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VIBRATION COMFORT OF THE VEHICLE EXPRESSED BY SEAT EFFECTIVE AMPLITUDE TRANSMISSIBILITY

Valentina Golubović-Bugarski [1], Snežana Petković [2], Željko Đurić [3], Goran Jotić [4]*

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RESEARCH ARTICLE

ABSTRACT: Research of the human body vibrations, carried out under controlled laboratory conditions, shows that human body is the most sensitive to vibrations in the frequency range that matches the biomechanical resonance. In the vertical direction, the resonance of the body is approximately 5 Hz, while in the horizontal direction the resonance occurs at frequencies less than 2 Hz. The vibrations of the vehicle have been transferred to the driver and passengers over the seats, which have the ability to attenuate or to amplify vibrations which human body is exposed to while driving. One way to determine the vibration behaviour of the seat is to measure the SEAT (seat effective amplitude transmissibility) factor, which represents the ratio between the vibrations measured on the seat and vibration measured directly on the floor under the seat. Measurement of vibrations in these two positions must be performed simultaneously. If the value of SEAT is less than 1, a seat attenuates vibrations and meets vibrational comfort, the value of SEAT greater than 1 indicates that a seat amplifies vibration, reducing vibration comfort. This paper gives results of SEAT factor investigation done on a hybrid vehicle, for different types of road surface and different modes of driving (electric power and internal combustion engine).

[1]*Valentina Golubović-Bugarski, PhD prof., University of Banja Luka, Faculty of Mechanical Engineering, Stepe Stepanovića 71, 78000 Banja Luka, BiH, ivalentina.golubovic-bugarski@mf.unibl.org (*Corresponding author)*
[2]*Snežana Petković, PhD prof., University of Banja Luka, Faculty of Mechanical Engineering, Stepe Stepanovića 71, 78000 Banja Luka, BiH, petkovic1961@gmail.com*
[3]*Željko Đurić, Assist., University of Banja Luka, Faculty of Mechanical Engineering, Stepe Stepanovića 71, 78000 Banja Luka, BiH, zeljko.djuric@mf.unibl.org*
[4]*Goran Jotić, Assist., University of Banja Luka, Faculty of Mechanical Engineering, Stepe Stepanovića 71, 78000 Banja Luka, BiH, goran.jotic@mf.unibl.org*

KEY WORDS: vibration comfort, seat effective amplitude transmissibility SEAT, hybrid vehicle

VIBRACIONA UDOBNOST VOZILA IZRAŽENA EFEKTIVNIM VREDNOSTIMA AMPLITUDNE KARAKTERISTIKE FUNKCIJE PRENOSA SEDIŠTA

REZIME: Istraživanje vibracija tela čoveka, realizovano u kontrolisanim laboratorijskim uslovima, pokazuje da je telo čoveka najosetljivije na vibracije u frekventnom opsegu koji odgovara biomehaničkoj rezonanci. U vertikalnom pravcu, rezonanca tela je približno 5 Hz, dok se u horizontalnom pravcu rezonanca javlja na frekvencijama manjim od 2 Hz. Vibracije vozila se prenose na vozača i putnike preko sedišta, koja imaju sposobnost da ublaže ili pojačaju vibracije kojima je telo čoveka izloženo tokom vožnje. Jedan od načina za određivanje vibracionog ponašanja sedišta je merenje SEAT faktora (efektivna vrednost amplitudne karakteristike funkcije prenosa sedišta) koji predstavlja odnos vrednovanog ubrzanja merenih na sedištu i ubrzanja merenih direktno na podu ispod sedišta. Merenje vibracija u ova dva položaja mora se vršiti istovremeno. Ako je vrednost SEAT-a manja od 1, sedište slabi vibracije i zadovoljava vibracionu udobnost, vrednost SEAT-a veća od 1 pokazuje da sedište pojačava vibracije smanjujući vibracionu udobnost. U radu su prikazani rezultati istraživanja faktora SEAT za hibridno vozilu na različitim tipovima kolovoza i u različitim režimima vožnje (električna energija i motor sa unutrašnjim sagorevanjem).

