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An Integrated Model of Static and Dynamic Measurement for Seat Discomfort

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Abstract. A driver interacts directly with the car seat at all times. There are ergonomic characteristics that have to be followed to produce comfortable seats. However, most of previous researches focused on either static or dynamic condition only. In addition, research on car seat development is critically lacking although Malaysia herself manufactures its own car. Hence, this paper integrates objective measurements and subjective evaluation to predict seat discomfort. The objective measurements consider both static and dynamic conditions. Steven's psychophysics power law has been used in which after expansion; $\psi = a + b\varphi_s^{\alpha} + c\varphi_v^{\beta}$ where ψ is discomfort sensation, φ_s^{α} is static modality with exponent α and φ_v^{β} is dynamic modality with exponent β. The subjects in this study were local and the cars used were Malaysian made compact car. Static objective measurement was the seat pressure distribution measurement. The experiment was carried out on the driver's seat in a real car with the engine turned off. Meanwhile, the dynamic objective measurement was carried out in a moving car on real roads. During pressure distribution and vibration transmissibility experiments, subjects were requested to evaluate their discomfort levels using vehicle seat discomfort survey questionnaire together with body map diagram. From subjective evaluations, seat pressure and vibration dose values exponent for static modality $\alpha = 1.51$ and exponent for dynamic modality $\beta = 1.24$ were produced. The curves produced from the Eq.s showed better R-sq values (99%) when both static and dynamic modalities were considered together as compared to Eq. with single modality only (static or dynamic only R-Sq = 95%). In conclusion, car seat discomfort prediction gives better result when seat development considered both static and dynamic modalities; and using ergonomic approach.

Keywords: Car Seat, Static Measurement, Dynamic Measurement, Seat Discomfort, Steven's Law, Psychophysics

1. INTRODUCTION

According to ergonomic classification, a driver's car seat is a workspace. It is exposed to both static and dynamic working conditions. Therefore, measurement and evaluation should consider both static and dynamic con-

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ditions. There are very limited numbers of past researches that combine static and dynamic conditions when studying seat discomfort. Of recent, the most referred literature is by Ebe and Griffin (2000a, 2000b). Applying Steven's Psychophysics Power Law (Stevens, 1975), Ebe and Griffin found that whenever seat stiffness which was the static discomfort being studied was high, dynamic discomfort was high, and vice versa. However, the research found that if the static discomfort was low but the dynamic discomfort was high, perception on discomfort was also high.

Gescheider (1997) as quoted by Hacaambwa and Giacomin (2007) suggested that the transformation from mechanical (objective) sensation (pressure or acceleration)to perceived (subjective) human discomfort response falls into the general category of psychophysical relationships. In many researches (Ebe and Griffin, 2000a; Ebe and Griffin, 2000b; Hacaambwa and Giacomin, 2007; Stevens, 1975), Steven's Power Law was applied to relate the objective measurement with human discomfort sensation.The Steven's Power Law is expressed as:

$$\Psi = k\varphi^{\beta} \tag{1}$$

where Ψ represents sensory modality in this case the magnitude of subjects discomfort, which is proportional to the stimulus intensity φ to a power n. Steven (1975) suggested that the exponent n for pressure (on hand palm) is 1.1 and for vibration (of 60Hz on finger) is 0.95.

Eq. (1) can be expanded into the summation of two (or more) stimulus effects (Ajovalasit and Giacomin 2007, Amman *et al.*, 2005, Giacomin and Fustes, 2005, Howarth and Griffin, 1990) and is expressed as:

$$\Psi = a + b\varphi_s^{\alpha} + c\varphi_v^{\beta} \tag{2}$$

where a, b and c are constants, φ_s and φ_v represent seat pressure and vibration magnitude and exponent α and β are exponents acquired from static the rate of increase in discomfort associated with the pressure and vibration magnitude.

This paper aims to produce an integrated model of that combines static and dynamic investigations on seat discomfort. The static condition being studied is the seat pressure distribution whilst the dynamic condition is the whole-body vibration.

