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Assessment of Passenger Ride Comfort during Vertical Vibration of Mid-size Saloon and Off-road Vehicles on Asphalt Roads

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ABSTRACT:

Ride comfort in road vehicles is related to vehicle vibration levels and the perception of passenger fatigue. In this study, vibration in vertical direction on the seat and floor are measured to characterise the ride comfort based on standard formulae and frequency analysis. A mid-size saloon vehicle and an off-road vehicle are driven on smooth, spalled and coarse asphalt road surfaces. To assess the vertical vibrations transmitted to the passengers, vibration dose values, Kurtosis, frequency response functions and power spectral densities of the compartment recorded signals were evaluated. Seat effective amplitude transmissibility value based on vibration RMS and vibration dose values were also evaluated. The results indicate that the vibration dose value increases in proportional to the vehicle speed and road roughness.

KEYWORDS:

Ride comfort; Automotive seat; Vibration dose values; Kurtosis; Power spectral density

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1. Introduction

Today, vehicle ride comfort has developed many facets which are as significant as safety and speed in assessing the physical characteristics of transportation. The road roughness and vehicle vibration play a predominant role in the subjective evaluation of the ride comfort and activity comfort. One of the main sources of the vibration in the vehicle cavity is the vibration due to the interaction between tyre and road surface. Basically the level of vibration is dependent on the speed of the vehicle, tyre pattern and the roughness of the road surface [1-2]. In designing a comfortable seat, it is important to understand the vibration environment to which individuals are exposed and how well they can tolerate this environment. Moreover, human sensitivity to low-frequency Whole Body vibration (WBV) has pointed to ride quality as an important need in seat vibration transmission to human. Passengers have a large influence on comfort, performance, and health.

A comfortable ride is essential for a vehicle in order to obtain passenger satisfaction. In this view, vehicle manufacturers are continuous seeking to improve vibration comfort. Many factors influence the transmission of vibration to and through the body. Transmission associated with the dynamic system depends on the frequency and direction of the input motion and the characteristics of the seat from which the vibration exposure is received. A questionnaire based study was conducted on public transport buses in India, in different routes together with vibration measurements on the seat and floor at vertical (z) and lateral (y) directions. The subjective study involved reading of a national Hindi newspaper, to obtain a subjective opinion and to quantify the difficulty in reading and also from the vibration measurements the seat accelerations were measured for suggesting the proper design of seats in public transportation buses. The preference technique method was adopted and the level of discomfort analyzed in 7-point Semantic scale. The conclusions from the seat location, postures adapted for reading and the vibration measurements served as useful guidelines for conducting experimental work in the laboratory [3].

The WBV in trains which constitutes one aspect of the physical environment that can cause discomfort to passengers was studied. New methods of assessment were presented using digital techniques. Accelerometers were usually mounted on the seat pan, the backrest and floor. Depending on the location, direction and standard to be used, a different method of signal processing and scaling was used for each accelerometer. Data were frequency weighted in order to model the human response to vibration in terms of location and direction. Several criteria systems have been defined to assist users in interpreting results. According to these criteria, previous measurements of vibration in trains have established that it is not usually considered severe, but, at worst, “strong, irregular, but still tolerable” or “a little uncomfortable” [4, 5].

Understanding of the resonance behaviour of the human body is important in the identification of vibration frequencies and body postures associated with back problems. Experimental modal analysis was applied to WBV. Eight subjects were exposed to vertical random vibration while adopting three different postures on a rigid seat without a backrest. Motions of the spine, pelvis and viscera in the mid-sagittal plane were derived from skin-mounted accelerometers and head responses were measured using a bite-bar. Eight modes of vibration response were extracted below 10 Hz. A principal resonance of the human body at about 5 Hz consisted of an entire body mode, in which the skeleton moved vertically due to axial and shear deformations of buttocks tissue, in phase with a vertical visceral mode, and a bending mode of the upper thoracic and cervical spine. A bending mode of the lumbar and lower thoracic spine was found with a pitching mode of the head in the next higher mode located close to the principal mode. The second principal resonance at about 8 Hz corresponded to pitching modes of the pelvis and a second visceral mode. When subjects changed posture from erect to slouched, the natural frequency of the entire body mode decreased, resulting in a decrease in the principal resonance frequency [6].

