CORRELATION OF OBJECTIVE AND SUBJECTIVE BUS-RIDE RATINGS

William H. Park and James C. Wambold, Pennsylvania Transportation Institute, Pennsylvania State University

This paper describes research concerning the establishment of a correlation between objective and subjective comfort ratings of vehicles traversing rough roads. The absorbed power comfort criterion was used in an amplitude-frequency-distribution format for the objective measure. The objective ratings were then correlated with passenger subjective responses obtained on a city bus traversing 17 distinct road segments. The correlation of absorbed power as an objective ride measure to the subjective evaluation for the bus data was successful. For some individual bus rides, the correlations were poor, but, when a sufficient number of rides were used to give a reasonable sample base, an excellent correlation was obtained and can be expressed mathematically as a logarithmic function. Finally, preliminary correlation of absorbed power with International Standardization Organization standards further enhanced the bus ride and absorbed power correlation numbers since the absorbed powers obtained were of the same order of magnitude for both correlations. Although it would then appear that one could just use International Standardization Organization standards, there is no way to add the effect of multidegrees of freedom. On the other hand, the absorbed power provides a method of adding the effects due to the three major directions plus the pitch and the roll.

•THE object of this research was to use vehicle acceleration versus time data to evaluate ride quality for the vehicle guideway system. The amplitude frequency distribution (AFD) techniques (1, 2, 3), as applied to the absorbed power (AP) (4, 5, 6) method of comfort evaluation previously used in automobile-road roughness studies by the investigators (7, 8, 9), were extended to include 3 degrees of freedom. This extended method was used to evaluate the subjective ride and acceleration data taken by researchers on a city bus. The subjective and objective ride ratings were then correlated (10).

BASIC STATISTICAL MEASURES

Measured records must be recognized as random signals of finite duration and, as such, they can be viewed and described in terms of three basic domains: time, amplitude, and frequency. At first glance, it would appear that the power spectral density (PSD) contains a complete description of amplitude variations, thus making any amplitude-distribution calculations superfluous. However, the ordinate of a PSD curve indicates only the average signal amplitude at a particular frequency. A large PSD value can conceivably be produced by either a few cycles of large amplitude or a large number with small amplitudes; the distinction cannot be made from the PSD curve alone. On the other hand, it is not possible to extract any information about frequency distribution from amplitude density curves. It is evident from these considerations that the PSD and amplitude density curves each contain unique information, and a simple method of combining the two representations is desirable.

An effective method for combining the information contained in both the PSD and the amplitude representations is to reduce the random time-history signal to a simple tabular array that displays both the height and the length features of the random data, the AFD (1, 2, 3). Here the coordinates (linear or logarithmic), amplitude [in feet (meters) or *g*] versus frequency [in hertz, revolutions per minute, or cycles per foot (per meter)], are divided into a number of finite bands. Numbers are computed and entered at each windowlike intersection of the bands. The numbers express the total number of signal peaks with the amplitude and frequency of that box in the array. The complete array of numbers thus identifies the random signal as a combined amplitude and frequency distribution. Thus, the AFD not only gives the frequency distribution but also shows the amplitude makeup and distribution of each frequency band.

CORRELATION OF OBJECTIVE WITH SUBJECTIVE RIDE RATINGS

Objective Ride Criterion

Objective ride measures used in this study are based on the concept of AP. This criterion was developed by researchers at the Army Tank Automotive Command (4, 5, 6) and is based on an energy flow rate that depends on the anatomical properties of the human body. The human body properties were determined experimentally, and AP was related to passenger subjective responses.

The information needed for the determination of AP is the acceleration at the interface of the passenger and the vehicle. The experimental data that were used as input had been obtained before initiation of this project and consisted of three-directional accelerations measured on the floor of a bus by using National Aeronautics and Space Administration (NASA) instruments. These accelerations in the vertical, longitudinal, and lateral directions were measured near the front of the bus and simultaneously near the center of the bus and were recorded on magnetic tape. Unfortunately, these accelerations were not measured at the passenger-seat interface but were used because of their availability in this initial project to determine the degree of correlation between the AP criterion and subjective passenger response. Impedance tests were run on the bus seats, and it was determined that their acceleration transfer functions were very close to unity in the frequency range of interest. This permitted the floor data to be used without modification. Other seats might not perform in this manner and may attenuate the signal near the body resonances. Therefore, all future comfort measurements should be made at the passenger-seat interface, or, if this cannot be done, seat transfer characteristics must be determined for each case and included in the analyses if the characteristics dictate it.

