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The use of seat effective amplitude transmissibility (SEAT) values to predict dynamic seat comfort

J.L. van Niekerk[a,*], W.J. Pielemeier[b], J.A. Greenberg[b]

[a] Department of Mechanical Engineering, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa
[b] Ford Research Laboratory, Ford Motor Company, SRL Bldg. Mail Drop 2115, P.O. Box 2053, Dearborn, MI 48121, USA

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Abstract

The Seat Effective Amplitude Transmissibility (SEAT) value is the ratio of the vibration experienced on top of the seat and the vibration that one would be exposed to when sitting directly on the vibrating floor. SEAT values have been widely used to determine the vibration isolation efficiency of a seat. In this article the subjective evaluations of six persons were compared to the SEAT values estimated from experimentally obtained transmissibility curves for 16 different automobile seats ranging from sedans to SUVs and pickups. A vertical rough road stimulus was used as input for both the subjective testing and the SEAT calculations. The SEAT values were estimated using the power spectral density of the vertical vibration input at the seat track and the measured transmissibility data to compute the response in the vertical direction at the seat top. The averaged, estimated SEAT values were compared to averaged measured values and significant correlation ($R^2 = 0.94$) was obtained. The subjective ratings were obtained on the Ford Vehicle Vibration Simulator using a paired comparison methodology that eliminated static comfort bias during the evaluation. The results indicated that there is good correlation ($R^2 = 0.94$) between the subjective ratings and the SEAT values when the subjective ratings and transmissibilities are averaged over the six subjects.

1. Introduction

Seating dynamics, and specifically the human perception of the dynamic comfort of a seat, is an area that is of increasing importance to automotive manufacturers catering for a market becoming more and more competitive and sophisticated. A major portion of the vibration

*Corresponding author. Tel.: +27-21-808-4251; fax: +27-21-808-4958.
E-mail address: wikus@sun.ac.za (J.L. van Niekerk).

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experienced by the occupants of an automobile enters the body through the seat. To date significant attention has been paid to the static comfort of seats while work on dynamic seat comfort is limited. However, the dynamic properties of suspension seats, for heavy vehicles and off-road equipment, have received particular attention [1].

When considering the vibration that a driver or passenger will experience in a vehicle it is important to consider the vehicle and human as a coupled dynamic system. In addition, there are usually a number of possible sources of vibration that can reduce the perceived comfort of the occupants. Two possible vibration sources are the road input at the tyre contact patches as well as the induced vibration from the power-train and ancillaries. The vibration from these sources is filtered by the structural dynamic transmission paths from the points of excitation to the seat tracks, which are usually attached to the floor-pan of the vehicle. The resultant vibration may be amplified in some frequency regions and attenuated in others, depending on structural resonance occurring in the transmission path. As a seat is constructed by combining a metal frame with springs and/or foam it will also result in additional modification of the vibration. In addition, since the human body can be modelled as a mechanical system consisting of masses connected by spring and dampers, the resultant transmissibility will also depend on the build, height and weight of the occupant as well as the dynamics of the seat [1]. Finally, it has been shown that human sensitivity to vibrations is a function of both frequency and direction. This should be taken into account when evaluating measured vibration levels to determine perceived human comfort.

To date various metrics and weighting functions have been proposed to establish a relationship between objective vibration measurements and subjective perceptions thereof. One of the earliest was by Pradko and Lee [2] who postulated that the power absorbed by the human is a good indication of both comfort and fatigue due to vibration exposure on a seat. In a later study by Varterasian and Thompson [3] the correlation between objective vibration measures and subjective human evaluation thereof was reported. In this study up to 16 subjects were asked to evaluate the comfort of six seats by directly comparing the ride on a pair of seats attached to a shaker and then choosing the most comfortable one. The objective measures consisted of the weighted root mean square (r.m.s.) acceleration measured at the seat top for a specific vibration input at the base of the seat according to ISO 2631 (1976) [4] and an empirically derived ride number, R:

$$R = K/ABf_n, \tag{1}$$

where K is an arbitrary "seat comfort" constant, A is the maximum amplitude of the seat transmissibility curve, B is the amplitude of the seat transmissibility curve at 10 Hz and f_n is the frequency, in Hz, where A occurs.

It was shown that in 60% of the cases the subjective choices of the occupants correlated with the ISO 2631 (1976) comfort criteria and if some seats, which had near identical dynamics, were removed the agreement increased to 65%. Using the ride number, R, the results improved to an agreement of 67% for all seats and 80% if only bucket seats were considered.

This was one of the earliest studies that validated the use of seat transmissibility data in assessing the dynamic comfort of a seat by making use of subjective evaluations. The ride number also included the three most notable attributes of a transmissibility curve, the amplitude at resonance, the resonance frequency and the amplitude at some higher frequency. In most applications there is a trade-off between higher damping, which reduces the amplitude at resonance but increase the transmissibility at higher frequencies, and lower damping, which has the opposite effect.

Other attempts at establishing metrics to evaluate dynamic comfort on seats include the work by Kozawa et al. [5], who proposed a ride meter that combined the weighted vibration intensity measured on the seat top (vertical), seatback (lateral) and the floor (vertical) to compute a vibration number (VN). The authors reported good correlation with subjective ratings when the system was installed on two vehicles with different suspension systems and driven over a "damaged pavement".

It is well known that parameters such as the level and the frequency content of the excitation, the posture of the human subject and the condition of the seat all influence the measured transmissibility. Attempts to deal with some of these have been addressed through at least three different approaches:

- using human subjects that are representative of the target population [1];
- using mechanical dummies to represent the human dynamics [6]; and
- using a mechanical indenter to measure the dynamic stiffness of a seat and then combining it with the measured, or predicted human impedance to estimate the transmissibility [7].

Some of the difficulties in measuring seat transmissibility, see Ref. [1], can be summarized as follows:

Non-linearity: Seats are non-linear due to the use of seat foam as well as the mechanical design of the structure and spring systems. In addition, the human body is inherently non-linear, and the combination of these two systems will result in a system that can only be approximated by a linear model around specific operating conditions.

Variation between human subjects: Clearly, build, weight and height will have a significant influence on the transmissibility of a seat–person combination due to the variation in weight distribution on the seat as well as the differences in the response of the human body.

Variation in testing procedure: The procedure whereby the transmissibility is obtained can induce additional variations in the measurements. Some of the known problem areas are posture, position of legs and feet, preconditioning of the seat, level and frequency content of excitation, etc.

Despite these reservations is it possible to obtain reliable, and repeatable estimates of seat transmissibilities as shown in Ref. [8] and in other published studies.

Currently, the most popular method used to evaluate dynamic seat comfort is the Seat Effective Amplitude Transmissibility (SEAT) value, which provides a numerical assessment of the seat isolation efficiency for a given vibration input at the base of the seat as described in Ref. [1]. This value can be calculated directly from measured data obtained by driving a vehicle on a test track or in a laboratory where a man-rated shaker is used to induce the base excitation. A man-rated shaker is one that can be used to expose human subjects to vibration in a safe and reliable manner [9,10]. In addition, SEAT values can be calculated from experimentally obtained seat transmissibility functions for a variety of vibration input spectra.

SEAT value is defined as

$$\mathrm{SEAT\%} = \frac{\text{vibration on the seat}}{\text{vibration on the floor}} \times 100, \tag{2}$$

where vibration on the seat and vibration on the floor can be represented by the r.m.s. or vibration dose value (VDV) of the measured signals.