Vehicle vibrations affect the health and comfort of the driver and passengers considerably. The effects of vertical vehicle vibrations on the driver were analyzed. A human biomechanical model with 11 degrees of freedom was achieved and was incorporated into a full vehicle model. The combined human-vehicle model was subjected to the road disturbance. After dynamic analysis of the proposed model, root mean square (RMS) acceleration responses of the human body parts over a certain frequency range were obtained. Physiological effects of the vibrations on the human body were analyzed using the criteria specified in ISO 2631. The effectiveness of a controller on the vibration isolation of human body was observed and the sliding mode controller was applied to the model. Comparison of the vibration effects for the uncontrolled and controlled cases of the human-vehicle model was presented. It can be concluded from the results that sliding mode controller considerably reduced WBV compared with the uncontrolled case and thereby improved the ride comfort satisfactorily [7].

All on-road and off-road vehicles are exposed to vibrations caused by unevenness of road or soil profile, moving elements within the machine. A higher prevalence of low back pain is found in drivers of off-road machinery than in other drivers. Significantly higher levels of low frequency vibrations were found in the cabin. Driving at high speed on a concrete surface was compared to driving slower on field road. Comfort values indicated that injury can result from long term driving on the field as well as on a concrete road. The seats with suspension systems are the main transmission paths of vibration towards the spine of the driver, their vibration attenuating characteristics played an important role in comfort assessment. The resonant frequency of seats with passive suspension system, used in agricultural machinery, lies in the low-frequency range in agricultural machinery. A seat with air suspension was found to attenuate better frequencies above 4 Hz and provides more comfort to the driver than a seat with a mechanical suspension [8].

The objective of the present work is to enhance the understanding on vehicle travel comfort which could be utilized by vehicle passengers and vehicle manufacturers in their work, and to analyze the imposed vibrations to the vehicle body in different driving situations. The evaluation of vehicle vertical vibration comfort which is the first step of the vibration comfort assessment. Analysis of road conditions parameters, such as the International Roughness Index (IRI), and their correlation with Kurtosis and the vibration dose value (VDV) can give useful information about the effect of road roughness on passenger vibration comfort.

2. Road test measurements data

Power Spectral Densities (PSD) will be calculated for all acceleration signals. The power spectra show the distribution of energy across the frequency spectrum. The best methodology for comfort evaluation, giving a single number value, is looked up. A single number estimate of vibration severity requires that the motion is weighted according to the relative importance of magnitude, frequency and duration. BS 6841 frequency weighting filter for vertical axis (bounce), Wi(f), as shown in Fig. 1 and Table 1, is used for WBV evaluation [9, 10]. All frequencies from the vehicle vibration acceleration data with least contribution to the discomfort are lesser in value (< 2 Hz). All frequencies with high contribution are higher in value (> 10 Hz).

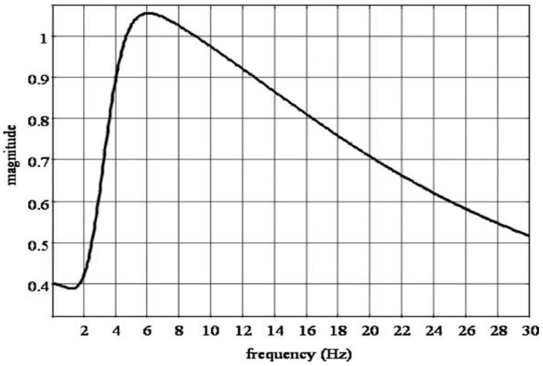


Fig. 1(b): Bode plot of vertical vibration magnitude vs. Frequency BS 8641weighting filter for comfort evaluation [9, 10]

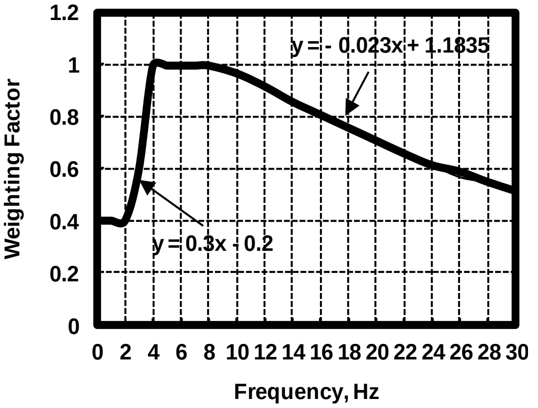


Fig. 1(b): Normalised plot of vertical vibration magnitude vs. Frequency BS 8641weighting filter for comfort evaluation [9, 10]

Table 1: BS 8641 normalized weighting function for vertical acceleration

Frequency, Hz	Weighting function
Less than 2	0.4
2 to 4	0.3 * Frequency - 0.2
4 to 8	1
Above 8	- 0.023 * Frequency +1.1835