AP can be computed from the acceleration data in either the time or the frequency domain for each direction. Since power is a scalar quantity, the total power can be obtained by summing the power in all three directions. For this study, the frequency method was used since the results would reveal those frequency bands that contribute to the greatest discomfort. The format for the calculations is shown by the following equation:

$$\text{average AP} = \sum_{i=0}^{N} K_i A_{i_{rms}}^2 \tag{1}$$

where

AP = absorbed power in watts,
$A_{i_{rms}}^2$ = root-mean-square of the acceleration at a given frequency, and
K_i = parameter used to transform the acceleration squared into AP at a given frequency.

Before the calculation details are given, the AFD concept for formatting the data will be presented.

Amplitude Frequency Distribution Format for Absorbed Power

The AFD method has been found useful in making comfort measurements because it readily identifies both amplitude and frequency bands of the acceleration inputs that are causing the discomfort to the vehicle passenger. Details of this method, which can be used directly on road roughness data, are given elsewhere (7). The acceleration data (either measured or determined from road roughness) for each of the three directions were filtered into eight frequency bands, and peaks were placed in six amplitude bands.

The seat acceleration AFD is the beginning point for comfort evaluation by the AP method. Equation 1 shows that the total AP for a vibration spectrum is the summation of the power at each frequency. The K_i values are for frequencies in hertz, which can be obtained by multiplying the midfrequency by the vehicle speed in feet (meters) per second. Since each block of the seat acceleration AFD has a midamplitude and a midfrequency value, the average AP attributable to each AFD can be calculated from equation 1. The resultant AP matrix is given in Table 1. This value of AP shown in each block, however, would be the power absorbed by a passenger subjected totally to an acceleration of that midfrequency and midamplitude value. Therefore, to account for the fact that the actual acceleration consists of various frequencies and amplitudes, the AP matrix is normalized by dividing each block by the maximum number of counts that would be shown by a sine wave of that midfrequency for that length of time. For example, the last column has a midfrequency of 11.314 Hz. Any amplitude sine wave of that frequency would produce 169.7 counts in that time. These numbers of counts could be termed M_i and are calculated for each frequency. By dividing the AP matrix by the M_i values, a new matrix is obtained that will be called the normalized absorbed power matrix (NAPM). Each block of the NAPM is then $K_iA_i^2/M_i$, which is equal to the AP contribution per count of the seat acceleration AFD. These values are given in the matrix in Table 2. The NAPM shows those areas that contribute the most to AP (or discomfort) and, thus, gives a picture of the amplitudes and frequencies that contribute to a comfortable ride.

For determination of AP for a particular ride segment, NAPM is multiplied block by block with the seat acceleration AFD to give the absorbed power AFD (APAFD) as given in Table 3. The APAFD gives the amount of power attributed to each frequency and amplitude block for the guideway and vehicle being examined. The AP for each frequency band can then be obtained by summing the blocks vertically, or the total AP can be obtained by summing all the blocks. The absorbed power AFDs for all segments for each ride are given elsewhere (10).

Correlation Method for Objective and Subjective Ride Ratings

Subjective ride ratings from the bus study were given by the two passengers seated directly over each instrument package used to record the floor accelerations. The correlation simply consisted of plotting the total AP for all three directions against the ride rating number assigned by the passenger.

TEST DATA PROCESSING

The computational program was developed for a hybrid computer in the College of Engineering of Pennsylvania State University. When a random signal has been stored, in continuous analog form on FM tape, or in discrete digitized form on IBM tape, processing the signal to determine its amplitude frequency distribution demands performance of two distinguishable but serially connected operations. The signal must be filtered in each of a number of narrow bandpass filters, and the amplitude peaks must be discriminated and counted for each filter's output. The technique used is shown in Figure 1.

To get a fairly precise characterization of the amplitude frequency distribution of a random signal requires quite a few relatively narrow (about an octave or less) frequency bands. This need presses against the limitations of cost and availability of hardware. Processing time is reduced dramatically if a random signal can be fed into a parallel set of filters that yields simultaneously the filtered outputs for all filter bands.