KLJUČNE REČI: vibraciona udobnost, efektivna vrednost amplitudne karakteristike funkcije prenosa sedišta SEAT, hibridno vozilo

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1. INTRODUCTION

Seat is a primary point of contact between the human body and the vehicle structure which generates the vibrations, therefore its role in the isolation of the whole-body vibrations is a very important. Proper design of a seat contributes largely in reduction of the vibration levels. Seat should be designed in such a way that the driver can drive the vehicle safely and effectively, it should have strength enough to protect the occupant in the event of an accident, it should have good static and dynamic comfort properties [11]. It is important to point out that the seat which is better in term of static comfort may be worse in the case of dynamic comfort. Figure 1 shows Ebe's model of seat discomfort which includes a consideration of both static and dynamic factors [3, 11]. This model shows overall comfort characteristics of two different seats, one being good at rest and the other being good for driving case. In first case, static comfort is high and dynamic comfort is less. However in second case, initial static comfort is less but its dynamic comfort is high. Therefore, seat „a" will be better for environments with large magnitudes of vibration but seat „b" will be better for environments with low magnitudes of vibration. It is up to the manufacturers to optimize the comfort for both cases.

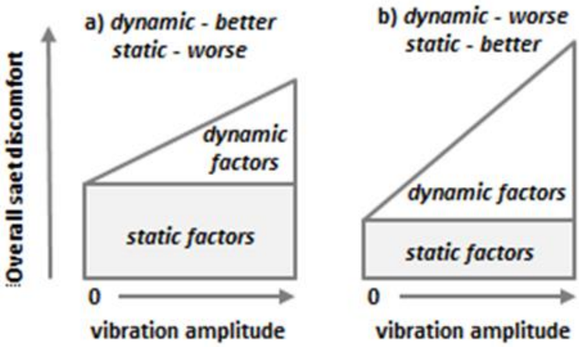


Figure 1. Ebe's model of the overall seat discomfort [3, 11]

Investigation of seat comfort showed that the ideal seat in any situation is a function of the seat static properties, the seat dynamic properties, the vibration to be controlled, and the human perception characteristics. It can be found in [11] that investigation of static parameters was done, for example driver posture [14, 13], contact pressures [15, 7], and thermal properties [12]. When it comes to dynamic comfort, laboratory studies of whole-body vibration have established a relationship between the magnitude, duration, frequency content, and waveform of the signal. The nature of the seat dynamic response is much complex than its static performance. The dynamic response of the seat is influenced by the dynamic properties of the human body, so the real occupant cannot be replaced by an inert mass as in static investigation. The transmissibility of a seat measured with one occupant will be slightly different when tested with a different occupant [17]. Also, the transmissibility of the seat measured while driving on a smooth surface will be slightly different when tested on a rough surface [4]. Present studies are mostly devoted to investigation of damping properties of the suspension seats in working machines, such as tractors [1, 5] and construction machines [2, 10].

2. THE EFFECTS OF VIBRATION ON COMFOR AND PERCEPTION

Thresholds of perception for continuous whole-body vibration vary widely among individuals. Approximately half of the people in a typical population, no matter standing or seated, can perceive a vertical weighted peak acceleration of 0.015 (m/s^2). A quarter of the people would perceive a vibration of 0.01 (m/s^2), but the least sensitive people would only be able to sense a vibration magnitude of 0.02 (m/s^2) or more, as it is described in ISO 2631-1 [8]. Regarding the vibration comfort in vehicles, a particular vibration condition may be considered to cause unacceptable discomfort. Many factors combine to determine the degree to which discomfort may be noted or tolerated. Acceptable values of vibration magnitude for comfort depend on passenger expectations with regard to trip duration, type of passenger′s activities during trip (reading, eating, writing) and many other factors (acoustic noise, temperature, etc.). However, comfort reactions due to vibration amplitudes may be classified as follows [8]:

- 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 vary uncomfortable
- Greater than 2 m/s^2 extremely uncomfortable.