3. Road roughness data analysis

There are three main sources of vibration transmitted to the vehicle passengers-road roughness, vehicle suspension and driver's behaviour including choice of vehicle speed. Within reasonable variations in these factors, road roughness plays a considerably greater part than the other two [11]. In vehicle research taking into account of acoustic quality, all of the three sources are playing important role. IRI is a general pavement condition indicator that summarizes the roughness qualities which affect the vehicle response IRI is the most appropriate roughness measure that relates to overall ride quality and overall surface condition [2]. The IRI value can be defined approximately from the following equation [11]:

$$\frac{a_{rms}}{IRI} = 0.16.\left(\frac{v}{80}\right)^{1/2} \qquad (1)$$

Where v (km/h) is the vehicle speed and a_{rms} is the vehicle floor RMS acceleration vibration (m/s^2). For this purpose, the Bruel & Kjaer accelerometer is installed on the floor of the compartment to measure the vertical vibration at specific speed. By using Eqn. (1), the IRI value of the road can be found at constant vehicle speed for each considered road surfaces.

Kurtosis is the fourth statistical moment signal, known as a global statistical parameter that is highly sensitive to the impulsiveness of the time-domain data. For discrete data sets it can be approximated by,

$$Kurtosis = \frac{\left(1/N\right)\sum_{n=1}^{N}\left(x(n)-\bar{x}\right)^4}{\left(1/N\right)\sum_{n=1}^{N}\left(x(n)-\bar{x}\right)^2} \qquad (2)$$

Where N is the number of data points taken in the signal, x(n) is the amplitude of the signal at the nth point. $\bar{x}$ is the mean value of all amplitudes. Kurtosis will be measured in different speeds as a road characteristic parameter and the variation due to road and speed conditions will be evaluated. Kurtosis value is approximately 3.0 for a Gaussian distribution. Higher Kurtosis value indicates the existence of numerous extreme data values, inconsistent with a Gaussian distribution. Kurtosis value less than 3.0 designates a relatively flat distribution.

4. Seat comfort parameters

In accordance with the requirements of ISO 2631-1 (1997) and European Directive 2002, the acceleration time histories are recorded to compute the following:

- Measurement of axis-weighted acceleration RMS time histories a_w (m/s^2);
- Estimated passenger daily vibration exposure A(8) (m/s^2) and VDV (m/s$^{1.75}$) forms;
- Crest factor (CF);
- Time to reach the Exposure Action Value(EAV) and Exposure Limit Value(ELV), when both specified in daily exposure to vibration A(8) form;
- Weighted RMS and VDV Seat Effective Amplitude Transmissibility (SEAT).

The weighted RMS. acceleration (in m/s²) of a discrete time-domain signal is given by:

$$a_{rms} = \sqrt{\frac{1}{T}\int_0^T a_w^2(t).dt} \qquad (3)$$

Where $a_w(t)$ is the weighted acceleration as a function of time. T is the duration of measurement. Substituting a_{rms} in Eqn. (1), the IRI values can be calculated. The smooth and bumpy roads are characterised using,

$$a_{rms} = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1} a_w(n)^2} \qquad (4)$$

Where $a_w(n)$ is the nth sample of the weighted acceleration. N is the total number of samples in the measurement.

The crest factor (CF) is calculated to determine the most suitable method of analysis using,

$$CF = \left|\frac{\max(a_w)}{a_{wrms}}\right| \qquad (5)$$

If the CF is greater than 3, then the VDV should be calculated in addition to the RMS acceleration. However, it is also useful to present the VDV for measurements with crest factors less than 3.

Due to vehicle motion by shock or impulsive speed changes, the use of time integrated fourth power of accelerations known as VDV is considered as more suitable parameter for vibration assessment. VDV is more sensitive to peaks than the basic evaluation method by using the second power of the acceleration time history as the basis for averaging. The measure of total exposure to vibration considers the magnitude, frequency and exposure duration. Thus VDV (m/s$^{1.75}$) is defined as,

$$VDV = \left(\int_0^T a_w(t)^4\,dt\right)^{1/4} \qquad (6)$$

$$VDV = \sqrt[4]{\frac{1}{f_s}\sum_{n=0}^{N-1} a_w(n)^4} \qquad (7)$$

Where $a_w(t)$ is the frequency-weighted acceleration. $a_w(n)$ is the current sample of the weighted acceleration. $f_s = T/N$ is the sampling frequency. T is the total period of the measurement. N is the total number of samples in the measurement.