2. METHODOLOGY

In order to integrate static and dynamic measurements of seat discomfort, separate measurement has to be carried out to obtain the exponent values of the Steven's Power Law for both modalities. Basically, three experiments were carried out for the purpose of this study. Firstly, static measurement was done by measuring the seat pressure distribution of subjects in a stationary car. On the other hand, dynamic measurement was done by recording of vibration in a real moving car. Subjective evaluation on seat discomfort was carried out in both conditions. Thirdly, both modalities were examined continuously and subjective evaluation was again carried out in the third experiment. The first experiment was to determine exponent α and the second one is to determine exponent β. Therefore, the relationship between discomfort and both of the modalities, seat pressure and vibration can be determined from the third experiment.

The number of subjects for each experiment varies as it involves subjective evaluations. It is quite difficult to get significance and highly correlated relationship between the objective and subjective measurements especially since all the experiments were carried out in the field and not in a controlled lab environment. Nevertheless, the subjects are from the same pool of subjects who has agreed and had given their consent to participate in all three experiments.

2.1 Seat Pressure Distribution Measurement

Real driver seat in a stationery vehicle from a Malaysian premium class sedan was used as the experiment set-up. Seat pressure distributions were recorded using a pressure mapping device (XSensor Technology Corporation) and continuously sampled at 5Hz for about an hour. The procedure and results has been discussed in detail previously in Deros *et al.* (2009a).

2.2 Whole-Body Vibration Measurement

For each subject, the measurement of the vibration was recorded for 20 seconds. Prior to the test, subjects' permission was given in the form of letter of consents after they were briefed on the procedures involved. The on road measurements were carried out between 9.30 am and 11.00 am so as to avoid busy traffic. Subjects were seated on the front passenger seat. The in-vehicle tests were carried out on smooth and paved road in Putrajaya, Malaysia. The car was driven at a constant speed at 80km/h. The same driver drove the car for each subject to minimize variability of driving condition for each test.

The measurement devices used were Bruel and Kjaer portable and multi-channel *PULSE* type 3560D with *Bruel and Kjaer* HAT type 4100 and *Bruel and Kjaer*isotron accelerometer model 751-100. The measurement software is also *Bruel and KjaerPulse Labshop*. The accelerometers were calibrated using the *Bruel and Kjaer* calibration exciter type 4294. The accelerometers were fixed on top of the front passenger-seat surface and on the floor below the seat.

2.3 Subjective Evaluation

Eleven healthy male subjects participated in the experiment. Each of them gave written consent to attend two 1 hour sessions for two different days. Their mean (SD) age, height, and weight were 20.2 (2.0) years, 169.6 (5.6) cm and 60.0 (7.6) kg. Subjective discomfort was assessed in Malay language using few related items from vehicle seat discomfort survey (VSCS) (Deros *et al.*, 2009b).

Subjects were required to assess discomfort from different modalities in the two different sitting conditions. For static evaluation, subjects were asked about pressure sensation which contributes to the discomfort of the seat. For dynamic evaluation, subjects were asked about the vibration that they felt from the seat. Finally, during the on-road experiments, the subjects were asked to evaluate the overall discomfort which include both pressure and vibration stimuli. Median data from different sessions were used for the analyses.

Subjects were briefed on how to fill in the questionnaire each time before the experiments took place and it took about 5-7 minutes average for them to complete the questionnaire each time. Each subject has to follow this protocol:

- They have to empty their back pocket, than sit on the driver seat.
- They were not allowed to adjust anything but the track adjustor (distance of the seat to the steering wheel). Seat back was fixed at 110° which was the average preferred driving angle for Malaysian (Mohamad *et al.*, 2009).
- For seat pressure distribution evaluation, they have to answer the VSCS at 5 different time intervals, the initial one right after they settled in the seat and then at each 10 minutes interval after that for three times and after 15 minutes for the final one. For vibration and overall evaluations, they were given the instruction to evaluate before the 20 seconds record time and then some time to do the evaluation right after it.

2.4 Data analysis

For objective measurements, data for seat pressure distribution however has to be changed first into S.I. unit; kgcm^{-2} from mmHg. Normalization on the 11 data was carried out in order to get significant relationship with discomfort using the Steven's Power Law. Minitab software was used to do the analyses as well as the normalization.For vibration, whole-body vibration was represented by vibration dose values (VDV) as suggested by BS6841 (1987).

