

EFFECTS OF THE SEAT CUSHION OSCILLATORY PARAMETERS ON VIBRATION EXPOSURE AND DYNAMIC SEAT COMFORT IN THE BUS

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The paper analyzed the influence of the passenger seat's cushion oscillatory parameters (stiffness/damping) on ride comfort and dynamic seat comfort. The analysis was done using a linear in-line oscillatory seat-human model with 4 degrees of freedom (DOF) defined in Matlab/Simulink. For the oscillatory excitations of the in-line model, the vertical accelerations of the bus floor under the users' seats were used. Bus floor accelerations were obtained by simulation using validated spatial oscillatory intercity bus model with 65 DOF defined in the ADAMS/View software. The ride comfort was assessed by the criteria of ISO 2631/1997 standard. The seat effective amplitude transmissibility (SEATrms) parameter was considered for analyzing the dynamic seat comfort. It was found that passengers in the rear part of the bus had a lower level of ride comfort than the passengers in the front part of the bus. The intensities of the bus floor vertical accelerations for the rear part were mainly concentrated in the frequency range of 5-10 Hz. Passengers at the rear had lower SEATrms values than those at the front. The SEATrms values increased noticeably with the increase in the cushion stiffness, but those values were below 100% for all considered users. Increase in the cushion damping slightly decreased SEATrms values.

Key words: Flexible shells, Orthotropy, Oscillations, Mixed finite element method, Galerkin method

INTRODUCTION

Bus users are exposed to the harmful effect of whole body vibration (WBV) bus ride. The basic oscillatory bus excitation is road roughness. Vibrations are transferred from the road to the bus user's body via the tires, the bus suspension system and the seats. Unlike the bus driver's seat, the passengers' seats are not equipped with suspension system and are rigidly suspended from the bus platform. Vibration damping at passengers' seats is done by elastic cushions. Seat cushion stiffness and damping characteristics influence vibrations transmission from the bus floor to users' bodies, and have an effect on the ride comfort.

The vehicle seat comfort can be divided into static comfort and dynamic comfort. Static seat comfort represents the comfort of the seat when the vehicle is stationary, and with no influence of disturbing forces and vibrations. Dynamic seat comfort refers to the seat overall comfort and includes the vibration effects on the users. The seat that is comfortable for users in static conditions can be uncomfortable in dynamic conditions when the vehicle is moving [05]. Seat dynamic comfort is associated with vibrations transmission from the vehicle floor to the user's body. The transfer of vibrations depends on the intensity and frequency of the excitation [13], the direction of the excitation [13], the sitting posture (erected/normal/slouched) [11] and the oscillatory characteristics of the seat. Dynamic seat comfort also depends on person's subjective feeling of the vibration effect. Vibrations of low frequencies (up to 12 Hz) affect the entire human body.

Human body is the most sensitive to vertical vibrations in the frequency range 4-8 Hz, and on the horizontal vibrations in the range 1-2 Hz. Vibrations of higher frequencies (above 12 Hz) have a local effect and affect particular part of the human body (e.g. arms, shoulders, head, legs, etc.).

Bus passengers' exposure to vibration depends on the position of their seats in the bus [16]. Experimental and simulation studies have shown that passengers in the front and rear part of the bus suffer high acceleration intensities [04] and [16]. In this paper, the influence of the seat cushion oscillatory parameters on the users' ride comfort and dynamic seat comfort were investigated. Two users at the front of the bus, whose seats are positioned on the front overhang and above the front axle, were taken into account. Two passengers in the rear part of the bus with the seats positioned in the last row at the rear overhang and above the rear axle were also analyzed. For the purpose of the analysis, the validated spatial oscillatory model of the intercity bus with 65 DOF built in the ADAMS/View software was used. The model was excited with the real road roughness - bad asphalt-concrete pavement registered at two tracks at speed of 64 km/h. Bus floor acceleration signals under the users' seat were obtained using the model. Vertical acceleration signals were used as the excitation for the in-line 4 DOF *human-seat* model. In-line model was defined in the *Matlab/Simulink*. Root-mean-square (*rms*) values of the weighted vertical acceleration are analyzed when assessing ride comfort.

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For the analysis of dynamic seat comfort, the SEATrms parameter is analyzed.

SEAT-HUMAN OSCILLATORY MODEL

Under the influence of vibration, the motion of human body depends on excitation frequencies. It has been found that the human body behaves as rigid at low oscillation frequencies, below 2 Hz [11]. At higher oscillation frequencies, the upper parts of the body (shoulders, arms and head) are loosely coupled and relatively move. At higher frequencies human body behaves as a complex mechanical oscillatory system [07]. Considerable number of biodynamic human body models with different number of masses and DOF exist in literature (2 DOF model [17]; 2 DOF model [02]; 2 DOF [06]; 4 DOF model proposed by ISO CD 5982 [08]; 4 DOF model [03]; 5 DOF model [12]). The parameters of these models were mainly determined by experimental measurement of the biodynamic responses of a seated human body when affected with vibration. Biodynamic responses are the quantities determined by three different biodynamic functions - driving point mechanical impedance (DPMI), apparent mass (APMS) and seat-to-head transmissibility (STHT) [10].

