SUBJECTIVE EQUIVALENCE OF VEHICLE INTERIOR NOISE AND LOW FREQUENCY RANDOM VERTICAL WHOLE-BODY VIBRATION

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ABSTRACT

Subjective equivalence is the point where the effect of noise is perceived to be the same as vibration. This paper aims to determine the subjective equivalence curve of vehicle interior noise and vertical whole-body random vibrations. The discomfort levels of noise and vibration were then determined. Twelve (12) seated subjects were exposed to thirty-six (36) paired combination of noise and vertical whole-body vibration for 5 seconds. The vibration stimuli consist of six (6) levels of random vertical whole-body vibration, magnitude ranging from 0.1 m/s^2 to 1 m/s^2 in the frequency range of 1 Hz to 20 Hz. The input noise was initially recorded in a vehicle travelling at 60 km/hr and reproduced with six (6) levels of sound pressure level ranging from 53 dB(A) to 82 dB(A). For each combined stimuli, each subject was asked to indicate which stimulus they prefer to reduce. A subjective equivalence contour was plotted and used to further understand how human perceive vibration and noise. The findings suggest that in combined noise and vibration environment, as the level of noise and vibration increase, the discomfort values for the two stimulus of noise and vibration will be different at the subjective equivalence point.

Keywords: Subjective equivalence, whole-body vibration, vehicle interior noise
I-INCE Classification of Subject Number: 49, 62, 79

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1. INTRODUCTION

Human response to noise and vibration is key towards understanding human overall comfort levels in vehicles. The terms comfort and discomfort are used to classify passenger satisfaction levels in vehicle cabins. Some researchers has suggested that in terms of seat comfort, the feeling of comfort can only be achieved in the absence of negative quality. This approach has led to the view that it is only possible to measure the level of seat discomfort rather than comfort [1-3].

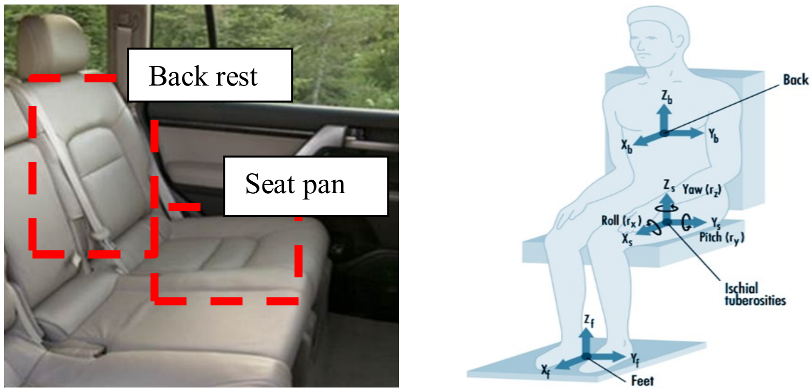
In general, human comfort levels in vehicle cabin is determined by both noise and vibration levels. The combination of whole-body vibration (WBV) and noise contributes to the comfort levels felt by vehicle users. Most studies on comfort levels in vehicle cabins have focused on the separate effects of WBV and noise on comfort. To study the effect of both noise and vibration on comfort levels, reactions to these different external stimuli have to be placed on the same subjective scale. One approach to do this is through the concept of subjective equivalence. Subjective equivalence formulation provides a pathway for experimental results to be used to assess complex the effect of both environmental noise and vibration on comfort to be assessed. It provides a method to measure the comfort level of subjects to noise and vibration on the same subjective scale and to predict the relative importance of reducing either noise or vibration in situations where both stimuli are present [4]. This research extends previous studies on subjective equivalence by focusing on the effects of interior vehicle noise and low frequency vertical WBV (1-20 Hz) in a passenger car on comfort levels. The objective of this study is to identify the subjective equivalence curve of vehicle interior noise and random vertical WBV and determine the discomfort levels to noise and vibration stimuli at the subjective equivalence point.

1.1 Comfort in vehicle cabin from noise and WBV

The current practice in Noise and Vibration Harshness (NVH) evaluates discomfort from noise and WBV as separate disturbing factors. WBV in vehicle occurs when the body is in contact with vibrating surfaces and is ideally assumed to affect all parts of the body. For vehicle drivers or passengers, most of the exposure occurs in the seated position [5]. The WBV is transferred from the vehicle to the body through the vehicle seat pan and back rest as indicated in Figure 1(a). Measurements of the vibration magnitude are conducted based on the principal basicentric reference axis according to ISO 2631:1 and BS 6841:1987 standards as depicted in Fig.1(b) [6,7].

