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FURTHER DEVELOPMENT IN RIDE QUALITY ASSESSMENT

NEWELL R. MURPHY, JR.

U. S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION, VICKSBURG, MISSISSIPPI

INTRODUCTION

Internationally, a growing concern has developed and widespread disagreement has occurred over the present methods for quantitatively describing and assessing the effects of vehicle vibrations on humans, and over the short- and the long-term effects of vibrations on drivers and occupants of heavy trucks, agricultural and earthmoving equipment, and military vehicles. None of the present methods is completely satisfactory; in fact, most criteria were developed for low-level "boulevard" rides and are highly suspect when applied to the severe vibrational levels encountered in earthmoving and military-type operations.

Today two predominant methods are used by the military to describe the effects of vehicle vibrations and human response: the absorbed power method (used largely in the United States) and the International Standards Organization (ISO) method (used extensively throughout European countries as well as in the United States). The two methods are similar in that both use frequency-weighted accelerations corresponding to human sensitivity to arrive at a single number which describes the vibration intensity. Portable ride meters have been developed to provide expedient field measurements of both absorbed power and the ISO accelerations.

In 1978, a NATO working group on mobility (NATO AC/225 (Panel II Working Group I)) composed of representatives from the United States, Canada, France, the Federal Republic of Germany, the Netherlands, and the United Kingdom adopted the Army Mobility Model (AMM) and its supporting absorbed power procedures for determining ride-limiting speeds for use in the model as comparison tools to provide a standardized reference for determining vehicle mobility performance. The AMM is also called the NATO Reference Mobility Model (NRMM). The use of absorbed power over the ISO method to describe effects of vehicle vibrations has caused resistance and concern, particularly among the European participants. The United States military and its NATO partners need agreed-upon, accepted standards to describe the various aspects of ride quality in meaningful terms for defining the vibrational effects on human health, safety, and performance of military tasks.

WHY ABSORBED POWER?

In 1968, personnel in the Mobility Systems Division at the Waterways Experiment Station (WES), in conjunction with the formulation and development of the components of the AMM, embarked on a comprehensive ride dynamics research and development program. The principal objective of the ride dynamics program was to develop a means for predicting ride-limiting speeds of vehicles as a function of terrain roughness. This objective required a quantitative measure of vehicle vibration that related to human acceptance of the vibration and response to vibration. WES decided to adopt a promising measure called absorbed power. This absorbed power quantity, purported to be a measure of the rate at which vibrational energy is absorbed by a typical human, had been developed only recently at the U. S. Army Tank-Automotive Command as a result of a comprehensive, closely controlled laboratory program (Pradko, Lee, and Kaluza 1966). An attractive feature of absorbed power is that it is conceptually a scalar quantity and the resultant response of vertical and horizontal vibrations can be determined by directly summing the absorbed power in each component.

Since 1968, the WES has conducted numerous field tests with virtually every type of wheeled and tracked vehicle in terrains throughout the world. The absorbed power quantity has worked well in fulfilling the principal objective of describing ride-limiting speeds. A criterion of 6 watts of absorbed power was chosen as an upper bound of vibration that will permit crew members to effectively perform their tasks. Test results revealed that beyond the 6-watt level, a vehicle occupant can do little else except hold tight. Results have also shown that highly competitive drivers and crew members will accept absorbed power levels regularly ranging up to 10, 20, or more watts for periods up to 10 or 12 minutes (Berry 1975). The same tests showed that these high absorbed power conditions frequently caused minor injuries and bruises and often produced severe vehicle damage and a high risk of accidents and cargo damage. Thus, it is recognized that the 6-watt absorbed power level is not an absolute human tolerance limit to vehicle vibration and that crew members will, if necessary, accept considerably higher absorbed power levels at the risk of injury and vehicle and cargo damage. A broader range of test results has shown, however, that quite often only a small increase in speed can be attained at 15 or 20 watts over that at 6 watts, because the 6-watt absorbed power levels usually occur when the vehicle's suspension begins "bottoming out" and producing discrete shock loads. Slight increases in speed beyond this point significantly increase the intensity and frequency of these shock loads, which in turn rapidly increase the absorbed power levels. These high absorbed power conditions are not considered to be an effective or meaningful measure of basic ride characteristics. While the use of ride speed limits based on higher absorbed power levels will increase projected vehicle speeds in isolated terrain situations, the overall vehicle performance throughout an area generally will not be materially increased, and relative performances of two or more vehicles in the same area will rarely be changed.