3. RESULTS AND DISCUSSION

Two experiments with 11 subjects investigated the discomfort caused by seat pressure and vibration. In order to determine the exponents' values, individual analyses correlated correlate one modality (pressure only or vibration only) to its respective discomfort subjective evaluations each time.

3.1 Seat Pressure Measurement and Evaluation

The pressure device measures in mmHg hence the data has to be transformed into kgcm^{-1}. Table 1 shows the median of two days average pressure from seat pan of four subjects in both mmHg and kgcm^{-2}. Only results from four subjects showed significant correlation between the objective and subjective evaluations. Deros *et al.* (2009a) showed that discomfort evaluation increase as time increases. Therefore, for this analysis, the discomfort evaluation was taken from the second interval i.e. after 10 minutes subject sat on the seat.

Kolich and Taboun (2004) reported strong linear relationship of few variables from their seat interface study and comfort index values. Hence, a multiple linear regression (using Minitab) was used here. The exponent for static discomfort was obtained from the slope of regression line in the log-log figure as shown in Figure 1 where $\alpha = 1.51$. Stevens (1975) suggested that exponent value more than 1, as obtained here, showed that discomfort increases rapidly with higher pressure values.The model produced R-Sq = 95%.

Table 1. Results from 4 subjects for seat pressure measurement and evaluation.

Subject	Median pressure		Static discomfort
	mmHg	Kgcm^{-1}	
2	88.78	1.95	34.2
8	81.48	1.91	30.2
9	86.12	1.94	33.7
11	88.61	1.95	34.5

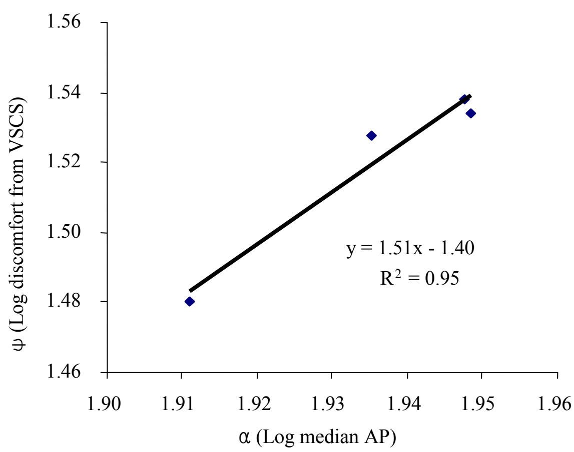


Figure 1. Relationship between discomfort and pressure felt by subjects.

The regression model produces predicted discomfort values that are so close to the evaluated values.

Anova analysis showed no significant difference between the estimated and the real one and is depicted in Figure 2.

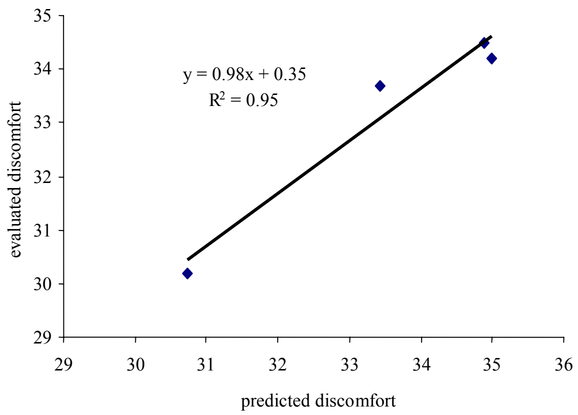


Figure 2. Validation analysis on discomfort model for static condition.

3.2 Vibration Measurement and Evaluation

Table 2 shows the result of vibration values and root mean square measured from the seat of the car. The respective subjective evaluation .

Table 2. Results from 4 subjects for seat vibration and evaluation.