When the output of a bandpass filter is available, the peak discrimination can be done. For a narrow bandpass filter the output is a quasisinusoidal signal with fairly uniform frequency but with varying amplitude. The function of peak discrimination is to detect when a peak has occurred, to determine in which of a spectrum of discrete amplitude levels the signal has peaked, and to record this even by updating an appropriate counter. The outputs of the several filters are digitized, and the peak discrimination and counting are done by purely digital means.

Hybrid Absorbed Power Program Method

The files created by the digitizing program are used by the AFD program. The peaks in the amplitude of the data are then found by comparing each digital sample with the sample preceding it and the one following it, until a maximum in the amplitude is found. For each cycle in the amplitude of the data, the peak value is found and stored in an array. In addition, the time in seconds (since the beginning of the test run) at which the peak occurred is also stored in the array. Insignificant amplitude peaks, down in the noise level, are ignored. Data are then printed out in a listing that gives the amplitude of each peak in the data, the time of the peak occurrence, the unadjusted AP, and the AP contributed by the peak. One such listing is provided for each frequency band of each degree of freedom. The peaks are now discriminated into the amplitude bands for the AFD, and the value of each peak is compared with the upper amplitude levels of the amplitude bands, starting with the lowest. Each amplitude band is tested until the upper level of that band exceeds the value of the peak. The number in the AFD array whose position is determined by that amplitude band and the frequency band being processed is then increased by 1. In this way, the number of peaks having each particular combination of amplitude and frequency can be determined. The unadjusted APAFD is then calculated by multiplying the number of peaks in the AFD for each amplitude-frequency combination by the square of the center amplitude of that amplitude band and then by multiplying this by the proper K factor for that frequency band. APAFD is calculated by dividing each value in the unadjusted APAFD by the maximum number of counts that could have occurred during the test run by a continuous sine wave having a frequency equal to the center frequency of the band containing the value. The AFD, unadjusted APAFD, and APAFD are printed out for each degree of freedom.

Objective Ride Data

Results obtained by processing the bus ride data are discussed in the following. The first part of the output listing gives the amplitude and frequency bands selected. This listing provides band limits, and, depending on the scales chosen (linear or log), the center frequencies and amplitudes are calculated and listed. This listing is not repeated until the next computer run when a different set of bands can be chosen.

The next part of the computer output consists of eight listings, one for each frequency band of each segment of bus data. The first column gives the time in seconds, after the beginning of the segment, at which a peak in the acceleration amplitude occurs. The second column gives the amplitude of this peak, and the third column gives the unadjusted AP which is used as an intermediate step in calculating AP. The fourth column gives the AP contributed by the amplitude peak. This is the actual power absorbed by the passenger because of this acceleration peak. This listing contains only those peaks with an acceleration amplitude of at least 0.02 *g*, so that insignificant peaks with small AP values are ignored. The listing is provided so that the time and amplitude of those peaks contributing large AP values can be identified. Table 4 gives a typical listing from run 7, segment 3, vertical motion, from front accelerometers.

Table 1. Absorbed power matrix for run 8, vertical motion.

Midacceleration (g)	Midfrequency (Hz) 0.088	0.177	0.354	0.707	1.414	2.828	5.657	11.314
0.401	0.00682	0.02746	0.11024	0.46851	2.04678	10.10910	12.14340	3.03440
0.257	0.00281	0.01132	0.04543	0.19309	0.84354	4.16625	5.00465	1.25056
0.165	0.00116	0.00466	0.01872	0.07958	0.34765	1.71703	2.06256	0.51539
0.101	0.00048	0.00192	0.00772	0.03280	0.14328	0.70764	0.85004	0.21241
0.069	0.00020	0.00079	0.00318	0.01352	0.05905	0.29164	0.35033	0.08754
0.044	0.00008	0.00033	0.00131	0.00557	0.02434	0.12019	0.14438	0.03608

Table 2. Normalized absorbed power matrix for run 8, vertical motion.