Paddan and Griffin [8] measured, evaluated, and assessed 100 different vehicles within 14 categories according to both BS 6841:1987 and ISO 2631:1997 standards. They determined that the ISO 2631 standards tend to underestimate any risk from exposure to WBV compared to when using the BS6841:1987 standard. The variation in results was due to different method of vibration quantification suggested by the two standards.

Using the same data, the effect of seating on exposures to WBV in vehicles had been quantified using Seat Effective Amplitude Transmissibillity (SEAT) values [9]. The result suggest that the overall average SEAT value was less than 100%, indicating vibration attenuation. The usage of different frequency weighting, W_b from BS6841:1987 and W_k from ISO 2631:1997 yielded SEAT values that differed by less than 6%.



(a) **(b)**

Fig.1. Whole-body exposure in vehicle seated position. (a) Vibration exposure location of seat pan and back rest, (b) Principal basicentric axes for vibration measurement.

Meanwhile, Basri and Griffin [10] studied the discomfort from a vertical sinusoidal WBV when sitting in vehicle seat inclined at 0° (upright), 30°, 60° and 90°(recumbent), with frequency ranging between 1 Hz and 20 Hz, and magnitudes ranging from 0.2 to 2 ms^{-1}. The results suggest that the back rest increased vibration discomfort at all inclination angles for frequencies greater than 8 Hz and that the discomfort was greater at the head and neck compared to the rest of the body.

Cvetanovic and Zlatkovic [11] conducted an evaluation of WBV risk in an agricultural tractor and determined that working more than one hour on the tractor will cause intense daily exposure to vibration with values higher than allowed by law. Azrah et. al. [12] conducted a study for the evaluation of exposure for metro passengers to WBV and recurrent shocks according to ISO 2631-1 standard and identified that different evaluation methods of root-mean squared and vibration dose value (VDV) may result in different risk levels of WBV exposure when calculating Health Guide Critical Zone (HGCZ).

For human response to combined noise and whole-body vibration, Huang and Li [13] conducted a study on subjective discomfort of human towards vibration in micro-commercial vehicles over four different road surfaces. The findings suggest that at a high vibration magnitude of 1.5 ms^{-2}, vibration containing more high frequency components caused greater discomfort than vibration containing less high-frequency components. Different models for vibration discomfort were also developed for different road condition and vehicle.

Altinsoy [14] conducted identification of quality attributes of automotive idle sounds and WBV. The findings suggest that sound level alone is insufficient to describe the complexity of idle sound and vibration perceptions. The intensity dependent attributes, signal-based attributes in terms of spectrum, temporal properties, comfort, and emotion-based attributes are required to characterize the idling noise, vibration, and harshness.

Furthermore, Jailani et. al [15] developed an index for vehicle acoustical comfort inside a passenger car by considering psychoacoustics parameter such as Zwicker loudness, sharpness, roughness, and fluctuation strength which was correlated to a road roughness index in this case the IRI (international roughness index). This index is believed to be an alternative for determining acoustical comfort without needing to perform a panel test.

1.2 Subjective equivalence of noise and vibration

Subjective equivalence is a psychological preference where perception towards one stimulus is assumed to be the same with other stimulus at certain levels of magnitude. In the scope of noise and vibration, the subjective equivalence can be elaborated into relative effect of either subjective equivalence of noise to vertical WBV, or vice versa. Steven's Power Law indicated the correlation of subjective magnitude (felt by the test subject) to the objective magnitude of the stimuli (input) [16, 17] as related through Equations 1 and 2.

$$\psi_n = k_n \varphi_n^{\alpha_n} \quad \text{Equation 1}$$

$$\psi_v = k_v \varphi_v^{\alpha_v} \quad \text{Equation 2}$$

Where ψ_n and ψ_v represent the subjective magnitudes of the stimuli, φ_n and φ_v are the objective magnitudes of the stimuli, k_n and k_v are constants, and α_n and α_v are the growth rates of subjective sensations produced by vibration and noise respectively.