Furthermore, where appropriate, the relevant frequency weighting filters should be applied to the signals before calculating either the VDV or the r.m.s. values to account for the human perception of vibration as prescribed in the relevant national and international standards. The most commonly used standards are ISO 2631, 1997 [11], and BS 6841, 1987 [12].

It is possible to measure or estimate SEAT values in a number of different ways. Firstly it is possible to use measured vibration data directly which is obtained when a person on a seat is exposed to a specific vibration input in a vehicle, by driving at constant speed over a repeatable road surface, or on a man-rated shaker, which can safely be used with human subjects, using synthetic or actual measured vibration input at the seat rails. Depending on the characteristics of the vibration it is possible to use either the weighted r.m.s. value of the signal, or, if there are significant transient amplitudes in the measured signals it is more accurate to use the VDV. If data with low crest factors (less than six) are being analysed it is sufficient to use the weighted r.m.s. values to calculate the SEAT values. The crest factor is the ratio of the peak to r.m.s. value for the data, and is a measure of how ‘‘peaky’’ or impulsive the data is. Finally, it is possible to compute SEAT values using r.m.s. either from direct measurements of the acceleration at the seat track and seat cushion, or to estimate the seat cushion vibration using transfer functions or transmissibility measurements for the seat/person combination. The last of these has several advantages, in that relating transmissibilities to subjective targets provides valuable information on how to engineer a seat to meet such targets. It is then also possible to compute the SEAT value for other types of excitation as long as the input at the seat track is defined, and seat transmissibility measurements are available that were obtained using similar levels of excitation.

There is however a number of limitations in using SEAT value as a reliable metric for human comfort. Firstly, there has not been a definitive study, which made use of high-quality psychophysical methods, which demonstrated the reliability of SEAT values to predict human comfort. Furthermore, a SEAT value corresponds to a particular vibration input at the base of the seat and therefore only reflects the comfort for that one particular input. To reliably calculate SEAT values it is important that the transmissibility used in the calculation be obtained from an estimate where the excitation was of a similar level to that of the input vibration. When the data contain signals with high crest factors, it is desirable to use VDV values that may not be accurately predicted by transmissibility models, which implies linear behaviour.

This article reports on a study by the vehicle vibration simulator (VVS) group in the Ford Research Laboratory where six subjects were exposed to vibration on 16 different seats to study the use of seat transmissibility data and SEAT values to predict the dynamic comfort of automotive seats. In Section 2, the experimental procedure to measure the seat transmissibility will be discussed and the method used to estimate the SEAT values for a particular road input will be presented in Section 3. In Section 4 the procedures used to obtain the subjective data are explained. Section 5 discusses the correlation between the subjective and objective data and Section 6 contains the conclusions and recommendations.

2. Experimental data

The Ford Motor Company’s VVS consists of a seat, floorpan and instrument panel modules and is described in detail by Meier et al. [13]. For this study only the seat module, which consists of a cube enclosing a six-degree-of-freedom hydraulic actuator, was used. The 16 seats used for this study were mounted rigidly to the cube with a footrest positioned to correspond with the floorpan of the associated vehicle and moved with the base of the seat. The backrests of all the seats were positioned at 24° of inclination while the subjects were allowed to adjust the seats fore and aft so that their legs and feet were comfortable. If the seat top or squab permitted adjustment of height or angle, the seat was set at the midpoint of the adjustment range. The resulting angle was generally within a few degrees of horizontal, and therefore produced very little error due to misalignment of the seat squab accelerometer pad with the excitation vectors at the seat track. There was a floorpan unit that was attached to the hydraulic shaker such that it moved with the seat track. The floorpan had a flat portion at the height of the floorpan of the car, and a rear portion at a 45° angle which was at the position of the pedals in the car, and was covered with a piece of thin carpeting. The participants were instructed to keep their hands in their laps, place their feet on the floorpan unit, lean against the backrest, and look straight ahead in an erect driving posture.

The choice of hands in the lap was made for a number of reasons. The main one was the practical matter that it was desirable to generate testing data by a method that could easily be replicated by others, including university laboratories and seat suppliers, and the inclusion of a steering wheel with appropriate mechanical properties would be impractical for this purpose. This was because to achieve the benefit of more closely duplicating the driving environment by holding the steering wheel with any effect that this might have on transmissibility, the steering wheel would need to move the way that it does in the car, particularly for larger amplitude, low-frequency motions. While the VVS steering wheel is capable of such behavior, most other laboratory shakers are not. In addition, for the transmissibility testing, the excitations were broadband white noise, rather than actual vehicle motions, and there is not a clear answer as to what steering wheel motions would be appropriate for such a case. It is certainly possible that a posture holding the steering wheel might affect the transmissibility, particularly in that it might alter the effective stiffness of the upper body in the longitudinal direction and thus the seat–body coupling to the seat back in that direction. However, given the lack of data available for seat back transmissibility under any circumstances, it was also felt that it was better to start with this simpler case that could be more easily replicated.

The control accelerometers of the VVS (PCB Model 393A03 seismic accelerometers) were used to measure the seat track acceleration, and a standard SAE seat accelerometer measurement pad (SAE Recommended Practice J1013, 1973) manufactured by Brüel & Kjær (Type 4322) was taped to the seat cushion with its centre 128 mm from the back of the intersection with the backrest to measure the seat top vibration. A similar device was taped on the backrest at a distance of 320 mm from the seat cushion. A sampling rate of 300 Hz was used with anti-aliasing filters set to 100 Hz.

The choice of locations for the seat pad accelerometers were made as follows. It was felt that it was desirable to standardize the locations and angles because the measured transmissibilities might be sensitive to these choices. A particular example of this relates to the height on the seat back of the longitudinal measurement, which might vary considerably with height since the seat back motion may be significantly due to a cantilever motion from the point at which the seat back angle adjustment pivots. A study was done with the six subjects employed in this study (described below), and five of the seats (spanning a variety of designs) to determine the single locations for each accelerometer pad which placed the pad nearest the maximum pressure region between the subject and the seat. Measurements were done at the seat back and top for all seats and subjects with a TekScan pressure distribution pad, which contained a matrix of thin pressure sensors on approximately 1 cm centers. In the case of the seat top, a location with the accelerometer pad center 128 mm from the intersection of the top and the back resulted in the maximum pressure regions in contact with the center of the seat pad for 29 out of 30 subject/seat combinations, and within 10 mm of the pad center for the remaining case. The seat back was more problematic, because many back cushion designs have a horizontal crease in them which results in a low-pressure region, and this location varies widely with seat design. The best compromise location was with the seat pad center at a height of 320 mm above the top/back intersection. This resulted in the pad center being within the region of maximum pressure for 25 out of 30 cases, and within about 20 mm of the center for the remaining five cases. Since the B&K SAE pad has a radius of over 100 mm, and is fairly stiff out to a radius of about 65 mm, these choices were felt to be reasonably representative of the vibration in the region of maximum pressure at a consistent location.