Midacceleration (g)	Midfrequency (Hz) 0.088	0.177	0.354	0.707	1.414	2.828	5.657	11.314
0.401	0.00515	0.01035	0.02079	0.04417	0.09849	0.23827	0.14311	0.01788
0.257	0.00212	0.00427	0.00857	0.01820	0.03976	0.09820	0.05898	0.00737
0.165	0.00087	0.00176	0.00353	0.00750	0.01639	0.04047	0.02431	0.00304
0.101	0.00036	0.00072	0.00146	0.00309	0.00675	0.01668	0.01002	0.00125
0.069	0.00015	0.00030	0.00060	0.00127	0.00278	0.00687	0.00413	0.00052
0.044	0.00006	0.00012	0.00025	0.00053	0.00115	0.00283	0.00170	0.00021

Table 3. Absorbed power amplitude frequency distribution determined from experimental acceleration for run 8, segment 1, vertical motion.

Midacceleration (g)	Midfrequency (Hz) 0.088	0.177	0.354	0.707	1.414	2.828	5.657	11.314
0.401	0.000	0.000	0.021	0.044	0.000	0.000	0.000	0.000
0.257	0.000	0.004	0.000	0.000	0.000	0.000	0.000	0.000
0.165	0.000	0.002	0.004	0.000	0.000	0.000	0.000	0.003
0.101	0.000	0.000	0.000	0.003	0.000	0.000	0.000	0.010
0.069	0.000	0.000	0.001	0.000	0.008	0.000	0.004	0.023
0.044	0.000	0.000	0.000	0.001	0.002	0.008	0.017	0.011

Figure 1. Determining joint probability density of random signal.

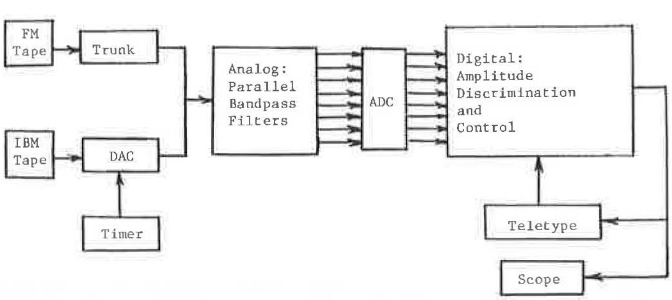


Table 4. Listing for run 7.

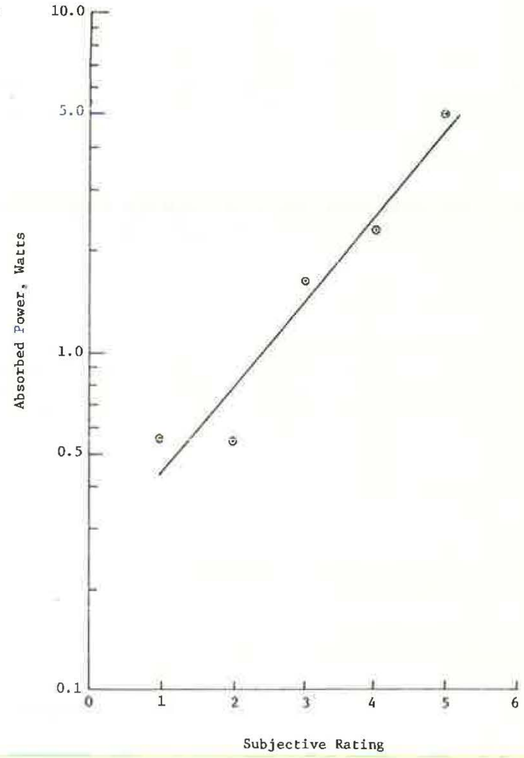
Time (sec)	Acceleration Amplitude (g)	Absorbed Power (W) Unadjusted	Normalized	Time (sec)	Acceleration Amplitude (g)	Absorbed Power (W) Unadjusted	Normalized
14.03	0.03	0.047	0.0011	42.14	0.04	0.091	0.0021
28.84	0.04	0.109	0.0026	45.00	0.06	0.228	0.0054
31.41	0.05	0.128	0.0030	81.91	0.03	0.047	0.0011
35.78	0.04	0.083	0.0020	96.03	0.03	0.047	0.0011

Table 5. Amplitude frequency output and absorbed power amplitude frequency distribution for run 7.

