EVALUATION OF WHOLE-BODY VIBRATION AND RIDE COMFORT IN A PASSENGER CAR

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(Received 28 August 2008; revised 26 May 2009; accepted 11 June 2009)

Abstract
Whole-body vibration transmission influences comfort, performance, and long-term health of the driver. This current study is an objective evaluation of vehicle comfort characteristics based on standard mathematical formulae and frequency analyses. A variety of types of road were selected and quantified from the International Roughness Index (IRI). To assess transmitted vibrations to the passengers, vibration dose values (LDL, VDV), kurtosis, frequency response functions (FRF-FRF), and power spectral densities (PSD-PSD) of the compartment recorded signals were evaluated. SEAT values based on VDV outputs qualified the seat suspension as a vibration isolator, whereas the FRF and PSD quantified that behaviour through frequency analyses. Results indicated that overall energy concentration was at frequencies lower than 30 Hz. Such low frequency excitations were well attenuated by seat suspension in the vertical direction but are amplified (up to five times in harsh conditions) by a backrest in the fore-aft trend. Totally, signals were amplified beyond 30 Hz, but amplitudes were still very low. It seems that backrest assembly still can be improved to become a better isolator. However, time to reach severe discomfort even in very harsh conditions was more than three hours, which describing exhibits the overall good quality of the vehicle suspension systems. Kurtosis and VDV correlate with IRI and may be used as two objective metrics, together with jury evaluation, to derive a vehicle vibration–comfort index in the future.

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1. Introduction

Vibration transmission to human passengers has 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 because of this, vehicle manufacturers are constantly 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. Vibrations up to 12 Hz affect the whole human organs, while those above 12 Hz have local effects. Low-frequency (4-6 Hz) cyclic motions like those caused by tires rolling over an uneven road can resonate through the body. Just one hour of
seated vibration exposure may cause muscle fatigue and make the user more susceptible to back injury.

This paper is a subdivision of a general research conducted to evaluate vibro-acoustical comfort inside the vehicle compartment. The first part was to define a vehicle acoustical comfort index using objective and subjective evaluations. Current This paper is an objective evaluation of vehicle vibration comfort, which is the first step of the vibration comfort assessment. Analysis of the 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 the passenger vibration comfort.

Then Further research opportunity is to may perform include a subjective vibration subjective evaluation (jury test), and then the results of the subjective and objective assessments may be used to define an index for vehicle vibration comfort. This index eliminates the need for further subjective estimations and can be a useful parameter in various correlation analyses and vibration comfort predictions. It is believed that specific results of a vibration comfort index are only valid for the exact vehicle type. Still Different manufacturers can use the same method to derive the vibration comfort index for their products. Methods and general results of the current research (like correlations conducted for VDV, IRI, kurtosis, and velocity) are applicable for other researches as well.

Human responses to whole-body vibration can be evaluated by two main standards, the British Standard BS 6841 (BS 6841) (1987) and the International Standard 2631 (ISO 2631) (1997). The BS 6841 considers a frequency range of 0.5-80 Hz. As shown in Fig. 1, this standard recommends measuring four axes of vibration on the seat (fore-aft, lateral, and vertical vibration on the seat surface as well as fore-aft vibration at the backrest) and combining these in an evaluation procedure that assesses vibration severity. The ISO 2631 suggests vibration measurements in the three translational axes on the seat pan, but only the axis with the greatest vibration is used to estimate vibration severity.

![Schematic of four-axis vibration of a driver as considered by BS 6841.](image)

Figure 1. Schematic of four-axis vibration of a driver as considered by BS 6841.
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, and Hinz et al.) Huston and Zhao examined how the shape, frequency, and amplitude of the mechanical shocks affect the comfort response of the seated human. Recently, the effects caused by different experimental design variables on subjective response and vibration accelerations were investigated by Jonsson and Johansson. 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 test vehicle was a mid-size Malaysian executive vehicle, Proton Perdana, with a V-6 type engine. It is a four-door sedan having a curb weight of 1336 kg. With 16-inch rims and Lotus-tuned suspension settings, the car handles well through tight corners and is a good high-speed cruiser. The vibration signals were measured while driving over four flat road surfaces, and the speed was controlled manually by the driver. As shown in Fig. 2, the selected roads were highway, pavement, suburban, and bumpy. Characteristics of the road surfaces are presented in Table 1. The highway had a flat, smooth surface including very occasional unevenness, which resulted in minimum disturbances. The pavement road was a cobbled street made by similar smooth stones with 5-mm thickness. Having a similar gap between the adjacent stones caused harmonic excitations with different periods at each axis. The suburban road had frequent random irregularities from 3 mm to 25 mm, which produced excessive casual vibration. The bumpy road was a suburban rough surface with high and sharp bumps up to 50 mm, which resulted in shock responses. The vehicle was driven at 20, 40, 60, and 80 km/h speeds over all roads except the bumpy road. The driving speed over the bumpy road was only 20 km/h. The vehicle was also tested at 100 km/h on the highway.
Figure 2. Road surfaces: a) highway, b) pavement road, c) suburban road, and d) bumpy road.