The accelerometer pads were at the angle of the associated seat surface in all cases. For the seat top, with the adjustment method described above, this was within about 7° of horizontal in all cases. Since the cosine of 7° is 0.992, this was taken to be representative of true horizontal and vertical, and the asymptotes of the resulting transmissibility magnitudes as the frequency approached zero was expected to be close to 1. For the seat back, the angle at the accelerometer location was adjusted to 24° from vertical in all cases. This angle is close to nominal "design intent" for many seats, which is why it was chosen. This results in the output of the transmissibility computations being either normal or tangential to the subject's back in the design intent position. However, it does have an effect on the transmissibility result. Since the cosine of 24° is 0.91, and the sine is 0.41, one expects the low-frequency magnitude asymptote of the vertical seat track input to vertical seat back output transmissibility to be about 0.9, and the same asymptote of the vertical seat track input to longitudinal seat track output transmissibility to be about 0.4. These are very close to the values observed in the plots in Figs. 3 and 4 for the corresponding data (Fig. 1).

Six subjects, three male and three female, participated in the study. They were selected to represent the average population in weight and height according to the criteria as shown in Table 1.

The base of the seat was excited in a purely vertical direction using Gaussian white noise over a bandwidth from 0.5 to 100 Hz with an overall r.m.s. acceleration level of 1.13 m/s^2 for a total duration of 60 s. The transmissibility was taken as the magnitude of the frequency response function estimated from the measured data using the H_1 estimator [14]. The averaged transmissibility for each seat was obtained by computing the average at each frequency line over the six subjects.

In all experiments a close watch was kept on the coherence to ensure that accurate transmissibility estimates were obtained. It was generally above 0.9 at all frequencies where excitation was provided, unless the transmissibility magnitude fell below 0.1, in which case low SNR at the output usually caused a drop in coherence. None of the seats had such a point within the 1–40 Hz range used here, however.

The averaged transmissibility data for all sixteen seats for the following three cases are presented in Figs. 2–4: vertical input at the seat base to vertical output at the seat cushion (Fig. 2);

Fig. 1. The VVS at the Ford Research Laboratory.

Table 1
Characteristics of human subjects

Gender and weight percentile	Weight w/o clothes (kg)	Height w/o shoes (m)	Subject number(s)
$1\times 5\%$ female	<53	1.47–1.56	4
$2\times 50\%$ females	59–66	1.57–1.67	2 and 3
$2\times 50\%$ males	70–90	1.68–1.78	5 and 6
$1\times 95\%$ male	>90	1.79–1.88	1

vertical input at the seat base to vertical output on the seat backrest (Fig. 3); vertical input at the seat base to longitudinal output at the backrest (Fig. 4).

The transmissibility asymptotes at 0 frequency in Figs. 3 and 4 are around 0.9 and 0.4 due to the 24° backrest angle, as predicted earlier.

3. Estimation of SEAT values from transmissibility data

As discussed in the introduction it is possible to measure or estimate SEAT values in a number of different ways. For the purpose of this work where data with low crest factors are being analysed it is sufficient to use the weighted r.m.s. values to calculate the SEAT values. This procedure can be completed in the frequency domain using the power spectral densities of the measured vibration and the relevant frequency weighting curves. The following equation describes this method [1]:

$$\mathrm{SEAT}\% = \left[\frac{\int G_{ss}(f)\,W_i^2(f)\,\mathrm{d}f}{\int G_{ff}(f)\,W_i^2(f)\,\mathrm{d}f}\right]^{1/2} \times 100, \tag{3}$$

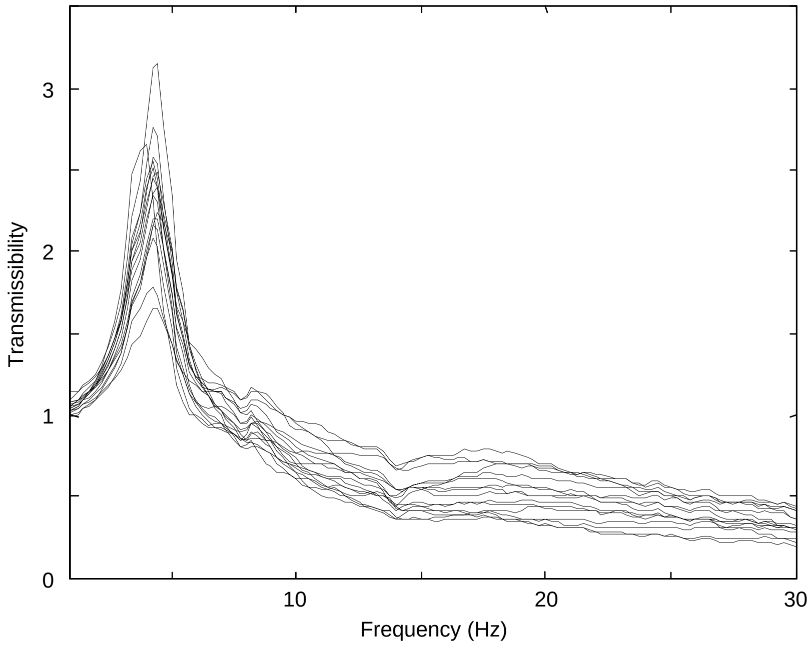

Fig. 2. Averaged transmissibility of all 16 seats for a vertical output at the seat top due to a vertical input at the seat base.

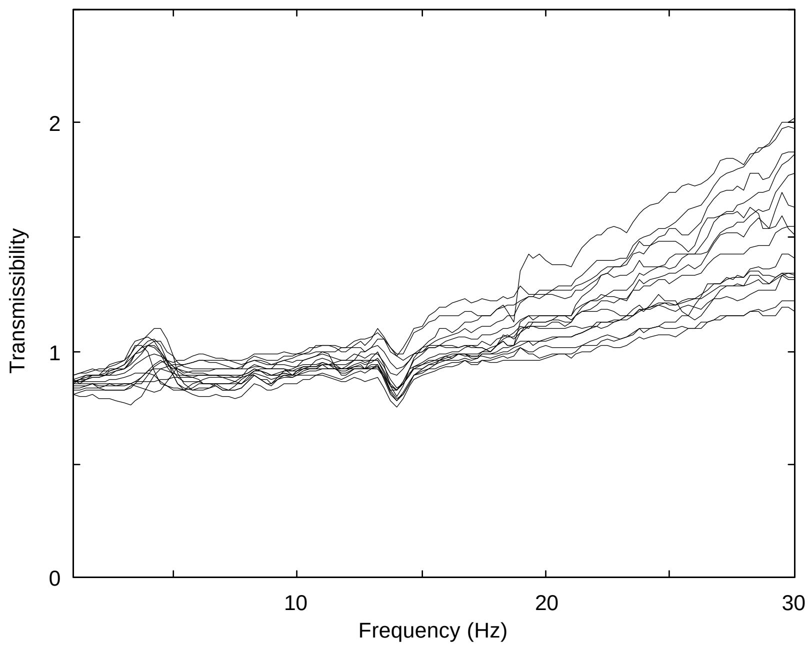

Fig. 3. Averaged transmissibility of all 16 seats for a vertical output at the seat back due to a vertical input at the seat base.