Item	Values							
Unadjusted AFD	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0
	0	1	0	0	0	0	0	1
	2	0	0	0	0	0	1	7
	0	0	1	1	6	1	5	28
	0	1	0	2	4	4	10	49
Normalized APAFD[a]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.003
	0.001	0.000	0.000	0.000	0.000	0.000	0.010	0.009
	0.000	0.000	0.001	0.001	0.017	0.007	0.021	0.014
	0.000	0.000	0.000	0.001	0.005	0.011	0.017	0.010

[a]Sum = 0.130.

Figure 2. Absorbed power versus subjective rating for bus data.



After the eight listings, the AFD is printed out and shows the number of peaks that occurred in each segment having a particular amplitude and frequency combination. A separate AFD is provided for each degree of freedom of each segment. Table 5 gives the AFD output for run 7, segment 3, vertical motion. This is a typical AFD, showing the approximate distribution found in most of the runs. In Table 5 the acceleration amplitude levels and frequency levels are set as follows:

Acceleration Amplitude (g)	Frequency (Hz)
0.03	0.06
0.05	0.12
0.08	0.25
0.13	0.50
0.21	1.00
0.32	2.00
0.50	4.00
	8.00
	16.00

The unadjusted APAFD and normalized APAFD are then printed out. These give the unadjusted AP and normalized AP contributed by each amplitude-frequency combination. The unadjusted APAFDs are not shown since they have no meaning; the normalized APAFD output is given in Table 5 for run 7, segment 3, vertical motion. The total unadjusted APAFB and the total normalized APAFD of the segment are printed out as a single number found by summing their respective values.

Subjective Ride Data

The subjective bus ride data used in the correlation studies were taken by experimenters of Old Dominion University and supplied by NASA. For runs 2 and 6, the subject assigned a number from 1 to 5 to the quality of the ride, where 1 was the best quality ride and 5 was the worst. Runs 7 and 8 were similar, except that the scale ranged from 1 to 6. The subjective data for runs 1, 3, 4, and 5 were unusable; therefore, the objective data for these runs were not processed. The objective and subjective data were tabulated for the correlation studies.

In a given run, all the AP values corresponding to a single subjective response number were averaged, and then standard deviation from this average was calculated. It was noted that a few extremely large acceleration values, especially in the lateral and longitudinal degrees of freedom, were causing large AP values where the subjective rating was small. These AP values were discarded because such accelerations were large enough to move the passengers from their seats and were unreasonable since the subjective responses were small.

A final composite correlation plot, combining the data for all segments of all runs from both accelerometers, was made. Although, in the individual plots, the curve was not always exponential as expected, the composite plot of all the data shown in Figure 2 is an exponential curve and fits the following equation:

$$S = 1.7245 \ln (3.96849 \text{ AP}) \tag{2}$$

where

S = subjective response and
AP = absorbed power in watts.

Appraisal of Results and Applications

The correlation results of AP as an objective ride measure to the subjective evaluation for the NASA bus data were successful. Individual segments and rides gave poor correlation since the data base was too small to give a reasonable random sample. However, when sufficient numbers of rides were used to give a reasonable sample base, excellent correlation was obtained, and the following logarithmical relation was shown by the data:

$$S = 1.7245 \ln (3.96849 \text{ AP}) \tag{3}$$

where

S = subjective rating (on a five-point scale) and
AP = absorbed power in watts.

Since there was a successful correlation of the bus data, a further correlation of International Standardization Organization (ISO) standards and the AP method was started (10). These two methods were found to agree rather well. In the whole-body frequency range, AP is slightly more conservative; in the 10 to 100-Hz range, the two agree; but, in the range equal to or lower than 2 Hz, AP is not so restrictive as ISO standards. Since AP only accounts for vibration effects and such things as motion sickness are not included, there is justification for the harsher requirements of ISO standards in this range. Since the two methods compare reasonably well, one can use either method as an overall criterion. However, the AP method has the distinct advantage that effects due to more than 1 degree of freedom can be determined by adding the effect of the individual degrees of freedom. It thus appears that, if the proposed ISO standards are to be used, a combination of ISO standards and the AP method would be in order.

When the bus-subjective and ISO standard correlations with AP have been made, it is useful to compare these two correlations. The following table gives the AP values (W) for both correlations (the ISO standards for 1-hour exposure).

