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PASSENGER RESPONSE TO RANDOM VIBRATION IN TRANSPORTATION VEHICLES

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PASSENGER RESPONSE TO RANDOM VIBRATION IN TRANSPORTATION VEHICLES

- LITERATURE REVIEW -

A. J. Healey

June, 1975

RESEARCH REPORT

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16. Abstract

Current interest in dynamics and vibration of ground transportation vehicles arises from the fact that excessive levels can lead to unsafe operation and give uncomfortable rides for passengers. The design of vehicle suspension systems and specification of roadway or guideway roughness levels hinge on the availability of ride quality criteria. Overdesign can lead to excessive cost. This report deals with a survey of available literature dealing with the effects of random vibration. The typical vehicle environment has broad-band characteristics. Narrow-band assumptions reducing to the use of well-known sinusoidal comfort criteria have been used in the past but recent research is being aimed at the assessment of the broad-band cases.

Some conclusions can be drawn. Firstly, passengers can distinguish between different levels of random vibration but coloration differences are hard to distinguish. Secondly, it appears, generally, that experimental research has involved relatively few subjects and the confidence level in criteria so far established is not high. Subsequent research is needed to verify the applicability of available criteria.

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EXECUTIVE SUMMARY

INTRODUCTION

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CONCLUSIONS

Some conclusions can be drawn. Firstly, passengers can distinguish between different levels of random vibration but coloration differences are hard to distinguish. Secondly, it appears, generally, that experimental research has involved relatively few subjects and the confidence level in criteria so far established is not high. Subsequent research is needed to verify the applicability of available criteria.

ABSTRACT

Current interest in dynamics and vibration of ground transportation vehicles arises from the fact that excessive levels can lead to unsafe operation and give uncomfortable rides for passengers. The design of vehicle suspension systems and specification of roadway or guideway roughness levels hinge on the availability of ride quality criteria. Overdesign can lead to excessive cost. This report deals with a survey of available literature dealing with ride quality criteria. Here, however, special emphasis is placed on that literature dealing with the effects of random vibration. The typical vehicle environment has broad-band characteristics. Narrow-band assumptions reducing to the use of well-known sinusoidal comfort criteria have been used in the past but recent research is being aimed at the assessment of the broad band cases.

Some conclusions can be drawn. Firstly, passengers can distinguish between different levels of random vibration but coloration differences are hard to distinguish. Secondly, it appears, generally, that experimental research has involved relatively few subjects and the confidence level in criteria so far established is not high. Subsequent research is needed to verify the applicability of available criteria.

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INTRODUCTION

This literature review began as part of a serious attempt at The University of Texas at Austin to categorize available criteria for transportation vehicle ride quality assessment. Ground Transportation Modes, and passenger (rather than freight) ride quality, were the target of the study. The overall study involves experimental verification of available criteria and the literature review formed the initial part of the work. As with all research studies, literature searches are continued throughout the work and this report is not necessarily complete.

It should be stressed from the beginning that the overall evaluation of riding quality is difficult because of the vague implication of the term "ride quality". Passenger perception of ride quality is highly variable. Sometimes, while a passenger may determine that the ride is disturbing, he may not be able to determine what aspects of the ride disturb him. Pressure, humidity, temperature, seat spacing, seat comfort, and noise all combine in the overall assessment of ride quality.

Probably the attribute of ride quality the most difficult to quantitatively assess lies in the vibrational characteristic. This is largely a result of relative insensitivity of human passengers to small changes in vibration intensity for the range of interest (i.e. 0.01 → 0.1g). While this may be construed erroneously to mean that passengers do not care about ride quality, it should be remembered that relaxing vehicle design specifications can have a large effect on the installation cost of fixed guideway systems. Thus design philosophy should be to make a transportation system as cheap as possible consistent with acceptable ride quality. In this context, the boundary of acceptable ride quality must be found. Further, it must be determined in such a way as to apply to the real vehicle environment.

In the area of interest, viz Human Response to Whole Body Vibration, many early studies have dealt with specific effects of impressed sinusoidal vibration. A summary of harmonic motion research is well documented by Hanes [1] and the combined results contribute to the recent International Standard "A Guide to the Evaluation of Human Exposure to Whole-Body Vibration" [2].

The experimental procedures usually involve the seating of human raters on a shake table. For simple harmonic motion inputs raters assess different amplitude levels as to the comfort level, often described in vague terms, such as, perceptible, slightly annoying, uncomfortable, etc. For each frequency a contour of constant comfort is then plotted in terms of amplitude versus frequency. Such a set of contours for constant comfort and different exposure times appears in Fig. 1, taken from [2].

The problem of applying such criteria as those in Fig. 1 is in the assessment of broad-band random excitation typically found in ground transportation. Equivalence cannot be based on r.m.s. levels because bandwidth over which to filter the random acceleration data is unknown and has a very strong influence over the results. Nevertheless, several experimenters have attempted the comparison of random and simple harmonic motion input effects on human comfort.