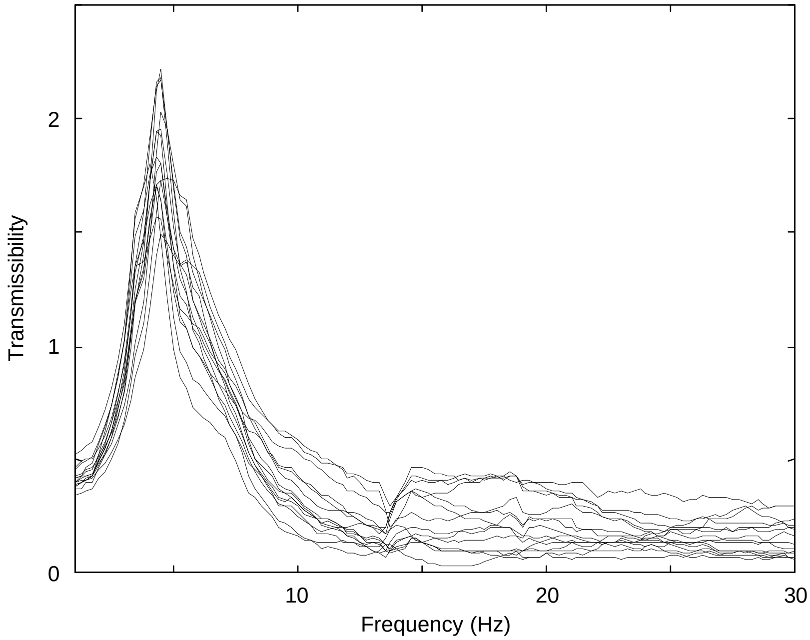

Fig. 4. Averaged transmissibility of all 16 seats for the longitudinal output at the seat back due to a vertical input at the seat base.

where $G_{ss}(f)$ is the seat vibration power spectral density, $G_{ff}(f)$ is the floor vibration power spectral density, and $W_i(f)$ is the relevant frequency weightings for the human response to the vibration in the position and direction of interest.

For this study the weighting curves as defined in the standard BS 6841 [12] were used.

If it is possible to reliably estimate the seat transmissibility, then the power spectral density on the seat can be calculated as

$$G_{ss}(f) = G_{ff}(f)|H_{fs}(f)|^2, \tag{4}$$

where $|H_{fs}(f)|$ is the seat transmissibility of the vibration from the floor to the seat. It is then possible to calculate the SEAT value as follows

$$\text{SEAT\%} = \left[\frac{\int G_{ff}(f)|H_{fs}(f)|^2 W_i^2(f)\,\mathrm{d}f}{\int G_{ff}(f)W_i^2(f)\,\mathrm{d}f}\right]^{1/2} \times 100. \tag{5}$$

In Eq. (5) it is clear that the effective "filter" that determines the overall value of the vibration experienced by the human subject is a combination of the seat transmissibility as well as the relevant frequency weighting representing the human sensitivity to vibration, i.e., $|H_{fs}(f)|W_i(f)$. The applied frequency weighting functions are listed in Table 2.

In this study, transmissibilities were measured for all possible combinations of three input axes (vertical, lateral, and longitudinal), and six output axes (vertical, lateral, and longitudinal seat top, and vertical, lateral, and longitudinal seat back), for a total of 18 combinations. However, since the seat back was angled at 24°, the vertical and longitudinal at the seat back were not truly

Table 2
Relevant frequency weighting for comfort according to BS 6841

Direction	Weighting
Seat top vertical (z)	W_b
Seat back vertical (z)	$0.4W_d$
Seat back longitudinal (x)	$0.8W_c$

vertical and longitudinal. This was touched on earlier in the experimental data section, and the predicted effect on the low-frequency asymptotes of some of the transmissibility functions shown in Figs. 3 and 4. Since the two cases in those figures potentially generated subjective effects for the vertical input stimulus used for the subjective data, these cases were included in the SEAT value computations. This raises the question of how to compute SEAT value when the input is vertical and the output is not parallel to it. A full description of the answer is given in the Appendix. The conclusion drawn in the appendix is that Eq. (5) should be modified to

$$\mathrm{SEAT\%} = \left[\frac{\int G_{ff}(f)|H_{fs}(f)|^2 W_i^2(f)\,\mathrm{d}f}{\int G_{ff}(f)\cos^2(\theta_{fs}) W_i^2(f)\,\mathrm{d}f}\right]^{1/2} \times 100, \tag{6}$$

where θ_{fs} is the angle between the floorpan input and seat output vectors, and W_i^2 is the same weighting function in both the numerator and denominator, corresponding to the direction of the output. When the input and output vectors are parallel, as in all prior SEAT value work, the cosine is 1, and Eq. (6) collapses back to Eq. (5). As described in the appendix, this equation gives a SEAT value of 100% for a rigid seat with an angled back, because the transmissibility in the numerator in that case is the same as the cosine in the denominator. This was the computation used for the transmissibility-based SEAT values in this paper.

In this study the input to the seat track was taken from measurements in a midsize family sedan travelling at 40 m.p.h. (64 km/h) over a rough road. The excitation from a pair of vertical accelerometers at the right and left front seat track bolts was averaged to produce a representative purely vertical stimulus. The power spectral density of this input, see Fig. 5, shows some major peaks around 14 and 20 Hz with most of the energy between 10 and 25 Hz. The time domain data was band limited between 2 and 40 Hz. The final excitation was 4 s long with an r.m.s. value of about 1.5 m/s^2 and a crest factor of 2.96. This vibration was replicated with r.m.s. and peak errors within 5% percent on the VVS.

To compare the existing subjective and objective data a variety of different approaches were investigated. Since the actual time data of the input, vertical seat track excitation, as well as the output, vertical vibration at the seat top, are available it was possible to calculate SEAT values (using r.m.s. or VDV) from these data points after applying the relevant filters in the time domain. In addition, since the estimated transmissibilities of all the different seats are available it was also possible to estimate the SEAT value (using r.m.s.) from the known input power spectral density. In addition, the SEAT value for the seat back longitudinal response could also be estimated from the measured transmissibility. (The time histories to compute these values directly are not available for the original 16 seats, for which subjective evaluations were obtained.) As the crest

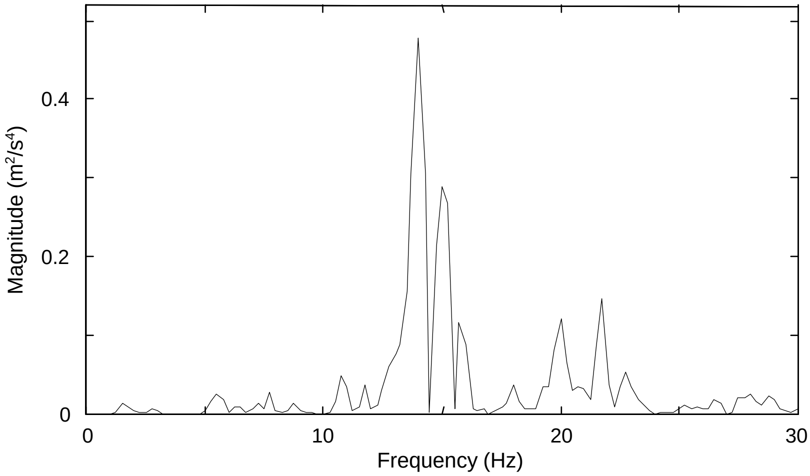

Fig. 5. Power spectral density of the vertical rough road input at the seat track.

factor for the data at hand is less than 6 in all cases only r.m.s. values were considered to calculate the SEAT values.

The more important question relates to averaging, and more specifically where and how this should take place. It was possible to compute averaged SEAT values for the 16 seats directly by making use of the filtered time domain data, and then averaging across all six subjects for each seat (direct method) or, by using the averaged transmissibility, over all six subjects, and the power spectral input density of the input as shown in Eq. 5 (indirect method).