In this paper, the analysis was performed using a linear in-line *seat-human* model (Figure 1). When defining seat-human model, a linear biodynamic human body model with 4 DOF proposed by Boileau and Rakheja [03] was used. In the seat-human model, the connection between the human body and the seat is represented by an elastic-damping element with an equivalent coefficient of stiffness **c4'** and an equivalent coefficient of damping **b4'**. Equivalent coefficients are determined based on the serial connection between seat cushion and human buttocks oscillatory parameters (Eqs. (1-2)). Parameter values for the linear *seat-human* oscillatory model are provided in Table 1.

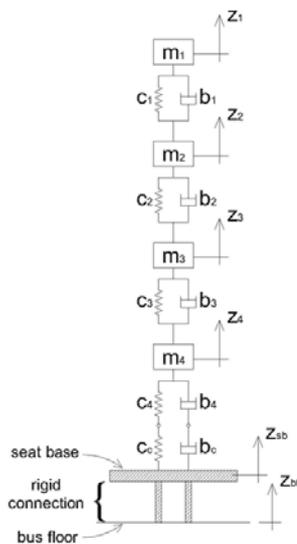


Figure 1: Oscillatory seat-human model

$$c_4' = \frac{c_4 \cdot c_c}{c_4 + c_c} \quad 1) \quad b_4' = \frac{b_4 \cdot b_c}{b_4 + b_c} \quad 2)$$

It should be noted that the seat cushion has non-linear characteristics of stiffness and damping. They depend on the human body mass, the amplitude and frequency of the excitation [19], as well as the characteristics of the cushion material. The seat cushion under load over time changes elastic characteristic, i.e. becomes stiffer and loses the ability to isolate vibration [01]. The paper analyzes the influence of different seat cushion stiffness/damping coefficient values on the vibration transfer from the bus floor to the users' bodies. Five different values of the stiffness/damping coefficients from the range of ± 50% of their nominal values are considered (cc=10000, 15000, 20000, 25000, 30000 N/m; bc=110, 165, 220, 275, 330 Ns/m).

Differential equations of motion for oscillatory model are given by Eqs. (3-6):

$$m_1 \ddot{z}_1 + b_1 \dot{z}_1 + c_1 z_1 - b_1 \dot{z}_2 - c_1 z_2 = 0 \quad 3)$$

$$m_2 \ddot{z}_2 + (b_1 + b_2) \dot{z}_2 + (c_1 + c_2) z_2 - b_1 \dot{z}_1 - c_1 z_1 - b_2 \dot{z}_3 - c_2 z_3 = 0 \quad 4)$$

$$m_3 \ddot{z}_3 + (b_2 + b_3) \dot{z}_3 + (c_2 + c_3) z_3 - b_2 \dot{z}_2 - c_2 z_2 - b_3 \dot{z}_4 - c_3 z_4 = 0 \quad 5)$$

$$m_4 \ddot{z}_4 + (b_3 + b_4') \dot{z}_4 + (c_3 + c_4') z_4 - b_3 \dot{z}_3 - c_3 z_3 = b_4' \dot{z}_{sb} + c_4' z_{sb} \quad 6)$$

On the basis of the differential equations, the oscillatory *seat-human* model was formed in the *Matlab/Simulink*. Figure 2 displays top level *Simulink* diagram. Since passenger's seat is not equipped with a suspension system, the signal of bus floor vertical acceleration is taken as model excitation input. Vertical acceleration of the mass m4 was analyzed as model response since it is an indicator of the user' WBV exposure.

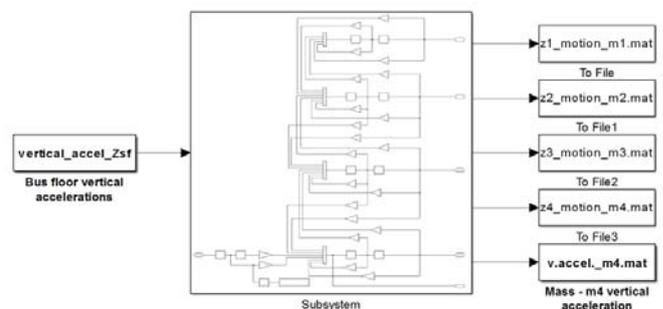


Figure 2: Top level Simulink diagram

Table 1: Parameters for seat-human model

Parameters of the model	Values	Parameters of the model	Values
m_1 - head and neck	5.31 [kg]	b_c - cushion damping	220 [Ns/m]
m_2 - chest and upper torso	28.49 [kg]	b_4' - equivalent damping	198.81 [Ns/m]
m_3 - lower torso	8.62 [kg]	c_1 - cervical spine stiffness	310000 [N/m]
m_4 - thighs and pelvis	12.78 [kg]	c_2 - thoracic spine stiffness	183000 [N/m]
b_1 - cervical spine damping	400 [Ns/m]	c_3 - lumbar spine stiffness	162800 [N/m]
b_2 - thoracic spine damping	4750 [Ns/m]	c_4 - buttocks stiffness	90000 [N/m]
b_3 - lumbar spine damping	4585 [Ns/m]	c_c - cushion stiffness	20000 [N/m]
b_4 - buttocks damping	2064 [Ns/m]	c_4' - equivalent stiffness	16364 [N/m]

Figure 3 shows acceleration transmissibility function of the seat. The resonant frequency of the seat is approximately 2.5 Hz. The values of the function are lower than one for frequencies above 3.5 Hz. The seat isolates vibrations at frequencies above 3.5 Hz.