Table 1. Characteristics of the road surfaces.

<table>
<thead>
<tr>
<th>Location</th>
<th>Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seremban-Melaka</td>
<td>Highway</td>
<td>Smooth highway</td>
</tr>
<tr>
<td>Putrajaya Taman-Perdana</td>
<td>Pavement road</td>
<td>Road consisting of small cobblestones</td>
</tr>
<tr>
<td>Kajang-UKM</td>
<td>Suburban</td>
<td>Poorly kept, rough country road</td>
</tr>
<tr>
<td>Kajang suburb</td>
<td>Bumpy</td>
<td>Road consisted of a series of bumps</td>
</tr>
</tbody>
</table>

Brue and Kjaer instrumentation series, namely, portable and multi-channel analyser PULSE type 3560D, PULSE Labshop software with four ENDEVCO Isotron (uniaxial) accelerometers model 751-100 and B & K triaxial accelerometer type 4506B were utilized in the measurement devices. The B & K calibration–exciter type 4294 was used to calibrate the accelerometers before and after the measurements. The dynamic frequency response of the uniaxial transducers was up to 10 kHz while that of the triaxial one was up to 5.5 kHz for the x axis and 3.0 kHz for the y and z axes. The sensitivity of both types of accelerometers was 10 mV/ms².

Figure 3. Schematic diagram of the experimental assembly and transducer mounting positions.

A schematic diagram of the vehicle seat and accelerometer mounting positions is shown in Fig. 3. The triaxial accelerometer was mounted on the passenger seat surface (occupied by a torso) to measure vertical, fore-aft, and lateral accelerations. Vertical and fore-aft vibrations at the seat base were measured using two single-axis accelerometers placed on a rigid beam and mounted on the front, left seat rail. A similar mounting beam, containing a single-axis accelerometer, was attached on the
top of the backrest to measure fore-aft vibration. A single-axis accelerometer was placed on a plate and used to measure the vertical acceleration of the floor. It was mounted on the floor beneath the front edge and centreline of the seat. Signals were acquired into the 18-channel PULSE data-acquisition and analysis system. The recording period was 60 s except for when on the suburban road, which is mentioned in Section 4.4. According to the aforementioned standards, excitations up to 80 Hz should be counted for whole-body vibration analysis. Therefore, the frequency span of measurements was chosen as 100 Hz in the Labshop software. The sampling frequency was automatically adjusted according to the Nyquist rule (2.56 multiplied by 100 Hz as the frequency span). Signals were bandpassed filtered to be in the range of 0.5 to 80 Hz.

3. Analysis

3.1. Frequency Analysis

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

The acceleration was frequency-weighted using the frequency weightings defined in the BS 6841 over the frequency range 0.5 to 80 Hz. The three frequency weightings and multiplying factors for the different axes are listed in Table 2. The frequency-weighting values are shown in Fig. 4.

<table>
<thead>
<tr>
<th>Location</th>
<th>Axis</th>
<th>Weighting</th>
<th>Multiplying factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seat</td>
<td>x</td>
<td>Wd</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>y</td>
<td>Wd</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>z</td>
<td>Wb</td>
<td>1.0</td>
</tr>
<tr>
<td>Backrest</td>
<td>X</td>
<td>Wc</td>
<td>0.8</td>
</tr>
</tbody>
</table>
3.2. Vibration Dose Values (VDVs).