When the subjective magnitudes of vibration and noise are assumed to be equal to each other, Equations 1 and 2 can be rewritten as Equation 3.

$$k_v \varphi_v^{\alpha_v} = k_n \varphi_n^{\alpha_n} \quad \text{Equation 3}$$

Taking the logarithmic of either the objective magnitudes due to noise and vibrations separately results in Equations 4 and 5 respectively.

$$\log_{10} \varphi_n = \log_{10}\left(\frac{k_v}{k_n}\right)^{\frac{1}{\alpha_n}} + \left(\frac{\alpha_v}{\alpha_n}\right)\log_{10}(\varphi_v) \quad \text{Equation 4}$$

$$\log_{10} \varphi_v = \log_{10}\left(\frac{k_n}{kv}\right)^{\frac{1}{\alpha_v}} + \left(\frac{\alpha_n}{\alpha_v}\right)\log_{10}(\varphi_n) \quad \text{Equation 5}$$

Equation 4 expresses the subjective equivalence of noise to vibration while Equation 5 expresses the subjective equivalence of vibration to noise. φ_n is the A-weighted sound pressure levels and φ_v is weighted vibration acceleration.

Considering the correlation of $L_{Aeq} \propto 20log_{10}(\varphi_n)$ and $a_{rms} \propto \varphi_v$ [15], the subjective equivalence of noise to vibration is then expressed in Equation 6.

$$L_{Aeq} = \log_{10}\left(\frac{k_n}{k_v}\right)^{\frac{20}{\alpha_v}} + 20\left(\frac{\alpha_n}{\alpha_v}\right)\log_{10}(a_{rms}) \quad \text{Equation 6}$$

Equation 6 suggests that the objective magnitude of noise can be predicted by knowing the vibration dose value which gives the same subjective feeling to human. The primary concern of the equation is the value of constant and growth rate which are determined from psychophysics experiment. The equivalent A-weighted sound pressure level, L_{Aeq} can be replaced by sound exposure level, L_{AE} whereby root-mean-squared vibration acceleration can be replaced in term of vibration dose values, a_{vdv}. These correlations will lead to Equation 7.

$$L_{AE} = \log_{10}\left(\frac{k_n}{k_v}\right)^{\frac{20}{\alpha_v}} + 20\left(\frac{\alpha_n}{\alpha_v}\right)\log_{10}\left(a_{vdv}\right) \qquad \text{Equation 7}$$

Other studies have found that the values of the first term in Equation 7, $log_{10}\left(\frac{k_n}{k_v}\right)^{\frac{20}{\alpha_v}}$ varies from 80.8 - 93.6 while the values for the second term in the equation, $20\left(\frac{\alpha_n}{\alpha_v}\right)$ varies from 20.2 – 33.0 [4, 16, 17]. This was for noise levels ranging from 59 to 100 dB(A) and recorded vibrations with magnitude ranging from 0.07 to 1.20 ms^{-2} . One study however had a value for $log_{10}\left(\frac{k_n}{k_v}\right)^{\frac{20}{\alpha_v}}$ of 51.9 and a value for $20\left(\frac{\alpha_n}{\alpha_v}\right)$ of 14.4 [18]. The difference in the values is theorized to be due to lower range of noise input ranging from 28 to 61 dB(A) and small vibration magnitudes ranging from 0.03 to 0.4 mms^{-1}.