An alternative experimental approach is to assess passenger response

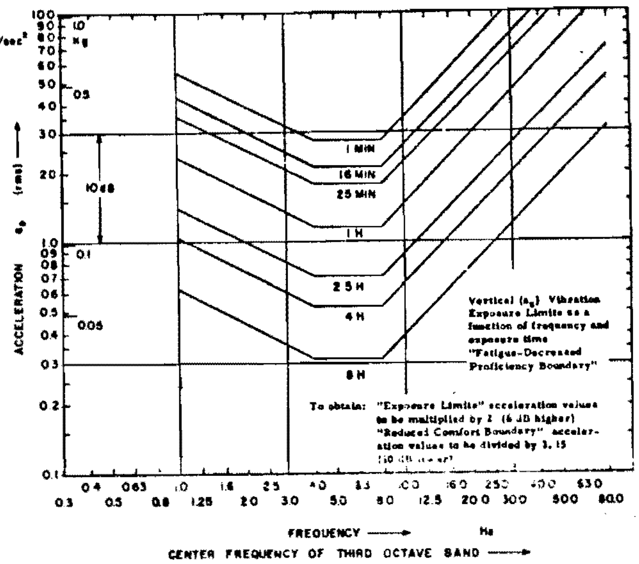


Fig. 1. Acceptable levels of vertical vibration amplitude versus frequency, from [2]

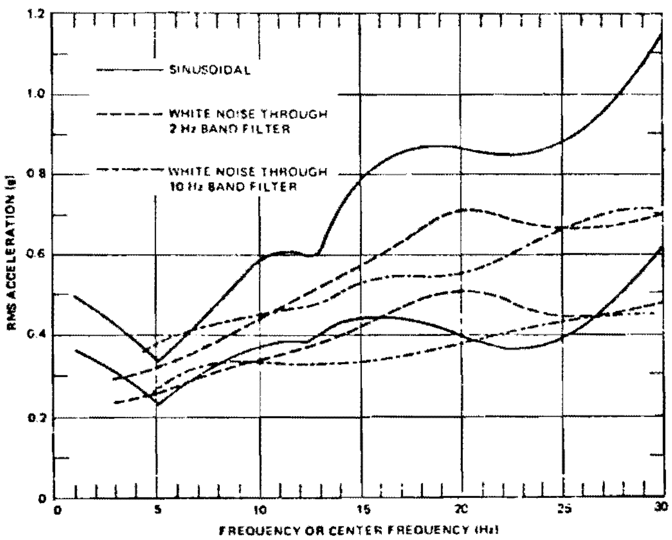
to rides as measured in field tests. Automobiles, buses, trains, helicopters, and aircraft have been employed. The method of approach has been to obtain ratings of several rides on a linear scale. Average ride ratings are then compared to some measure (usually a scalar measure) such as r.m.s. acceleration or rate of peak exceedances. Correlation of objective and subjective measures has in general been poor in view of the small number of raters typically used. There is ample evidence to suggest, however, that passengers do respond to different levels of vibration but, up to the beginning of this work, poor data correlation has led to the development of criteria of uncertain validity.

This summary is divided into two parts, dealing with laboratory test results and field test results respectively. Throughout, emphasis is placed on effects of random vibration, and only that literature dealing with experimental research to examine human response to random vibrations is considered.

LITERATURE SUMMARY OF LABORATORY EXPERIMENTS

Laboratory experiments deal with human subjects who are exposed on shake tables to various degrees of acceleration. The equipment is sophisticated and even simulates (c.f., the Passenger Ride Quality Apparatus (PRQA) in [3]) part of a vehicle passenger compartment.

Pradko and Lee [4] compared sinusoidal excitation results with random excitation filtered to bandwidths of 2 Hz and 10 Hz separately where the filter center frequency could be adjusted to fall in the same range as that of the sinusoidal vibration (0-30 Hz). The three curves illustrate (Fig. 2) that in the low frequency range there is little to distinguish them. At higher frequencies, between 10 and 30 Hz, it appears that the corresponding levels of comfort are attained for lower r.m.s. values of the filtered random vibration compared to the pure sinusoidal vibration. This indicates that



Note: Upper and lower curves for each condition bracket the true values of the mean with 90% confidence.

Subjects judged tolerance as a condition in which pain, loss of physical stability or advanced stages of blurred vision were considered unacceptable.

At least some different subjects used for the different conditions.

Fig. 2 Comparison of the Effects of Sinusoidal and Random Vibration on Human Tolerance passengers are less tolerant of equivalent random vibrations. Further it seems that increasing the filter bandwidth from 2 to 10 Hz results in equivalent comfort at a lower r.m.s. value. In a British study [5] the opposite result was found and it was concluded that passengers were generally more tolerant of random vibrations of equivalent r.m.s. acceleration levels. Fig. 3 shows Woods' [5] comparison for the comfort level defined as "some unpleasant effects - cannot be ignored". The random vibration was obtained using a white noise generator, a coloration filter to give the effect of wind gust loading on an aircraft and a second order low pass filter where the bandwidth was made equivalent to the sinusoidal frequency in the comparison. Little additional literature has been found to resolve this controversy.

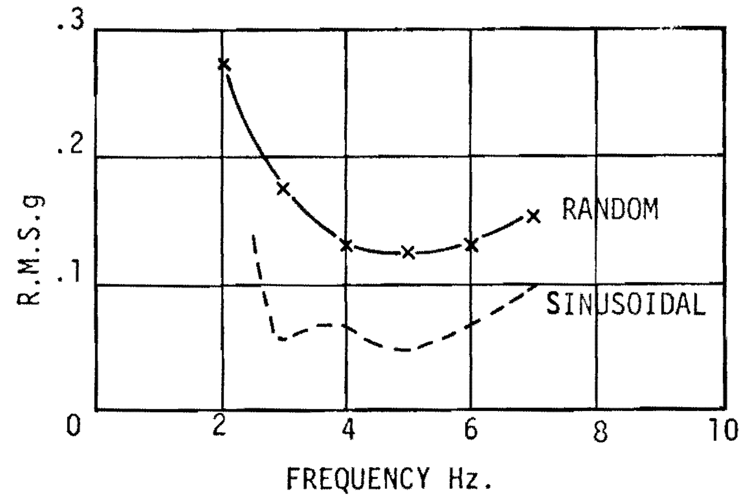


Fig. 3 Comparison of the levels of random and sinusoidal vibration for "Some unpleasant effects - cannot be ignored," from Woods [5]