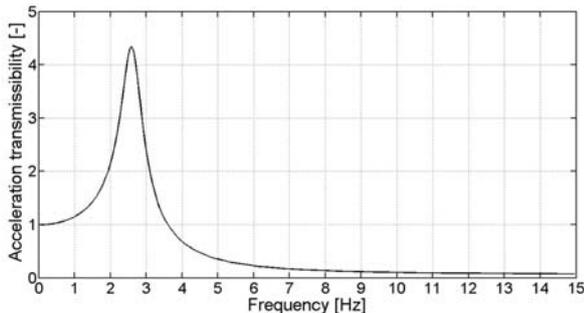


Figure 3: Acceleration transmissibility function for user's seat

BUS MODEL AND THE SEAT-HUMAN MODEL EXCITATIONS

In the spatial oscillatory intercity bus model (Figure 6), real unevenness of the asphalt-concrete pavement in poor condition was introduced (Figure 4). A measuring vehicle registered roughness irregularities along two tracks (left and right) on a 161 m long section at a speed of 64 km/h. Roughness irregularities were taken from the PROFILES database of RoadRuf software [14].

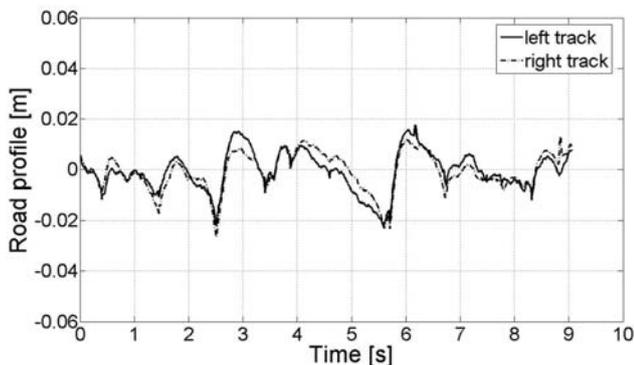


Figure 4: Road roughness on the left and right tracks

The validation of the bus model was done by comparing the bus floor vertical acceleration signals determined by measurement and simulation. Vertical acceleration

signals were taken on floor below the passenger's seat positioned above the rear axle and below driver's seat. The model validation is shown in more detail in [15]. It should be pointed out that the excitation signal presented in Figure 4 was used for the purpose of simulation.

Figure 5 shows the intercity IK 301 bus with the basic geometric parameters (Figure 5a) and the seat layout on the front, middle and rear part of the bus (Figure 5b). Figure 6 shows spatial bus model built in the ADAMS/View software. Figure 6 also displays the position of markers on the bus floor below the users' seats for registering vertical accelerations.