When the motion of a vehicle includes shocks or impulsive velocity changes, the VDV is considered more suitable for vibration assessment.\(^4,10\) It gives a measure of the total exposure to vibration, taking account of the magnitude, frequency, and exposure duration. The VDV reflects the total, rather than the average, exposure to vibration during the measurement period and is considered more suitable when the vibration signal is not statistically stationary.\(^10\) It is calculated by the fourth root of the integral with respect to the time of the square of the acceleration after it has been weighted. The use of the fourth-power method makes the VDV more sensitive to peaks in the acceleration waveform. Intermittent vibration can be defined as interrupted periods of continuous or repeated periods of impulsive vibration, or continuous vibration that varies significantly in magnitude. Thus, the VDV is defined as:

\[
VDV = \left( \frac{1}{T} \int_0^T a(t)^4 \, dt \right)^{1/4}
\]

(1)

where \(a(t)\) is the frequency-weighted acceleration time history, and \(T\) is the period of time over which vibration occurs.\(^4,5\) According to the BS 6841, vibration magnitudes and durations which produce VDV values in the region of 15 ms\(^{−1.75}\) will usually cause severe discomfort. The exposure period required for the VDV to reach a tentative action level of 15 ms\(^{−1.75}\) can be calculated as:

\[
T_{15} = \left( \frac{15}{VDV} \right)^{1/4} \cdot t
\]

(2)

where \(T_{15}\) is the time (in seconds) required to reach a VDV value of 15 ms\(^{−1.75}\), and \(VDV\) is the VDV measured over the period of \(t\) seconds. The VDV provides a suitable measurement of the total severity for whole-body vibration. According to BS 6841, excessive exposure to vibration may increase the risk of
tissue damage in the body. Basically, the VDV shows the total amount of vibration that is received by the human over a period of time. Having this value conduces to calculate the T15 level as the severe discomfort criteria. Hence, in short sentence, VDV and T15 determine the amount and the severity of vibration over a period of time.

3.3. Multi-Axis Vibration.

The British Standard BS 6841 specifies that when evaluating multi-axis vibration, the fourth root of the sum of the fourth powers of the VDV in each axis should be determined to give the total vibration dose value, \( VDV_{total} \), for the environment:

\[
VDV_{total} = \left( VDV_{xx}^4 + VDV_{yy}^4 + VDV_{zz}^4 + VDV_{xb}^4 \right)^{\frac{1}{4}}
\]

(3)

where \( VDV_{xx} \), \( VDV_{yy} \), and \( VDV_{zz} \) are the VDV in the x, y, and z directions on the seat, respectively, and \( VDV_{xb} \) is the VDV in the x direction on the backrest.

3.4. International Roughness Index (IRI)

Ride quality depends on vibration exposures induced by the road surface. IRI is the most common metric to describe road roughness. It has become recognized as a general-purpose roughness index and is strongly correlated to most kinds of vehicle responses that are of interest.

![Schematic of a road profiler.](image)

**Figure 5.** Schematic of a road profiler.

Engineers use road profilers (road meter system) for IRI measurement. The key importance of IRI is that road profiler users have shared experiences measuring IRI. As shown in Fig. 5, it is a quarter (one corner) of the car system, which includes...
one tire and axle, suspension spring, and damper. It accumulates suspension motion while traveling over the road. Roughness is measured as the accumulated suspension stroke normalized by the total traveled distance. IRI is usually presented in engineering units such as mm/m, m/km, or inc/mile. It is highly correlated with acceleration of vehicle passengers (ride quality) and tire load (vehicle controllability). Roads around the world may have different names and visual characteristics, but researchers can compare vibration analyses results for roads with similar IRIs.

3.5 Kurtosis of Vibration Signals.

Kurtosis is the fourth statistical moment, 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

\[
K = \frac{1}{n\sigma^4} \sum_{j=1}^{n} (x_j - \bar{x})^4
\]

where \(K\) is kurtosis, \(n\) is the number of discrete data, \(\sigma\) is the standard deviation, \(x_j\) is any data, and \(\bar{x}\) is the average of total data. The kurtosis value is approximately 3.0 for a Gaussian distribution. Higher kurtosis indicates the existence of numerous extreme data values, inconsistent with a Gaussian distribution, while that which is lower than 3.0 designates a relatively flat distribution.