Hornick and Lefritz [6] studied the effects of long-time exposure to random vibration primarily from a pilot vigilance and tracking performance point of view. The experimental input was random, with a shaped power spectrum having energy at the 1 Hz, 7 Hz and 10 Hz frequencies and finally band passed in the 1-12 Hz range for obtaining r.m.s. levels of 0.1, 0.15 and 0.2 g's. The general conclusions were that no serious long term effects need be anticipated. The need for realistic ride criteria was mentioned but not completely addressed in the work.

Holland [7] also studied long term random vibration effects. He shows that response time is degraded after 6 hours exposure. The vibration input had a power spectral density composition peaked at 2 and 5 Hz where the power density at 5 Hz was one-tenth of the power density at 2 Hz. The power reduced rapidly on both sides of the peaks. Unfortunately, no attempt was made to rate comfort levels. Acceleration r.m.s. levels up to 0.16 g were used and it was concluded that tracking errors significantly increased with g level.

Holloway and Brumaghin [8] performed many detailed experiments in a simulator. Twelve test subjects were used, each seated in a typical airline seat, and during the tests vibrations levels were increased until each subject rated the level as "annoying" and then "objectionable". The tests involved combined frequency and combined axis (vertical and lateral) excitation. Frequencies of 1.5, 4 and 7 Hz were combined using narrow-band filtered white noise inputs so that percentage contributions for each frequency in the total power could be varied. Tables I and II give the results of "objectionable" levels in r.m.s.g., from which it is difficult to extract any significant trend. Comparing conditions 2, 7 and 10, the influence of the 4 Hz component is seen to be extremely small. Apparently we are to believe that total power rather than spectral composition is the determining factor in an "objectionable" ride. Comparison of Table 1 with Table 2 illustrates the common assertion that vibration in the lateral direction is generally less tolerable than that in the vertical direction. Again, however, spectral composition does not appear to be very significant.

More important is the effect of combined axis excitation. Figs. 4 and 5 show how the presence of lateral accelerations of equivalent spectral composition degrade the objectionable level of vertical vibration. In Fig. 5, the combined axis objectionable threshold is suggested as a design criterion [8]. The authors comment on the use of a small sample of subject in the experiment. Only 12 were used. These all had flight experience and ranged from 24 to 35 years of age.

A more recent report from Lee and Pradko [9] discussed the concept of using a scale measure, "absorbed power," of the intensity of ride vibrations. The "absorbed power" is computed using the average of the mechanical power input to a passenger at each point of contact with the vehicle. This average power can be related through a frequency domain impedance transfer function to the power spectral density of the excitation acceleration. The total power in a sense is a frequency weighted mean square acceleration number with the human impedance as a weighting function.

Pradko and Lee [4] state that absorbed power closely agrees with subjective response of raters in rank-ordering different rides. Only ten subjects were used, however, and the statistical correlation between subjective ranking and "absorbed power" was not given and Hanes [1] shows that the validity may be questionable. Nevertheless, the general concept of

CONDITION NO.	PERCENT* 1.5 Hz	4 Hz	7 Hz	NO. OF FREQUENCIES	OBJECTIONABLE ACCELERATION (RMSg)
1	100	0	0	1	.105
2	0	100	0	1	.065
3	0	0	100	1	.064
4	50	50	0	2	.073
5	50	0	50	2	.065
6	0	50	50	2	.081
7	33	33	33	3	.070
8	50	25	25	3	.078
9	25	50	25	3	.092
10	25	25	50	3	.072

*Table entries indicate percent of Total Power Contributed by Vibration at each Center Frequency.

TABLE 1 - OBJECTIONABLE ACCELERATIONS OF COMBINED-FREQUENCY VERTICAL VIBRATION [8]

CONDITION NO.	PRECENT* 1.5 Hz	4 Hz	7 Hz	NO. OF FREQUENCIES	OBJECTIONABLE ACCELERATION (RMSg)
1	100	0	0	1	.053
2	0	100	0	1	.075
3	0	0	100	1	.092
4	50	50	0	2	.065
5	0	50	50	2	.082
6	50	0	50	2	.074
7	33	33	33	3	.068
8	50	25	25	3	.083
9	25	50	25	3	.068
10	25	25	50	3	.086

*Table Entries Indicate Percent of Total Power Contributed by Vibration at Each Center Frequency.