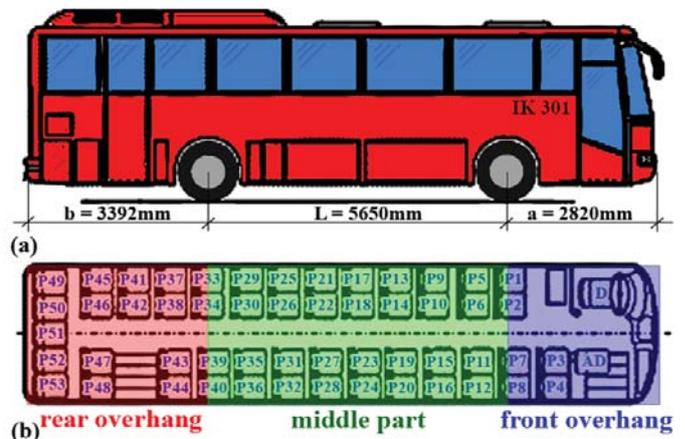


Figure 5: Intercity bus IK 301 a) basic geometry parameters, b) seats layout

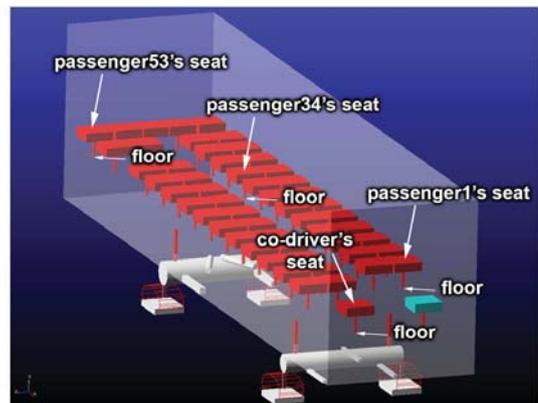


Figure 6: Spatial bus oscillatory model in ADAMS/View

As an example, Figure 7 shows the bus floor accelerations below the passenger53's seat. It is noticed that the vertical acceleration of the floor has the greatest intensity. Figure 8 comparatively displays the bus vertical accelerations below users' seats at the front and rear part of the bus. It is noted that the bus floor vertical acceleration below the passenger53's seat has the greatest intensity and pronounced peaks. Accelerations presented in Figure 8 were introduced as input signals in the oscillatory human-seat model (Figure 2).

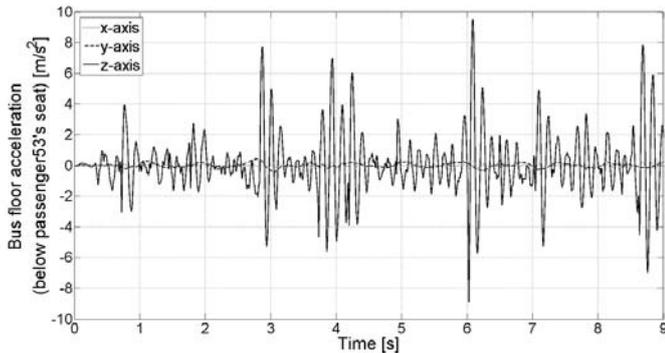


Figure 7: Bus floor accelerations below the passenger53's seat

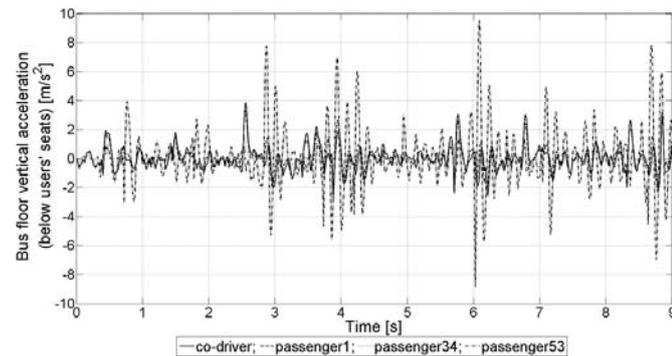


Figure 8: Bus floor vertical accelerations below bus users' seats

Figure 9a shows the power spectral density (PSD) of bus floor vertical accelerations. It is noted that the acceleration intensities for the rear part of the bus are concentrated in the frequency range 5-10 Hz. These accelerations are markedly higher values than those for the front part of the bus. At lower frequencies (around 1 Hz), PSD of the bus floor vertical accelerations for the front part are higher values compared to accelerations for the rear part.

PARAMETERS FOR WBV EXPOSURE ANALYSIS

Standard ISO 2631/1997 recommends two parameters for estimating WBV effects, total rms value of weighted acceleration and Vibration Dose Value (VDV). The total rms value is the basic parameter and includes three translational accelerations along x, y and z axes acting on human body through the seat. In this paper, only vertical acceleration is taken into account because of the highest intensities.

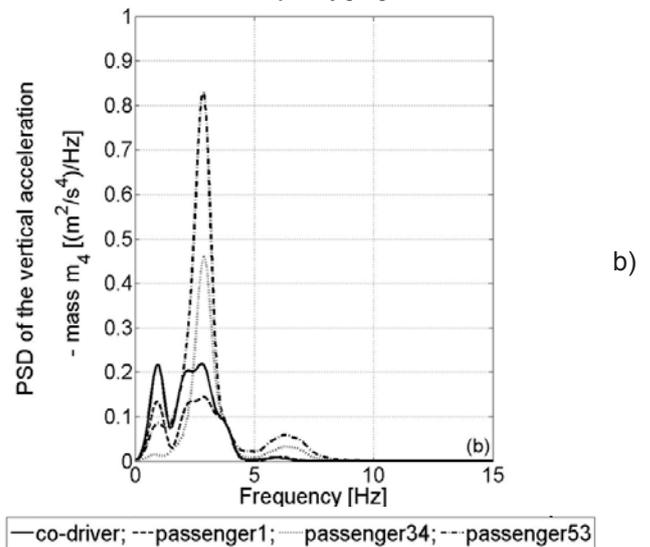
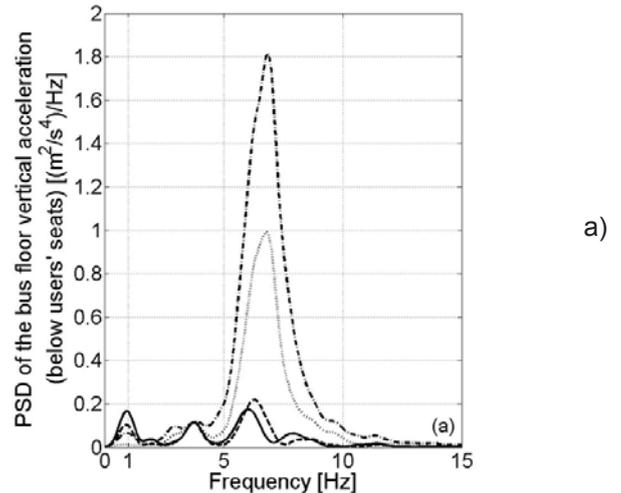


