teka pump	Special vehicle	76	179

The measurement of corrected vibration acceleration taken with the help of the overall evaluation method was made in the measuring system presented in Fig. 2.

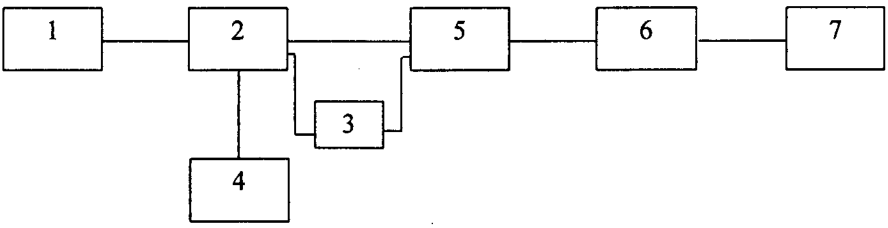

FIG. 2. System used for measuring the corrected acceleration values of vibration: *1* – piezoelectric converter of vibration acceleration, *2* – vibration amplifier WH-30, *3* – magnetic logger MAS 54, *4* – correction filter, *5* – function multiplier, *6* – averaging system, *7* – d.c. meter.

Effective corrected acceleration was measured by means of a detecting element (of generating type) PD - 3 S equipped with an amplifier WH - 30 of frequency range of 0.5 - 150 Hz. Correction filters consistent with the standard PN-91/N-01352 were used.

The maximum error of the slotted line was 11% (it did not exceed 20% according to the standard PN-91/N-01352).

In order to be able to compare the results, the investigations were carried out in four vehicles Tatra 815 and in a special vehicle Teka pump with Liaz chassis.

The measurements were taken during normal usage in Tatra vehicle with one operating main combustion engine and with an auxiliary motor to move the tank containing concrete. In the special vehicle Teka pump, however, there operated the main engine and the pump to concrete feed. In both vehicles the measurements were taken on drivers' seats and additionally in the special Liaz

- Teka pump vehicle on the platform for operating the pump. The acceleration was measured in longitudinal, transverse and vertical directions. On the basis of the measurements of the efficient and peak values of vibration acceleration, the values of peak factor were established (Table 6).

The evaluation of the impact of vibration of general influence was made according to the assumptions of Sec. 2, on the basis of corrected vibration acceleration value, comparing the vibration to the permissible values determined by the noxiousness limit (Table 2), for three vibration directions.

Table 2. Corrected acceleration values determining the limits of comfort, noxiousness and harmfulness. [m/s^2] 31.

Corrected acceleration values	Vertical vibrations Z	Transverse vibrations Y	Longitudinal vibrations X
Comfort limit	0.17	0.13	0.13
Noxiousness limit	0.55	0.4	0.4
Harmfulness limit	1.1	0.8	0.8

4. Results and evaluation of experimental research

Corrected acceleration values of the seat of a loaded vehicle Tatra 815 for the velocity range 20, 40 and 60 km/h in the three directions X, Y, Z are shown in the Table 3, while corrected acceleration values of an unloaded vehicle are presented in the Table 4.

The research proved that measuring values of vibration acceleration of longitudinal and transverse directions assumed smaller values than those obrained for vertical direction.

In the case of exceeding the vibration acceleration corresponding to the permissible noxiousness limit values, the time of vibration influence in Tatra 815 vehicles within the whole working shift was calculated with regard to the acceleration values of an averaging vehicle (as an arithmetic mean of four vehicles), and the maximum acceleration values obtained during the measurements (the vehicle of the worst parameters on the seat).

Table 5 presents the permissible times of travel by Tatra 815 vehicle for vertical vibration in the case of a loaded and unloaded vehicle for individual rates of travel, allowing for the permissible time $t_{\mathrm{dop\ max}}$ and assuming the highest value of corrected acceleration of the vehicle 2.

Table 3. Corrected acceleration values of vibration on seat of a loaded vehicle Tatra 815 in m/s^2.

Special vehicles	Vibration direction	Corrected acceleration values m/s^2			Comfort limit m/s^2	Noxiousness limit m/s^2	Harmfulness limit m/s^2
		$V = 20$ km/h	$V = 40$ km/h	$V = 60$ km/h			
Vehicle 1	X	0.14	0.12	0.28	0.13	0.4	0.8
	Y	0.13	0.13	0.15	0.13	0.4	0.8
	Z	0.44	0.59	0.58	0.17	0.55	1.2
Vehicle 2	X	0.14	0.19	0.20	0.13	0.4	0.8
	Y	0.11	0.24	0.23	0.13	0.4	0.8
	Z	0.61	0.91	0.75	0.17	0.55	1.2
Vehicle 3	X	0.13	0.16	0.20	0.13	0.4	0.8
	Y	0.18	0.20	0.18	0.13	0.4	0.8
	Z	0.42	0.68	0.58	0.17	0.55	1.2
Vehicle 4	X	0.19	0.21	0.24	0.13	0.4	0.8
	Y	0.21	0.23	0.23	0.13	0.4	0.8
	Z	0.64	0.92	0.72	0.17	0.55	1.2
Averagin gvehicle	X	0.15	0.17	0.23	0.13	0.4	0.8
	Y	0.16	0.2	0.20	0.13	0.4	0.8
	Z	0.53	0.80	0.66	0.17	0.55	1.2

The vibration measurements were taken in service conditions for constant rates of 0, 20, 30, 40 and 50 km/h. additionally, vibration were also examined at the vehicle standstill, generated in the main engine and the pump (detecting element was placed where feet pressed the platform). The peak coefficient, treated as the ratio of the peak value to the efficient value for one- minute measurement, did not exceed the value 6 [28].

Table 4. Corrected acceleration values of vibration on seat of an unloaded vehicle Tatra 815 in m/s^2.