Table 2 - OBJECTIONABLE ACCELERATIONS OF COMBINED-FREQUENCY LATERAL VIBRATION [8]

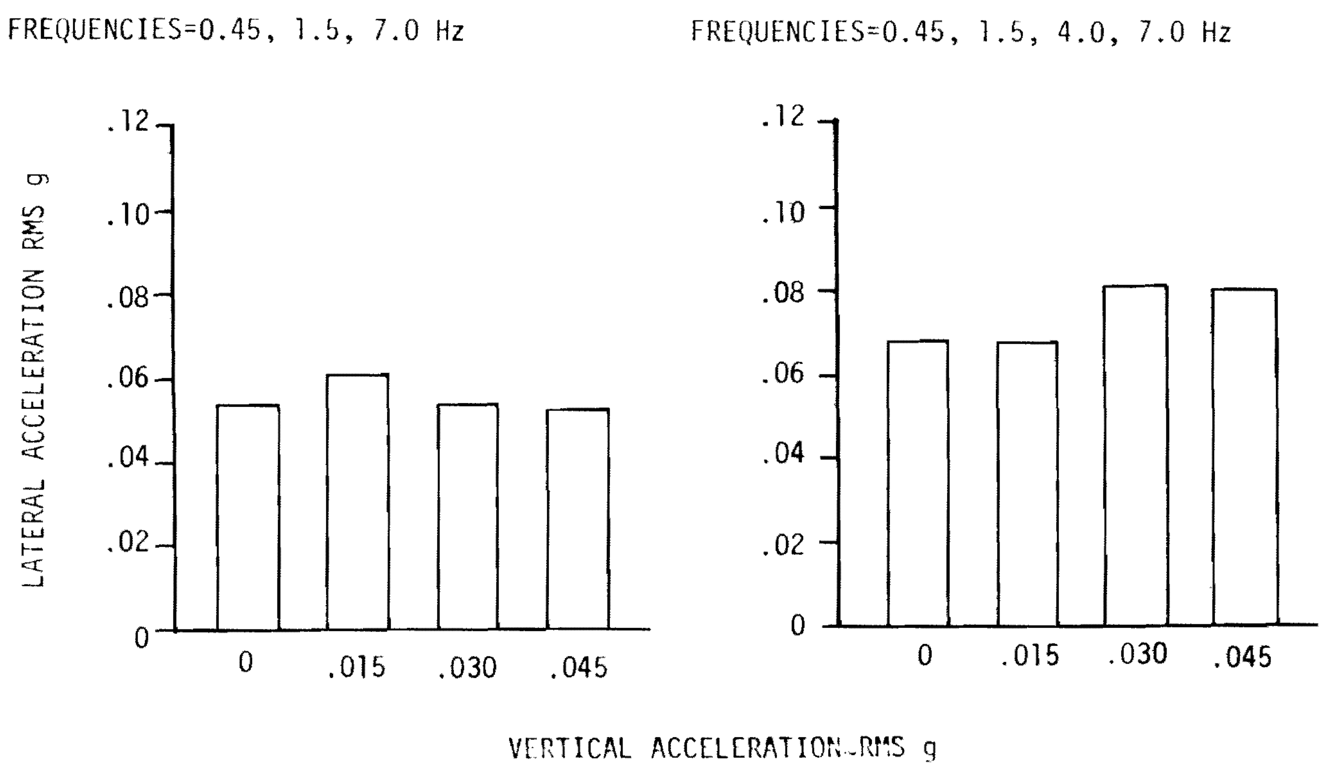
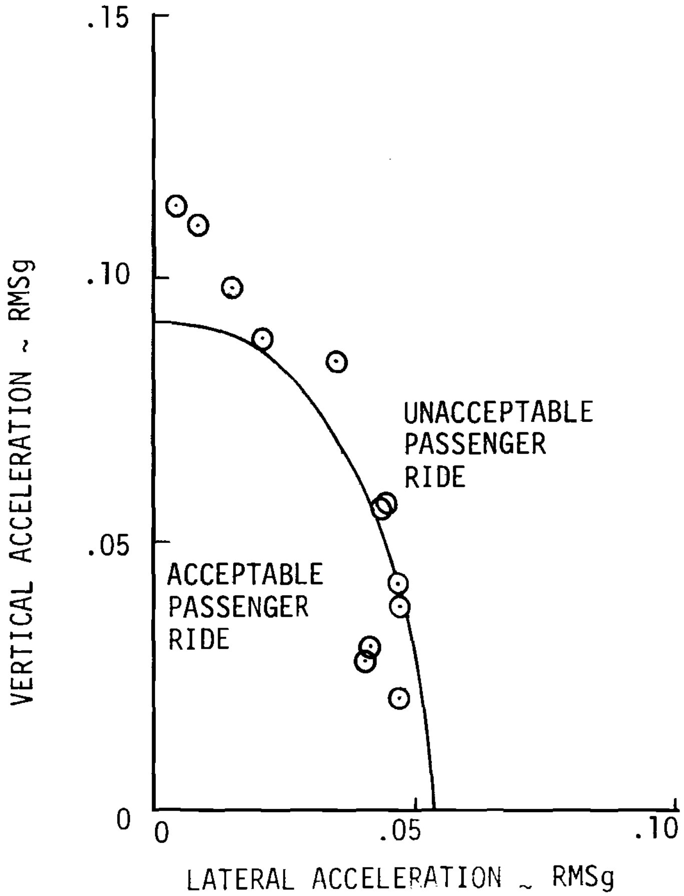


Fig. 4. Objectionable Levels of Two-Axis Vibration
Lateral Acceleration Varied at Constant Accelerations of Vertical Vibration, from [8]



NOTES:
1) TEST DATA NORMALIZED TO 2 HERTZ
2) TEST DATA INCLUDED ACCELERATION COMPONENTS AT .45, 1.5, 4.0, AND 7.0 HERTZ
3) TEST DATA ARE OBJECTIONABLE THRESHOLDS

Fig. 5. Comparison Between Two-Axis Vibration Test Results and Ride Comfort Criterion, From [8]

utilizing a frequency weighted mean square measure to collapse a random signal into a scalar number seems to be worthwhile. The question of which transfer function to use, however, has not yet been satisfactorily answered.