1.3 Subjective equivalence of vehicle interior cabin noise and low frequency vertical WBV

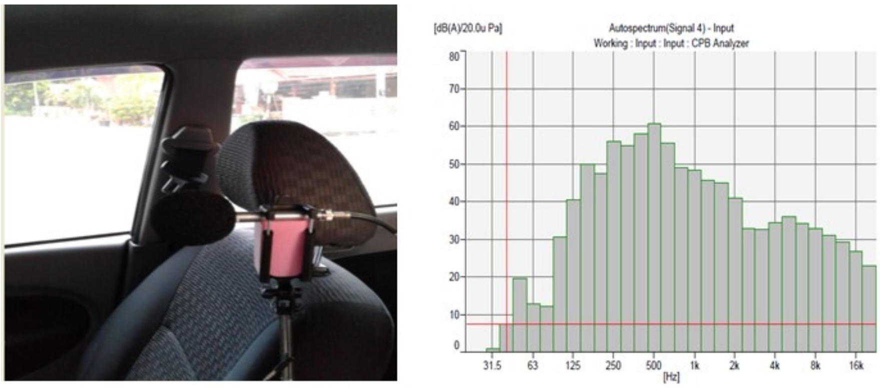
Human response to noise and vibration is a complex phenomenon especially in the presence of both stimulus. This is especially true for the discomfort felt in a vehicle travelling along a relatively smooth road. It is theorized that this feeling of discomfort is driven primarily by combination of two stimulus: vehicle interior noise with vertical WBV. To better understand which stimuli has a bigger effect on the feeling of discomfort, and hence should be the focus on future mitigation efforts, this study will determine the subjective equivalence of vehicle interior noise to vertical WBV. To better approximate the vertical body vibration felt when travelling along a relatively smooth road, the focus is only on low frequency (1 – 20 Hz) WBV while the noise will be based on the reproduced noise obtained measured in a vehicle travelling along a relatively smooth road. The results can then be used to better address the feeling of discomfort in vehicles travelling under the same general conditions.

2. METHODOLOGY

This research uses a combination of field measurement and lab experiment to investigate the subjective equivalence of interior cabin noise to low frequency WBV.

2.1 Field measurement

The noise data were measured using a four door passenger vehicle (sedan car) manufactured in 2007. The vehicle is in good condition and had undergone periodic servicing. The data measurement was taken for 60 seconds at a vehicle speed of 90 km/h on a highway road. The noise were collected using Pre-polarized Free-field ½ inch microphone B&K type 4189 with a sensitivity of 53.2 mV/Pa mounted at the hearing level of a seated person in vehicle as shown in Figure 2(a). Data recording was carried out using an ADASH A4400 VA4 Pro Vibration analyser and sample results of noise spectrum at 63.7 dB(A) is shown in Figure 2(b).



a) b)

Fig.2. Noise measurement in vehicle, a) The position of microphone in vehicle cabin and b) the noise spectrum at 63.7 dB(A).

2.2 Noise and vibration stimuli production

The noise recorded was the reproduced in a lab setting. The mono sound was converted to stereo and the noise level were applied to a B&K portable Head and Torso simulator system through Bower and Wilkins P7 headphone. Six (6) levels of A-weighted sound pressure levels (SPL) were reproduced at magnitudes of 53.9, 63.7, 70.4, 77.1, 80.0, and 82.0 dB(A). These values can be converted to the respective sound exposure values, L_{AE} by applying the equation suggested by Bruel and Kjaer [18] as given by Equation 8.

$$L_{eq} = SEL - 10\log_{10}\left(\frac{T}{T_0}\right) \qquad \text{Equation 8}$$

Where T is the time duration for one event occurrence, T_0 is taken as 1s and SEL is the sound exposure level.

The six (6) levels of random vibration stimuli were generated by electrodynamic shaker with frequency range of 1 to 20 Hz for a vibration root-mean-square magnitude of 0.1, 0.2, 0.3, 0.5, 0.8, and 1 ms^{-2}. The combination of 36 random paired noise and vibration was imposed on the subject for 5 seconds per stimuli.

2.3 Experimental set up

The experiment was conducted at the Science and Technology Research Institute in Defence, Malaysia (STRIDE) vibration lab. 12 subjects consisting of 9 males and 3 females participated in the experiment with a median age of 25 years (ranging from 18 to 33 years), median height of 168 cm (ranging from 156 to 178 cm), and median weight of

70 kg (ranging from 55 to 97 kg). The subjects were exposed to 36 random combination of noise and vibration for 5 seconds per stimuli. The noise was delivered through headphones and the vibration was delivered through a shaker expander. The subjects were seated directly on the shaker expander while their feet were placed on a static footrest as shown in Figure 3.

Initially, the subjects were exposed to 3 levels of sound and 3 levels of vibration magnitude separately as part of the training phase of the experiment. The objective phase of the experiment was to familiarise the subject to the sound and vibration levels separately. Then for the experiment, for each combination, the subjects were asked to identify which stimuli they preferred to reduce, either noise or vibration. The subject were given a hand held device to hold throughout the experiment to record their response for each stimuli presented. The result from the hand held device were then compiled at the end of the experiment.

Fig. 3. Experiment set-up with human subject giving response to noise and vibration delivered through headphone and vibration shaker with static footrest.