3. SEAT EFFECTIVE AMPLITUDE TRANSMISSIBILITY FACTOR

The vibration isolation efficiency of a seat may be expressed by means of The Seat Effective Amplitude Transmissibility factor (SEAT) [11]. This dimensionless factor is dependent on the vibration spectrum, seat transmissibility and subject response frequency weighting. It shows the capability of a seat design to attenuate the vibrations generated in a vehicle, i.e. to protect the driver from excessive vibrations. The SEAT value is defined as:

$$\text{SEAT\%} = 100 \times \frac{\text{ride comfort on seat}}{\text{ride comfort on floor}} \tag{1}$$

A seat would improve ride comfort when SEAT factor is smaller than 1 or, expressed in percentage, when SEAT% is less than 100%. If the value exceeds these limits, the seat actually amplifies vibrations and, thus, worsens ride comfort. According to ISO 10326-1 Mechanical vibration – laboratory method for evaluating vehicle seat vibration [9], the measurement of the SEAT involves determination of the vibration magnitudes at two positions, as depicted in Figure 2:

- on the seat pan, which represents the interface between the human body and the seat
- at the base of the seat, that is at the place of vibration transmission to the seat, Figure 2.

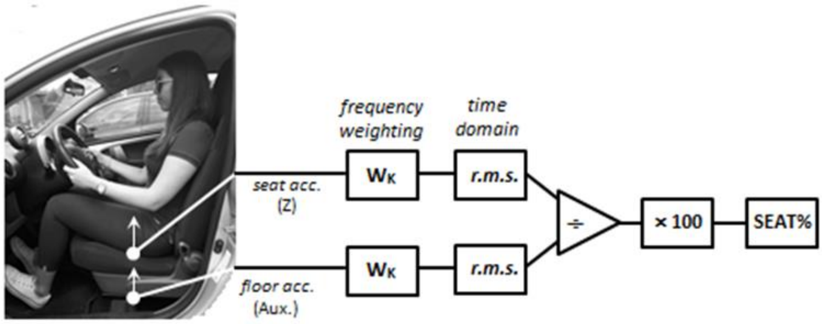


Figure 2. Graphical representation of the SEAT measurement

Measurements at these two points are done simultaneously and the SEAT is computed as the ratio between these two magnitudes. The magnitude of the vibrations is measured in terms of weighted acceleration root mean square values (r.m.s) or vibration dose values (VDV). Therefore, the SEAT expression becomes either:

$$SEAT_{rms}\,\% = 100 \times \frac{a_{w,seat}}{a_{w,floor}} \tag{2}$$

$$SEAT_{VDV}\,\% = 100 \times \frac{VDV_{seat}}{VDV_{floor}} \tag{3}$$

The r.m.s. is expressed in (m/s2) and defined as:

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2(t)\,dt\right]^{\frac{1}{2}} \tag{4}$$

where:
$a_w(t)$ is the frequency weighted acceleration (using W_k weighting) as a function of time in (m/s^2),
T is the duration of measurement in (s).

The VDV is expressed in ($m/s^{1,75}$) and defined by the relation:

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

where:
$a_w(t)$ is the frequency weighted acceleration (using W_k weighting) as a function of time in (m/s^2),

T is the duration of measurement in (s).

Whether to use r.m.s. or VDV depends on the vibrations encountered during the measurement. If the vibration history is rather smooth, then RMS vibration magnitude is preferable. If, however, the vibrations included transients and shocks, it is recommended to compute SEAT based on VDVs.

The SEAT factor measurement belongs to the category of whole-body vibrations measurement. The way in which humans perceive vibration depends on different factors, including the vibration frequency content and direction. People are most sensitive to whole-body vibration within the frequency range of 1 to 20 Hz, but there are different human sensitivities to vibration in different directions of excitation. When measuring whole-body vibration at the seat, ISO 2631 requires the use of *Wk* weighting in the Z-direction, whereas *Wd* is used for the acceleration in the X- and Y-directions.

When assessing a seat′s ability to attenuate vibrations, it is important to keep in mind that seat and driver must be seen as one system. The driver will add mass to the seat, which preloads the seat springs, and changes the resonance behavior. Further, depending on posture, the seat-driver combination will lead to a more or less stiff system (e.g., vibrations will be different if the driver sits relaxed or if feet are pressed against the floor). Thus, depending on the driver's body and posture, the performance of seats can be very different. What constitutes a "good" SEAT value depends on the vehicle type [6, 14]. For example, vibration in cars usually has substantial components at about 10 Hz, which can be easily isolated by conventional seats. Car seats therefore often have SEAT values in the range of 60 to 80%.

