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AUTOMOBILE RIDE QUALITY EXPERIMENTS CORRELATED TO ISO-WEIGHTED CRITERIA

A. J. Healey, R. K. Young,
and C. C. Smith

The University of Texas at Austin

SUMMARY

As part of an overall study to evaluate the usefulness of ride quality criteria for the design of improved ground transportation systems an experiment was conducted involving subjective and objective measurement of ride vibrations found in an automobile riding over roadways of various roughness.

Correlation of the results has led to some very significant relationships between passenger rating and ride accelerations. The latter were collapsed using a frequency-weighted root mean square measure of the random vibration. The results suggest the form of a design criterion giving the relationship between ride vibration and acceptable automobile ride quality. Further the ride criterion is expressed in terms that relate to rides with which most people are familiar.

This report deals with the design of the experiment, the ride vibration data acquisition, the concept of frequency weighting and the correlations found between subjective and objective measurements.

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INTRODUCTION

Understanding the contributing factors of "good ride quality" and criteria for design of vehicle suspension and isolation systems has been of interest in the transportation community for some time.

Ground transport vehicles ride over road and railways which are, in general, rough. Smooth riding is not always achieved. Vibrational characteristics impressed on passengers are generally random with some dominant harmonics and usually, some form of mechanical isolation system is provided to insure smooth riding while at the same time, secure holding to the road or rail.

Early approaches to classify contributing factors to ride quality involved separate experiments with humans on shake tables. With sinusoidal excitation, subjects were asked to rate various vibration amplitudes at select frequencies. Averages of ratings then yielded curves of constant levels on a plot of amplitude in g's versus frequency as in Fig. 1 from [1]*. The records of measured vehicle accelerations, while random in nature, sometimes contained dominant frequency components. Where obvious components could be identified from measured acceleration records, examination of the record led to average amplitudes for each of these components. Comparison with laboratory shake-table results then yielded an average rating for each component. Components were combined into a composite rating using the tenth root of the sum of rating each raised to the one tenth power [2].

This approach, however, leaves something to be desired in many situations where the riding vibrations are in fact random with broad band characteristics. It is certainly possible to calculate a mean square value for a broad-band random signal but this value cannot be associated with any particular frequency. Alternatively, filtering using a narrow-band filter centered at some particular frequency may be used to compute an equivalent root mean square value at that center frequency, but the question of what band with filter to use is central to the issue and unknown.

Because of the general shape of the lines of constant comfort shown in Fig. 1, it is apparent that humans are more sensitive to frequency components in the 4-15 Hz range than to components in either the lower or higher range. Reflecting this fact for broadband random signals, acceleration power spectra values are weighted in that mid-frequency range by the inverse of a response curve such as is Fig. 1. The root mean square or the frequency-weighted root mean square accelerations are then used as measures of the ride. This approach has been used and is discussed by Van Deusen [3] and Butkunas [4]. In this work, better correlation with passenger rating than previously found is sought.

Discussion of the techniques of acceleration measurement and data reduction follow after a discussion of the general design of the experiment in which r.m.s. and frequency-weighted r.m.s. acceleration measures for a number of rides are compared with passenger subjective responses.

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*Numbers in brackets indicate references.

DESIGN OF THE EXPERIMENT

General Considerations

The experiment was based on rides in a late model Buick Century automobile over selected roadways around the Austin, Texas area. A total of thirty-six subject raters and a total of six routes each having three sections of roadway were used in the study. Since each ride involved a driver (same throughout the experiment) and three passenger raters, a total of 216 rides would have to be required if each rater was to rate each section. This would be extremely lengthy to carry out and it was decided on the basis of previous experience dealing with road pavement rating that twelve raters for each ride would be sufficient. In this design three raters were used on each excursion and in all, each rater rated six rides while each ride was rated by twelve raters. The design requires the repeatability of conditions from one day to the next and several test runs were made initially to develop driver technique such that repeatability could be insured.

Background variables such as personality measures, age and type of car normally driven were recorded for each rater so that correlation with ratings could be explored later.

A partial tabulation of the experiment is given in Fig. 2. Six sections were chosen for each excursion. Repetition four times of each excursion in different order with other subjects provided the required number of tests to average within subject variables and ride variables.

Routes

In this experiment the highway sections were divided into six routes. Each route contained three sections of highway and within each route, one of the sections was chosen as relatively rough, one medium and one smooth. These routes were chosen for convenience and were all located near Austin. They were chosen also to have as wide as possible variation of irregularity.

Design

Each subject rode over two routes and made six ratings of ride quality. To avoid the possibility of bias in the ratings of ride quality, sequence of sections within routes was randomized systematically. That is, the three sections in each route were either traversed in a single fixed order (1, 2, 3 or in reverse order (3, 2, 1). In addition, the sequence or relative roughne varied from one route to another such that approximately one-third of the tim the first section rated was smooth, one-third of the time it was medium and o third of the time it was rough. Similarly, the second and third rated sectio were about equally often smooth, medium or rough. In this way if subjective ratings change systematically with time because of such variables as boredom or fatigue, then these sources of bias are distributed approximately equally over the ratings of the various sections within routes.