THE ISO METHOD

In 1974, after a decade of serious committee deliberations, the ISO published a standard for describing human response to whole-body vibrations that was approved by 19 countries including the United States (ISO 1978). The ISO standard defines numerical limits for exposure to vibrations in terms of weighted root-mean-square (rms) accelerations in the frequency range of 1 to 80 Hz according to three criteria of increasing intensity--preserving comfort, working efficiency, and safety or health. These three limits are referred to, respectively, as the "reduced comfort boundary," "fatigue-decreased proficiency boundary," and the "exposure limit boundary." The preferred method of evaluation is to compare separately each rms acceleration level for 1/3-octave bands of specified center frequencies against the recommended level at each frequency. This procedure assumes that in regard to human tolerance there are no significant interactions between frequencies. An alternate method, which appears to be a more accurate representation for complex vibrations, sums the weighted accelerations to give an overall rms level expressed by a single quantity (Allen 1975). This single quantity method led to the development of portable ride meters. One such meter was built in the United States in 1978 by Endevco for the Society of Automotive Engineers (SAE) Ad Hoc Ride

Meter Task Force in accordance with specifications cited in ISO 2631 and SAE J1013. For vibrations occurring in more than one axis simultaneously, each axis is evaluated separately and vectorially summed. There has been much disagreement over the use of this method and a number of deficiencies have been highlighted by its critics. The most notable deficiencies cited are the lack of empirical support in a number of important areas, in particular the time-dependency relations on human response (Obsorne 1983).

Because of these disagreements and concerns and other unanswered questions, a joint United States-Federal Republic of Germany effort was recently initiated to resolve these major issues. As a part of the Future Armored Vehicle Research (FAVR) program, a joint United States-Federal Republic of Germany ride test and evaluation program is scheduled to begin at Trier Proving Ground in May 1984, with similar follow-on tests in the United States. The main emphasis will be to jointly study and compare the results of the two methods.

Over the past 15 years of testing, WES has developed a large, unique data base containing detailed vertical, horizontal, and rotational acceleration measurements, along with the corresponding human subjective comments and ratings, terrain measurements, and vehicle characteristics. These data are stored on analog FM magnetic tape. As a starting point for this study, selected vibration data representing a wide variety of vehicles and terrain conditions are currently being reprocessed to analyze and compare relations produced by other proposed quantities, particularly the ISO standard.

This paper describes briefly some of the initial results of using only vertical vibration data from recent tests with a pair of wheeled vehicles to compare and evaluate the relative merits of the absorbed power and ISO criteria. Discussions include similarities between the two methods, the relations (or lack of relations) between subjective ratings and the absorbed power and ISO quantities, some notable deficiencies common to both, and the effects of psychological influence. Evidence indicating the validity of the 6-watt absorbed power level as a reasonable driver-imposed criterion of acceptability is presented along with plans for future work.

COMPARISON OF ABSORBED POWER AND ISO FILTERS

Human response to vibrations depends upon the frequency of the vibration. Curves of constant comfort or equal perceptions of vibrations as a function of frequency have been measured by many investigators. The precision and definition of these curves have improved with the progressive improvements in equipment and measuring instruments. Regardless of the improvements in precision, they all present basically the same characteristic trough shapes. For example, the keenest sensitivity of a seated subject exposed to vertical (buttocks-to-head) vibrations is in the range from 4 to 8 Hz. This range of maximum sensitivity is attributed to physical resonances of body parts and internal organs. Precise experiments and measurements indicate the most sensitive frequency of a seated subject to vertical vibration occurs at about 4.5 Hz, which is the resonance of the viscera. This critical resonance will vary somewhat among humans due to differences in body structure. Most likely, the less precise curves are better overall general representations of human sensitivity.