Seat vibration isolation performance was indicated by SEAT values. SEAT can be calculated from the frequency-weighted RMS accelerations on the seat surface and vehicle floor, a_{seat} and a_{floor}, using,

$$SEAT\% = 100 * RMS\ a_{seat} / RMS\ a_{floor} \qquad (8)$$

Current standards recommend that if the input motion contains shock, the SEAT value is determined using the VDV on the seat surface and vehicle floor, VDV_{seat} and VDV_{floor}, using:

$$SEAT\% = 100 * VDV_{seat} / VDV_{floor} \qquad (9)$$

When the SEAT value is greater than 100%, the seat is amplifying the vibration. When the SEAT value is below 100%, the seat is attenuating the vibration. Note that for each axis in the examples presented, the SEAT is not below 100%, i.e. the seat does not attenuate the vibration magnitude [12, 13].

The data acquired was measured for 10 second. However, this was measured in such a way as to represent the vibration levels experienced by the passenger related to the normal 8-hour work period. The required parameters were then computed and extrapolated to cover the entire duration of exposure. Subsequently, the weighted RMS and VDV parameters were computed. The EU directive sets the limits on hand arm and WBV in terms of risk, and does not cover passenger comfort [14]. The exposure limits are defined as an “action value” and a “limit value” and the RMS values and VDV values are given. The resulting RMS values should then be compared with the limit and action values stated in the directive which are given in Table 2.

Table 2: Daily EAV and ELV for WBV [15]

Measure	EAV	ELV
RMS A(8) m/s^2	0.5 – 1.15	1.15
VDV $m/s^{1.75}$	9.1 - 21	21

Once the vibration magnitude is obtained for the vertical axis, it is possible to calculate the length of time that a vehicle may be operated before reaching the ELV or EAV thresholds given in Table 2. The time, in hours, to reach the EAV and ELV using RMS calculations is given by,

$$T_{EAV_{A(8)}} = 8x0.5^2 / a_w^2,\ T_{EAV_{A(8)}} = 8x1.15^2 / a_w^2 \qquad (10)$$

Where a_w is the weighted RMS vibration magnitude at the vertical-axis. The time, in hours, to reach the EAV and ELV using VDV calculations is given by,

$$T_{EAV_{VDV}} = t(9.1/VDV)^4,\ T_{ELV_{VDV}} = t(21/VDV)^4 \qquad (11)$$

Where *t(h)* is the measurement duration. VDV is the weighted vibration magnitude at the vertical-axis.

5. Experimental setup and measurements

The test vehicles were a mid-size saloon vehicle (MSV) and an off-road vehicle (ORV). Table 3 gives the description of vehicles used in the measurements. The vehicle working conditions were set at constant speeds from 20 to 100 km/h. The characteristics of selected road surfaces used in this study are presented in Table 4. Fig. 2(a) to (c) show the photographs of these road surfaces. The vehicle was driven at 20, 40, 60, 80 and 100 km/h speeds over the three road surfaces considered. The vibration measurements were made in all three road surfaces and the vibration samples were acquired with integration period of one second. Each individual measurement is of 10 seconds duration using multi-channel analyzer.

Table 3: Test vehicles description

Parameters	MSV	ORV
Front suspension system	Macpherson strut with shocks & coil spring, 1 piece lower control arm.	Coil springs over shocks, upper and lower A-arms.
Rear suspension system	Coil springs over shocks, trailing arms, three lateral links.	Multi leaf springs and shocks.
Tyre size	175/70 R13	175/70 R16

Table 4: Description of road surfaces used in the test

Type of road	Road surface appearance	Road surface characteristics
Smooth Asphalt	Smooth asphalt, no wear or weathering, small stones, smooth surface.	Low overall level, higher frequency greater proportion of noise, no "roar"
Spalled Asphalt	Asphalt mechanically roughened to re-surfacing, pattern not complete random, large polished stones, moderately dense aggregate	Pure tone, moderate "roar," high overall level
Coarse Asphalt	Asphalt, small medium rough stones, very dense aggregate	Broadband "roar" medium overall level.

Fig. 2(a): Smooth asphalt road surface

Fig. 2(b): Spalled asphalt road surface

Fig. 2(c): Coarse asphalt road surface

Un-weighted accelerations on the vehicle floor and on the passenger seat were measured using Bruel & Kjaer accelerometers type 4514B-001. The vibration amplitudes recorded from the vehicle floor and passenger seat during travel are investigated for possible artefacts and any unclear signals detected are removed. The measurement of vibration at a passenger body/seat interface requires that accelerometer is located between passenger body and seat. The accelerometer must move with the interface. They must not alter the dynamic properties of either the seat or the passenger body. They must offer little impedance to movement over the frequency range of interest. For this reason, a thin disc of 0.25 m diameter is used. It is rigid device that compresses the seat in a similar way to passenger buttocks. Vertical accelerations were measured. Under each working condition, the vibration signals at the vehicle floor and the passenger body/seat were measured by using Bruel & Kjaer portable, multi-channel PULSE type 3560-B-X05 analyzer, Bruel & Kjaer PULSE labshop and measurement software type 7700. Figs. 3 and 4 show a schematic of the measurement instrumentation. The schematic representation of experimental setup is shown in Fig. 5.