Subjects

Thirty-six subjects in the experiment were divided in three groups. The 12 subjects of Group 1 rode over two different routes, the 12 subjects of Group 2 rode over two other routes and the 12 subjects of Group 3 rode over still another pair of routes. The 24 subjects of the first two groups were obtained from introductory psychology classes and served in the experiment to fulfill a laboratory requirement. Group three was composed of some non-studer being wives of faculty or female secretaries.

Procedure

The subjects served in the experiment three at a time. In each case the) met at the University of Texas and were driven from there to the appropriate site with two in the back seat and one in the passenger's seat. For all tests the car and the driver were the same. Care was taken by the driver to maintai the same standard conditions from one rating session to another. That is, talking between the subjects was not encouraged and the driver remained serioL and as business like as possible to emphasize the serious scientific nature of the project. Upon reaching the section to be rated, the car was driven over it at a standard 80.5 km/hr (50 mph). After completing the ride over the section the subjects rated ride quality using a 1 (rough) to 5 (smooth) rating scale. Ratings were anchored by instructing each subject to use a rating of "1" to indicate "the worst ride I can think of" and to use a rating of "5" to indicate "the best ride I can think of." Fig. 3 shows the rating form used.

Based on the above, each highway section had associated with it a) a number (12) of individual ride ratings and b) a measured acceleration record. During separate tests, vibration records were obtained for each ride. The car was loaded by two passengers and the recording equipment which took the place of the third passenger. The same driver was used. Sufficient number of trials insured the repeatability of data gathered in this manner. At 32.2 km/hr (20 mph) some trouble with repeatability was found but this seemed to disappear at the test speed of 80.5 km/hr (50 mph). Measured accelerations for both vertical and transverse directions were recorded as discussed in [5].

The important variables to be correlated here were the average rating for each ride with r.m.s. and frequency-weighted r.m.s. acceleration records.

ACCELERATION MEASUREMENT AND DATA REDUCTION

For each test section used, a separate recording was made of the acceleration response of the body of the Buick Century. A location below the drivers seat was chosen, close to the pitch and roll axis. With an automobile such as the Buick Century, roll and pitch acceleration components contribute a small amount to the total vertical and lateral motions and variations in rating due to position in the car were not distinguished. The acceleration response was measured using the 3-axis ride accelerometer developed by NASA [6]. This accelerometer system has a bandwidth of about 100 Hz and is accurate to 5% from 0 to 25 Hz.

The measurements of both vertical and transverse acceleration were recorded on a TEAC tape recorder. A test duration of about 15 seconds was used. The analog tape recording was then digitised using the HR2115A processor run by the Texas Highway Dept. with a 100 Hz bandwidth aliasing filter. A sample rate of 434 Hz insured that aliasing errors were minimized in the digitising process [7] and the digitised data were processed on the University of Texas C.D.C. 6600 system.

A data sequence of 4096 points was selected from each record. The mean value was extracted and the power spectral density of each record was computed using a fast fourier transform algorithm.

In the computation of power spectra, the raw power spectral density values obtained on the basis of a finite number of points must be smoothed by averagin adjacent points. In our work, the smoothing was done over three, five and nine times the discretisation frequency (0.106 Hz) for the 0-1 Hz, 1-10 Hz and 10-217 Hz ranges respectively. Thus smoothed power spectral density values were obtained as a sequence

$$\bar{p}_0, \bar{p}_1, \bar{p}_2 \cdot \cdot \bar{p}_k -- \bar{p}_{n-1}$$

Details of the computation procedure are given in [8].

The mean square value x^2 of each record was then obtained by summing individual raw power spectral density values p_k and dividing by the total record time T. Thus,

$$x^2 = \frac{1}{T} \sum_{0}^{n-1} p_k$$

and the root mean square (r.m.s.) value is then $\alpha = (\overline{x^2})^{1/2}$

In dealing with the frequency weighting concept the 8 hour ISO Standard (Fig. 1) was used as a basis. If the inverse curve of Fig. 1 is designated by A(f) then the frequency weighting of each raw power spectral density value p_k is achieved by a weighting constant w_k. Where

$$w_k = \frac{A^2(f')}{\frac{1}{(b-a)} \int_a^b A^2\,(f)\,df}$$

and the argument f' is made to correspond to k times the discretisation frequency of 0.106 Hz. The denominator above was introduced to normalize the weighting constant and corresponds to the mean square value of A(f) in the range of interest. The lowest frequency, a, was taken to be 0.1 Hz and the upper frequency, b, was taken to be 40.0 Hz. The vertical and lateral weighting functions are given in Figs. 4 and 5.

For each ride in the experiment, then, an r.m.s. and a frequency-weighted r.m.s. (w.r.m.s.) value was obtained for both vertical and lateral acceleration.

RESULTS

Initial Data Analysis

Each highway test section was identified by a Texas Highway Dept. number. Rides over each test section gave rise to twelve individual ratings. Table I below gives the mean rating R for each test section as well as the measured r.m.s. and w.r.m.s. values for vertical and lateral acceleration.