Any method that purports to evaluate vibrations in terms of human sensitivity must account for this frequency dependency. The frequency-weighting can be accomplished numerically by appropriately weighting the Fourier spectra of the vibrations. The frequency-weighting is more readily accomplished in the analog domain through the use of band-pass filters. As mentioned previously, portable ride meters have been developed that filter input accelerations and produce on-the-spot measures of absorbed power and ISO ride values. Figure 1 shows a comparison of the absorbed power and the SAE/ISO ride meter filters for vertical vibrations. The standard ISO frequency-weighting factors specified in ISO 2631 are shown as discrete points. It is seen that the absorbed power and the ISO filters have the same basic shape. The absorbed power filter peaks (zero attenuation) at 4.5 Hz, while the SAE/ISO filter peaks at 5.8 Hz. The absorbed power filter is more restrictive because it attenuates (reduces) accelerations more heavily at frequencies beyond the 4.5-Hz peak. It is also seen that the curve representing the SAE/ISO filter of the Endevco ride meter corresponds very closely to the discrete points representing the standard ISO frequency-weighting factors. Obviously, because of these similarities, the respective quantities calculated from accelerations processed by these filters and frequency-weighting factors will produce similar performance patterns.

COMPARISON OF ABSORBED POWER AND ISO RESULTS

WES began its first comparison of the absorbed power and the ISO methods this past summer (1983) as part of a comprehensive analysis to resolve apparent discrepancies in results obtained from ride tests with a light dune buggy vehicle. This dune buggy had exceptionally stiff suspensions that produced extremely high acceleration and absorbed power levels, even on relatively smooth test courses. The absorbed power levels measured for the dune buggy were consistently two to three times higher than those measured on conventional vehicles for similar test conditions. The high absorbed power levels were not the issue. The issue that caused the concern was that the subjective ratings of three experienced WES test drivers consistently rated these unreasonably high absorbed power levels as acceptable rides. Numerous supplemental ride tests were conducted on the same test courses with two additional vehicles and three drivers to obtain "head to head" data for direct comparisons. One of the two vehicles was an M151 jeep which had a gross weight and size similar to that of the dune buggy. The principal performance results presented in this paper are limited mainly to data from representative tests with the dune buggy, one reference vehicle (an 8x8, 14-ton* armored vehicle), and one driver. These relations are representative of the relations obtained when comparing the combined results of the three vehicles and three drivers.

Figures 2 and 3 graphically depict the respective absorbed power and ISO ride meter results from tests with the two vehicles on two test courses. More detailed data are presented in Table 1. Figure 2 shows how vertical absorbed power and ISO weighted acceleration vary with speed for the two vehicles on a test course (course 4) of moderate surface roughness. The

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* U. S. customary units of measurement used in this report may be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	2.54	centimetres
miles	1.609347	kilometres
pounds (force)	4.448222	newtons
tons (force)	8896.444	newtons

exposure-limit time dependency boundaries representing the ISO acceleration limits for the most sensitive frequency region (4 to 8 Hz) of five selected exposure times are shown on the plots. The drivers' subjective ratings, based on a scale of increasing severity from 1 to 10, are also shown adjacent to the respective data points. The subjective rating scale used at WES to express the drivers' perception of ride quality is given below:

Subjective Index	Perception
1-2	Barely noticeable
3-4	Strongly noticeable
5-6	Uncomfortable
7-8	Extremely uncomfortable
9-10	Recommended limits (not willing to take for any sustained period of time)

Past experience indicates that when WES drivers are allowed to drive at their discretion, under guidelines of achieving the maximum safe speed, the subjective ratings fall within a range of about 6 to 7. This indicates that ride conditions with subjective ratings greater than 6 or 7 are really conditions of stress levels beyond the criteria of acceptability.