LITERATURE SUMMARY OF FIELD EXPERIMENTS

Field experiments with human raters in a riding environment fall into categories of rating with automobiles, rating with trains, rating with helicopters, and rating with aircraft. This part of the summary will be correspondingly divided.

Rating with Automobiles

Ride rating in automobiles has a long history. Early work by Jacklin and Liddle (1933) [10] employed seven subjects with an accelerometer placed on the rear seat of the car. Several roadway sections were used, and passengers reacted when, as speed increased, the ride became "disturbing". Analysis of the accelerometer record just after that point led to a comfort level boundary in terms of average acceleration as a function of frequency. A formula was given for this acceleration boundary as

$$Ae^{.045f} = (4.5 - 0.9 \cos 1.57f) \text{ ft/sec}^2$$

Later separate directions were studied and equations for "disturbing" levels in the vertical, longitudinal, and transverse directions were given as

$$\text{vertical} : Ae^{0.13f} = 8.5 \quad ft/sec^2$$

$$\text{longitudinal} : Ae^{.057f} = 4 \quad ft/sec^2$$

$$\text{transverse} : A = 2.75 \quad ft/sec^2$$

How the "random" vibration records were analyzed to result in an amplitude versus frequency envelope is not certain. It seems that considerable "eyeball" judgement was used in manual examination of vibration records.

Later, Van Eldik Thieme [11] attempted unsuccessfully to determine a ride criterion based on actual ride vibration data and using previous criteria based on sinusoidal tests of Dieckmann [12] and Janeway [13]. Janeway had earlier derived a vibration limit on the basis of automobile measurements but this was given in terms of allowable amplitudes for particular frequency components in an acceleration record. Again, the problem here is that a broad-band random vibration was being represented in discrete frequency terms.

During the 1960's and more recently, many attempts were made to improve the understanding of ride performance evaluation. Aspinal [14] at the British Motor Industries Research Association described subjective response experiments with seven different test automobiles and twelve raters for rides over selected routes. Vertical accelerations were measured, and subjective rank order was obtained for each ride. Objective measured records were analyzed with an analog wave analyzer and integrated over 15 seconds for each frequency in the range of 3/4 to 25 Hz. Using a record/playback tape speed ratio of 1/4, actual frequencies for analysis of 3-100 Hz were obtained. Each frequency resulted in a mean acceleration, which was weighted according to both the Janeway and Dieckmann limits. The rank ordering of rides was compared (objective versus subjective) with generally high correlation. Unfortunately, no actual values of r.m.s. accelerations were given although general conclusions showed that lack of vertical vibration was the most important factor in deciding rank order of the ride.

Versace [15] drove nine subjects in a 1959 sedan automobile over a variety of test roads and used a technique of cross-modality matching to yield subjective responses to the ride. The level of a noise was set by each subject to correspond to the intensity of the ride sensation. Recorded accelerations were averaged and mean square velocity, acceleration, and jerk values were found. Integration times of 10 and 20 seconds were found to give the best correlations between the vibration and noise measurements but no criterion was established and the degree of experimental correlation was not given precisely.

Later, Van Deusen [16] and Butkanas [17] used frequency weighting filters to process acceleration signals and to obtain r.m.s. measures of the random data. Van Deusen describes a military vehicle study and discusses the effects of using different frequency weighting functions for assessing mean square accelerations. Functions found by inverting constant comfort limits of Janeway, Dieckmann, and his own were found and inner correlated for each of several test rides. Unfortunately only five test subjects were used, making the significance of the study poor. Correlation coefficients with subjective ride evaluation based on the product-moment methods were all less than 0.733.

Butkanas [17] discussed the use of frequency weighted mean square acceleration obtained by random signal analysis using analog components to make a "ride meter". Certainly, a scalar index may be produced in this fashion but questions of how it relates to subjective evaluation and the effects of different weighting filters yet remain unanswered.

Road Serviceability

Most of the above has dealt with rating of ride vibrations. There is, however, a separate path of research emphasizing rating of roadway roughness. The relationships are close in view of the fact that road roughness constitutes a large part of the total vibration excitation in automobiles.

Roadway roughness is more recently characterized by an elevation power spectral density as given by Houboult [18]. The general method of subjectively rating highway roughness was developed by Carey and Irick [19]. The introduction of their Serviceability Index concept is a similar attempt to the "absorbed-power" concept to reduce a generally random signal to a single number index which may correlate with subjective ratings. Walker and Hudson [20] employed a profilometer for measuring roadway roughness profiles and conducted a rating study using typical Ford and Plymouth sedan automobiles riding over eighty-seven different highway test sections. Fifteen raters rated each test section on a 0 to 5.0 scale. The average rating for each section gives a "Present Serviceability Index" (S.I.) for that section.

Later, Walker and Hudson [21], using regression analysis, arrived at an equation model employing 32 degrees of freedom, which correlated extremely well with the serviceability index value for each test section. In the equation model the S.I. value is related to logarithmically formulated average elevation estimates in select frequency bands:

$$S.I. = 3.24 - 1.47x_1 - 0.133x_2 - 0.54x_3 + 1.08xc_1 - 0.25xc_2 + 0.08x_2x_3 - 0.91x_3x_4 + 0.67x_6x_{10} + 0.49k$$

where $x_i = \log A_i + \beta_i$

$xC_i = \log C_u + \gamma_i$

A_i is the average of the right and left track amplitude (in inches) in the frequency band from 0.023i to 0.023 (i + 1) cycles per foot

C_i is the average of the difference between right and left track amplitude (inches)

$\beta_1 = 2.081$; $\beta_2 = 4.065$; $\beta_3 = 4.544$; $\beta_4 = 4.811$; $\beta_6 = 5.113$; $\beta_{10} = 5.467$

$\gamma_1 = 3.053$; $\gamma_5 = 5.659$

k = 1 for rigid pavement and 0 for flexible pavement.