Table I.

[All accelerations are in g units]

Highway Section No.	R	r.m.s. Vertical	r.m.s. transverse	w.r.m.s. vertical	w.r.m.s. transverse
1	3.19	0.042	0.022	0.080	0.089
2	2.72	0.063	0.027	0.132	0.136
3	2.94	0.046	0.021	0.094	0.096
5	4.35	0.027	0.014	0.055	0.049
6	2.83	0.060	0.026	0.130	0.104
7	4.31	0.025	0.026	0.051	0.062
8	3.50	0.042	0.016	0.086	0.057
9	4.16	0.027	0.014	0.045	0.065
10	4.25	0.034	0.014	0.049	0.047
12	3.17	0.059	0.023	0.109	0.070
15	2.75	0.068	0.029	0.116	0.097
36	4.25	0.035	0.013	0.045	0.041
37	2.41	0.064	0.024	0.138	0.067
39	2.33	0.054	0.032	0.128	0.164
41	3.00	0.055	0.023	0.124	0.092

Only fifteen section numbers appear above since sections 5 and 37 were used twice in making up routes for two subject groups. They have, as a result, a basis of twenty-four ratings in the computation of the average. Section 35 has been excluded from the analysis since some errors were suspected in the measurement of its transverse acceleration.

The data in Table I has been analysed to yield product moment correlation coefficients defined as

$$r_{xy} = \frac{\frac{1}{N}\sum_{i=1}^{N} x_i y_i - \bar{x}\bar{y}}{\sigma_x \sigma_y}$$

Also, the first order significance and the significance of the quadratic term were computed. The correlation coefficient relates the degree of statistical correlation between two independent sequences and usually indicates significant relationships if values of $r_{xy} > 0.5$ are obtained.

As an added presentation of the data, Figs. 6-9 are provided here in which the r.m.s. vertical and transverse and the w.r.m.s. vertical and transverse accelerations are plotted versus the rating R. Also given is the appropriate correlation coefficient r_{xy}.

Examining Fig. 6 it is apparent that the r.m.s. vertical acceleration is extremely well correlated with the average rating. The correlation coefficient of 0.93 is rarely obtained in statistical experiments. The significance level based on the assumption of normality was better than 10^5.

Comparing Figs. 6 and 7 it is apparent, however, that transverse accelerations generally do not correlate so well with the ratings. The correlation coefficient of 0.779 is still significant but lower than that of the vertical acceleration. The point to the high right hand side which seems to be outside the main concentration of data is from section 7. This is a relatively good quality section of U.S. 71 -- a 4 lane highway. This section has the distinction of giving approximately equal r.m.s. levels of both vertical and lateral accelerations. The roughness characteristics are such that the vertical roughness of each wheel track is low (0.68 cm (0.267 in.) and 0.60 cm (0.237 in.) r.m.s. for right and left respectively) but their differences are relatively important thus inducing larger than expected transverse accelerations. Vertical and transverse r.m.s. accelerations are generally correlated. Here the correlation coefficient was 0.702.

Effect of Using ISO Weighting Function

The correlations with the ISO-weighted r.m.s. vertical and transverse accelerations are shown in Figs. 8 and 9. These show that correlation is definitely improved to 0.95 by use of the weighting function for the vertical acceleration but the data is more spread out for the transverse case (r_{xy} = 0.704). Now, some sections exhibit strong values of weighted r.m.s. acceleration and the same range of values is covered by both components. Apparently, raters respond more to the vertical sensation in the case of the automobile.

Use of Acceleration Vector Measure

There are two ways to combine vertical and lateral accelerations: either as a sum or as a product. Here it seems reasonable to make the vector sum of the two components, combining them into a vector magnitude. The correlation of the r.m.s. magnitude and the w.r.m.s. magnitude is given in Figs. 10 and 11. The correlation coefficients are respectively 0.909 and 0.931.

Again, the use of the ISO weighting functions has improved the correlation coefficients. Also, it is apparent that the magnitude values correlate worse than the vertical w.r.m.s. which in this test was found to be the best correlator with mean ride rating. The latter fact is attributed to the inclusion of transverse accelerations which generally correlate worse than their vertical counterparts.

Significance Levels

Significance levels were computed for each plot shown in Figs. 4-9. The two worst values were found as expected with the transverse accelerations being 0.0004 and 0.0023 for the r.m.s. and w.r.m.s. values respectively. All others had significance levels less than 10^{-4}. This means that the probability, assuming normality, of finding this correlation through a random test is less than 10^{-4}.

Variability of ratings by individual subjects played a relatively small role. That is, the variability of individual ratings accounted for about 5% of the total variability while variability of the means accounted for about 95% of the variability.

Other Analysis

A large amount of information was gathered from each subject. In this section a detailed account of the analyses attempting to find relationships between these variables will be given.