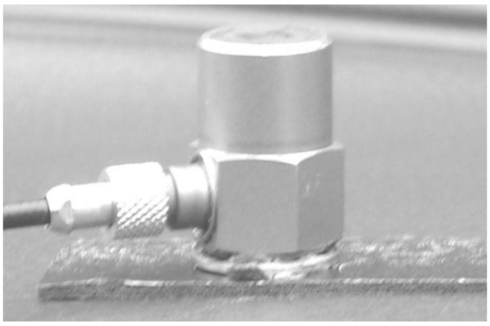
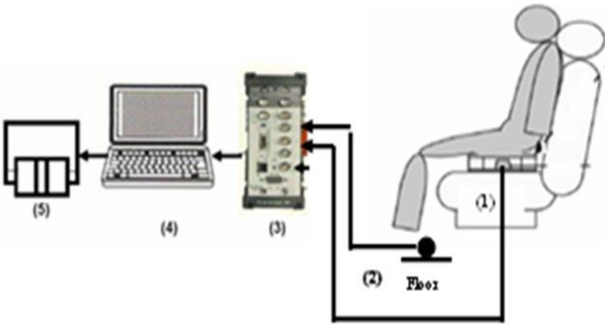


Fig. 3: Accelerometer mounted at the vehicle floor

Fig. 4: Accelerometer mounted on vehicle seat



1. Seat Accelerometer
2. Vehicle Floor Accelerometer
3. Multi Channel Analyzer (PLUS)
4. Computer (Lab Shop)
5. Printer

Fig. 5: Schematic representation of experimental setup

6. Results and discussions

For illustration of results, the case of MSV on spalled asphalt road surface at a speed of 80 km/h is taken as sample. Figs. 6 and 7 show the samples from experimental raw signals of time history results taken on the floor and seat. Samples from the FFT of un-weighted and weighted vibration acceleration measurements in vertical direction were truncated for the frequency range of interest up to 25 Hz for the vehicle floor and seat and are shown in Figs. 8 and 9 respectively. A good seat should have a peak frequency at least 1.4 times lower than the peak frequency of the vehicle floor where the seat is mounted. It is noticed that the weighted vibration acceleration at the peak frequency for seat is amplifying rather than attenuating due to poor design and improper maintenance of seat.