Figure 9: PSD of the vertical acceleration for a) bus floor, b) mass m4

Rms value of the weighted vertical acceleration is calculated by Eq. 7. ISO 2631/1997 standard specifies Wk filter for vertical acceleration weighting [09].

$$\ddot{z}_{rms,w} = \left(\frac{1}{T} \int_0^T \ddot{z}_w^2(t) dt \right)^{1/2} \tag{7}$$

where $\ddot{z}_w(t)$ is the weighted vertical acceleration in function of time; T is the duration of the simulation.

Comfort criteria proposed by ISO 2631/1997 are used to assess the vibration effects, Table 2.

Table 2: Comfort assessment

Vibration intensity	Comfort assessment
< 0.315 [m/s ²]	not uncomfortable
0.315 - 0.63 [m/s ²]	a little uncomfortable
0.5 - 1.0 [m/s ²]	fairly uncomfortable
0.8 - 1.6 [m/s ²]	uncomfortable
1.25 - 2.5 [m/s ²]	very uncomfortable
> 2.0 [m/s ²]	extremely uncomfortable

According to [09], WBV exposure assessment using *rms* value of the weighted acceleration is limited and depends on Crest Factor (CF) value (Eq. 8). The high CF values indicate that the acceleration signal contains shock vibrations.

$$CF = \frac{|\ddot{z}_{\max(w,seat)}|}{\ddot{z}_{rms(w,seat)}} = \frac{\max |\ddot{z}_{w,seat}(t)|}{\left(\frac{1}{T} \int_0^T \ddot{z}_{w,seat}^2(t) dt\right)^{1/2}} \quad 8)$$

where $\max|\ddot{z}_{w,seat}(t)|$ is the maximum absolute value of the weighted vertical acceleration at the seat.

When CF value is greater than 9, the ISO 2631/1997 standard specifies additional parameter VDV for the assessment of the WBV effect (Eq. 9). This parameter is more sensitive to the acceleration peaks compared to the basic parameter and considers the fourth power of the weighted vertical acceleration.

$$VDV = \left(\frac{1}{T} \int_0^T \ddot{z}_w^4(t) dt\right)^{1/4} \quad 9)$$

PARAMETER SEAT

Dynamic seat comfort assessment can be done by parameter SEAT. This is an objective measure that is often used to compare isolation characteristic of the seats equipped with different suspension systems when excited with the same input signals [01]. Although all passenger seats have the same seat cushion oscillatory parameters, the bus floor excitations are not the same. In this paper, the parameter SEAT is used to compare the isolation characteristics of the users' seats in the function of their position on the bus platform.

$$SEAT_{rms} [\%] = \frac{\ddot{z}_{rms(w,seat)}}{\ddot{z}_{rms(w,floor)}} \cdot 100 = \frac{\left(\frac{1}{T} \int_0^T \ddot{z}_{w,seat}^2(t) dt\right)^{1/2}}{\left(\frac{1}{T} \int_0^T \ddot{z}_{w,floor}^2(t) dt\right)^{1/2}} \cdot 100 \quad 9)$$

where $\ddot{z}_{rms(w,seat)}$ and $\ddot{z}_{rms(w,floor)}$ are rms values of the weighted vertical accelerations on the seat and the bus floor below the seat respectively.

Standard ISO 2631/1997 recommends VDV for assessing the parameter SEAT when acceleration signal contains pronounced peaks, Eq. 11.

$$SEAT_{VDV} [\%] = \frac{VDV_{seat}}{VDV_{floor}} \cdot 100 = \frac{\left(\frac{1}{T} \int_0^T \ddot{z}_{w,seat}^4(t) dt\right)^{1/4}}{\left(\frac{1}{T} \int_0^T \ddot{z}_{w,floor}^4(t) dt\right)^{1/4}} \cdot 100 \quad 10)$$

where VDV_{seat} and VDV_{floor} are vibration dose values for seat and bus floor below the seat respectively.

SEAT value greater than 100% indicates that the seat amplifies bus floor vibrations; if the SEAT value is equal to 100%, the seat do not isolate floor vibration, and there is no improvement in ride comfort; the seat attenuates some vibration if SEAT value is less than 100%.

RESULTS ANALYSIS AND DISCUSSION

The paper analyzes the WBV exposure of bus users and dynamic comfort of their seats. Exposure to WBV was determined by the weighted vertical acceleration of the mass *m4* and VDV. The SEAT parameter was used to analyze dynamic seat comfort.