4. MEASUREMENT METHODOLOGY

The research task in this paper was to evaluate the vibration (dynamic) comfort of a hybrid vehicle by measurement of the Seat Effective Amplitude Transmissibility factor (SEAT). A hybrid vehicle efficiently combines the internal combustion engine (ICE) and electric power (EV) from the battery.

In this investigation, Toyota C-HR (1,8 l Hybrid Petrol) was used, Figure 3, having performances as follows: engine power 98 Hp or 72/5200 kW/rpm, max torque 142/3600 Nm/rpm; electric motor power 53 kW, max torque 163 Nm, max voltage 600 V; battery type Ni MetalHibrid, nominal voltage 201,6 V, number of battery modules 28, battery capacity 6,5 Ah.

a) b)

Figure 3. a) test car, Toyota C-HR, b) energy monitor in the car showing driving mode

The final goal of investigation was to find out how vibration comfort depends on the type of vehicle power mode, i.e. whether driving in electric mode provides better vibration comfort compared to driving in internal combustion engine mode. Also, our intention was to find out the effect of the road surface quality to the vibration comfort, the influence of the driving speed, as well as the influence of the driver′s weight.

The measurements were made by driving the car on the four roads, with different conditions:

- the new motorway (Laktaši – Gradiška), Figure 4a: straight, well maintained smooth road surface without any damage; the car was driven at about 50-60 km/h in EV mode and 70-120 km/h in ICE mode; the driver′s weight was about 100 kg
- the fast road (Banja Luka-Laktaši): straight and little bumpy due to ruts; the car was driven at about 50 km/h in EV mode and 70-100 km/h in ICE mode; the driver′s weight was about 100 kg
- the city street (in Banja Luka): well-maintained surface of the road, but the driving was with a lot of slowing down and braking, at about 40-50 km/h in EV and 60 km/h in ICE mode; two drivers, A (100 kg) and B (60 kg), participated in the experiment
- the suburban street (in Banja Luka), Figure 4b: the road surface is in a poor condition and characterized by a series of pot-holes and bumps; the car was driven at about 40-50 km/h in EV mode and 60 km/h in ICE mode; two drivers, A (100 kg) and B (60 kg), participated in the experiment.

a) b)

Figure 4. Roads where measurements were done. a) motorway, b) suburban street

Each of the measurement sessions durated about 3 minutes. As mentioned before, for evaluation of the SEAT factor it is necessary to simultaneously measure the vibration signals on the seat and on the vehicle's floor. To perform two channels measurement, we used following equipment, Figure 5:

- Human Vibration Analyser type 4447
- Seat pad, with built in triaxial accelerometer type 4506
- Uniaxial accelerometer type 4507 (all by Bruel&Kjaer).

a) b) c)

Figure 5. a) The analyzer 4447, b) seat pad strapped to the cushion, c) uniaxial accelerometer on the floor

The Human Vibration Analyzer Type 4447 complies with the technical requirements of ISO 8041:2005 Human responses to vibration - Measuring instrumentation, and can perform measurement compliant with the standards pertaining to human vibration [16]. The instrument possessed the pre-set frequency weightings for hand-arm (W_h) and whole-body (W_d and W_k) vibrations. Uniaxial and triaxial accelerometers are the piezoelectric vibration sensors which capture the measured signals and deliver it to the analyzer for processing. The uniaxial accelerometer is mounted on the floor, at the place of the vibration transmission to the seat, Figure 5c. The accelerometer is best mounted on a rigid part of the floor using glue, a strong magnet or double-sided thin adhesive tape. In this investigation, we used double-sided adhesive tape. The triaxial accelerometer is mounted in the seat pad which is located on the seat cushion, Figure 5b. It is necessary to tape or strap it to the cushion in such a way that the accelerometer is located midway between the ischial tuberosities of the seat occupant. The analyzer 4447 is only set up to evaluate SEAT in the vertical direction, i.e. it compares the vertical vibration at the floor (vibration signal marked by Auxiliary) with vibrations along the Z-axis of the Seat Pad (vibration signal marked by Z), as depicted in Figure 2. The whole-body weighting W_k is applied for the Z and the Auxiliary signals when carrying out SEAT measurements.

