Evaluating Automobile Road Vibrations Using BS 6841 and ISO 2631 Comfort Criteria

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Abstract: Evaluation of human exposure whole-body vibration and shock can be carried out in a variety of ways. The most common used standards for predicting discomfort are BS 6841 and ISO 2631 which offer different frequency weightings and multiplying factors to allow for different sensitivity of the body in different axes. For analysis methods based on acceleration, vibration dose value, *VDV*, gives the highest correlations between vibration magnitude and discomfort. In this study, in order to evaluate vibration characteristics of a passenger car, vibration signals were measured while driving with different speeds over five road surfaces. Accelerations were measured in the vertical, fore-aft, and lateral directions on the seat and fore-aft direction on the seat backrest. Root-mean-square values and power spectral densities of the recorded signals were evaluated to assess transmitted vibrations to the passengers. Results show that generally, vibration level increases as the speed rises. Evaluations according to ISO 2631 give lower *VDV* values (by about 18%) compared to that of BS 6841.

Keywords: Whole-body vibration, comfort ride, vibration dose value, automobile.

1. Introduction

A comfortable ride is essential for a vehicle in order to obtain passenger satisfaction. In this view, vehicle manufacturers are continuously seeking to improve vibration comfort. The transmission of vibration to the human body will have a large influence on comfort, performance and health. Many factors influence the transmission of vibration to and through the body. Being a dynamic system, the transmission associated with it will depend on the frequency and direction of the input motion and the characteristics of the seat from which the vibration exposure is received.

Vibration within the frequency range up to 12 Hz affects the whole human organs, while the vibrations above 12 Hz will have a local effect [1]. Low frequencies (4-6 Hz) cyclic motions like those caused by tyres rolling over an uneven road can put the body into resonance. Just one hour of seated vibration exposure can cause muscle fatigue and make a user more susceptible to back injury.

Currently, there are two main standards for evaluating vibration with respect to the human responses to whole-body vibration; British Standard BS 6841 (1987) and International Standard ISO 2631 (1997). BS 6841 considers a frequency range of 0.5-80 Hz [2]. This standard recommends the measurement of four axes of vibration on the seat (fore-aft, lateral and vertical vibration on the seat surface and fore-aft vibration at the backrest) and combining these in an evaluation procedure before assessing the vibration severity. ISO 2631 suggests that vibration is measured in the three translational axes on the seat pan but only the axis with the most severe vibration is used to assess vibration severity [3].

The current trend in vibration research is to use multi-axis values. This may be seen in studies such as those by Paddan and Griffin [4] and Hinz et al [5]. Most recently, the effects caused by different experimental design variables on subjective response and vibration accelerations is investigated by Jonsson and Johansson [6]. In this study, ride comfort and vibration characteristics of a passenger car were investigated at different vehicle speeds. The vehicle was driven over smooth and rough road surfaces.

2. Equipment and Procedure

The study was conducted in a Proton car, Malaysian product. The vibration signals were measured when driving over five road surfaces. The roads, shown in Fig. 1, were a highway, an urban road, a pavement road, a suburban road and a bumpy road. The characteristics of the road surfaces are presented in Table 1. The vehicle was driven at 20, 40, 60 and 80 kph over all roads except the bumpy road. The driving velocity over the bumpy road was only 20 kph. On the highway, the vehicle was also tested at 100 kph.

A tri-axis accelerometer was mounted on the seat surface to measure vertical, fore-aft and lateral accelerations. A mounting beam containing a single-axis accelerometer was placed on the top of the backrest and used to measure fore-aft acceleration. A single-axis accelerometer was placed on a plate and used to measure vertical acceleration of the floor. It was mounted on the floor beneath the front edge and centerline of the seat. The signals from the accelerometers were acquired (usually over a period of 60 s) into a 16-channel Pulse data acquisition and analysis system. The sampling rate of the acceleration data was 256 Hz and was band pass filtered to be in the range from 0.5 to 80 Hz.