Figure 10 shows the vertical acceleration of the user's mass *m4*. It is noticed that the passengers in the rear of the bus are exposed to higher vertical acceleration intensities. Table 3 gives the *rms* values of the vertical acceleration for the bus floor below the users' seats and for the users' mass *m4*. The *rms* acceleration values on the floor are of higher values, indicating that passenger seats attenuate vertical vibration.

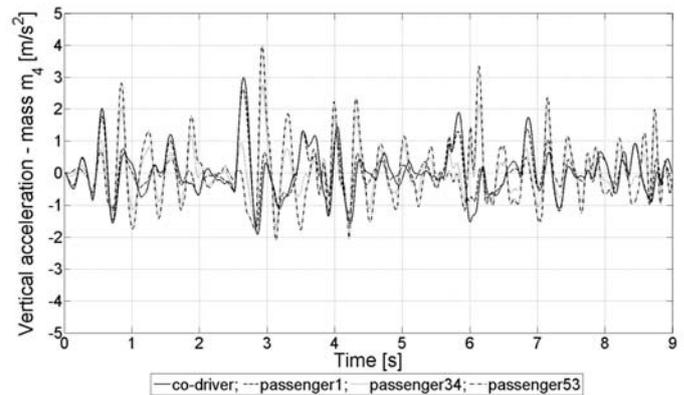


Figure 10: Vertical accelartions of the mass *m4*

Figure 9b shows the PSD of the mass *m4* vertical accelerations. Accelerations' intensities are concentrated at lower frequencies near the resonance frequency of the seat (about 2.5 Hz) and are of lower values compared to the vertical accelerations of the bus floor. Passenger53 has the highest PSD acceleration value, approximately 0.8 (m2/s4)/Hz.

Bus users' exposure to WBV

Figure 10a shows the change in *rms* values of the weighted vertical acceleration for bus users in the function of the seat cushion stiffness and for the nominal damping value. Passenger53 has the highest *rms* acceleration values, and apparently the lowest ride comfort. When cushion stiffness increasing, *rms* acceleration increases considerably for all bus users.

Figure 10b shows the change in *rms* values of the weighted vertical acceleration in function of the seat cushion damping and for the nominal stiffness value. When cushion damping increasing, *rms* acceleration gradually decreases for all bus users. Higher damping values provide somewhat better ride comfort.

Table 3: Rms vertical acceleration values for bus floor and mass m4

	co-driver	passenger1	passenger34	passenger53
Floor rms vertical acceleration [m/s ²]	0.811	0.782	1.456	2.018
Mass m4 rms vertical acceleration [m/s ²]	0.738	0.621	0.698	0.973

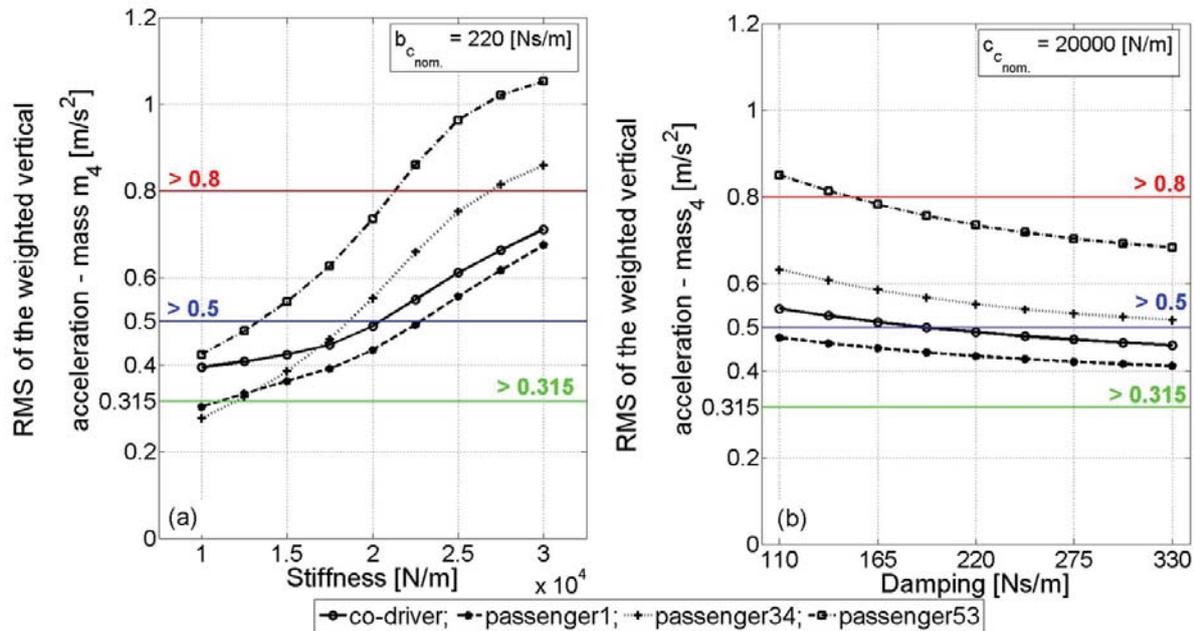


Figure 10: Change of rms value of the weighted vertical acceleration in the function of a) seat cushion stiffness for nominal damping, b) seat cushion damping for nominal stiffness

Table 4 gives the calculated rms values of the weighted vertical acceleration and VDV parameters for the nominal values of the seat cushion's oscillatory parameters. Table 4 also provides an estimate of the ride comfort according to [09]. Bus users in the front part have better ride comfort than the passengers at the rear bus part. The calculated CF value is approximately the same for all users (approximately equal to 4). In Table 4, calculated VDV values are also given. Higher VDV values for rear passengers indicate lower ride comfort level compared to passengers in the front part of the bus.