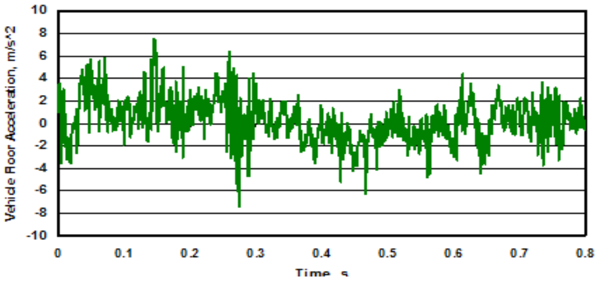


Fig. 6: Time history of MSV floor vibration on spalled asphalt road

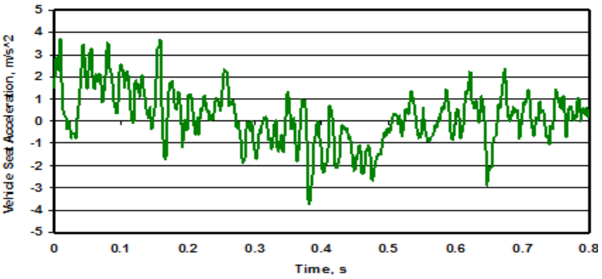


Fig. 7: Time history of MSV seat vibration on spalled asphalt road

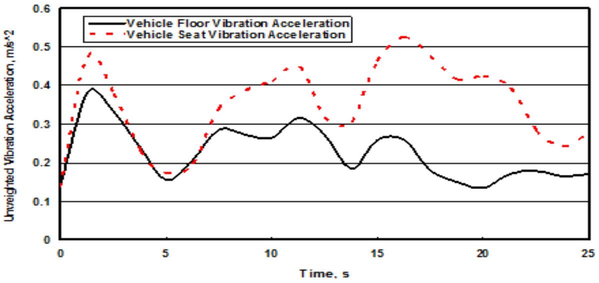


Fig. 8: FFT of MSV floor un-weighted vibration on spalled asphalt road surface

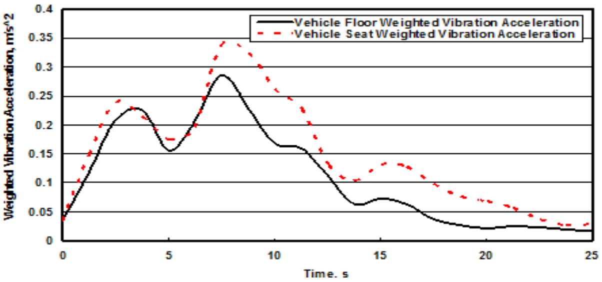


Fig. 9: FFT of MSV floor weighted vibration on spalled asphalt road surface

The samples of weighted acceleration vibration in terms of FRF analysis between these signals is presented in Fig. 10. The seat structure was a good isolator of vibration below the entire frequency range of 25 Hz. In the frequency ranges of 3 - 4 Hz and 6 - 6.5 Hz, the signal was amplified. Samples of calculated PSD for all the weighted vibration acceleration signals are shown in Fig. 11. On the seat surface, the energy distribution in the vertical direction tends to be concentrated around lower frequencies.

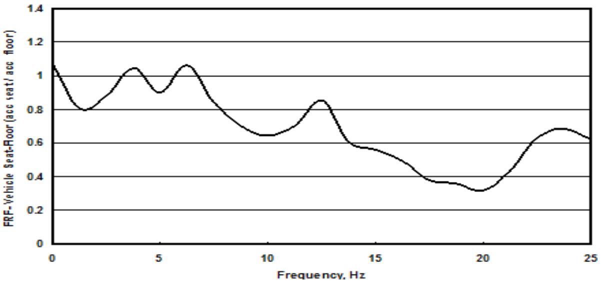


Fig. 10: FRF of MSV floor and seat vibration acceleration at 80 km/h on spalled asphalt road

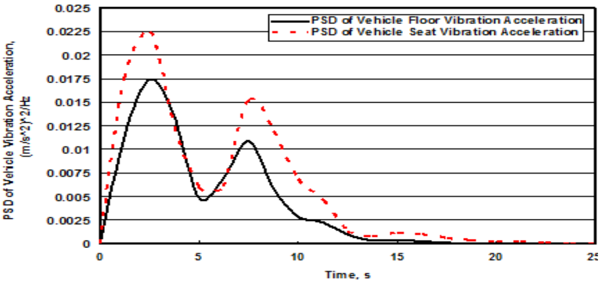


Fig. 11: PSD of MSV vibration acceleration at 80 km/h on spalled asphalt road

The Kurtosis and IRI data for MSV and ORV on the three tested asphalt road surfaces are given in Table 5. It can be observed that nearly all the Kurtosis values are lower than 3.0, therefore, they are in flat distribution. Moreover, the IRI values are proportional to Kurtosis values, which indicate that human perceives more peak impulses when driving on high surface roughness roads.

Table 5(a): Road surface roughness parameters for MSV

Vehicle Speed, km/h	Smooth Asphalt Kurtosis	IRI	Spalled Asphalt Kurtosis	IRI	Coarse Asphalt Kurtosis	IRI
20	2.13	6.13	3.19	9.31	2.57	3.93
40	2.14	5.43	3.14	8.72	2.72	4.48
60	2.24	4.87	2.66	9.74	2.83	8.23
80	2.68	4.56	2.47	11.6	2.91	7.44
100	2.87	4.39	2.23	11.9	3.08	8.09

Table 5(b): Road surface roughness parameters for ORV

Vehicle Speed, km/h	Smooth Asphalt Kurtosis	IRI	Spalled Asphalt Kurtosis	IRI	Coarse Asphalt Kurtosis	IRI
20	3.40	4.41	3.75	6.6	1.98	3.26
40	2.61	7.76	3.51	6.82	2.33	7.26
60	2.06	8.19	3.39	6.92	3.07	8.80
80	2.04	9.10	3.37	7.06	3.18	8.93
100	2.00	9.32	3.21	8.11	3.23	8.99

A comparison of SEAT estimation based on weighted RMS (a_w) and VDV for MSV and ORV is shown in Fig. 12 and Fig. 13 respectively. For coarse asphalt road conditions, the SEAT estimation based on VDV behaves higher value than that for RMS (a_w) in all vehicle speeds except for 40 km/h. A comparison of the exposure action (T_{EAV}) value estimation based on VDV is shown in Fig. 14. Tables 6 to 13 summarise the calculated seat comfort parameters in accordance with equations in Section 4 for MSV and ORV. From the experiments, strong low frequency content of vibration often contains peak components of vibration. Therefore, for comfort assessment in the frequency range up to 25 Hz, it is more appropriate to use a FFT analysis and SEAT estimation based on VDV rather than weighted RMS (a_w) in vertical direction.