For both vehicles increases in speed produce corresponding increases in absorbed power and ISO acceleration. However, absorbed power and ISO do not increase at the same rate. Also, for any selected speed the absorbed power and ISO acceleration for the dune buggy are about twice the magnitudes of those recorded for the 8x8 vehicle. Yet, the driver's subjective ratings are consistently lower for the dune buggy at corresponding levels of absorbed power and ISO acceleration. According to the recommended ISO exposure limits, the results in Figure 2 indicate the 8x8 vehicle can be driven over test course 4 or a course of similar roughness at a speed of 20 mph for up to an hour and can be driven at speeds in excess of 50 mph for about a half hour. These same ISO limits indicate the dune buggy can be driven at a speed of 20 mph over such a course for only about 16 or 18 minutes, and at speeds beyond 40 mph the permissible ISO exposure time is less than one minute.

Figure 3 shows results similar to those of Figure 2 except the surface roughness of the test course is much more severe. The severity of the test course is reflected by the rapid increase in both absorbed power and ISO acceleration with increases in vehicle speed. Again, at any selected speed both the absorbed power and the ISO accelerations for the dune buggy are about twice the corresponding magnitudes recorded for the 8x8 vehicle. Also, the drivers' subjective ride severity ratings are lower for the dune buggy at corresponding levels of absorbed power and ISO acceleration. Noteworthy are the overall high subjective ratings. This particular driver, like the other two WES test drivers, is considered to be fit, tough, and competitive. As mentioned before, based upon their discretionary driving habits, subjective ratings greater than about 6 or 7 reflect levels beyond their self-imposed acceptability criteria. Figure 3 shows that the driver's subjective ratings for both vehicles are largely in the range from 7 to 10, indicating that the ride quality of the majority of the tests on this course exceeded the driver's criteria of acceptability. Subjective ratings of 8 to 10 mean the rides were exceptionally tough. The data in Table 1 reveal that these tests ranged from a maximum duration of about one minute to a minimum of 6 seconds. Based on combined consideration of the ISO recommended exposure limits and the high subjective ratings, it appears that neither of the two test vehicles could be driven at speeds beyond about 10 mph on terrains with such levels of surface roughness for periods longer than about half an hour.

SIMILARITIES BETWEEN ABSORBED POWER AND ISO RESULTS

Figures 2 and 3 clearly show certain similarities in the manner that absorbed power and ISO acceleration increase with increases in speed as well as similar correlations with driver subjective ratings. Figure 4 illustrates further correspondence between the two ride quality measures. The two plots in Figure 4 reflect relations between ride-limiting speeds and terrain surface roughness for the dune buggy at three arbitrarily selected levels of absorbed power and ISO acceleration, respectively. This limiting speed versus surface roughness relation is exactly the type of format required as input to the AMM/NRMM to depict vehicle ride performance relations. The ride performance relationships are very similar for both the absorbed power and the ISO acceleration measures. In fact, the relation for the 20-watt absorbed power level is almost identical to that for the 25-minute ISO level (the 25-minute exposure limit corresponds to an ISO acceleration level of 3.6 m/sec^2). Consequently, if so desired, the ride-limiting speeds based on the 6-watt absorbed power level customarily used in the AMM/NRMM to describe ride performance could be replaced with ride-limiting speeds based on either a more suitable absorbed power level or a preferred level of ISO acceleration or permissible exposure time. The AMM/NRMM requires a limiting speed-surface roughness relation to describe ride performance regardless of the criteria used to determine the limiting speeds.