Generally interstate highways fall in the 4-5 range, U.S. highways fall in the 3-4 range, and secondary roads yield an S.I. in the 2-3 range.

A high degree of correlation existed between the predicted S.I. value, using the 32 band model and the means of the ratings. A product-moment correlation coefficient of 0.9 was found. While this type of experiment is designed largely to rate road quality, the ride comfort rating should be expected to closely follow the good correlation obtained even though the exact form of the equation model for ride comfort may be different from that used in road quality studies.

A number of other studies of road quality evaluation exist but do not shed any further light on the subject. It should be pointed out that most experiments dealing with field tests have been conducted by driving the vehicles in a straight path. The specific effects of induced lateral vibrations do not appear in the literature.

Rail Vehicle Tests

Early attempts at evaluating railway vehicle ride quality [22, 23, 24, 25] were based on converting the measured vibration records into equivalent amplitudes for each of the obvious harmonic motion components present. Batchelor [22] describes "eyeball" approximation analysis of vibration records for estimating average amplitudes for the basic low frequency component present (see Fig. 6). An average amplitude for the low frequency component of acceleration was then compared with sinusoidal constant comfort contours obtained separately by Reiher and Meister [26]. While these

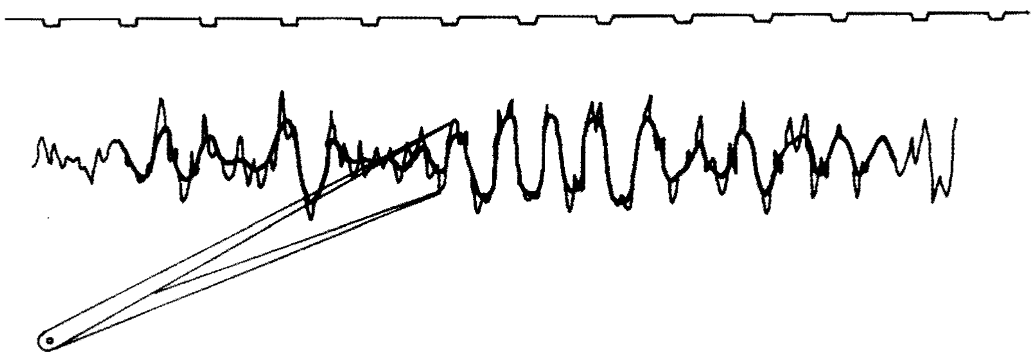


Fig. 6. Eyeball Estimating, from Batchelor [22]

approaches may be valid for the case where dominant frequency components can be easily identified (such as those due to periodic hunting or rigid body bouncing on lightly damped suspensions), this will not always be the case. Estimation of average amplitudes of frequency components submerged in generally broad-band random signals always raises the question of what bandwidth over which to average. This latter question still remains unanswered.

Batchelor suggests that multifrequency indexes be combined using the 10^{th} power:

$$R = \sqrt[10]{R_1^{10} + R_2^{10}}$$

Later work by Vinje [27] attempted to compare straight r.m.s., frequency weighted mean square, and the "absorbed power" measures of actual random vibrations recorded on two trains. Unfortunately no conclusions can be relied on since only six subjects were used on the first train and nine on the second train. No significant correlation at all existed between the ratings and any measure of vibration.

Experiments with Helicopters and Aircraft

Many ride quality programs have been started by individual aircraft companies with specific internal aims. Some of these are described in the 1972 symposium on vehicle ride quality [28]. Only a few programs have attempted to study the relationships between passenger evaluations and ride quality design criteria.

Early work, as with railway cars, led to analysis of dominant harmonic components and comparison with established sinusoidal constant comfort contour plots. Such attempts are described by Best [29], Getline [30], Zand [31], and Whitby [32], and are summarized by Bryce [33].