Each subject was given a personality test and a measure of "neuroticism" was obtained. On this basis the subjects were divided into a high-neurotic group--those subjects scoring 10 or above--and into a low-neurotic group--those subjects scoring 5 or lower. After this, ratings of ride quality were again analyzed. However, no difference was found between high and low neurotic groups with means of 3.23 and 3.38 respectively.

Another personality inventory measured degree of extroversion-introversion The hypothesis tested here was that the extrovert being more aware of his surroundings would be more influenced by the quality of the ride with the consequence that a rough ride would be rated rougher and a smooth ride would be rated smoother than would the case for the introvert who would be less influenced by external than internal cues.

Again subjects were divided into two groups with introverts being defined as those who gave scores of 12 or lower on the scale and with extroverts being defined as those who scored 19 or higher on the same scale. As in the previous analysis ratings of ride quality were analyzed and again ratings varied directly as a function of the acceleration. No difference in ratings was found as a function of extroversion-introversion. However, the interaction between extroversion-introversion and rating was in the predicted direction with ride ratings on roads rated as rough being rated as rougher by the extroverts than by the introverts. Unfortunately, this interaction was not reliable, and the hypothesis of random occurrence cannot be rejected. No other sources of variability approached significance.

The Gottschaldt figures test was also administered. As in the previous analyses, subjects were divided into low and high scorers on the test and the two extreme groups were compared on the basis of their ride quality ratings. Again, subjects scoring high or low on the Gottschaldt test tended to give essentially the same ratings.

The intercorrelations between seven variables were determined. The seven variables were total score (the sum of the six ratings made by each subject), the difference between the ratings for the rough rated roads and the ratings for the smooth rated roads, age, size of car (rated on a 1-4 scale) and scores from the Gottschaldt, Neuroticism and Extroversion-Introversion scales. Of the 21 correlations computed only the correlation between age and total rating was significant. In a subsequent analysis all other variables were held constant and again the same correlation was significant. In general, as age increased the overall rating of ride quality increased. This somewhat counter intuitive result suggests that younger adults are more critical of ride quality than are older adults. These data are also somewhat in agreement with the data of Group III--the older non-student group which was not included in subsequent analyses after the initial analysis indicated that this group gave smoother ratings to rough-rated roads than to medium-rated roads. That is, age and rated quality of ride are positively related in Groups I and II while at the same time the older subjects of Group III are unable to differentiate between a rough and a medium surface road. Thus, age appears to be a variable which is related to rating of ride quality and as such needs to be more thoroughly investigated.

Numerous other analyses were made in the course of the analysis of these data. Most of these other analyses were done by holding one or more variables constant to determine what effect this had on some other variable. The relatively few significant differences found in these analyses were roughly equivalent in frequency to the number of significant differences which would be expected on the basis of chance occurence.

Relationships Between Roadway Roughness and Ride Quality

In previous experiments [9] dealing with the rating of roadway roughness (not ride quality) the concept of a roadway servicability index (S.I.) has bee explored. The S.I. value of a section of highway is computed from a formulati of average roughness amplitudes in certain wavelength bands. The roadway roughness in this case has to be measured. Both right and left wheel tracks a included. Each Texas Highway Department test section has thus associated with it an S.I. value. These lie in the general range of 2-3 for secondary roads, 3-4 U.S. highway (good quality) and 4-5 for good quality Interstate highway.

In a separate computation the ratings of the first two groups of raters were compared with test section S.I. values. Extremely good correlation resulted as shown in Fig. 12 with a correlation coefficient of 0.91 and a significance level less than 0.01.

The importance of Fig. 10 is to show generally that ride ratings between 4 and 5 correspond to good quality rides over good quality Interstate highway. Lower values, between 2 and 3, for example, correspond to riding over two lane secondary roads. Thus the ride scale may be translated into meaningful sensations to the majority of our automobile-highway driving population.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Several conclusions can be drawn from this work as follows:

1. There is a highly significant correlation between the average rating of a particular automobile ride and the r.m.s. vertical acceleration.
2. Measured lateral accelerations do not correlate as highly as the vertical component with average ride ratings.
3. The use of a frequency weighting function based on the ISO Standard appears to improve the statistical correlation between acceleration level and passenger rating.
4. The use of the acceleration magnitude (i.e. $((\text{vertical})^2 + (\text{lateral})^2)^{1/2}$) appears to improve the correlation slightly.

Recommendation

It is suggested that Fig. 11 be used as a basis for automobile ride quality design. Ride Index values between 4 and 5 correspond generally to the quality of ride found in a Buick Century riding over Interstate quality roadbeds. Ride Index values between 3 and 4 generally correspond to riding over good quality two-lane highways while the 2-3 range corresponds to riding over secondary roadbeds at 80.5 km/hr (50 mph).