3.6 SEAT Values.

Seat comfort is usually assessed by making vibration measurements on the surface of the car seat based on the BS 6841. Seat isolation performance was indicated by Seat Effective Amplitude Transmissibility \(\text{SEAT}\) (Seat Effective Amplitude Transmissibility) values, which can be calculated from frequency-weighted r.m.s. accelerations on the seat surface and seat base, \(a_{\text{seat}}\) and \(a_{\text{base}}\), respectively:\n
\[
\text{SEAT}_{\text{rel}} (%) = \frac{a_{\text{seat}}}{a_{\text{base}}} \times 100
\]

Current standards recommend that if the input motion contains shocks, the SEAT value is determined using the \(\text{VDV}_{\text{seat}}\) and \(\text{VDV}_{\text{base}}\) on the seat surface and seat base, \(\text{VDV}_{\text{seat}}\) and \(\text{VDV}_{\text{base}}\) as:

\[
\text{SEAT}_{\text{sh}} (%) = \frac{\text{VDV}_{\text{seat}}}{\text{VDV}_{\text{base}}} \times 100
\]

The SEAT value is a measure of how well the transmissibility of a seat is suited to the spectrum of entering vibration, taking into account the sensitivity of the seat occupant to different frequencies. SEAT values less than 100% indicate isolation or attenuation.
of vibration. It allows for the comparison of seat performance on a variety of road surfaces.

4. Results and Discussion 

**RESULTS AND DISCUSSION**

Figure 6 shows variations of $V_D V$ at different vehicle speeds over different roads except the bumpy road, where it was not possible to get data at different speeds. It may be seen that for each road surface, $V_D V$ values grew as the vehicle speed increased. At each speed, the measured $V_D V$ value over rough road surfaces (suburban and pavement) was greater than that over the smooth road (highway). The suburban road had the highest $V_D V$ increase in the speed range of 20 km/h to 40 km/h. As the vehicle speed increased, the smooth road surface showed a small $V_D V$ increase.

![Graph of VDV vs Velocity](image)

**Figure 6.** Variations of $V_D V$ values at different velocities over different roads.

<table>
<thead>
<tr>
<th>Road type</th>
<th>Velocity (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavement</td>
<td>20 32 h 20m, 40 12 h 50m, 60 11 h, 80 6h 15m</td>
</tr>
<tr>
<td>Suburban</td>
<td>219 h, 12 h 10m, 9h, 5h 15m</td>
</tr>
<tr>
<td>Bumpy</td>
<td>3 h 45m, -</td>
</tr>
</tbody>
</table>

**Table 3.** Time required to reach $15 ms^{-1.75}$ $V_D V$ on rough road surfaces.

The required exposure periods for $V_D V_{total}$ on the rough road surfaces to reach the action level of $15 ms^{-1.75}$ were listed in Table 3. On the smooth road, the needed time to reach $15 ms^{-1.75}$ $V_D V_{total}$ was so long in all speeds that it is not
It is feasible to suppose that a driver can continuously drive such a long period of time. Therefore, it can be concluded that other reasons factors other than seat and cabin ergonomics may be considered affect driver's comfort while driving on well-maintained, smooth roads.

4.1. IRI Evaluation

In this study, IRI (mm/m) is approximately related to the vehicle speed as follows:

\[ \frac{a_{\text{floor}}}{IRI} = 0.16 \left( \frac{v}{80} \right)^2 \]  

(7)

where \( a_{\text{floor}} \) is the frequency-weighted floor acceleration (r.m.s.) in the vertical direction and \( v \) is the vehicle speed in kph. For each road, using frequency-weighted floor acceleration values given in Table 4, the IRI values are calculated at different velocities and then averaged.

<table>
<thead>
<tr>
<th>Road type</th>
<th>20 km/h</th>
<th>40 km/h</th>
<th>60 km/h</th>
<th>80 km/h</th>
<th>Average IRI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highway</td>
<td>0.14</td>
<td>0.24</td>
<td>0.30</td>
<td>0.35</td>
<td>2.08</td>
</tr>
<tr>
<td>Pavement</td>
<td>0.5</td>
<td>0.65</td>
<td>0.71</td>
<td>0.8</td>
<td>5.46</td>
</tr>
<tr>
<td>Suburban</td>
<td>0.51</td>
<td>1.0</td>
<td>1.08</td>
<td>1.3</td>
<td>8.65</td>
</tr>
<tr>
<td>Bumpy</td>
<td>0.78</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9.75</td>
</tr>
</tbody>
</table>

4.2. Kurtosis Evaluation

To investigate whether or not the random vibration signals were Gaussian, a kurtosis parameter of the z-axis frequency-weighted floor accelerations were evaluated for different road surfaces at 20 km/h and 80 km/h.