3. Analysis

3.1 Frequency analysis

Power spectral densities were calculated for all acceleration signals. The power spectra show distribution of energy across the frequency spectrum. Evaluations were performed according to the recommendations in BS 6841and ISO 2631. This involved the application of frequency weightings, the use of multiplying factors to allow for different sensitivity of the body in different axes, the calculation of root-mean-square (r.m.s.) and vibration dose values (VDVs) and the summation of values over different axes.

The acceleration was frequency-weighted using the frequency weightings defined in BS 6841 and ISO 2631 over the frequency range 0.5 to 80 Hz. The frequency weightings and multiplying factors for different axes, as specified in BS 6841 and ISO 2631, are listed in Table 2. The frequency weighting values defined in BS 6841 and ISO 2631 are shown in Fig.s 2 and 3, respectively. The frequency weightings for vertical vibration on the seat, Wb in BS 6841, applies less weight to low frequencies and more weight to high frequencies, compared to Wk in ISO 2631.The root-mean-square vibration values were calculated from the frequency-weighted accelerations.

3.2 Vibration Dose Values (VDVs)

When the motion of a vehicle includes shocks or impulsive velocity changes, root mean square (r.m.s.) acceleration has no relation to comfort or injury. The VDV gives a measure of the total exposure to vibration, taking account of the magnitude, frequency and exposure duration. For analysis methods based on acceleration, VDV gives the highest correlations between vibration magnitude and discomfort. VDV reflects the total, rather than the average, exposure to vibration over the measurement period and is considered more suitable when the vibration signal is not statistically stationary [7]. The VDV ($ms^{-1.75}$) is defined as [2, 3]:

$$VDV = \left(\int_0^T a(t)^4 \, dt \right)^{1/4} \tag{1}$$

where a(t) is the frequency-weighted acceleration time history and T is the period of time over which vibration occurs. According to the procedure in ISO 2631, assessments should be based on the axis giving the greatest VDV value on the seat.

According to BS 6841, vibration magnitudes and durations which produce vibration dose values in the region of 15 $ms^{-1.75}$ will usually cause severe discomfort [2, 8]. The exposure period required for the vibration dose value to reach a tentative action level of 15 $ms^{-1.75}$ can be calculated as [9]:

$$T_{15} = \left(\frac{15}{VDV_t} \right)^4 t \tag{2}$$

where T_{15} is the time (in seconds) required to reach a VDV value of 15 $ms^{-1.75}$ and VDV_t is the VDV measured over the period of t seconds. ISO 2631 [3] suggests a “health guidance caution zone” with VDVs at 8.5 $ms^{-1.75}$ and 17 $ms^{-1.75}$. Above the caution zone health risks are likely to occur.

3.3 Multi-axis vibration

British Standard 6841 [2] specifies that when evaluating multi-axis vibration, the forth root of the sum of the fourth powers of the VDVs in each axis should be determined to give the total vibration dose value, VDV_{total} , for the environment

$$VDV_{total} = \left(VDV_{xs}^4 + VDV_{ys}^4 + VDV_{zs}^4 + VDV_{xb}^4\right)^{1/4} \qquad (3)$$

where VDV_{xs}, VDV_{ys} and VDV_{zs} are the VDV in the x, y and z-axis on the seat, respectively, and VDV_{xb} is the VDV in the x-axis on the backrest.

4. Results and Discussion

Fig. 4 shows variations of VDVs, evaluated according to BS 6841, at different vehicle velocities over different roads. It may be seen that for each road surface, VDV values rise as the vehicle velocity increases. At each velocity, the VDV values measured over rough road surfaces (suburban and pavement) are greater than that over smooth roads (highway and urban roads). The suburban road has the highest VDV increase in the velocity range of 20 kph to 40 kph. As the vehicle velocity increases, smooth road surfaces show small VDV increase. Same results may be concluded from Fig. 5 that shows a similar pattern of VDV (evaluated according to ISO 2631) variations at different vehicle velocities over different roads. However, evaluations according to ISO 2631 give lower VDV values (by about 18%) compared to BS 6841.