As an example, Table 5 provides an estimate of the ride comfort for passenger34 in the function of his seat cushion oscillatory parameters. For nominal damping value, when stiffness increasing, the ride comfort level is reduced from "comfortable" to "uncomfortable". For the nominal stiffness value, the rms acceleration decreases gradually with the increase in damping values. However, ride comfort level for the passenger34 does not change and the estimate is "fairly uncomfortable".

Estimation of the users' seat dynamic comfort

Table 6 shows SEAT values calculated by two procedures for the nominal values of the seat cushion oscillatory parameters.

Users at the bus front have higher SEAT values than the passengers in the rear of the bus. The values of both SEAT parameters slightly differ for each individual bus user.

Since the calculated CF values are less than 9 (Table 4), the effect of the seat cushion oscillatory parameters on vibration attenuation will be analyzed by SEATrms only.

Figure 11a shows the change of SEATrms in the function of seat cushion stiffness for the nominal damping value. For all stiffness values and for all bus users, the SEATrms values are lower than 100%, indicating that the seats attenuate vertical vibrations. For the maximum cushion stiffness of the 30000 N/m, SEATrms value for co-driver is approximately equal to 100% (the seat does not attenuate vertical vibration). SEATrms values are approximately the same for both passengers at the rear of the bus for the entire range of cushion stiffness. SEATrms values are lower for the passengers at the rear compared to those at the front of the bus. Both passengers' seats at the bus rear part attenuate vibrations with the highest acceleration intensities in the frequency range (5-10 Hz).

Table 4: Characteristic parameters for ride comfort assessment

	co-driver	passenger1	passenger34	passenger53
Rms value of the weighted vertical acceleration [m/s²]	0.489	0.434	0.554	0.737
Comfort assessment (ISO 2631/1997)	Little uncomfortable	Little uncomfortable	Fairly uncomfortable	Fairly uncomfortable
CF [-]	4.047	4.229	3.921	4.089
VDV [m/s^{1.75}]	1.234	1.086	1.392	1.892

Table 5: Ride comfort assessment in function of seat cushion oscillatory parameters for passenger 34

For nominal cushion damping value ($b_c=220$ [Ns/m])			For nominal cushion stiffness value ($c_c=20000$ [N/m])		
Stiffness (N/m)	Weighted rms vertical acceleration (m/s ²)	Comfort assessment (ISO 2631/1997)	Damping (Ns/m)	Weighted rms vertical acceleration (m/s ²)	Comfort assessment (ISO 2631/1997)
-50%	0.276	Comfortable	-50%	0.633	Fairly uncomfortable
-25%	0.385	Little uncomfortable	-25%	0.587	Fairly uncomfortable
Nominal value	0.554	Fairly uncomfortable	Nominal value	0.554	Fairly uncomfortable
+25%	0.754	Fairly uncomfortable	+25%	0.532	Fairly uncomfortable
+50%	0.860	Uncomfortable	+50%	0.517	Fairly uncomfortable

Table 6: SEAT values for nominal seat cushion oscillatory parameters

	co-driver	passenger1	passenger34	passenger53
SEATrms [%]	66.711	58.763	37.182	35.785
SEATVDV [%]	63.767	57.134	34.525	33.717

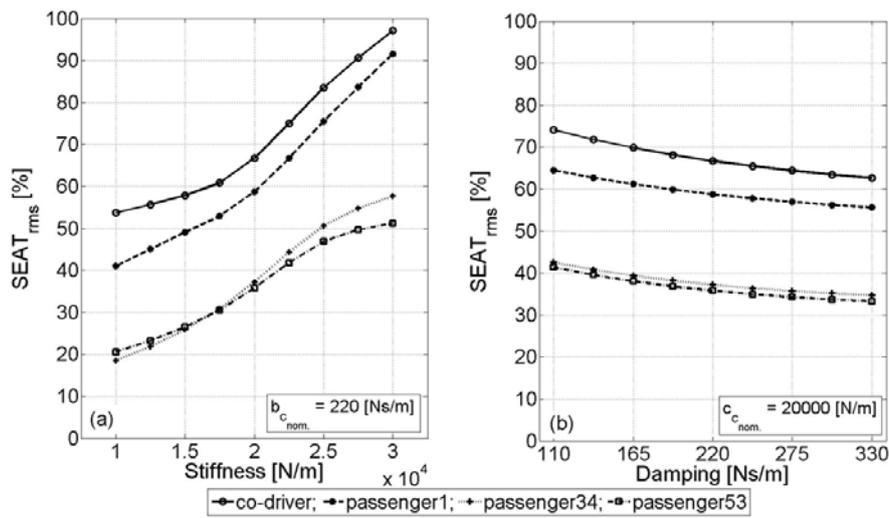


Figure 11: Change of parameter SEATrms in the function of a) seat cushion stiffness for nominal damping value, b) seat cushion damping for nominal stiffness value