\( \text{a)} \)
Figure 7. Variations of kurtosis and VDV-VDV versus IRI values: a) 20 km/h and b) 80 km/h.

Figure 7-a shows the variations of kurtosis and VDV-VDV with changes in IRI changes (from Table 4) at 20 km/h. The right axis of each graph corresponds to VDV-VDV. It may be seen that kurtosis values increased as the road roughness (IRI) increased. This indicates a deviation of the acceleration signals from the Gaussian distribution as the IRI increased. On all the roads, VDV-VDV values had an increasing trend as the road roughness increased. As expected, driving on rough road surfaces induces higher peaks and impulses. This resulted in more kurtosis and VDV-VDV values and less objective driver comfort. Hence, road roughness could be compensated through slowing down and thereby improving the ride quality. Similar results may be concluded from Fig. 7-b, which shows variations of kurtosis and VDV-VDV versus road roughness at 80 km/h.

4.3. SEAT Values Evaluation

Figure 8 shows the comparison of VDV_{seat} and VDV_{base} for driving over the road surfaces at the specified speeds. Obviously, data points lie under a 45-degree diagonal starting at the origin. It shows SEAT values of less than 100% and isolation of vibrations.
Figure 8. Comparison of the $VDV_{seat}$ and $VDV_{base}$ values on the road surfaces.

4.4 Frequency Analysis of Vibration Signals.

All signals (except for the suburban road) were acquired over a period of 60 s, and the frequency span of analysis was 100 Hz. The PULSE analyzer was adjusted in a way that an arbitrary number of 3200 lines were implemented in Fast Fourier Transform (FFT) analysis to achieve a high-frequency resolution of 31.25 mHz (100/3200).
**Figure 9.** FRF between seat base and seat–surface signals while driving on the pavement road at 20 km/h.

**Figure 10.** Autospectrum of the seat–surface vibration signal while driving on the pavement road at 20 km/h.
The analyzer automatically detected the mean square of each signal and divided it by the bandwidth to calculate the PSD value. Such narrowband analysis showed high coherency correlation near, close to unity, between seat-surface and seat-base signals. The Frequency Response Function (FRF) analysis between these signals for the pavement road, at a speed of 20 km/h, is presented in Fig. 9. This graph implies that the seat structure was a good isolator of vibration below 30 Hz, while after that, the signal was amplified. But it was not a critical issue because, as shown in Fig. 10, the amplitude of the signal after 30 Hz was still very low and had a small effect on the passenger.

For the suburban road, in order to ensure similar conditions and better repeatability of results, a limited length of the road with the aforementioned characteristics was selected. The acquisition period varied from 20 s at 20 km/h to 3 s at 80 km/h, considering the road-length limitation. Therefore, to have the signal at the FFT analyzer output, the number of FFT lines was adjusted from 1600 lines at 20 km/h to 200 lines at 80 km/h with an equal frequency span of 100 Hz. Thus, the frequency resolution was 62.5 mHz at 20 km/h (100/1600) and 500 mHz at 80 km/h (100/200). The PSDs of the vertical and fore-aft direction data that were measured on the seat surface and seat base while driving at 20 km/h on the suburban road are shown in Fig. 11. This figure shows how the accelerations at the base and seat surface were distributed over the frequency range up to 80 Hz. In the vertical direction, the measured acceleration on the seat surface (Fig. 11a) was comparable to the acceleration on the base (Fig. 11b). Base excitations were attenuated by the seat-isolation system up to 30 Hz. Accelerations were amplified at frequencies beyond that, but the magnitudes were very low.

On the contrary, however, acceleration on the base (Fig. 11d) was amplified in the fore-aft direction up to 30 Hz. Base vertical and fore-aft accelerations were mostly in the range below 30 Hz, which indicates a concentration of energy at low frequencies.
Figure 11. PSDs of vibration data measured at the seat surface and base while driving on the suburban road at 20 km/h: a) seat vertical direction, b) base vertical direction, c) seat fore-aft direction, and d) base fore-aft direction.
Figure 12. PSD of vibration data measured at the seat surface and base while driving on the suburban road at 80 km/h: a) seat vertical direction, b) base vertical direction, c) seat fore-aft direction, and d) base fore-aft direction.