PSYCHOLOGICAL IMPLICATIONS

Human reaction to vibration is a complicated dependency upon both physiological (physical) and psychological (mental) disturbances. Neither absorbed power nor ISO acceleration nor any other measure of purely physical motions can account for the psychological effects. Recalling the subjective index rating mentioned previously, the perception definitions deal only with thresholds caused by interactions of vehicle motions. However, without fail, during driver interviews regarding rides that were rated in the range of 8 to 10, the principal objection was attributed to lack of control of the vehicle. Although this reason does not fit into the perception definition, the psychological implications cannot be isolated or removed from the subjective ratings. This psychological influence of vehicle controllability depends strongly on the nature of the vibrations. That is, a ride composed of high-intensity, uniform accelerations will be perceived quite differently from one composed of low- to medium-intensity accelerations made up of recurring impulses and shock loads. This is a condition of high crest factors; i.e., ratio of maximum peak to rms accelerations where the ISO limits are admittedly questionable. It is the occurrence of harsh shock loads that often catapult driver and vehicle into the air and along with inducing momentary pain and possible injury seriously hinders the driver's capability to control the vehicle. This psychological distinction between uniform motions and motions composed of recurring impulses is the principal cause of the discrepancies in the subjective ratings recorded for the dune buggy.

Table 2 lists the respective speeds and driver subjective responses recorded from arbitrarily selected levels of absorbed power and ISO acceleration for the two test vehicles and three test courses with three levels of surface roughness.

Subtle yet important effects of psychological influence on the measures of performance can be seen in the table. Both absorbed power and ISO acceleration reflect the same effects. For example, for any given level of either absorbed power or ISO acceleration, the speeds of the 8x8 vehicle are about twice as high as the corresponding speeds for the dune buggy. According to current procedures for evaluating ride performance, the 8x8 vehicle would be considered far superior to the dune buggy. However, for any given level of either absorbed power or ISO acceleration, the subjective ratings are consistently higher for the 8x8. This difference in ratings says that a 6-watt ride in the 8x8 feels rougher or more severe than a 6-watt ride in the dune buggy.

Comparison of representative acceleration-time histories of the two vehicles reveals that, in fact, the dune buggy accelerations generally were rather uniform throughout and did not exhibit significant impulses or shock loads. This uniformity is attributed to the extremely stiff rear suspensions combined with the vehicle's "tail-heavy" weight distribution that prevented suspension "bottoming" and thus the associated shock loads. This condition is in contrast to the soft suspensions and high wheel travel on the 8x8 which produced gentle, low-frequency, high-displacement motions. These soft suspensions on the 8x8 resulted in low-intensity acceleration-time histories with dispersed harsh shock loads occurring when the suspensions "bottomed out." The intensity and frequency of these shock loads were moderate on relatively smooth courses but rapidly increased with increases in both speed and surface roughness.

The relations illustrated in Figure 5 provide an even broader understanding of this phenomenon between the dune buggy and the 8x8. Figure 5 is a standard ISO graph depicting the rms acceleration magnitudes for each of the standard 1/3-octave band center frequencies recorded from ride tests with the two vehicles. The results of the dune buggy ride reflect considerably higher absorbed power and ISO (summed) accelerations, yet lower subjective ratings than the 8x8. These two rides, which were both less than 15 seconds' duration, were very near the limits that the driver could tolerate.

The predominant acceleration for the dune buggy occurs in the 3- to 5-Hz range where both absorbed power and ISO acceleration are most sensitive. The dune buggy acceleration at the most sensitive absorbed power frequency (4.5 Hz) is nearly three times that of the 8x8. This explains the higher absorbed power level for the dune buggy. On the other hand, the predominant acceleration for the 8x8 is concentrated between 1 and 2 Hz where vertical absorbed power and ISO accelerations are much less sensitive. This low-frequency (1- to 2-Hz) acceleration predominance is characteristic of most conventional vehicles. Suspensions are customarily tuned to produce a sprung-mass resonance in the frequency range of 1 to 2 Hz and thereby isolate occupants from irritable vibrations in the 4- to 8-Hz region. It appears, at least for short duration travel, that drivers are more willing to accept the rather high uniform vibrations in the 4-to 8-Hz range caused by ultra-stiff suspensions rather than endure the recurring harsh jolts that occur from the softer conventional suspensions which tune the major resonances to the 1- to 2-Hz range.