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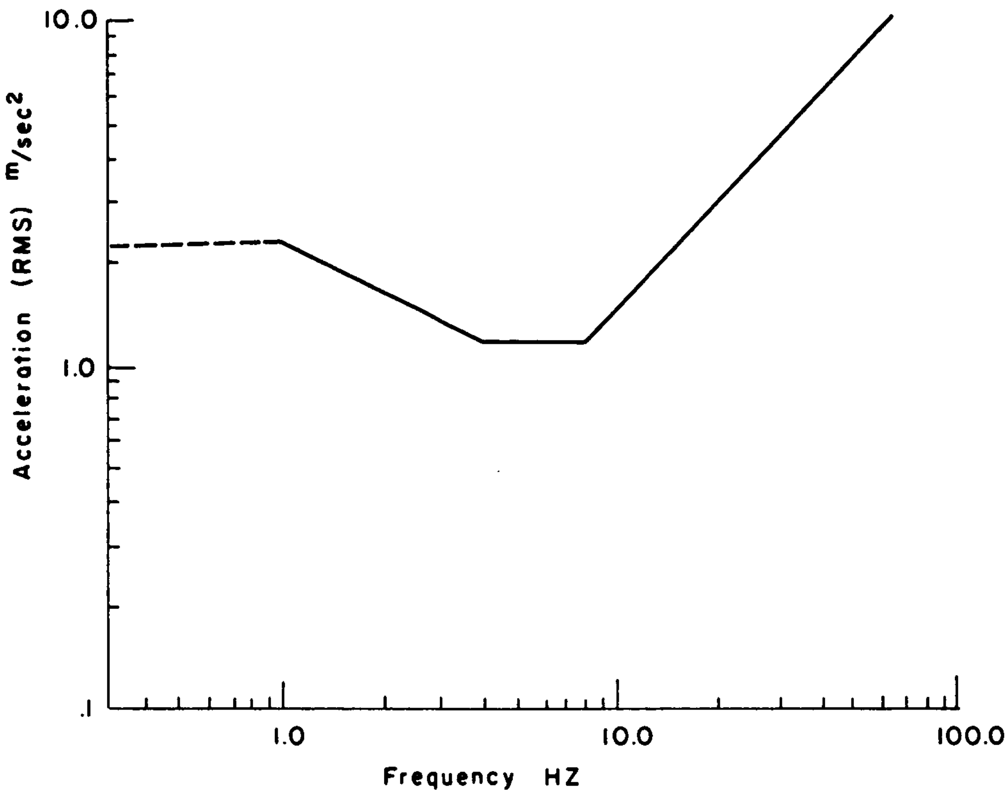

Figure 1.- International Standard 8 hour limit.

Route #1 and #2		Subject Name	First Route			Second Route		
			1st	2nd	3rd	1st	2nd	3rd
	Repl. 1							
	Repl. 2							
	Repl. 3							
	Repl. 4							

Figure 2.- Partial tabulation of the experiment.

RATING FORM

1. How would you rate the car ride you have just taken?

worse ride I can think of   1   2   (3)   4   5   best ride I can think of

2. How would you rate your mood right now?

worse mood I can think of   1   2   3   (4)   5   best mood I can think of

3. How would you rate the weather right now?

worse weather I can think of   1   2   (3)   4   5   best weather I can think of

your name Thompson, Peggy   date 3-6-74 section Number 1-4

Figure 3.- Rating form.

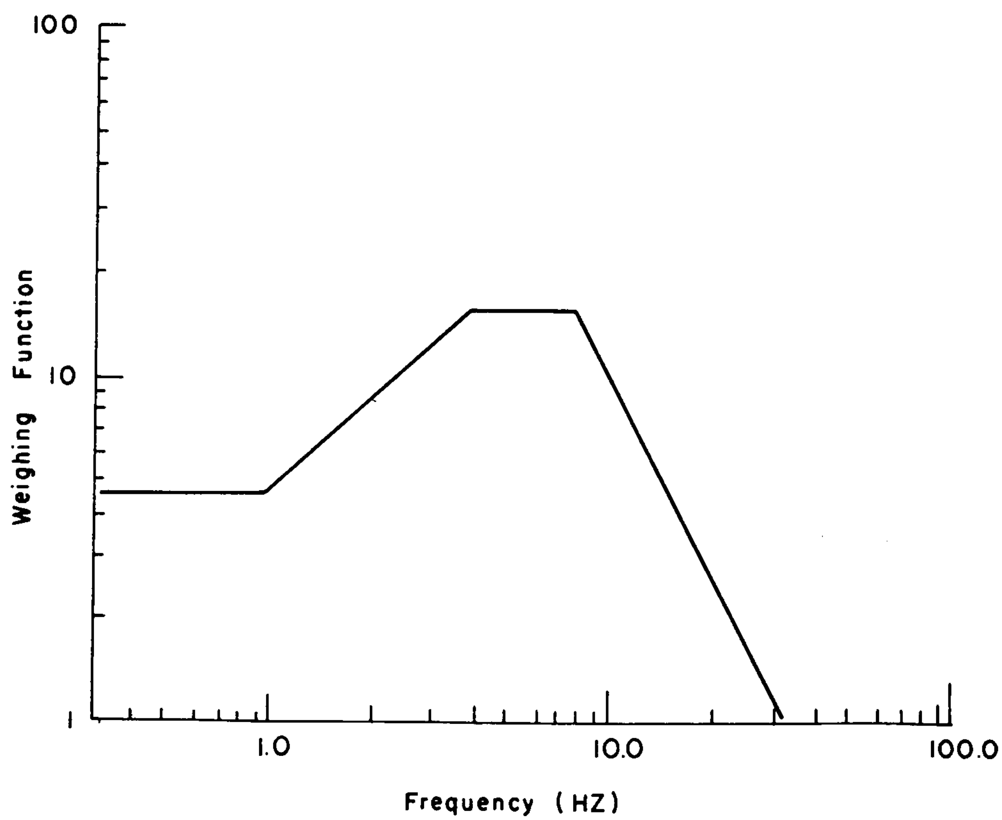

Figure 4.- ISO weighting function - vertical; b = 40 Hz.