The exposure periods required the VDV_{total} on the rough road surfaces to reach the action levels of 15 $ms^{-1.75}$ and 8.5 $ms^{-1.75}$ were listed in Tables 3 and 4, respectively. On the smooth roads, the time taken to reach 15 $ms^{-1.75}$ and 8.5 $ms^{-1.75}$ VDV were too high. Therefore, it may be concluded that ergonomic considerations other than vibration would determine driver's comfort when driving on well-maintained smooth roads.

4.1 International Roughness Index (IRI)

Ride quality depends on the experienced vibrations induced by road roughness. International Roughness Index, IRI, is the most common way to describe road roughness. IRI is defined as the accumulated suspensions stroke in a car divided by the distance traveled by the car. IRI value (in mm/m) for each road relates to the velocity as follows [10]

$$\frac{a_{floor}}{IRI} = 0.16\left(\frac{v}{80}\right)^2 \qquad (4)$$

where a_{floor} is the frequency-weighted floor acceleration (r.m.s.) in vertical direction and v is the vehicle velocity in kph. For each road, using frequency-weighted floor acceleration values, given in Table 5, the IRI values were calculated at different velocities. The IRI value for each road, listed in Table 5, represents an average of IRI values at different velocities.

It is known that the induced vibration to the body is a function of the wavelength (which determines the frequency of the vibrations) and amplitude of the roughness. However, the frequency that occurs when driving over a specific irregularity depends on the traveling speed. Thus, vehicle speed can have a direct effect on the vibration level, depending on the type of road surface.

Fig. 6.a shows the variations of VDV values (evaluated according to BS 6841) in terms of the IRI values for four road surface types, at 20 kph. Except for the suburban road, the VDV values have an increasing trend as the road roughness increases. As expected, driving on the rough road surfaces induces more peaks and impulses to the passengers. This results in more VDV values and less comfortable driving. Therefore, road roughness could be compensated through slowing down and thereby improving the ride quality. Similar results may be concluded from Fig. 6.b that shows variations of VDV values in terms of the road roughness, at 80 kph.

5. Conclusions

This study was conducted to investigate vibration characteristics of a passenger car and the transmission of vibration to the passengers. Five roads were considered for the tests. It was shown that for each road surface, VDV values rise as the vehicle velocity increases and at each speed, rough road surfaces have more VDVs than that of the smooth roads. The variations of VDV values in terms of road roughness for different road surfaces were investigated in the context of comfortable ride. It is found that VDV values increased as the road roughness (IRI value) was increased.

Acknowledgements

First author would like to acknowledge the automotive laboratory facilities provided by the Department of Mechanical and Materials Eng., Faculty of Eng., UKM, Malaysia, during his sabbatical leave from IUT. This study conducted under research grant provided by MOST (Ministry of Science, Technology and Environment of Malaysia) through IRPA grant [03-02-02-0016 SR0003/07-02]..

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Table 1. Characteristics of the road surfaces.

Location	Type	Characteristics
Seremban-Melaka	Highway	A smooth highway
Putrajaya Main-square	Smooth urban	A broad smooth urban road
Putrajaya Taman-Perdana	Pavement road	A road consisted of small cobblestones
Kajang-UKM	Suburban	A poorly kept rough country road
Kajang suburb	Bumpy	A road consisted of a series of bumps

Table 2. Frequency weightings and multiplying factors as specified in BS 6841and ISO 2631 for seated person.

Location	Axis	Weighting		Multiplying factor	
		BS 6841	ISO 2631	BS 6841	ISO 2631
Seat	x	Wd	Wd	1.0	1.4
	y	Wd	Wd	1.0	1.4
	z	Wb	Wk	1.0	1.0
Backrest	x	Wc	Wc	0.8	0.8

Table 3. Time required to reach 15 $ms^{-1.75}$ VDV (as specified in BS 6841) on rough road surfaces.