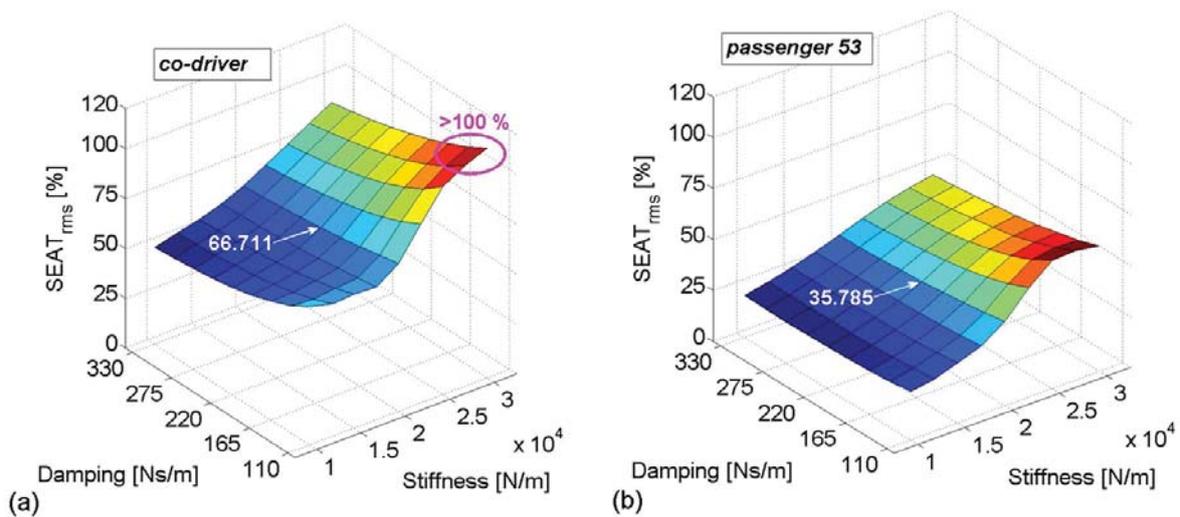


Figure 12: Change of parameter SEATrms in the function of seat cushion oscillatory parameters for a) co-driver, b) passenger53

Figure 11b shows the change of SEATrms in the function of the damping cushion for nominal stiffness value. With increase in the damping, SEATrms decrease slightly.

Figure 12(a-b) shows a change in the SEATrms value for co-driver and for passenger53 in the function of seat cushion stiffness and damping. SEATrms values for passenger53 are lower compared to those for co-driver. For low cushion damping and large stiffness, the co-driver's seat amplifies the vertical vibrations that are transmitted from the floor to its body (SEATrms value is greater than 100%).

CONCLUSION

The paper analyzes the intercity bus users' ride comfort and dynamic comfort of their seats in the function of the seat cushion oscillatory parameters for a real road roughness. For the analysis, a linear in-line oscillatory

seat-human model with 4 DOF was used. As a model excitation, the vertical accelerations of the bus floor under the users' seats were used. Vertical accelerations of the floor were obtained by simulation using the validated spatial model of the intercity bus built in the ADAMS/View module. Bus model was excited with bad asphalt-concrete road roughness.

The ride comfort rating was performed using the criteria of ISO 2631/1997. Passengers in the rear of the bus are exposed to higher values of vertical acceleration. Passengers at the rear have lower level of ride comfort compared to users in the front of the bus. Rms values of the weighted vertical acceleration increase for all users with the increase in the cushion stiffness. Rms values decrease with the increase in the cushion damping.

Spectral analysis of the bus floor vertical acceleration showed that the acceleration intensities are concentrat-

ed in the frequency range of 5-10 Hz. The highest floor acceleration is below the passenger seat at the rear bus overhang. Passengers' seats increase acceleration at frequencies that correspond to resonant seat frequency (around 2.5 Hz). Seats attenuate the vibrations above 3.5 Hz.

SEATrms are of lower values for the passengers at the rear than for the front bus passengers. Seats attenuate the highest floor vertical acceleration values for both passengers in the rear part of the bus in the frequency range 5-10 Hz. SEATrms values are approximately the same for both passengers at the rear of the bus. For all analyzed cushion stiffness values and for all users, SEATrms values are lower than 100%, indicating that the seats attenuate vertical vibrations. With the increase in the seat cushion damping, SEATrms value decreases slightly.

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