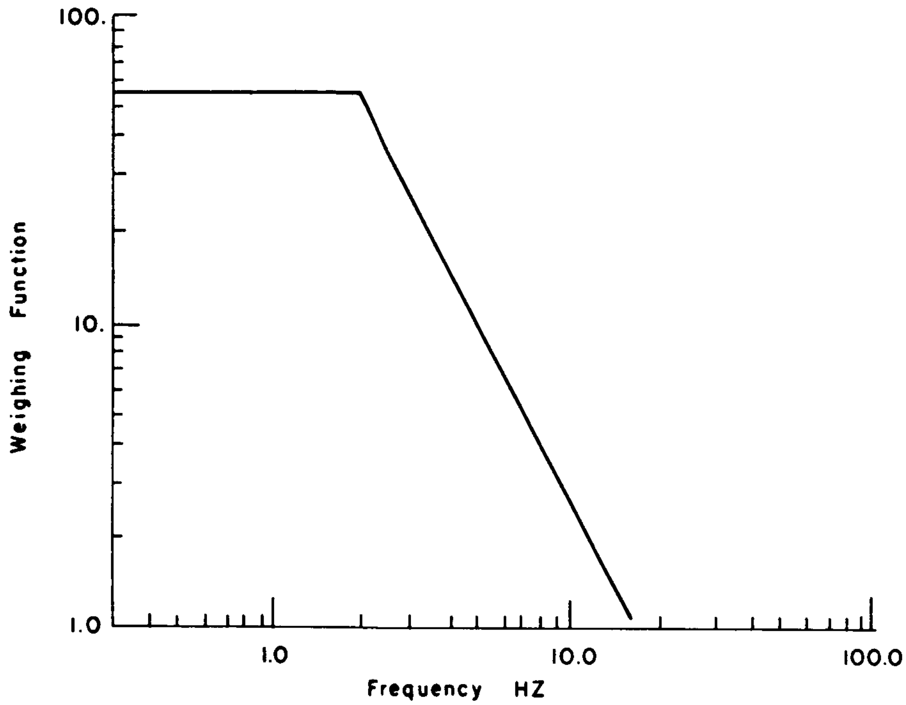

Figure 5.- ISO weighting function - lateral; b = 40 Hz.

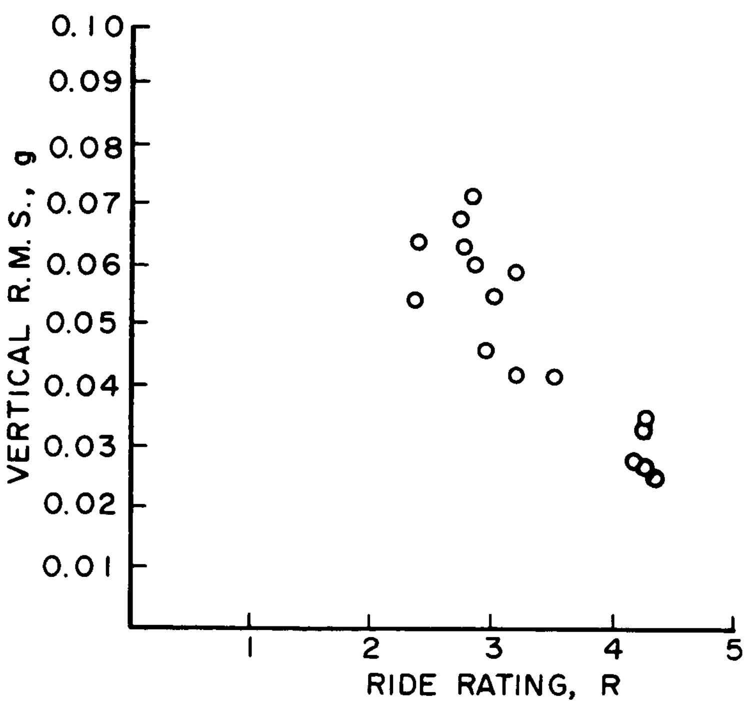

Figure 6.- R.M.S. vertical acceleration versus mean ride rating (correlation coefficient: 0.93).