This subjective willingness (as well as health implications) may well be reversed for long duration travels, such as occur during operations of agricultural and earthmoving equipment. This possible contrast between the effects of short- and long- duration vibrations provides a high potential for application of adaptive (adjustable) suspensions. It is interesting that the single-valued ISO accelerations obtained for the dune buggy by summing over the frequency spectrum is more restrictive than the worst single frequency.

One other psychological factor worth noting is that observation of the subjective ratings in Table 2 reveal that, for any given level of absorbed power or ISO acceleration, the ratings increase with increases in surface roughness. That is, a 6-watt ride feels rougher on a rough course than it does on a smooth course.

HOW GOOD IS THE 6-WATT LIMIT?

There has been quite a bit of controversy and dissent over the use of the 6-watt absorbed power level as a ride-limiting criterion. The reason for its initial selection was a direct outcome of the results of Pradko, Lee, and Kaluza's laboratory study which established the absorbed power concept and subsequent 6-watt limit. The limits of its validity were explained earlier in this paper. The criterion has served well for many years as a sound, consistent measure of practical operational limits. It is not a human tolerance limit; experience has shown that competitive drivers and crews will accept considerably higher absorbed power levels for short durations, even at the risk of injury. However, test results have indicated the 6-watt level may be a good measure of a driver's self-imposed criteria of acceptability.

Figure 6 shows the relative and cumulative frequency distributions of the vertical absorbed power recorded at the driver's seat of a light wheeled vehicle while negotiating two cross-country mobility traverses. These data reflect the same WES driver in the same vehicle. The driver was instructed to drive the well-marked traverses at the fastest safe speed. There were a number of occurrences of factors other than ride, such as slopes, curves, and vegetation, that restricted the speed. However, it is seen that the percent of time the driver spent at ride levels above 6 watts was relatively small (3 minutes or 6 percent on one course and 10 minutes or 21 percent on the other course). Similar results have been obtained with other drivers when instructed to drive at their discretion for extended durations. However, experience has shown that the same driving instructions for short courses and short durations (1 minute or less) generally result in speeds limited by vehicle control and usually considerably higher absorbed power levels. In any instance, for rather long durations the 6-watt level appears to be a driver-preferred limit.

PLANS FOR FUTURE WORK

As mentioned previously, plans are being formulated under the FAVR program for a joint United States-Federal Republic of Germany program to begin in May 1984 to study the relative merits of the absorbed power and ISO procedures. Work will continue at WES using the existing data base to study and evaluate the merits of the two methods and other proposed criteria. Emphasis will be placed on the following areas:

Effects of impulses and shock loads on ride criteria.

Detailed analysis of crest factor levels and their effects on ride criteria.

Influence of rotational motion.

Effects of multi-axis vibrations on ride criteria.

Effects of duration of exposure.

Effects of vibrations on recumbent subjects.

CONCLUSIONS

Based on the results of this preliminary analysis, it is concluded that for short distance travel and limits based on safety and health:

Absorbed power and ISO weighted accelerations produce similar ride performance relations.

Human response to vibration is heavily influenced by psychological effects.

- At equal levels of intensity, rides with high crest factors feel more severe than rides with uniform acceleration.
- At equal levels of intensity, rides feel rougher on rough courses than on smooth courses.

Neither absorbed power nor ISO weighted accelerations account for psychological influences.

Vehicle control and not high vibration levels are the principal limits for short-duration travel.

Rides composed of recurring jolts tend to hinder vehicle controllability and are more objectionable than rides composed of more uniform motions.