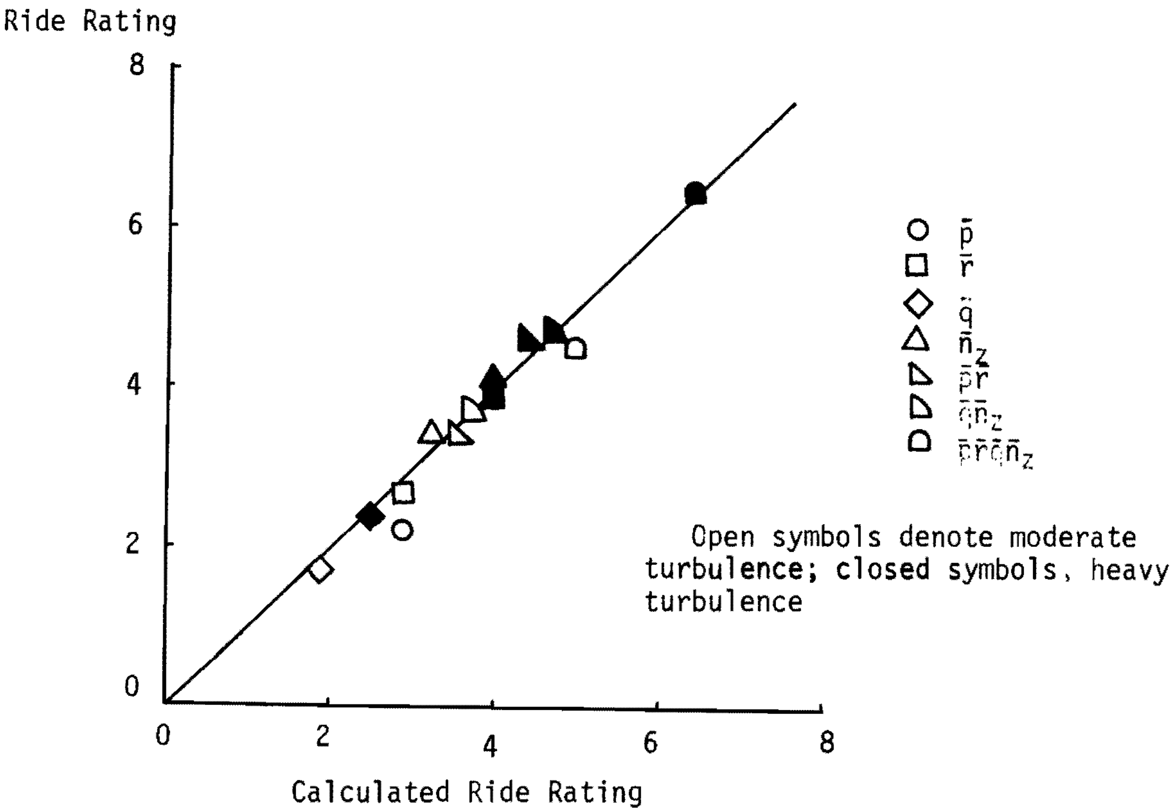
Recent work is hard to find in the literature but the efforts of Jacobson and Kuhlthau [34] and Seckel and Miller [35] appear to be the most significant.

Seckel and Miller [35] utilize root mean square values of the measured random motions, including the roll rate, yaw rate and normal acceleration components. Rating the ride quality on a 1 to 10 scale, they proposed a criterion

$$\frac{R - 1}{10 - R} = 0.18\,\overline{r^2} + .0024\,\overline{p^2} + 8.0\,\overline{a^2} \quad \ldots \qquad (7)$$

where $\overline{r^2}$ = mean square yaw rate,deg/sec; $\overline{p^2}$ = mean square roll rate,deg/sec; $\overline{a^2}$ = mean square normal acceleration, g's.

Extremely good correlation with experimentally obtained ride ratings was obtained, as shown in Fig. 7. The choice of the form of the left hand side of the equation above is dictated by the low and high level asymptotes, 1.0 and 10.0 respectively. That is, R = 1.0 is designed to correspond to no motion and R = 10 is designed to correspond to infinite mean square accelerations.



$$\frac{R-1}{10-R} = .018\,\overline{r^2} + .0024\,\overline{p^2} + 8.0\,\bar{n}_z$$

Fig. 7 Correlation with experimental ratings [35]

With a somewhat similar approach Jacobson and Kuhlthau [34] presented two criteria which were developed based on data taken in short-haul flight using three aircraft, a YS-11, an F-227 and a B-737. Tape-recorded acceleration measurements were analyzed for spectral composition of the six degrees of freedom (vertical, longitudinal and transverse linear motion and pitch, roll and yaw rotational motion). The form of the criterion for comfort on a 1.0 to 5.0 scale was found by least squares fit to the subjective rating for 100 flights to be

$$C = 1.8 + 11.5\ \bar{a}_{vert} + 5.0\ \bar{a}_{trans} + 1.0\ \bar{a}_{long} +$$

$$0.25\ \bar{a}_{pitch} + 0.4\ \bar{a}_{roll} + 1.9\ \bar{a}_{yaw} \quad . \; . \; . \qquad (8)$$

An alternate criterion based on frequency weighted mean square values was also given as

$$C = 1.8 + \sum_{1}^{6} \gamma_j\ \overline{\alpha_j^2} \quad . \; . \; . \qquad (9)$$

where

$$\gamma_1 = 10.6;\ \gamma_2 = 2.0;\ \gamma_3 = 0.1;\ \gamma_4 = 0.{>};\gamma_5 = 0.3;\ \gamma_6 = 0.15$$

and $\overline{\alpha^2}$ is the frequency weighted mean square acceleration for each of the six degrees of freedom where the frequency weighting function used was

$$1.0 \quad \text{for } 0 < f < 2.0 \quad ; \quad f^{0.6} \quad \text{for } 2 < f \leq 5.0$$

$$(5.0)^{0.6}\ f_1 \quad \text{for } 5.0 < f \leq 20.0 \quad ; \quad f^{-1} \quad \text{for } 20 < f$$

as given by Rustenberg [36].

Use of the same weighting function for each directional component does not seem to be sensible and the difference between the two criteria given appears to lie largely in the use of sums of root mean square quantities in Eqn. 8 and sums of mean square quantities in Eqn. 9.

Jacobson notes that the number of points whose predicted comfort rating differs from the average passenger response by more than one was approximately 10%. Eqn. 8 gave a slightly better correlation than Eqn. 9.

Unfortunately there were only one or two subject ratings per flight although each of nine subjects rated a minimum of six flight segments. Thus, while the study was heavily oriented toward acceleration measurements, subject ratings of each condition were too small to form a meaningful average.

The form of both criteria suggest the importance of vertical and lateral components of acceleration in dominating the ride quality. The authors suggest a comfort index of 3.5 be used for design satisfying 68% of the passengers. This results in the simple design equation

$$\bar{a}_V = 0.5\ \bar{a}_T + 0.075 \quad (\bar{a}_V \text{ in g units}) \ldots \qquad (10)$$

and is shown in Fig. 8.