In this study the two methods were compared with the existing data. The relevant results are shown in Table 3.

The first correlation concerned the measured and calculated SEAT values using the averaged transmissibility curves and from Fig. 6 it is clear that there was good correlation ($R^2 = 0.94$) between these values. This result gives one confidence to make use of appropriately estimated seat transmissibility data to calculate averaged SEAT values for the given input using the power spectral density of the input. This result is in line with a previous study [15], reporting similar success in estimating SEAT values using *averaged* transmissibility data.

If all 96 individually measured SEAT values were correlated with the estimated SEAT values using the individual transmissibility functions the correlation was slightly less ($R^2 = 0.83$) than if only the averaged values were compared.

4. Subjective data

The collection of unbiased subjective data comparing dynamic seat comfort for different seats is inherently difficult for two main reasons. First, to use realistic excitations for the seat, one must use either an actual vehicle or some type of mechanical simulator, each of which present problems. The actual vehicle has several disadvantages. One is the bias presented by the evaluator knowing what type of vehicle they are in, which is difficult to disguise. A greater factor is the inherent time

Table 3
Estimated averaged SEAT values and the subjective rating for 16 seats

Seat number	Type of vehicle	From time data (direct method)	From transmissibility data (indirect method)			Subjective rating
		Vertical seat top	Vertical seat top	Longitudinal seat back	Vertical seat back	
1	Sedan	55.3	49	50	9	16.5
2	Minivan	65.4	62	53	8	14.8
3	Pickup	49.7	46	38	9	17.2
4	Minivan	52.5	48	46	8	16.8
5	SUV	54.5	47	47	8	16.4
6	SUV	52.3	51	48	8	15.6
7	Sedan	72.3	69	70	9	13.7
8	SUV	55.8	52	40	9	15.3
9	Sedan	79.8	78	64	8	11.6
10	Sedan	57.1	52	41	8	15.1
11	Sedan	79.0	75	61	9	11.9
12	Sedan	65.3	60	45	8	14.2
13	Sedan	63.2	60	43	9	14.2
14	Sedan	65.7	59	58	9	14.7
15	Sedan	65.3	61	66	9	14.0
16	Sedan	68.8	61	58	8	14.1

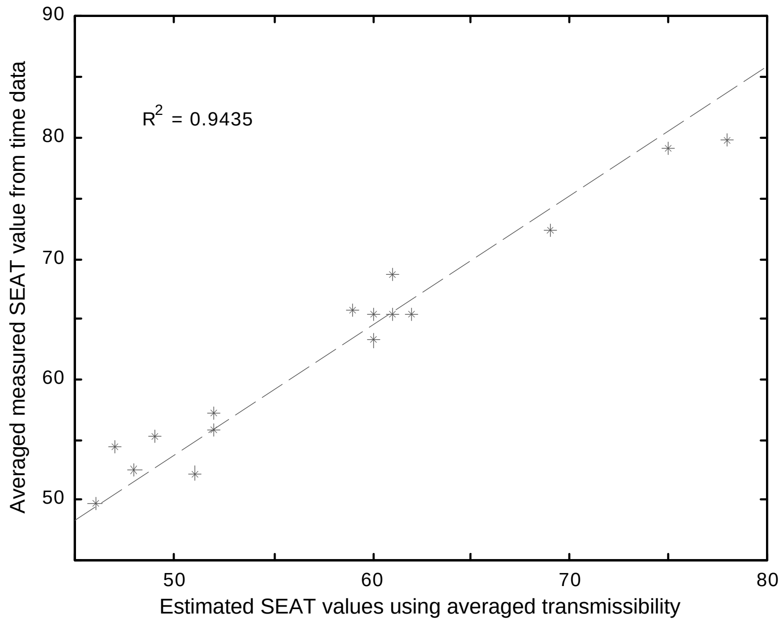

Fig. 6. Correlation between SEAT values from measured time data (direct method) and calculated using the averaged transmissibility for the 16 seats (indirect method).

lag between evaluating different vehicle/seats, which makes accurate comparisons difficult. Compounding this is the difficulty in ensuring that the test conditions such as vehicle speed, wind, portion of the test track, etc., are reproduced for each vehicle/seat. Furthermore, to really ensure that only seating dynamics are being compared, one must ensure that all of the seats are compared in essentially identical vehicles. This can present problems mounting the seats, and in ensuring that the vehicle delivers identical vibration in spite of mounting point and bracket modifications. On the other hand, man-rated simulation systems that can realistically reproduce road input are rare and expensive, and even if they are available, the time lag to change seats can make accurate comparison difficult.

The second inherent difficulty in comparing dynamic seat comfort from different seats is the bias in judgment introduced by the static comfort of each seat. Ebe and Griffin [16] have shown that varying static comfort affects the judgement of dynamic comfort. They have developed quantitative models for such effects [17]. However, these models only account for the stiffness of a block of foam, and cannot be applied directly to real seats which vary in contour, seat covers, and other seat components. The models also do not account for the effect of posture on static comfort. Therefore, if the static comfort of one seat is better than another, how does a subject factor that out in comparing the dynamic comfort of the seats?

The study done on the Ford VVS on these 16 seats was designed to control both of the above problems using a new method known as virtual seat simulation. The VVS is used to generate a reference vibration that is *the same at the seat cushion* for every seat and every subject. This is then used as a comparison or reference standard, and various alternative stimuli are played at the seat track (and therefore filtered by the seat properties) and evaluated against the reference in back-to-back comparisons. Seats are compared to each other through their relationship to the standard. This solves the time delay problem because the stimuli are played immediately back-to-back. It solves the static comfort bias problems because both stimuli in a comparison are experienced on the same seat, so the static comfort is identical. The reference standard is similar to the comparison alternatives played at the seat track, so that it is reasonable to compare them.

The stimulus used to obtain subjective data using the virtual seat simulation method was measured in a vehicle on a moderately rough road. The spectrum of this stimulus is given in Fig. 5. The scaled version of this used to produce the virtual reference stimulus had an r.m.s. magnitude at the seat track of about $1.6\,m/s^2$. Only the vertical component of the acceleration recorded on the test track was reproduced. This stimulus is the basis for both the virtual reference stimuli that are identical at the seat cushion, and the scaled level alternatives that are identical at the seat track. Playing an intermediate level version of the scaled alternatives on a randomly chosen seat with a randomly chosen subject, and then measuring the resulting vibration at the seat cushion generated the virtual reference stimulus. This was then reproduced at the cushion of each seat for each subject using the virtual seat method.

The virtual reference stimulus was then paired with a series of scaled copies of the rough road stimulus that were *the same at the seat track* for each seat. Subjects were asked to indicate whether the reference or the current scaled alternative was more comfortable for each pair. Better seats would improve the comfort of all of the scaled alternative stimuli, so that a more severe version (at the seat track) would match with the virtual reference (at the seat cushion). Poorer seats would reduce the comfort of all of the scaled alternative stimuli, so that a milder version (at the seat track) would match with the virtual reference (at the seat cushion). This paired comparison procedure typically involved 5–7 levels of scaled alternative stimuli, and presentation of about 80 or 90 pairs, and took about half an hour per seat and subject. The result of this hour of work (0.5 h for convergence of virtual reference, and 0.5 h for paired comparisons) per seat and subject is probably the most accurate, unbiased subjective data on comparative dynamic seat comfort ever collected.