3. RESULTS AND DISCUSSION

The response of each stimuli presented were analysed to identify the subjective equivalence of noise and vertical WBV. The percentage of subjects preferring to reduce noise were analysed and correlated with the respective noise and vibration level as indicated in Table 1. In general, the results from Table 1 shows that for the same level of noise, the percentage of subjects preferring to reduce noise decreased as the vibration level increases. Whereby for the same level of vibration, the percentage preferring to reduce noise increased as the noise level increases. These result suggest some masking effect where higher levels of vibration starts to dominate the feeling of discomfort and tend mask the discomfort due to noise. Similarly, at high enough noise levels, the discomfort due to noise dominates masking the effect of noise due to vibration levels

Table 1. Percentage of subject preferring to reduce noise

	Root-mean-square vibration level (ms^{-2})					
	a_{rms1} (0.1)	**a_{rms2} (0.2)**	**a_{rms3} (0.3)**	**a_{rms4} (0.5)**	**a_{rms5} (0.9)**	**a_{rms6} (1.0)**
L_{AE1} (60.9 dB(A))	58%	67%	33%	17%	8%	8%
L_{AE2} (70.7 dB(A))	92%	83%	58%	25%	8%	8%
L_{AE3} (77.4 dB(A))	100%	92%	67%	58%	33%	17%
L_{AE4} (84.1 dB(A))	100%	100%	75%	75%	33%	25%
L_{AE5} (87.0 dB(A))	100%	100%	100%	83%	58%	33%
L_{AE6} (89.0 dB(A))	100%	100%	100%	100%	83%	63%

The percentage of subjects preferring to reduce noise were also plotted against the sound levels for each vibration magnitude as shown in Figure 4. It can be observed from Figure 4 that for all vibration levels the percentage of subjects preferring to reduce noise increases as the sound level is increased. This increase is however typically not linear. For lower vibration levels (a_{rms1} and a_{rms2}) the percentage of subjects preferring to reduce noise rises at a faster rate at the lower noise levels (60 – 75 dB(A)) as opposed to the higher noise levels (75 – 90 dB(A)). For higher vibration levels (a_{rms4}, a_{rms5}, and a_{rms6}) the percentage of subjects preferring to reduce noise rises at a faster rate at the higher noise levels (75 - 90 dB(A)) as opposed to the lower noise levels (75 – 90 dB(A)). For a_{rms3}, the percentage of subjects preferring to reduce noise rises at relatively linear rate for increases in the sound levels.

These results seems to indicate that at lower vibration levels, small increases in the noise levels for noise below 75 dB(A) have a greater impact on the subjects' discomfort compared to increases in the noise levels for noise above 75 dB(A). At higher vibration levels, small increases in the noise levels for noise below 75 dB(A) have a lower impact on the subjects' discomfort compared to increases in the noise levels for noise above 75 dB(A).

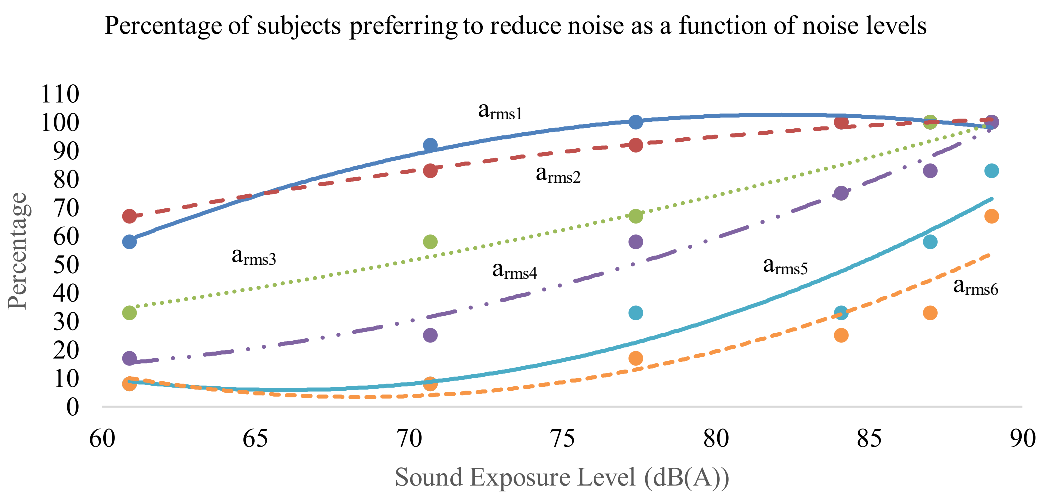


Fig. 4. Percentage of subjects preferring to reduce noise as a function of noise levels.