Figure 12 shows the PSD of vertical and fore-aft vibration data while driving on the suburban road at 80 km/h. Similar results may be concluded from seen in Fig. 12. On the seat surface in the vertical direction, the energy distribution tended to be more concentrated towards the higher frequencies. Amplification of the fore-aft signal is achieved in low frequencies. This kind of energy observation is a powerful tool to check the capabilities of seat structures in very the early stages of design even on the test rig.

5. Conclusions

The IRI values (road roughness) indicated that the current study covered a wide variety of typical roads ensuring that outputs are valid at different conditions. The study locations was ranging from a highway, with an IRI value as low as 2.08, to a bumpy road, with having an IRI value as high IRI value of as 9.75. The kurtosis value increased with the IRI, which showed a deviation of the acceleration signals from the Gaussian distribution at higher IRIs.

It was found that the VDV (Vibration Dose Values) were proportional to both vehicle speed and road roughness (IRI). Rough roads exhibit higher VDV variation as the vehicle speed changes. In other words, differentiation of the VDV with respect to speed is higher in harsh road conditions. The comparison of VDV values at seat surface and base (SEAT value) was a qualitative inspection of seat suspension, and it verified the isolation of vibration. Further frequency analysis gives deeper insight into the matter. The FRF (Frequency Response Function) is the transfer function between the seat base and surface, to the transfer function between them, and it shows that excitations were damped up to 30 Hz by the seat and amplified beyond that range (in the vertical direction). The autospectrum of the seat-surface signal indicated that vibrations have low amplitudes even after the amplifications at frequencies higher than 30 Hz. Generally, graphs showed that energy concentration was at low frequencies—below 30 Hz. At the backrest in the fore-aft direction, excitations were amplified up to five times at severe conditions of driving at a high speed on a rough surface. Therefore, backrest assembly still can still be improved to become a better isolator in this direction. However, the T15 value, even at an extremely harsh road condition (i.e., the bumpy road), for more than three hours, was still more than 3 hours described suggests overall good quality of the vehicle suspension system and seat isolation. Finally, this study shows that kurtosis and the VDV of vibration signals correlate with road roughness (IRI) and may be used later as two objective metrics for vibration comfort estimation.

Acknowledgements
This study was conducted with support from IUT and UKM while Dr. H. Nahvi was on sabbatical leave from IUT. The first author would like to acknowledge the automotive laboratory facilities provided by the Department of Mechanical and Materials Eng., Faculty of Eng., UKM, Malaysia.

References

Table 1. Characteristics of the road surfaces.
Table 2. Frequency weightings and multiplying factors as specified in BS 6841 \(^4\) for seated person.
Table 3. Time required to reach \(15 \text{ ms}^{-1.75} VDV\) on rough road surfaces.
Table 4. Frequency-weighted floor acceleration \((\text{ms}^{-2}, \text{r.m.s.})\) for different roads and velocities and the corresponding average \(IRI\) values.

Figure 1. Schematic of four axis vibration of driver as considered by BS 6841.
Figure 2. Road surfaces: a) highway, b) pavement road, c) suburban road, d) bumpy road.
Figure 3. Schematic diagram of the experiment assembly and transducer mounting positions.
Figure 4. Frequency weightings used for analysis of acceleration signals \(^4\).
Figure 5. Schematic of a road profiler.

Figure 6. Variations of \(VDV\) values at different velocities over different roads.
Figure 7. Variations of kurtosis and \(VDV\) versus \(IRI\) values: a) 20 \(\text{kph}/\text{km/h}\), b) 80 \(\text{kph}/\text{km/h}\).
Figure 8. Comparison of the \(VDV_{\text{seat}}\) and \(VDV_{\text{base}}\) values on the road surfaces.
Figure 9. FRF between seat base and seat surface signals while driving on pavement road at 20 \(\text{kph}/\text{km/h}\).
Figure 10. Autospectrum of seat surface vibration signal while driving on pavement road at 20 \(\text{kph}/\text{km/h}\).
Figure 11. PSD of vibration data measured at the seat surface and base while driving on the suburban road at 20 \(\text{kph}/\text{km/h}\): a) seat vertical direction, b) base vertical direction, c) seat fore-aft direction, d) base fore-aft direction.
Figure 12. PSD of vibration data measured at the seat surface and base while driving on the suburban road at 80 \(\text{kph}/\text{km/h}\): a) seat vertical direction, b) base vertical direction, c) seat fore-aft direction, d) base fore-aft direction.