5. DISCUSSION OF THE MEASUREMENT RESULTS

The r.m.s. vibration magnitudes (expressed in m/s^2) measured along the Z-axis of the Seat Pad (marked by Z) and at the vehicle's floor (marked by Aux), together with the values of the SEAT factor are presented in the Table 1.

Table 1. Results of vibration measurement at the seat and at the floor of the vehicle and SEAT factor

	Type of road	Drive mode/ driver	Velocity (km/h)	r.m.s. (m/s^2)		SEAT	SEAT %
				Z	Aux		
1	new motorway	EV / A	55	0,1253	0,1631	0,7684	76,84
2			60	0,1208	0,1640	0,7363	73,63
3			60	0,1137	0,1591	0,7149	71,49
4		ICE / A	70	0,1221	0,1710	0,7142	71,42
5			90	0,1441	0,1995	0,7225	72,25
6			110	0,1830	0,2392	0,7652	76,52
7	fast road	EV / A	60	0,1759	0,2181	0,8066	80,66
8		ICE / A	70	0,2028	0,2606	0,7784	77,84
9		ICE / A	90	0,2768	0,3429	0,8071	80,71
10	city street	EV / A	60	0,2091	0,2888	0,7239	72,39
11		ICE / A	50	0,2569	0,3327	0,7721	77,21
12		EV / B	40	0,3116	0,4034	0,7726	77,26
13	suburban street	EV / A	35	0,4102	0,5593	0,7334	73,34
14		EV / B	40	0,4826	0,6443	0,7491	74,91
15		ICE / A	45	0,4305	0,5726	0,7518	75,18

Analysing the measurement results, the SEAT factor takes values between 71.42 % and 80.71%. For all measurement conditions, it can be seen that the increase of the vibration amplitude measured on the vehicle’s floor results in increase of the vibration measured on the seat, giving the Seat Effective Amplitude Transmissibility average value of 75.44%. This means that 75.44% of vibration generated by driving is transmitted from the vehicle's structure to the driver's seat.

It is interesting to analyze vibration amplitudes measured at the seat and on the floor of the vehicle for different driving conditions. For the approximate values of driving speed (40-60 km/h for EV; 45-70 km/h for ICE), vibration amplitudes are lowest for measurements done along the new motorway. This is expected due to the excellent quality of the road surface, which is well maintained and smooth, and the road is relatively in a straight line, with minimum curvatures. The level of vibration is noticeably increasing with the decline in the quality of the driving surface (motorway / fast road / city streets / suburban streets), for both drive modes, EV (Figure 6a) and ICE (Figure 6b).

a)

b)