The preference percentage curves in Figure 4 were then used to generate the 25th, 50th, and 75th percentile contours of preference to reduce noise as shown in Figure 5. The linear regression of the 50th percentile was considered to be the subjective equivalence of noise and vibration i.e. the point at which the noise input is subjectively equivalent to the vibration input. The linear regression of the 50th percentile results in Figure 5 was used to determine the subjective equivalence correlation of noise and vibration in Equation 7 and is given by Equation 9.

$$L_{AE} = 80.345 + 35.913 \log_{10} a_{rms} \qquad \text{Equation 9}$$

Where L_{AE} is the sound exposure level in dB(A) and a_{rms} is the vibration level in ms^{-2}. Comparing the results for $log_{10}\left(\frac{k_n}{k_v}\right)^{\frac{20}{\alpha_v}}$ obtained from Equation 9 shows that the correlation value, 80.3 are in line with the values obtained from previous studies, 80.8 – 93.6 [4, 16, 17]. Meanwhile, comparing the results for $20\left(\frac{\alpha_n}{\alpha_v}\right)$ obtained from Equation 9 shows that the correlation value are slightly higher, 35.9 compared to the ranges obtained from previous studies, 20.2 – 33.0.

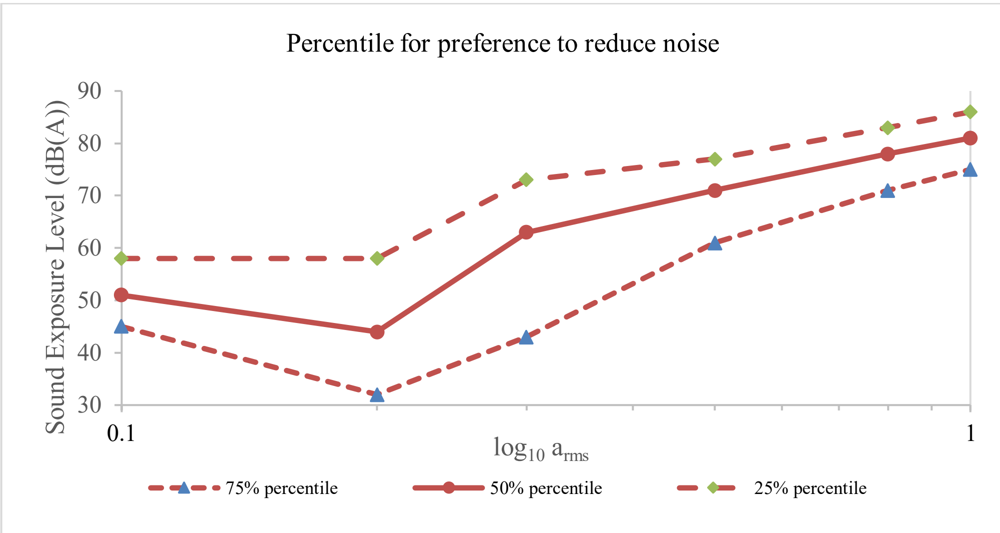


Fig. 5. The 25th , 50th and 75th percentile of preference to reduce noise. The 50th percentile trend line was assumed to be the subjective equivalent point of noise and vibration.

Equation 9 was also used to identify subjective equivalent values of noise and vibration for different vibration levels shown in Table 2. The results in Table 2 suggest that there are vibration magnitudes and corresponding noise exposure levels at which humans will subjectively consider to be the same. This equivalence values can be a potential approach to quantify discomfort from noise and vibration when viewed as combined modalities.