The subjective rating scale used was a just noticeable difference (JND) scale, which refers to the size of the smallest change in whole body vertical vibration that a typical subject can detect [18,19]. One JND is about a 10% increase in the level of vibration. Alternative seat track stimuli were scaled to be 3 JNDs apart in magnitude, requiring 33% increases between them ($1.1^3 = 1.33$).

The two-interval forced-choice decision process was analysed using standard techniques as follows. The selection operation by the subject is modelled as a noisy process where the subject has a certain probability of choosing the reference against each alternative, depending on how far apart they are in comfort. The sequence of trials in which the subject is forced to choose the reference or the alternative on each trial with these underlying probabilities is called a set of Bernoulli trials. A set of trials at one alternative level gives an estimate of the underlying probabilities. The probability of choosing the reference x times out of n trials is given by a binomial distribution [20]. The accuracy of the estimate depends upon the number of trials and the underlying probability. The binomial distribution allows confidence intervals to be estimated given that information. The plot of the resulting probabilities and confidence intervals as a function of the JND level of the alternatives is called a psychometric function. The point on the psychometric function at which the probability of choosing the virtual reference versus the alternative is 50:50 is the point at which they match in the subject's perception, and that JND level is assigned to the seat as the subjective rating. This means that higher JND levels are better, because they indicate that the seat attenuated the vibration of a higher-level input alternative at the seat track enough to match with the reference.

The result of averaging the resulting subjective ratings over the six subjects, shown as a function of seat, is plotted in Fig. 7, along with the associated confidence intervals. The average confidence intervals were obtained by appropriately combining those from the individual subjects' psychometric functions used to obtain the subjective ratings. These results have been sorted from best to worst rating. It is clear from the size of the confidence intervals that significant

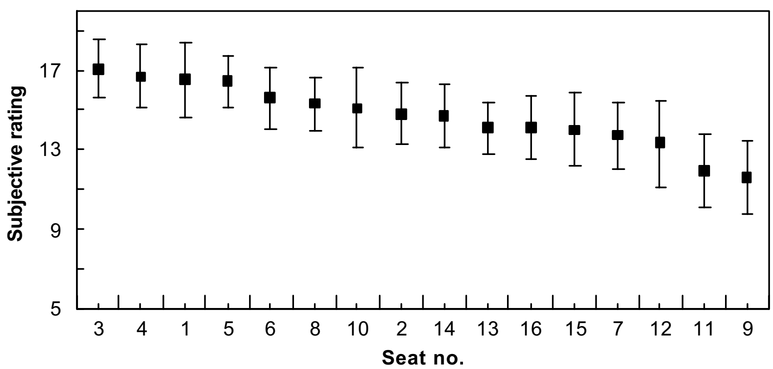

Fig. 7. Mean and 95% confidence levels for subjective ratings.

differences between the seats are present. Based on an ANOVA of the data, the seats can be separated into at least three significantly distinct groups for classification. This is the data used for the averaged subjective ratings in subsequent sections. The mean values of the subjective ratings are listed in Table 3.

5. Correlation of objective and subjective data

Trying to correlate *individual* subjective ratings and measured SEAT values in the vertical direction at the seat top results in good to poor correlation. The results where each subject's subjective rating is correlated against the measured individual SEAT values in the vertical direction at the seat top are shown in Fig. 8.

It is interesting to note in Fig. 8 that subjects 1 and 2 seem to be less sensitive to different levels of vibration, or find it more difficult to discriminate between different vibration levels, since the slopes of the curve-fit (−0.10 and −0.070) is smaller than for subjects 4 and 6 with slopes of −0.15 and −0.30, respectively. This reduction in sensitivity also leads to lower correlation between their subjective ratings and the measured SEAT values. Subject 6, with the highest correlation ($R^2 = 0.77$), also has the steepest slope and hence this subject seems to be much more sensitive to vibration. The complete correlation data is presented in Table 4.

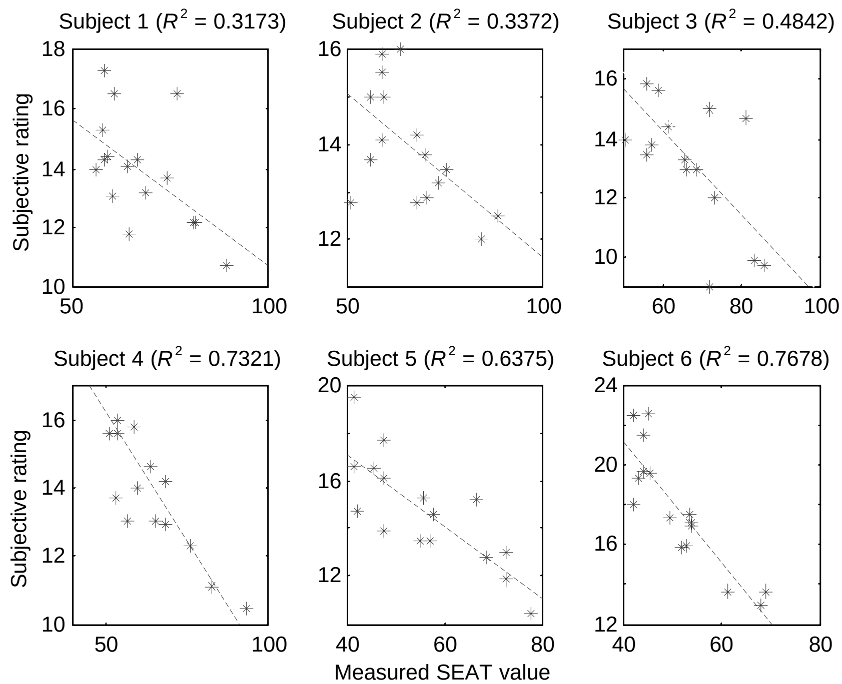

Fig. 8. Correlation between individual measured SEAT values (vertical track input to vertical output at the seat top) and the individual subjective ratings.

Table 4
Correlation between individual subjective ratings and measured SEAT values

Subject no.	R^2	Slope
1	0.32	−0.10
2	0.34	−0.07
3	0.48	−0.14
4	0.73	−0.15
5	0.64	−0.15
6	0.77	−0.30

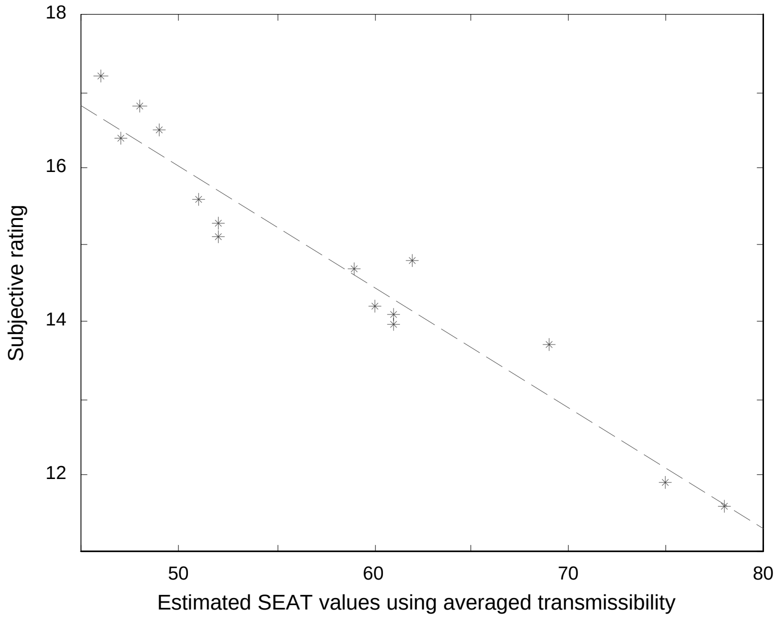

Fig. 9. Correlation between estimated SEAT values (vertical track input to vertical output at the seat top) and the subjective ratings ($R^2 = 0.9364$).