Subject	Median vibration		Dynamic discomfort
	Weighted VDV ($ms^{-1.75}$)	Weighted rms (ms^{-2})	
2	1.290	0.324	10.8
8	1.817	0.452	18.4
9	1.803	0.453	17.1
11	2.117	0.530	19.3

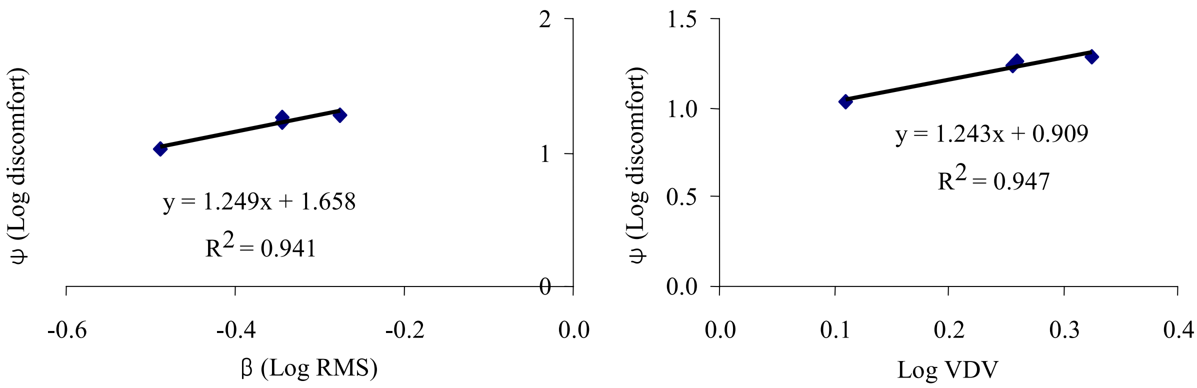
The first impression that a car made in static condition or until the first five minutes in the laboratory is commonly know as 'showroom feel'. However the more important perception is afer a while of driving the car (Giacomin and Braccco, 1995; Giacomin *et al.*, 2004; Johansson and Nilsson, 2006). When driving starts, vibration becomes one of the main factor that contributes towards seat discomfort. The subjective evaluation was done during driving condition on smooth road at 80km/h. The driving condition was selected because from previous pre-test, it provided enough vibration to be clearly perceived by the subjects. Furthermore, it is safer and more manageable for the driver to facilitate the evaluation process as compared to paved road condition.

From Eq. (1), ψ represented vibration discomfort evaluated and it is a function of either weighted r.m.s acceleration or VDV calculated from the seatpan.

The results as depicted in Figure 3 showed very significant relationship between both weighted r.m.s acceleration and VDV with the discomfort evaluation where R-Sq were as high as 95% and if β is the exponent for Steven's power law, the value is 1.25 with weighted RMS and 1.24 with VDV. The model can predict discomfort very well as shown in Figure 4.

The exponent value from the power law as suggested by Steven (1975) was 0.95 for vibration at 60Hz felt at fingertip. The exponent β determined from this study was found to be similar with Hacaambwa and Giacomin (2007) as shown in Table 3.

As cited by Hacaambwa and Giacomin (Hacaambwa and Giacomin, 2007), Teghtsoonian (1971) suggested that 87% from Power Law exponent variation was caused by the difference in the excitation input. As compared to the excitation input from Table 3, the vibration excitation input for this study was quite low which range between $0.5ms^{-2}$ to $0.9ms^{-2}$ measured vertically fromthe floor beneath the seat occupied by subjects.



(a) with RMS (b) with VDV

Figure 3. Relationship of whole-body vibration and discomfort through (a) RMS and (b) VDV.

Table 3. Exponent value from literature reviews as dicussed by Hacaambwa and Giacomin (Hacaambwa and Giacomin, 2007).

Research	Exponent β and vibration condition
Miwa(1968)	B = 0.46 for vibration below $1ms^{-2}$ r.m.s β = 0.60 for vibration above $1ms^{-2}$ r.m.s.
Shoenberger and Harris(1971)	β = 0.94 sinusoidal vertical vibration 0.8-5.6ms-2 r.m.s.
Jones and Saunders (1974)	β = 0.93 vertical vibration
Shoenberger(1975)	β = 1.43 vibration 0.71-$5.6ms^{-2}$
Hempstock and Sanders(1976)	β = 1.2-1.43
Fothergill and Griffin (1977)	β = 1.13 sinusoidal vibration 0.175-2.8 ms-2 r.m.s.
Hiramatsu and Griffin (1984)	β = 0.964 sinusoidal vibration 0.5-2.5ms-2 r.m.s.
Howarth and Griffin (1988)	β = 1.4 for x-axis β = 1.2 for z-axis
Ruffel and Griffin (1995)	β = 1.14
Ebe and Griffin(2000)	β = 0.929