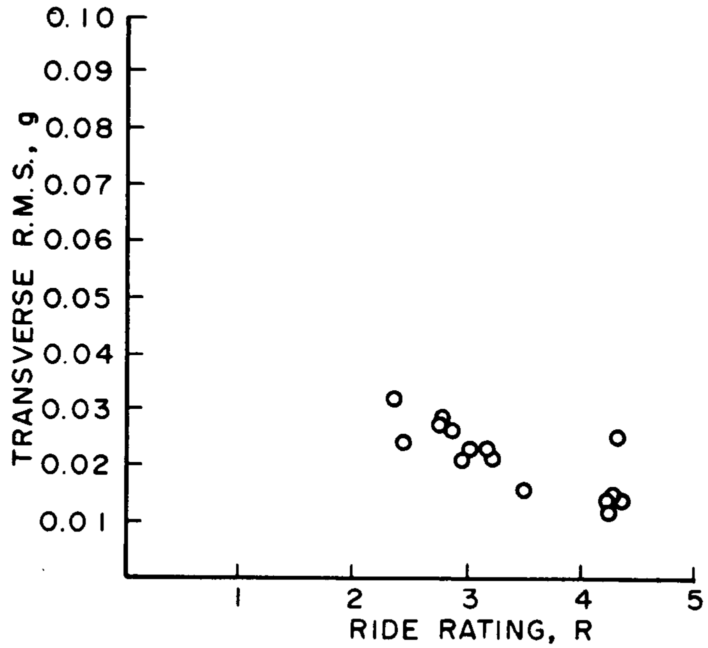

Figure 7.- R.M.S. transverse acceleration versus mean ride rating (correlation coefficient: 0.77).

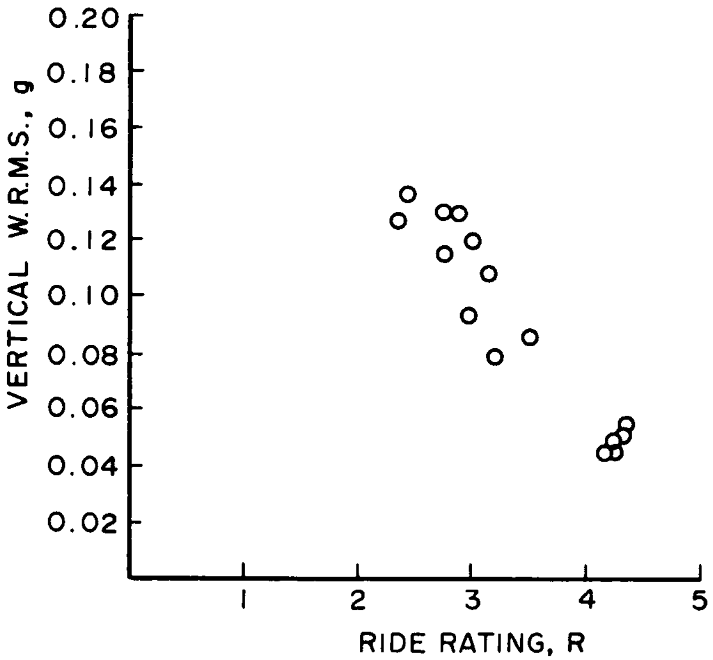

Figure 8.- ISO weighted vertical acceleration versus ride rating (correlation coefficient: 0.95).

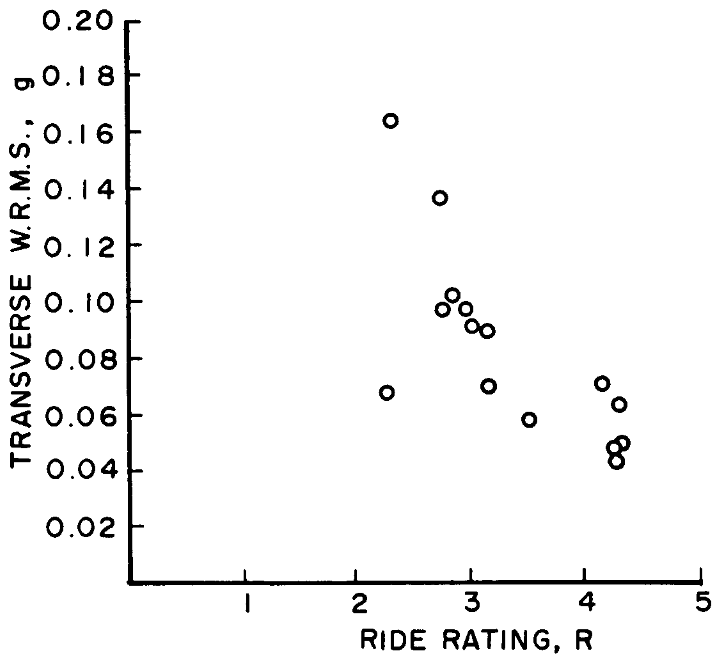

Figure 9.- ISO weighted transverse acceleration versus mean ride rating (correlation coefficient: 0.704).