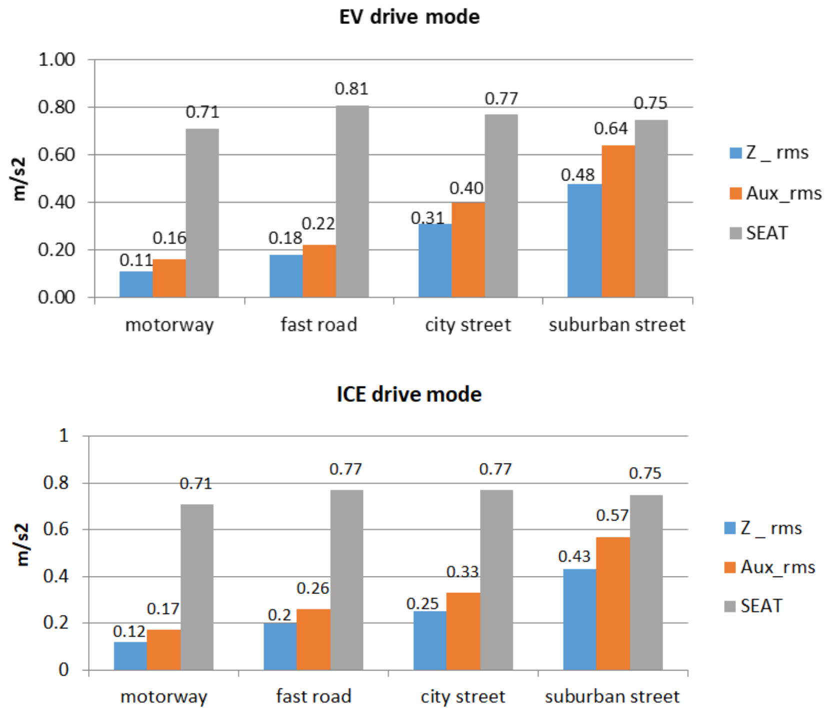
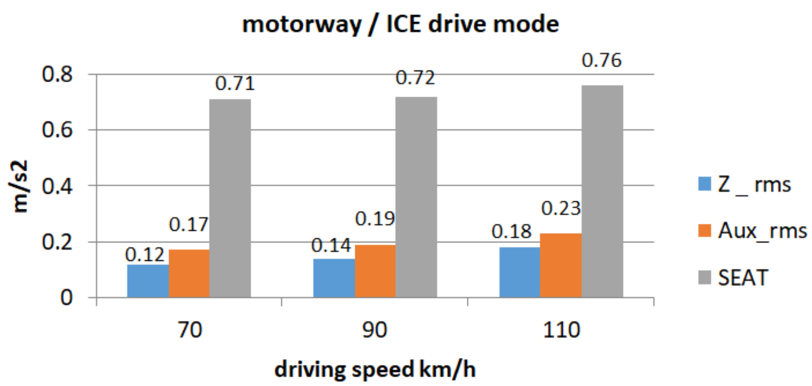


Figure 6. Vibration amplitude values (Z and Aux) and SEAT factor for different type of roads: a) EV drive mode, b) ICE drive mode

Comparing the vibration values measured for the same type of road and drive mode, but different driving speeds, one can conclude that there is no significant difference between vibration values for EV mode (due to insufficient difference of driving speeds, 55 – 60 km/h). However, regarding ICE drive mode, it can be seen that vibration values increase as driving speed increases, Figure 7a (driving on the motorway) and 7b (driving on the fast road).

a)



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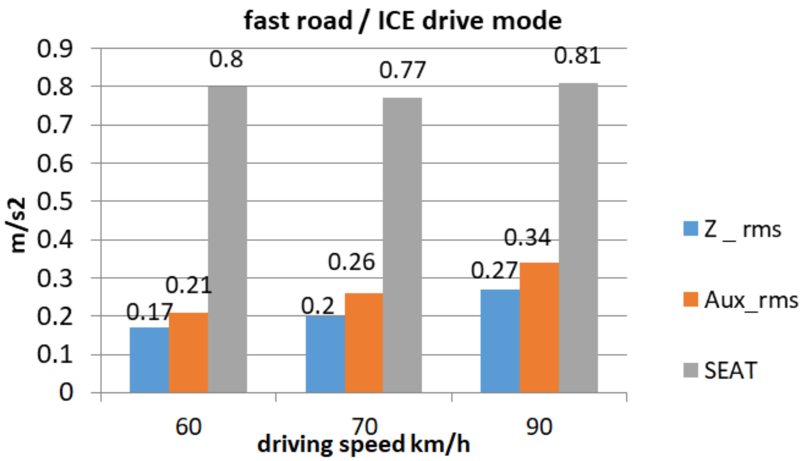
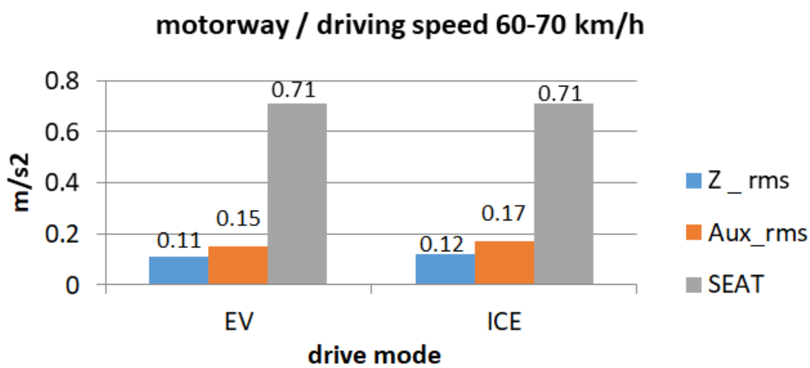