	Velocity (kph)			
Road type	20	40	60	80
Pavement	32 h 20m	12 h 50m	11 h	6h 15m
Suburban	219 h	12 h 10m	9 h	5 h 15m
Bumpy	3 h 45m	-	-	-

Table 4. Time required to reach 8.5 $ms^{-1.75}$ VDV (as specified in ISO 2631) on rough road surfaces.

	Velocity (kph)			
Road type	20	40	60	80
Pavement	18 h 10m	3 h 20m	3 h	1h 50m
Suburban	44 h 50m	2 h 45m	2 h 20m	1 h 35m
Bumpy	2 h 35m	-	-	-

Table 5. Frequency-weighted floor accelerations (ms^{-2} , r.m.s.) evaluated according to BS 6841 and IRI values for different roads and velocities.

	Frequency-weighted floor acceleration				
Road type	20 kph	40 kph	60 kph	80 kph	IRI value
Highway	0.14	0.24	0.30	0.35	2.08
Urban	0.17	0.27	0.32	0.41	2.68
Pavement	0.5	0.65	0.71	0.8	5.46
Suburban	0.51	1.0	1.08	1.3	8.65
Bumpy	0.78	-	-	-	9.75

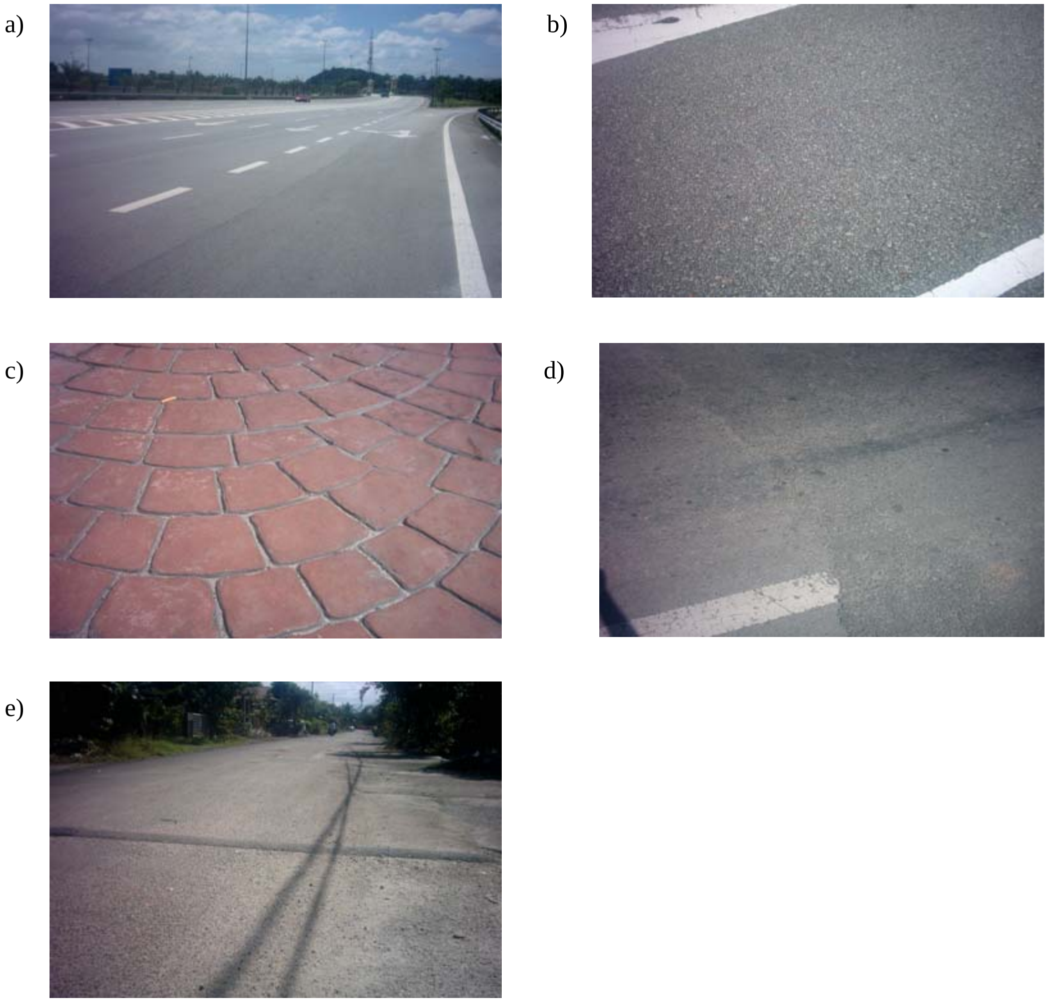

Fig. 1. Road surfaces: a) highway, b) urban road, c) pavement road, d) suburban road, e) bumpy road.

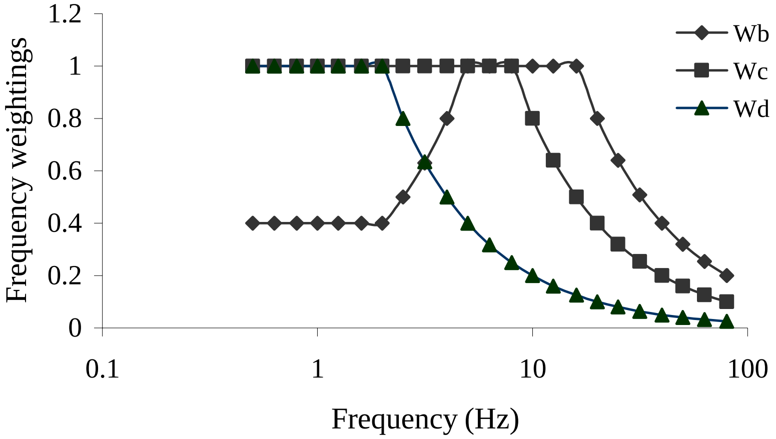

Fig. 2. Frequency weightings used for analysis of acceleration signals as specified in BS 6841.

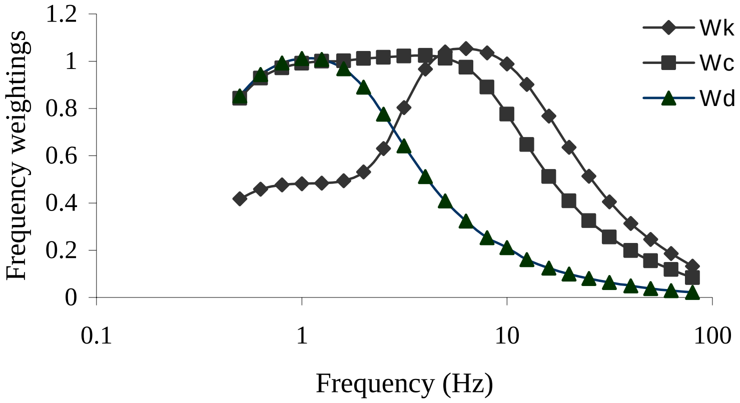

Fig. 3. Frequency weightings used for analysis of acceleration signals as specified in ISO 2631.

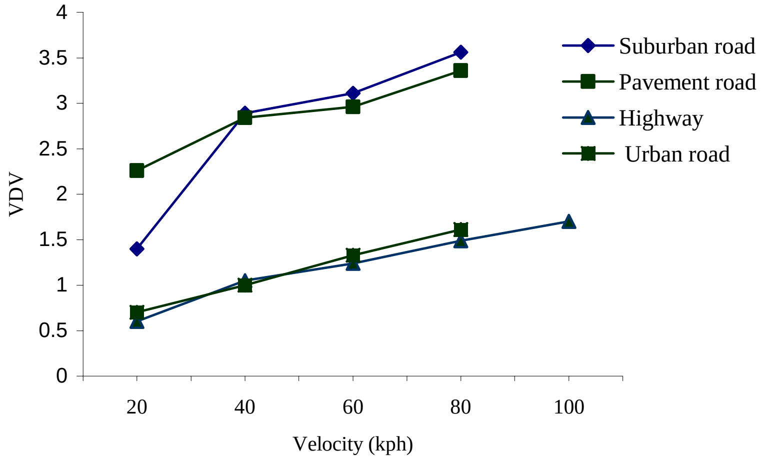

Fig. 4. Variations of VDV values, , evaluated according to BS 6841, at different velocities over different roads.