Special vehicles	Vibration direction	Corrected acceleration values m/s^2			Comfort limit m/s^2	Noxious-ness ness limit m/s^2	Harmful-ness limit m/s^2
		$V = 20$ km/h	$V = 40$ km/h	$V = 60$ km/h			
Vehicle 1	X	0.13	0.19	0.28	0.13	0.4	0.8
	Y	0.11	0.15	0.20	0.13	0.4	0.8
	Z	0.34	0.69	0.70	0.17	0.55	1.2
Vehicle 2	X	0.13	0.19	0.20	0.13	0.4	0.8
	Y	0.19	0.20	0.16	0.13	0.4	0.8
	Z	0.65	1.00	0.85	0.17	0.55	1.2
Vehicle 3	X	0.15	0.18	0.25	0.13	0.4	0.8
	Y	0.16	0.18	0.20	0.13	0.4	0.8
	Z	0.56	0.84	0.97	0.17	0.55	1.2
Vehicle 4	X	0.13	0.19	0.22	0.13	0.4	0.8
	Y	0.15	0.22	0.20	0.13	0.4	0.8
	Z	0.87	0.98	0.89	0.17	0.55	1.2
Averagin gvehicle	X	0.14	0.19	0.24	0.13	0.4	0.8
	Y	0.15	0.19	0.19	0.13	0.4	0.8
	Z	0.60	0.88	0.85	0.17	0.55	1.2

Table 5. Permissible times of travel by Tatra 815 vehicle in [min].

Sort of vehicle	Unloaded			Loaded		
Rate of travel	$V = 20$ km/h	$V = 40$ km/h	$V = 60$ km/h	$V = 20$ km/h	$V = 40$ km/h	$V = 60$ km/h
Permissible time of travel $t_{\text{dop max}}$ [min]	192	145	154	355	175	258

The official gazette announcing current legislation No. 79 item 513 of 17 June 1998 recommends adhering to the permissible weighted acceleration values of vibration in three ranges of values of the peak coefficient. The given normative values are binding if any other detailed regulations do not define lower values. The standard PN–91/S–04100 used by the author to evaluate the vibration influence gives lower permissible values, therefore it was applied to the process of estimation in accordance with the above mentioned official gazette. The results of measurements of the corrected acceleration of the seat vibrations and of the pump operation stand are shown in the Table 6.

Table 6. Corrected acceleration values of vibrations of seat and Teka pump operation stand during travel and during pump operation (measurement of vibration on the platform).

	Vibration direction	Corrected values of vibrations				
		$V = 0$ km/h	$V = 20$ km/h	$V = 30$ km/h	$V = 40$ km/h	$V = 50$ V km/h
Driver's seat	X	0.02	0.13	0.16	0.18	0.19
	Y	0.02	0.11	0.13	0.15	0.21
	Z	0.03	0.35	0.40	0.58	0.78
Pump operation stand - platform engine operation	X	0.08	–	–	–	–
	Y	0.03	–	–	–	–
	Z	0.11	–	–	–	–
Pump operation stand - platform (joint main engine and pump operation)	X	0.12	–	–	–	–
	Y	0.05	–	–	–	–
	Z	0.18	–	–	–	–

On the basis of the results of the measurements of vibration acceleration on driver's seat (Table 6), it was certified that the biggest threat of vibration influence on a driver occurs for a vertical component of vibration for the velocity ranges of 40 and 50 km/h. The multiplication factor for exceeding the noxiousness limit KGU amounts correspondingly to 1.05 and 1.56 [28].

The permissible times of vibration influence of special vehicle Liaz - Teka pump within the whole working shift $t_{\nu\ \mathrm{dop}}$ which were calculated on the basis of the formula (2.9), are given in the Table 7.

Table 7. Permissible times of travel by special vehicle Liaz -Teka pump in [min].

Rate of travel km/h	$a_{w\ rmdop}$ m/s^2	$a_w(\nu)$ m/s^2	$t_{\nu\ \mathrm{dop}}$ (min)
40	0.55	0.58	431
50	0.55	0.78	238

5. Conclusions

Experimental research on special vehicles for concrete transport Tatra 815 and Liaz - Teka pump, allowed to formulate the following conclusions concerning the evaluation of the degree of influence of general vibration on drivers and the operating personnel:

• for horizontal, longitudinal and vertical vibration, the limit of comfort was exceeded for almost all rates of travel chosen for the research, however, the limit of noxiousness was not exceeded;

• for vertical vibration, the violation of the noxiousness limit appears for nearly all the range of the measured rates of travel, concerning both the loaded and unloaded vehicles;

• the permissible time of travel by Tatra 815 vehicle of the most disadvantageous vibration acceleration for the rate of 40 km/h, cannot exceed 145 minutes for an unloaded vehicle, and 175 minutes for a loaded one.

Experimental research on the special Liaz - Teka pump vehicle enabled the formulation of the following conclusions:

• the measurements of corrected values of the seat vibration acceleration in the Liaz - Teka pump vehicle, in horizontal, longitudinal and transverse directions (X, Y) did not reveal violation of the noxiousness limit for the examined rates of travel;

• the most serious threat concerning the influence of vibration on a driver occurred for a vertical component at the rate of 40 km/h and 50 km/h, for the reason that the noxiousness limit was violated; the determined permissible times of travel are given in the Table 7;

• the permissible time of travel (Table 7) cannot exceed 238 minutes within the working shift which should be realised through proper planning of the driver worktime;

• the measurements of the corrected vibration values in horizontal, longitudinal and transverse directions of the pump operation stand (Table 6) did not show any violation of the comfort limit, neither did they show violation of the noxiousness limit considering the vertical direction, which proves the examined workstand to be proper.

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