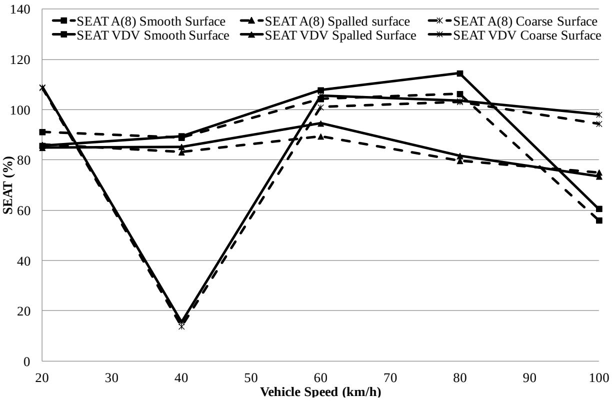


Fig. 12: MSV results: SEAT estimation based on RMS (a_w) vs. VDV

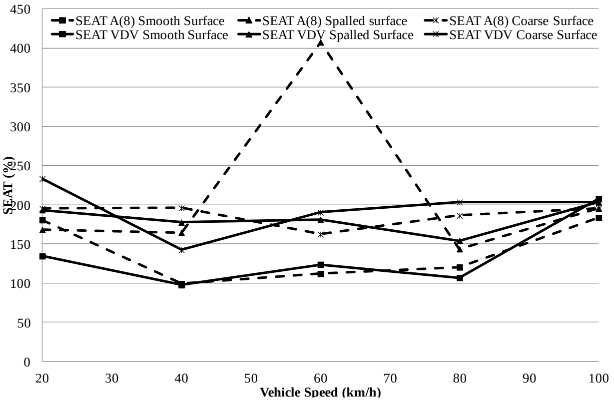


Fig. 13: ORV results: SEAT estimation based on RMS (a_w) vs. VDV

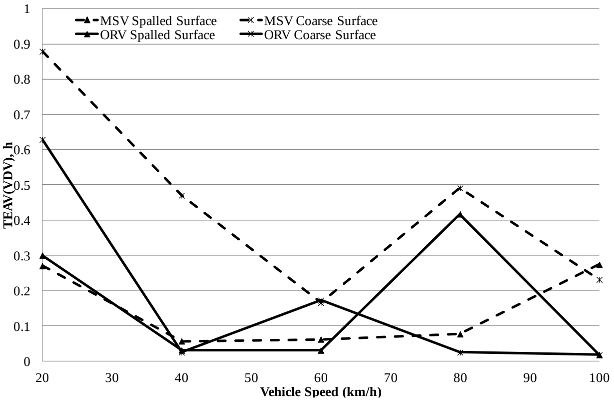


Fig. 14: TEAV (VDV) results – MSV vs. ORV

Table 6: Results summary for MSV on smooth asphalt road surface

Vehicle Speed, km/h	a_w, m/s^2	CF	SEAT A(8),%	TEAV (A(8)), h	TELV (A(8)), h	VDV 8h (m/s$^{1.75}$)	SEAT VDV (8h),%	TEAV (VDV), h	TELV (VDV), h
20	0.080	3.52	91.17	311.426	1647.443	1.5376	85.68	0.3408	9.6645
40	0.056	3.47	88.90	626.163	3312.400	0.6277	89.53	12.268	347.92
60	0.085	3.50	104.3	275.773	1585.494	1.5744	107.8	0.3099	8.7914
80	0.107	3.44	106.3	174.136	921.178	1.9789	114.5	0.1242	3.5224
100	0.091	3,23	56.01	284.219	1503.518	0.8889	60.62	3.0502	86.503

Table 7: Results summary for MSV on spalled asphalt road surface

Vehicle Speed, km/h	a_w, m/s^2	CF	SEAT A(8),%	TEAV (A(8)), h	TELV (A(8)), h	VDV 8h (m/s$^{1.75}$)	SEAT VDV (8h),%	TEAV (VDV), h	TELV (VDV), h
20	0.082	3.85	86.08	294.753	1559.241	1.6302	84.89	0.2697	7.6499
40	0.139	3.26	83.10	103.421	547.097	2.4126	85.29	0.0562	1.5944
60	0.124	3.75	89.41	130.865	692.274	2.3594	94.57	0.0614	1.7431
80	0.137	3.09	79.69	106.436	563.045	2.2339	81.67	0.0764	2.1692
100	0.103	3. 06	75.09	188.910	999.334	1.6241	73.47	0.2737	7.7632