Subsequent extension of the work to a slightly larger rating group was described in [37] with little differences.

Many other articles have appeared, mostly dealing with the assessment of vehicle vibration environment but without extensive subjective rating, and the goals of such efforts are not in line with the search for useful evaluative criteria.

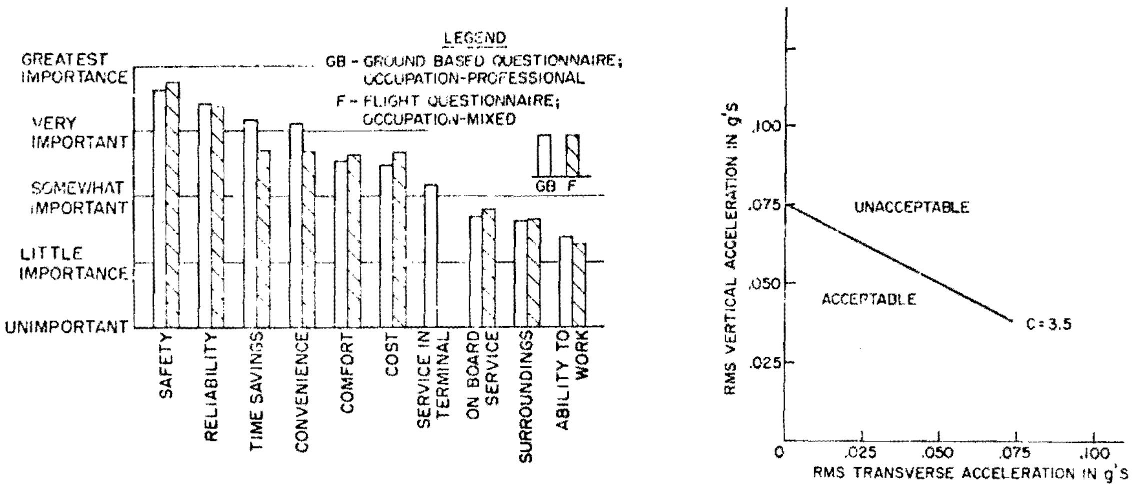


Fig. 8. The Relative Importance of "Comfort" and Suggested Criterion from Jacobson and Kuhlthau [34]

Summary and Conclusion

This review has been written to provide the reader some background concerning previous work done and knowledge relating very specifically to comfort criteria for assessing random vibrations in passenger transport vehicles. Experiments both with shake tables and actual vehicles in field tests have been conducted. The following conclusions are drawn:

1. Regarding the subjective response experimentation, there is a large volume of literature dealing with sinusoidal vibration and most early work employing measured random acceleration data from field tests has attempted to analyze ride records and convert the data into equivalent r.m.s. values for various obvious frequency components. Comparison with simple harmonic motion criteria then follows. While this approach may be valid for narrow-band random vibrations, it does not apply when broad-band ride vibrations are encountered.

2. There are conflicting results relating to the relative comfort of pure and narrow-band random inputs. It is not certain, for example, whether or not equivalent power random inputs are less tolerable than pure tone inputs.
3. Where multi-component narrow-band random inputs exist, it appears that passenger comfort rating responds to total power input rather than individual component power.
4. Random lateral accelerations are less tolerable than corresponding vertical vibrations.
5. The preferred method of quantifying broad-band random accelerations is to use power spectral techniques. The use of a frequency weighting function to give a frequency weighted mean square acceleration appears to be meritorious. This is the basis of the "absorbed power" index. The question of which frequency weighting function to use remains to be discussed.
6. There is evidence that passengers can rate random vibrations. It appears from field tests with aircraft that vertical and lateral r.m.s. g levels dominate in contributing to discomfort.
7. Criteria based on sums of r.m.s. accelerations for different degrees of freedom appear to correlate well with subjective ratings of passengers.
8. Frequently the number of ratings for each test ride have been too small to provide convincing correlation between subjective and objective measurements.

Prognosis for the Future

The vibrational environment encountered in transportation vehicles is extremely variable. It appears that a single criterion, simply constructed, is desirable but will not describe the multiplicity of expected conditions. It is the opinion of this author that select tests with a good balance between objective and subjective data acquisition will be necessary to define acceptance criteria for different situations. As and when new and different vehicle concepts (such as constrained track P.R.T.) are introduced the projection of satisfactory vibration levels will have to be done cautiously, using the nearest available criterion followed by continued experimentation. Only in this way will we gradually build up quantitative understanding of the ride-quality design picture.

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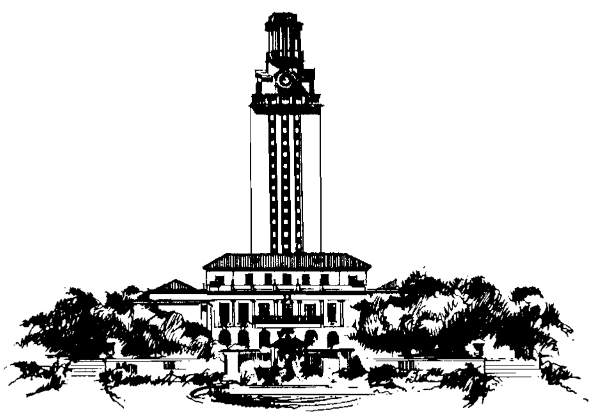

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