For short-duration travel, drivers are more willing to accept rather high uniform accelerations in the sensitive frequency range (4 to 8 Hz) rather than endure recurring harsh jolts that occur from the softer conventional suspensions which tune major resonances to the 1- to 2-Hz range.

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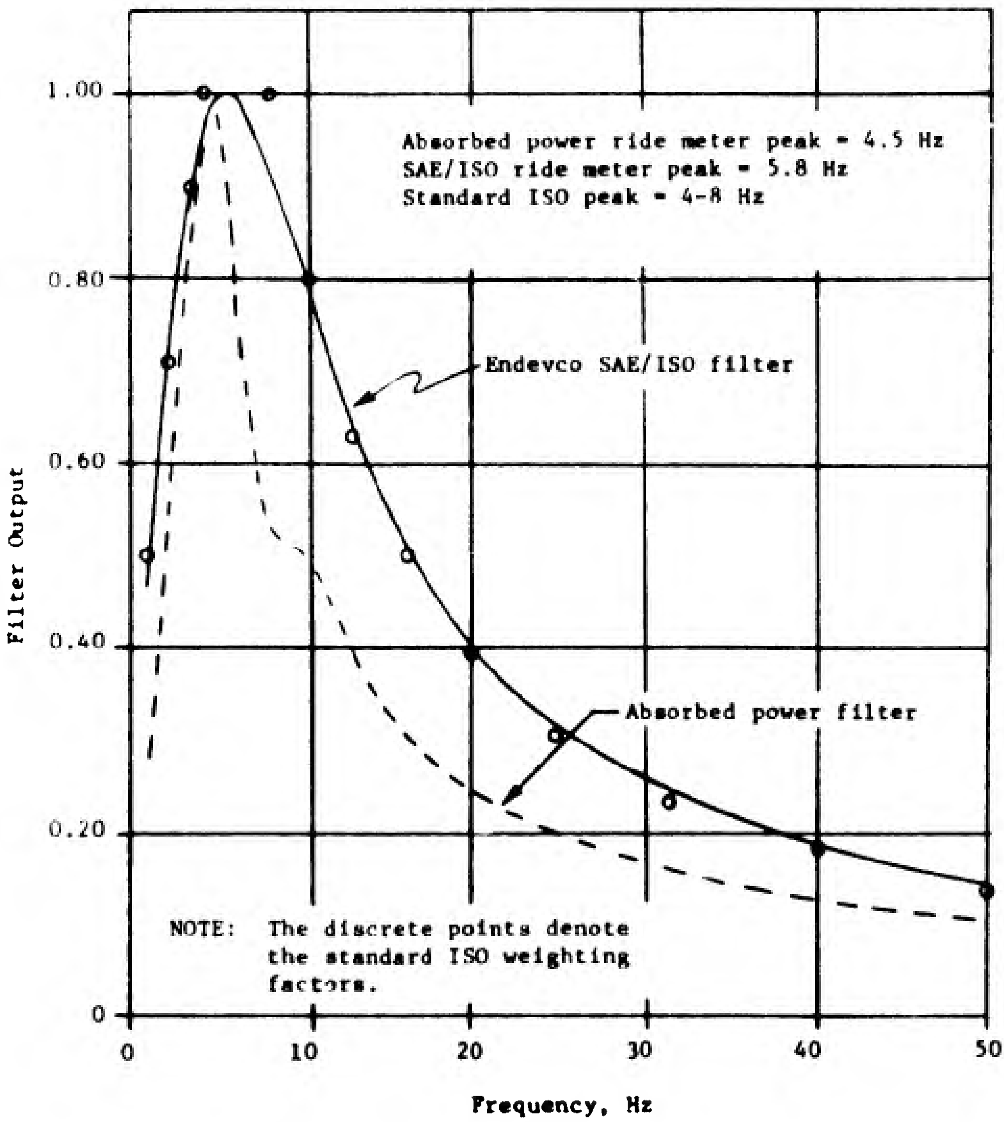