Figure 7. Vibration amplitude values (Z and Aux) and SEAT factor for ICE mode and different driving speeds: a) driving on the motorway, b) driving on the fast road

Comparing the vibration values measured for the same type of road and approximately equal driving speed, but for the different drive modes, it can be concluded that EV mode produces lower vibration than driving in ICE mode, as shown in Figure 8a (driving on the motorway), 8b (driving on the fast road) and 8c (driving on the city street).

a)



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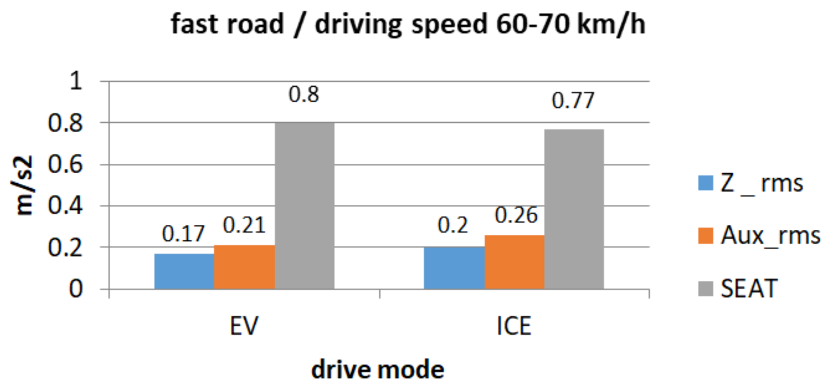

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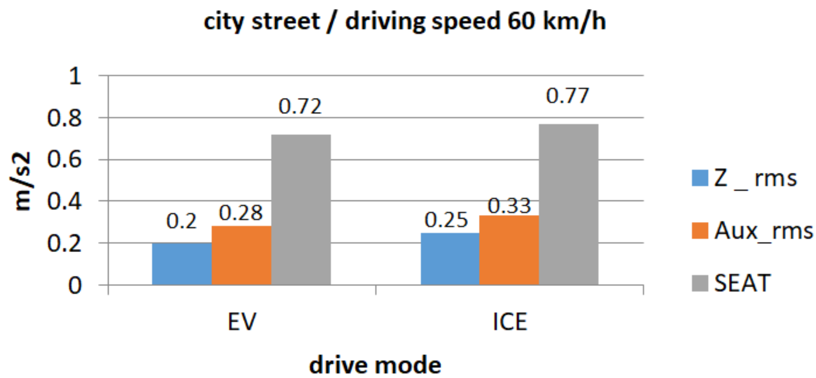
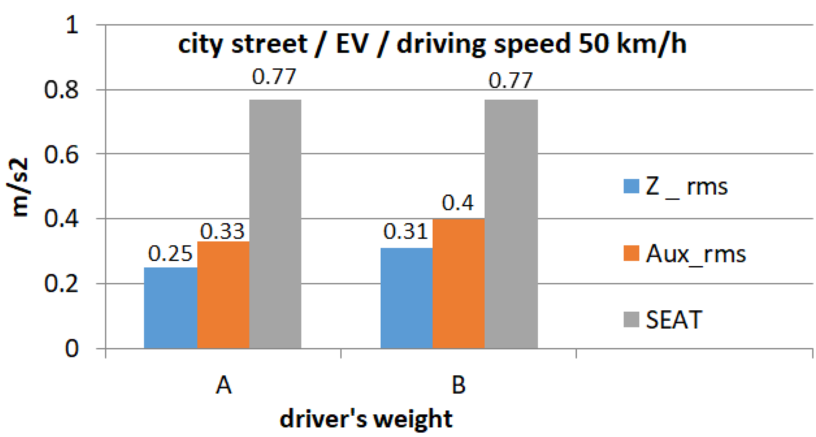


Figure 8. Vibration amplitude values (Z and Aux) and SEAT factor for different drive modes: a) driving on the motorway, b) driving on the fast road, c) driving on the city street