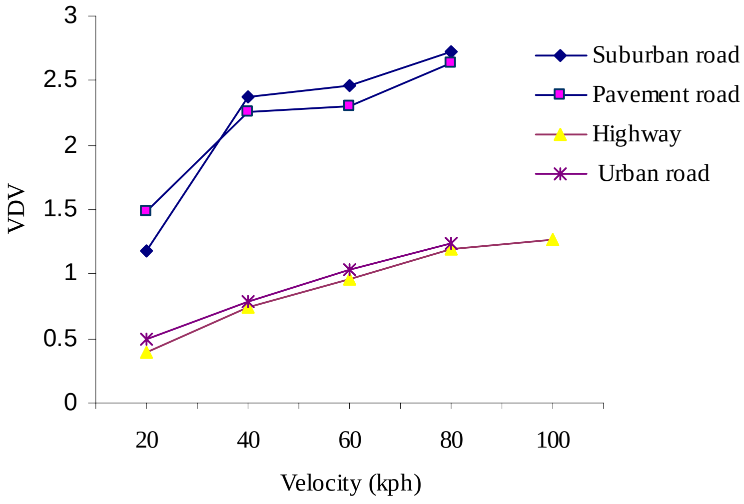

Fig. 5. Variations of VDV values, evaluated according to ISO 2631, at different velocities over different roads.

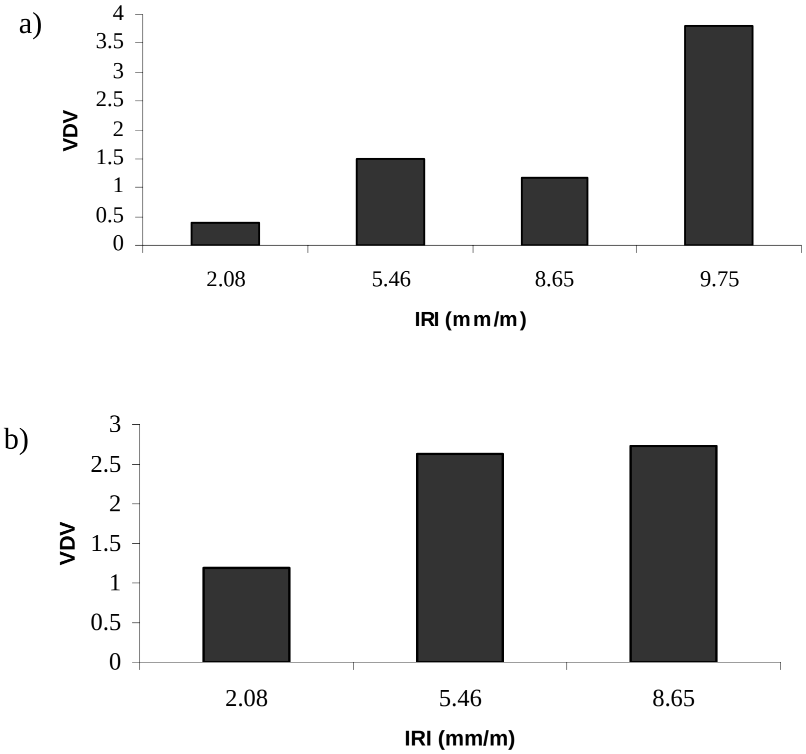

Figure 6. Variations of VDV values (BS 6841) versus IRI values at: a) 20 kph, b) 80 kph.