The next step was to investigate the correlation between the averaged, estimated SEAT values and the averaged, subjective ratings obtained in the subjective evaluation study. The estimated SEAT values were used as there was not a significant difference between the measured and the estimated SEAT values as shown in Fig. 6. In Fig. 9 the SEAT values for vertical vibration at the seat top are compared to the subjective ratings and again good correlation, $R^2 = 0.94$ for the estimated SEAT values in only the vertical direction at the seat top were obtained. These results are encouraging as it is the first time that such high correlation between subjective ratings and SEAT values, in a well-constructed experiment making use of high-quality psychophysical methodologies was obtained.

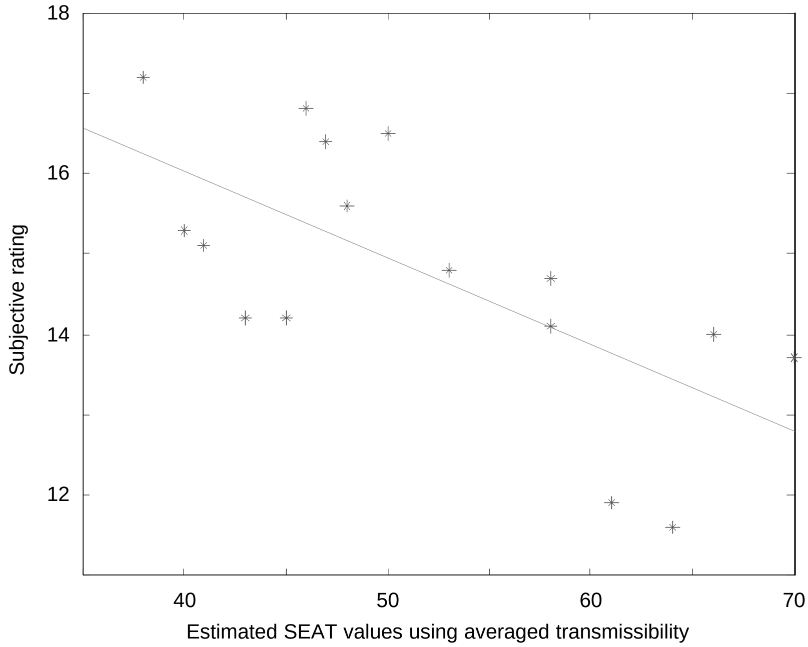

Fig. 10. Correlation between calculated SEAT value (vertical track input to longitudinal output at the seat back) and subjective rating ($R^2 = 0.456$).

However, correlation between the SEAT values calculated at the seatback in the longitudinal direction and the overall averaged subjective ratings does not seem to correlate well ($R^2 = 0.46$) as shown in Fig. 10. The general trend that smaller SEAT values in this direction do correspond with an *increase* in dynamic comfort is however noticeable in Fig. 10.

A more acceptable way to combine multi-axis vibration is to compute the geometric mean, as in Ref. [1]. If this approach is extended to combining SEAT values from a single input at the seat track, as is the case, then

$$Comb_1 = \sqrt{Top\,Z^2 + Back\,X^2 + Back\,Z^2}. \tag{7}$$

This results in a correlation of $R^2 = 0.78$ which is in fact worse than that obtained by only considering the contribution from the vertical direction at the seat top. One reason for this may be that the SEAT values in the vertical direction at the back are very small (8–9 compared to a range of 47–78 for the SEAT values at the seat top) and there is also no correlation between these vertical seatback values and the subjective ratings. Therefore, it may be more prudent to use only the vertical seat top and longitudinal seat back values as shown in

$$Comb_2 = \sqrt{Top\,Z^2 + Back\,X^2}. \tag{8}$$

This results in $R^2 = 0.78$ which again can be related to the fact that there seems not to be a good correlation between the subjective rating and the longitudinal response at the back. However, it seems that the contribution from seat back in the vertical did indeed have a small effect in improving the correlation. This may also have something to do with the way in which the subjects

Table 5
Correlation of SEAT value combination

Combination	Description	R^2
Seat top vertical	*Top Z* only	0.94
Seat back longitudinal	*Back X* only	0.46
$Comb_1$	Geometric mean of *Top Z*, *Back X* and *Back Z*	0.78
$Comb_2$	Geometric mean of *Top Z* and *Back X*	0.78

decided to evaluate the vibration by concentrating their attention on the vertical component at the seat top, as it was the most prominent.

The results of the correlation for these four different combinations are listed in Table 5.

From the table it seems that the best one can do is to only consider the vertical seat top response when attempting to correlate objective measurements to subjective ratings.

6. Discussion and conclusions

These results indicate that good correlation exists between averaged SEAT values and dynamic comfort for vertical rough road stimuli. This means that it may be useful and possible to set targets for seat design using SEAT values. However, it is important to realize what the limitations of this research are. Achievement of a correlation coefficient of $R^2 = 0.94$ was only possible by paying attention to a number of key details, and the result is still only known to apply to rough road stimuli, which in practice means stimuli whose energy is concentrated around the wheel hop frequency of the vehicle, or about 12–16 Hz. The key details include careful measurement of the transmissibility on a shaker system that is rated for human subjects, the use of a broadband stimulus for this measurement which is similar in amplitude to the road excitation targeted, the use of a large enough and diverse enough jury of human subjects to make the transmissibility measurements, and the availability of a vibration measurement at the seat track which is representative of the vehicle that the seat is designed for. Good results can be avoided by ignoring any one of these details.

The best seat, according to the averaged subjective ratings is seat 3 with an overall rating of 17.2. The worst seat is seat 9 with an overall subjective rating of 11.6. The averaged transmissibility of these two seats, as well as an average seat, seat 12 with an overall subjective rating of 14.2, are shown in Fig. 11. When one considers the power spectral density of the input (Fig. 5) it is clear that most of the energy in the input is concentrated in the frequency range from 10 to 25 Hz with dominant peaks at 14, 15, 20 and 21.8 Hz. It is therefore obvious that a seat with low transmissibility in this frequency range will transmit the least vibration and will therefore be judged to be the best. This is then also the case with the subjective evaluations.