Subjective Ratings	ISO Standards (avg)	Bus Ride
1	0.15	0.45
2	—	0.80
3	1.50	1.44
4	—	2.56
5	5.88	4.57

With the exception of the very good ride, the two correlations give AP levels that are very similar. Even the very good ride (subjective rating of 1) is close in terms of overall rating: range of 0.45 to 4.57 AP for the bus data and of 0.15 to 5.88 AP for the ISO standards.

CONCLUSIONS

This study has shown that the AP criterion of comfort measurement does indeed correlate well with subjective passenger response based on 3 degrees of freedom. Additiona research should be undertaken to correlate objective with subjective ride measures for other types of transportation systems and for additional degrees of freedom.

REFERENCES

1. A. D. Brickman, J. C. Wambold, and J. R. Zimmerman. An Amplitude-Frequency Description of Road Roughness. HRB Special Rept. 116, 1971, pp. 53-67.

2. J. C. Wambold and J. R. Zimmerman. Hybrid Programs for Calculating the Joint Probability of Amplitude and Frequency of a Random Signal. Trans., Analog/Hybrid Computer Education Society, West Long Branch, N. J., Vol. 3, No. 7, July 1971, pp. 133-144.
3. J. C. Wambold and W. H. Park. A Data Processing Method Giving a Better Physical Description of Random Signals. Proc., 20th International Instrumentation Symposium, 1974, pp. 371-375; Instrumentation Technology, Vol. 21, No. 6, June 1974, pp. 36-40.
4. F. Pradko and R. A. Lee. Vibration Comfort Criteria. Society of Automotive Engineers, Publ. 660139, 1966.
5. F. Pradko and R. A. Lee. Analytical Analysis of Human Vibration. Society of Automotive Engineers, Publ. 680091, 1968.
6. F. Pradko, R. A. Lee, and V. Kauluz. Theory of Human Vibration Response. American Society of Mechanical Engineers, Publ. 66-WA/BHF-15, 1966.
7. A. D. Brickman, W. H. Park, and J. C. Wambold. Road Roughness Effects on Vehicle Performance. Pennsylvania Transportation and Traffic Safety Center, Pennsylvania State Univ., Rept. TTSC 7207, 1972.
8. J. C. Wambold, W. H. Park, and R. G. Vashlishan. A New Random Data Description and Its Use in Transferring Road Roughness to Vehicle Response. American Society of Mechanical Engineers, Paper 73-DET-26, Sept. 1973.
9. W. H. Park, J. C. Wambold, and R. G. Vashlishan. Prediction of Objective Passenger Comfort From Road Profile. American Society of Mechanical Engineers, Paper 73-DET-114, Sept. 1973.
10. J. C. Wambold and W. H. Park. Objective Ride Quality Evaluation. Pennsylvania Transportation Institute, Pennsylvania State Univ., Rept. PTI 7412, March 1974.

SPONSORSHIP OF THIS RECORD

GROUP 2—DESIGN AND CONSTRUCTION OF TRANSPORTATION FACILITIES
W. B. Drake, Kentucky Department of Transportation, chairman

PAVEMENT DESIGN SECTION
Carl L. Monismith, University of California, Berkeley, chairman

Committee on Surface Properties-Vehicle Interaction
W. E. Meyer, Pennsylvania State University, chairman
Glenn G. Balmer, Frederick E. Behn, Andrius A. Butkunas, A. Y. Casanova III, Michael W. Fitzpatrick, William Gartner, Jr., Ralph C. G. Haas, Douglas I. Hanson, Don L. Ivey, William F. Lins, David C. Mahone, Paul Milliman, Alexander B. Moore, E. W. Myers, Arthur H. Neill, Jr., Bayard E. Quinn, John J. Quinn, Frederick A. Renninger, Rolands L. Rizenbergs, Hollis B. Rushing, Richard K. Shaffer, George B. Sherman, Elson B. Spangler, James C. Wambold, M. Lee Webster, E. A. Whitehurst, Ross G. Wilcox, Dillard D. Woodson

Lawrence F. Spaine, Transportation Research Board staff

The organizational units and the chairmen and members are as of December 31, 1974.