Table 2. Suggested subjective equivalence value of vibration and noise

Vibration level (a_{rms} in ms^{-2})		Noise level (SEL in dB(A))
0.1		44.43
0.2		55.24
0.3	Subjectively having the same feeling of discomfort as	61.57
0.5		69.53
0.8		76.86
1		80.35

3.1 Discomfort from noise and vibration at the point of subjective equivalence.

The term subjective equivalence can be interpreted as a point where the effect of one stimuli is subjectively perceived to be the same as the effect of another stimuli. In the case of noise and vibration, the subjective equivalence curve approximates the level where human response towards noise is subjectively the same as human response towards vibration. The discomfort from noise and vibration were approximated by Huang [15] as

$$\psi_n = 0.119 \times 10^{0.0035L_{AE}} \quad \text{Equation 10}$$
$$\psi_v = 70.9 \times {a_{vdv}}^{0.947} \quad \text{Equation 11}$$

Where ψ_n and ψ_v are the discomfort from noise and vibration respectively, L_{AE} is the sound exposure level and a_{vdv} is the vibration dose value. At the point of subjective equivalence, the gap in discomfort from noise and discomfort from vibration can be understood to be the difference in perception of noise and vibration. The discomfort values of noise and vibration at the point of equivalence are shown in Figure 6. The vibration dose values were estimated using eVDV as given by Equation 12.

$$eVDV = 1.4 \times a_{rms} \times t^{0.25} \quad \text{Equation 12}$$

Where t is exposure time of 5 seconds. It can be observed from Figure 6, that though the discomfort from vibration varies linearly with increases in the vibration dose values, the discomfort from noise does not. Additionally the discomfort from vibration was determined to be constantly higher than the discomfort from noise as the vibration dose value was increased.

The finding suggest that as the level of noise and vibration gets higher, the discomfort values for noise and vibration will be significantly different at the point of subjective equivalence. In other words, at the same level of discomfort from noise and vibration, the discomfort values for each stimuli is different because human perceive noise and vibration differently.

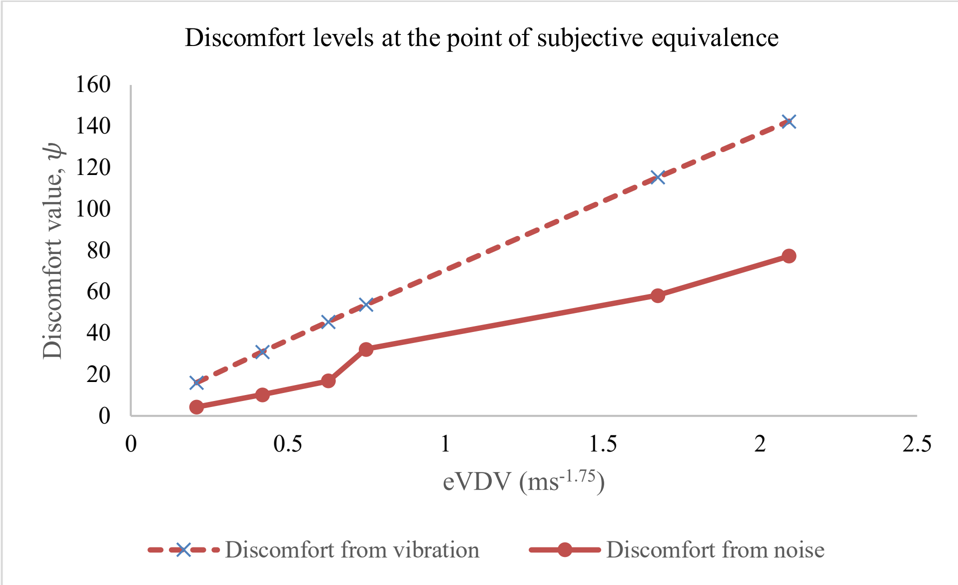


Fig. 6. Discomfort values of noise and vibration at the point of subjective equivalence.

4. CONCLUSION

The subjective equivalence curve of random vertical whole-body vibration and vehicle interior noise were determined through psychophysics experiment. The subjective equivalence was then used to how humans perceive vibration and noise differently. The discomfort values from noise and vibration was then determined from the subjective equivalence results. The finding suggest that in combined noise and vibration environment, as the level of noise and vibration increase, the discomfort values for the two stimulus of noise and vibration will be significantly different at the subjective equivalent point. Specifically:

1. The subjective equivalence from vehicle interior noise and low frequency vertical whole body vibration have been identified as $L_{AE} = 80.345 + 35.913\log_{10} a_{rms}$.
2. The difference in discomfort due to noise and due to vibration were analysed at the subjective equivalent point (same level of subjective feeling). It was determined that the discomfort due to vibration is consistently higher that the discomfort due to noise and becomes even more apparent and the vibration value does increases.

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