Regarding the influence of the driver's weight, it can be seen that greater driver's weight (A - 100 kg, B - 60 kg) produces lower vibration transmission to the seat pan, Figure 9a (driving on the city street) and 9b (driving on the suburban street).

a)



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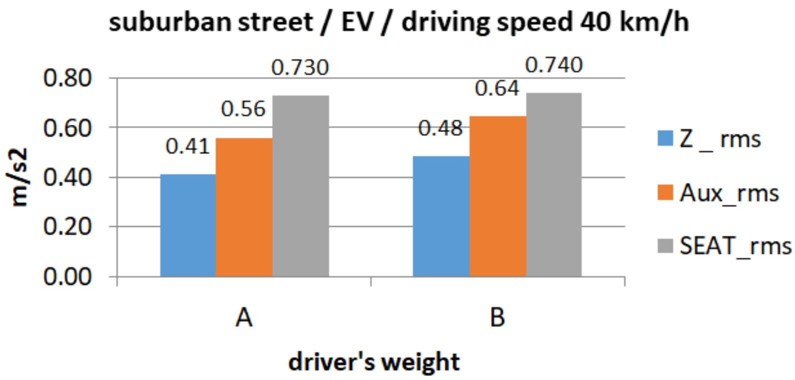

Figure 9. Vibration amplitude values (Z and Aux) and SEAT factor for different driver's weight: a) driving on the city street, b) driving on the suburban street

6. CONCLUSIONS

An investigation of the vibration comfort of a hybrid vehicle Toyota C-HR was done in this paper. A total of 16 measurements were performed and the measured Seat Effective Amplitude Transmissibility factor, expressing vibration seat comfort, was in the range between 71.42% (vehicle rides over new motorway with smooth road surface) and 80.71% (vehicle rides over fast road with a lot of ruts). Although the measured SEAT values varied within 10%, the average value of the SEAT for all performed measurements is around 75%, which can be considered as good dynamic comfort estimation for this category of vehicles (passenger cars). Vibration amplitudes measured on the vehicle's floor and at the driver's seat show that the vibration comfort can be rated as "not uncomfortable" (vibration amplitude less than 0.315 m/s^2), except for driving over the suburban streets where the vibration comfort is rated as "a little uncomfortable" (for vibration amplitude between 0.315 m/s^2 to 0.63 m/s^2).

Regarding the measured vibration amplitudes on the vehicle's floor and the driver's seat, we can conclude following:

- The vibration amplitude depends on the type of road the vehicle is riding on and the quality of its surface. The best vibration comfort is achieved by driving on a motorway where the road surface is smooth, with no damages. This applies to driving modes, electrical power and internal combustion engine mode. For some environments, a major contributor to the vibration is the roughness, or tidiness, of road. So, keeping the road in good condition and repairing the damages would improve the mechanical (vibration) environment for the vehicle
- Increasing the driving speed increases the vibration amplitudes, which reduces dynamic comfort. For many vehicles, lower vibration is received by passengers if the speed of the vehicle is limited
- At the same driving conditions, i.e. the same type of road and approximately the same speed, EV drive mode gives a lower vibration level (for about 15 %) than drive in ICE mode. Even though the engine of the vehicle can be the main contributor to the vibration exposure, we concluded that the lower vibration generated in EV mode is associated with the lower driving speed, since the hybrid vehicle activates the EV mode at lower driving speeds

- At the same driving conditions (the same type of road, the same driving mode and approximate speed), it was shown that the driver of the lower weight was exposed to higher vibrations. Conventional foam seats, such as car seats, have a resonance at 4 to 5 Hz, which coincides with the frequency where the human body is most sensitive to vibration. However, the drivers weight generally has only small effect to vibration response. Several other factors, such as subject size, posture, backrest contact and backrest angle, foot-support position and support for the arms can have significant effects on seat transmissibility.

Commonly cars are purchased on the basis of comfort evaluation just in the showroom, whereby attention is paid only to static comfort, neglecting the dynamic and temporal aspects of seating comfort. It is much better for purchasers to test-drive the vehicle for an extended period of time and evaluate the vehicle's dynamic comfort, which is especially important for high-mileage business drivers.

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