Table 8: Results summary for MSV on coarse asphalt road surface

Vehicle Speed, km/h	a_w, m/s^2	CF	SEAT A(8),%	TEAV (A(8)), h	TELV (A(8)), h	VDV 8h (m/s$^{1.75}$)	SEAT VDV (8h),%	TEAV (VDV), h	TELV (VDV), h
20	0.061	3.869	108.7	525.608	2251.781	1.2134	109.0	0.8787	24.919
40	0.077	3.464	13.78	336.302	858.909	1.4188	15.56	0.4700	13.330
60	0.097	3.482	101.0	213.907	1176.769	1.8430	105.5	0.1651	4.6827
80	0.086	2.887	103.1	268.031	357.979	1.4036	103.5	0.4907	13.918
100	0.103	3.144	94.41	189.971	288.790	1.6946	98.09	0.2310	6.5505

Table 9: Results summary for ORV on smooth asphalt road surface

Vehicle Speed, km/h	a_w, m/s^2	CF	SEAT A(8),%	TEAV (A(8)), h	TELV (A(8)), h	VDV 8h (m/s$^{1.75}$)	SEAT VDV (8h),%	TEAV (VDV), h	TELV (VDV), h
20	0.045	3.42	180.5	969.547	5128.902	2.7763	134.4	0.0321	0.9093
40	0.036	3.63	99.06	1564.68	8277.160	0.6514	97.44	10.579	300.05
60	0.064	4.19	111.9	489.535	2589.645	1.3092	123.7	0.6484	18.391
80	0.158	4.16	120.2	80.086	423.657	3.1924	106.8	0.0183	0.5201
100	0.083	3.85	183.5	293.101	1550.503	1.5562	207.3	0.3248	9.2111

Table 10: Results summary for ORV on spalled asphalt road surface

Vehicle Speed, km/h	a_w, m/s^2	CF	SEAT A(8),%	TEAV (A(8)), h	TELV (A(8)), h	VDV 8h (m/s$^{1.75}$)	SEAT VDV (8h),%	TEAV (VDV), h	TELV (VDV), h
20	0.087	3.29	168.2	261.936	1385.642	1.5875	193.3	0.2999	8.5059
40	0.153	3.68	164.5	85.132	337.762	2.8150	177.5	0.0303	0.8603
60	0.386	2.01	407.7	13.399	70.879	2.8218	181.1	0.0300	0.8519
80	0.090	2.88	143.4	245.475	1298.563	1.4620	154.1	0.4168	11.822
100	0.191	3.30	195.3	54.592	288.791	3.2358	203.2	0.0173	0.4927

Table 11: Results summary for ORV on coarse asphalt road surface

Vehicle Speed, km/h	a_w, m/s^2	CF	SEAT A(8),%	TEAV (A(8)), h	TELV (A(8)), h	VDV 8h (m/s$^{1.75}$)	SEAT VDV (8h),%	TEAV (VDV), h	TELV (VDV), h
20	0.069	3.87	195.1	425.668	2780.466	1.3194	233.2	0.6285	17.826
40	0.111	3.46	195.8	162.365	1779.037	2.9656	142.3	0.0246	0.6984
60	0.095	3.48	162.3	222.452	1131.568	1.8238	190.2	0.1721	4.8818
80	0.172	2.89	186.2	357.9797	1417.885	3.0621	203.3	0.0244	0.6144
100	0.191	3.14	195.3	54.591	1004.945	3.2358	203.2	0.0173	0.4927

7. Conclusions

There are several standardized methods of measurement and assessment of WBV in moving vehicles. This paper discussed the fundamental principles of these methods including a description of the measurement hardware and the necessary calculations that need to be carried out in order to show compliance with the relevant international standards. The accelerations at the seat (and/or floor) of the vehicle at various speeds are measured. It was found that VDV is proportional to the vehicle speed and IRI. Rough roads exhibit higher VDV variation as the vehicle speed changes. FRF between vehicle floor and seat acceleration in vertical direction was analysed. For comfort assessment in the frequency range up to 25 Hz, it is more appropriate to use a FFT analysis and SEAT estimation based on VDV rather than weighted RMS accelerations in vertical direction.

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