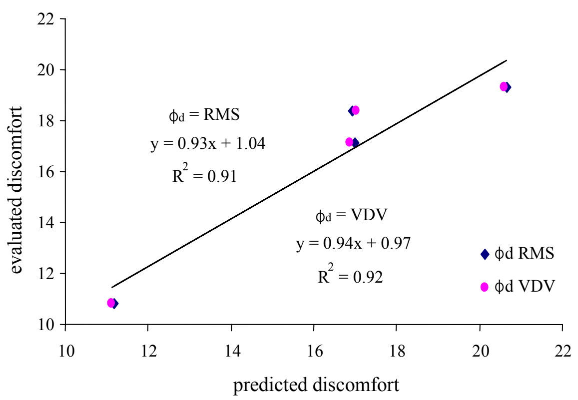


Figure 4. Validation analyses on discomfort model for dynamic condition.

3.3 Overall Discomfort

The third experiment was similar to the second experiment where measurement and evaluation were done in the same car at the same constant speed, at 80km/h. However, subjects we required to consider both pressure and vibration discomfort during the subjective evaluation. For overall discomfort, five data showed good correlation between the objective measurement and subjective evaluation. Table 4 showed the pressure data and vibration dose values from 5 subjects and the respective overall discomfort evaluations.

From data in Table 4, the constants *a*, *b* and *c* in Eq. (2) were obtained by using the exponent values in section 3.1 and section 3.2. In real driving condition, subjects could not differentiate clearly which modality that affects their discomfort the most. The interaction between modalities is usually being considered as well (Ebe and Griffin 2000b). Therefore, Eq. (2) becomes;

$$\Psi = a + b\varphi_s^{n_s} + c\,\varphi_v^{n_v} + d\varphi_s^{n_s}\varphi_v^{n_v} \tag{3}$$

where *d* is another constant for the interaction magnitude. From multiple regression analysis, $a = -23.5$, $b = 948$, $c = 4.86$ and $d = -81.7$ with R-sq = 99%. The relationship between the measured and evaluated discomfort with the predicted through the model is shown in Figure 5.

Table 4. Results from 5 subjects for overall measurement and evaluation.

Subject	Median: Weighted VDV($ms^{-1.75}$)	Median: Pressure data(mmHg)	Overall discomfort
1	1.82	89.96	18.41
3	1.31	74.85	9.20
6	1.87	69.19	8.99
9	2.12	90.58	19.32
10	1.43	89.71	18.20

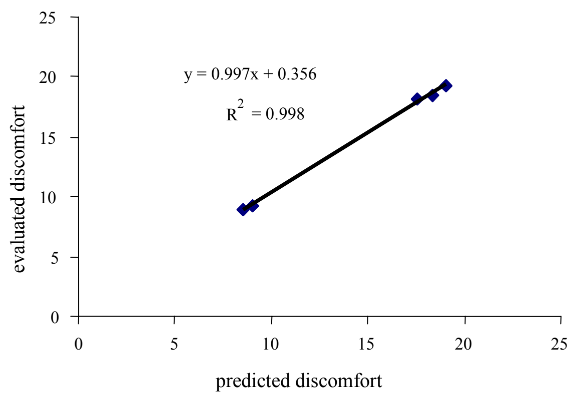


Figure 5. Relationship between the evaluated and the predicted discomfort values.

4. CONCLUSION

An integrated model that combines both static and dynamic modalities on seat discomfort has been established by applying Steven's psychophysics power law. Static condition being studied is the average pressure from the seat pressure distribution and the dynamic condition is the vibration dose value from whole body vibration experienced from the seat when the car is on the move. From exclusive analyses on each modality, the exponent values obtained were; $\alpha = 1.51$ *and* $\beta = 1.24$. It is also shown when both static and dynamic modalities were considered together, it gives better result with R-sq = 99% as compared to equation with single modality only (static or dynamic only R-Sq = 95%). As a conclusion, car seat discomfort studies should consider both static and dynamic modalities not just in measurement but also to include subjective evaluation.

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