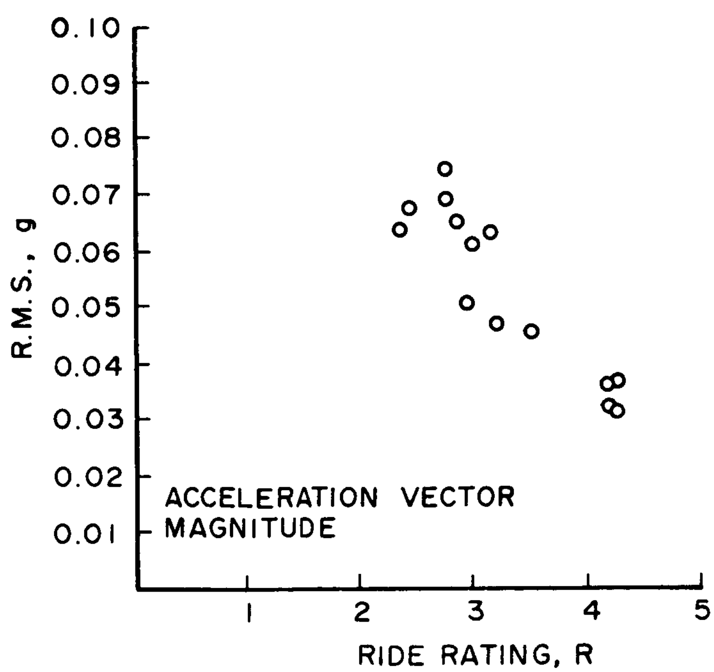

Figure 10.- R.M.S. acceleration vector magnitude (correlation coefficient: 0.909).

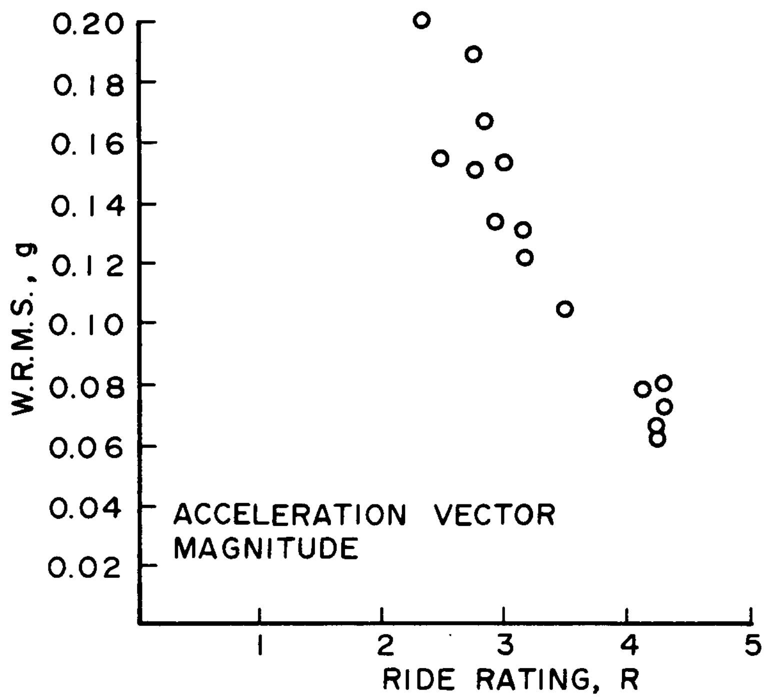

Figure 11.- ISO weighted acceleration vector magnitude versus mean ride rating (correlation coefficient: 0.931).

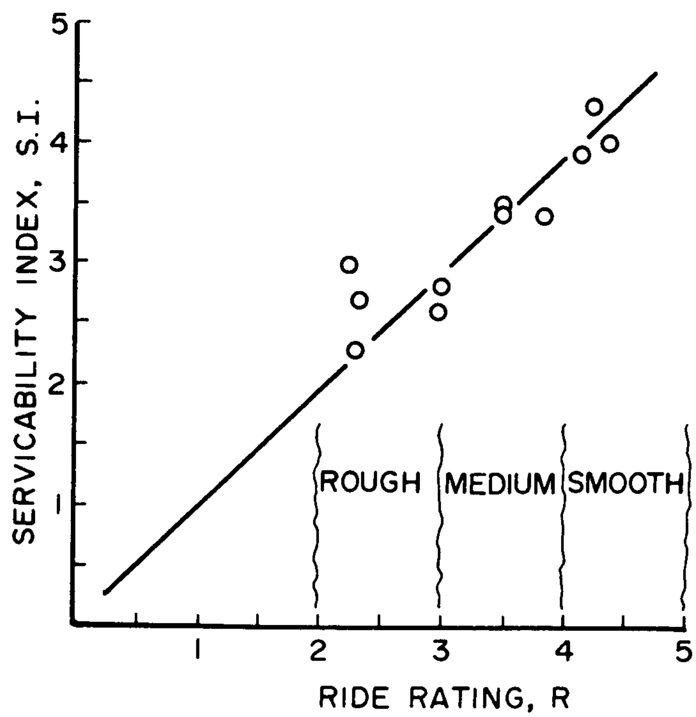

Figure 12.- Roadway servicability index versus mean ride rating.