The need for an adequate jury of subjects is emphasized because in practice it has been observed that this requirement is often ignored as unimportant. Note that the subjective/objective correlation gave R^2 values ranging from 0.32 to 0.77 for individual subjects. One might argue that this is because of noisy subjective data, but further note that the correlation of measured to the estimated SEAT values only achieved a correlation of 0.83 if averaging over subjects was not

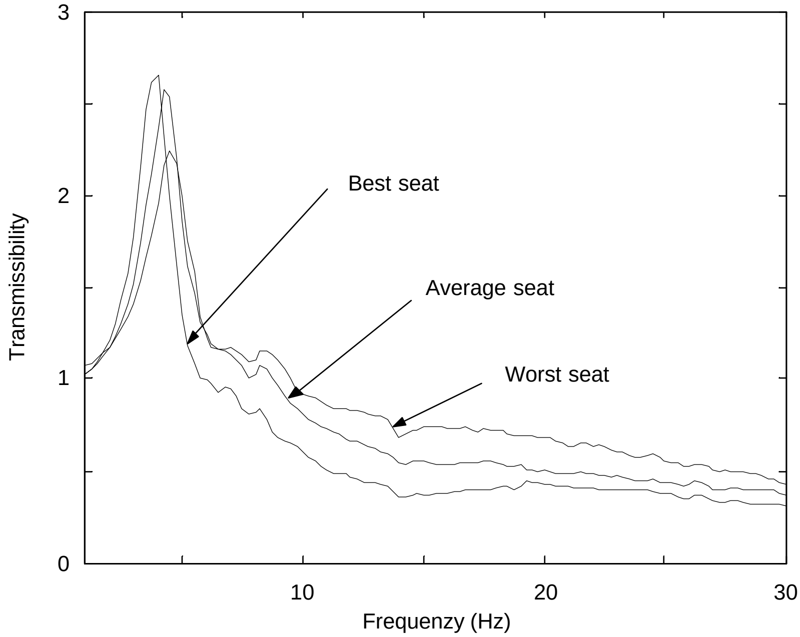

Fig. 11. Comparison of best (#3, SR = 17.2), average (#12, SR = 14.2) and worst seats' (#9, SR = 11.6) transmissibility curves.

employed, and that correlation involves only objective data. The most striking result of this work is the enormous improvement in both the SEAT estimation correlation and the subjective/objective correlation when averaged over six carefully chosen subjects. It appears that the individual variations in the subjective preferences average out to leave a common preference element on the subjective side of the correlation, and that elements of the measurements on the objective side also average out, probably involving factors such as subject to subject variation, individual subject variability over time, and subject non-linearity which is not captured by a linear transmissibility model. Given the extremely poor nature of the individual subjective/objective correlations, it is remarkable that as few as six subjects are sufficient to effect such a large improvement.

The final item is the need to extend this validation work to include additional road inputs, and to establish which of the various possible human weighting functions is most effective. The latter will require stimuli with significant excitation both within and outside the 16–20 Hz bands where the W_b (from BS 6841) and W_k (from ISO 2631) weightings differ. It also needs to be shown that SEAT value works for inputs, which are more broadband, where the shape of the weighting curve must really mediate between the contributions at different frequencies. The rough road stimulus used in this study has most of its energy at a single frequency, and thus does little to test this balance.

Appendix A. How to handle cross-axis transmissibilties in computing SEAT values

When trying to decide how to compute SEAT values for combinations of input and output which are not in the same direction, two interpretations have arisen in past discussions. One is that there actually is a cross-transmissibility present in the seat which causes vibrations in one direction to be converted to vibrations in another direction. A second is that the vibrations in the output direction are simply the component of the input vibration that is in the output direction, modified by system mechanical properties along that component direction. A closer examination of the definition of SEAT value and of the data seems to support the second interpretation rather than the first.

Looking at the data, if the output vibration is simply based on the component of the input vibration that is in the direction of the output, then one should see the following. In all input/output cases that are truly perpendicular, there should be no appreciable output at all. The only cases where there should be appreciable output are where the output is not truly perpendicular to the input, and then the output should show evidence of scaling in amplitude by the cosine of the angle between the input and output. Both these things prove to be true upon examination of the data. When the current study was done, all possible combinations of input output transmissibilities were computed. There were three input axes, and six output axes (three at each seat pad), for a total of 18 possible combinations. Of these, all were negligible except for eight. Four of these were truly parallel in, parallel out cases: i.e., vertical track in, vertical top out; longitudinal track in, longitudinal top out; lateral track in, lateral top out; and lateral track in, lateral back out. Because the seat back was angled 24°, there were four cases where the input–output combination was neither parallel nor perpendicular: vertical track in, vertical back out; vertical track in, longitudinal back out; longitudinal track in, longitudinal back out; and longitudinal track in, vertical back out. The other 10 cases are perpendicular and showed negligible coupling. The four angled cases showed gains at low frequency (below any of the resonances of the seat system) that reflected the cosine of the angle between the input and output. Thus the two cases where the angle was 24°: vertical track in, vertical back out, and longitudinal track in, longitudinal back out; have low-frequency gains around 0.9, which approximates the cosine of 24°. The two cases where the angle was $90 - 24 = 66°$: vertical track in, longitudinal back out, and longitudinal track in, vertical back out; have low-frequency gains around 0.4, which approximates the cosine of 66°. The two cases with vertical input were illustrated in the body of the paper in Figs. 3 and 4, and the low-frequency transmissibility matches the 0.4 and 0.9 gains quite well.

If one turns to the definition of SEAT value, one sees in the Handbook of Human Vibration [1, p. 405] the statement: "Therefore, a SEAT value of 100% means that sitting on the floor (or on a rigid seat) would produce similar vibration discomfort, "and in the glossary on p. 846, it states, "In general, the SEAT value is the ratio of the frequency-weighted and time-averaged vibration measured on the seat to the vibration in the same axes on the floor conditioned by the same frequency weightings and time averaging." To interpret the role of SEAT value for the case where the seat back is at an angle, one clearly cannot use the floor analogy in the first statement, but rather must employ the "(or on a rigid seat)" alternative that appears there. If one combines that with the identical axis, identical weighting part of the glossary definition, one finds that one must treat the angled back as follows: the input vibration in the denominator must be scaled by the cosine of the angle between the input and output measurement, and then weighted using the human weighting curve appropriate to the output direction, and the output vibration weighted by the same human weighting curve. When factoring in the transmissibility to compute the numerator, the input and the transmissibility replace the output vibration, just as in parallel input–output cases. Thus the SEAT value computation for this case must be

$$\mathrm{SEAT\%} = \left[\frac{\int G_{ff}(f)|H_{fs}(f)|^2 W_i^2(f)\,\mathrm{d}f}{\int G_{ff}(f)\cos^2(\theta_{fs}) W_i^2(f)\,\mathrm{d}f} \right]^{1/2} \times 100, \tag{A.1}$$

where θ_{fs} is the angle between the floorpan input and seat output vectors, and W_i^2 is the same weighting function in both the numerator and denominator, corresponding to the direction of the output. This satisfies the parallel input and output requirement of the glossary definition (by modifying the input vector with the cosine), and the identical weighting function on input and output requirement of the glossary definition. It also satisfies the formulation that one would arrive at in order to achieve the reasonable 100% SEAT value for a rigid seat. This is because the transmissibility in the numerator for the rigid seat would be the same cosine function that appears in the denominator, and with identical weightings in both, the ratio would be 1, and the SEAT value 100%. This also collapses to the existing formulation of SEAT value for the parallel input/output case because the angle is zero and the cosine is 1 in that case.

On the other hand, there is little evidence for the first interpretation of cross-axis SEAT value, namely, that the system converts vibrations along one axis to vibrations along another. In that case, there would be no particular reason to expect the cosine of the input–output angle to scale the transmissibility at low frequency. It would also be appropriate to use, for example, the vertical human weighting function for the input vibration and the longitudinal human weighting function for the output, which would contradict the HHV glossary definition of SEAT value. If the SEAT value were defined that way, with different human weightings on the input and output, the SEAT value would not be 100% for a rigid seat either. Thus the case appears to be fairly strong for the formulation of Eq. (A.1).

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