Figure 1. Comparison of normalized filters for vertical vibration, Endevco SAE/ISO filter, absorbed power filter, and standard ISO filter

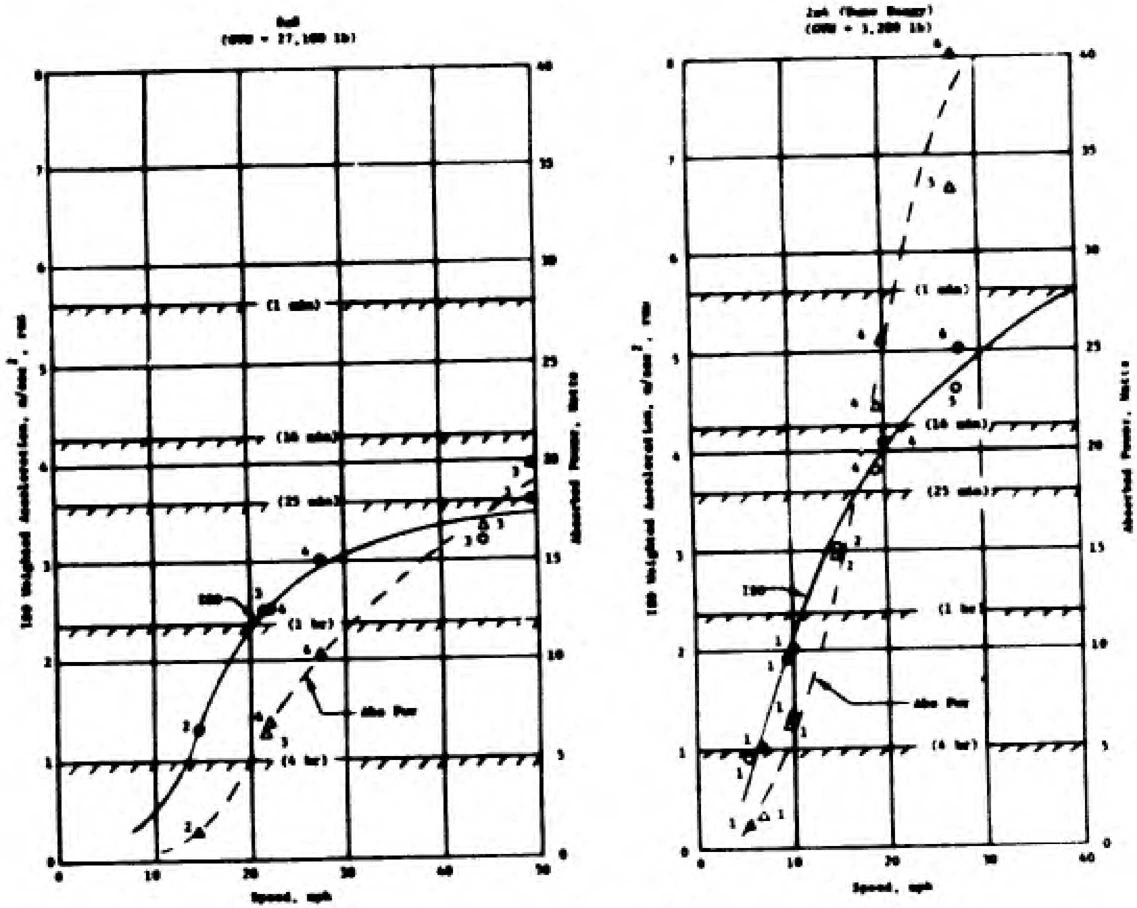


Figure 2. Comparison of vertical ISO weighted acceleration and absorbed power versus speed for the 6x6 and the 2x4 Dune Buggy during ride tests on Letourneau test course No. 4 (surface roughness = 1.1 in. (rms)). (NOTE: Numbers adjacent to data represent driver's subjective rating index.) Time lines represent ISO exposure limit boundaries.

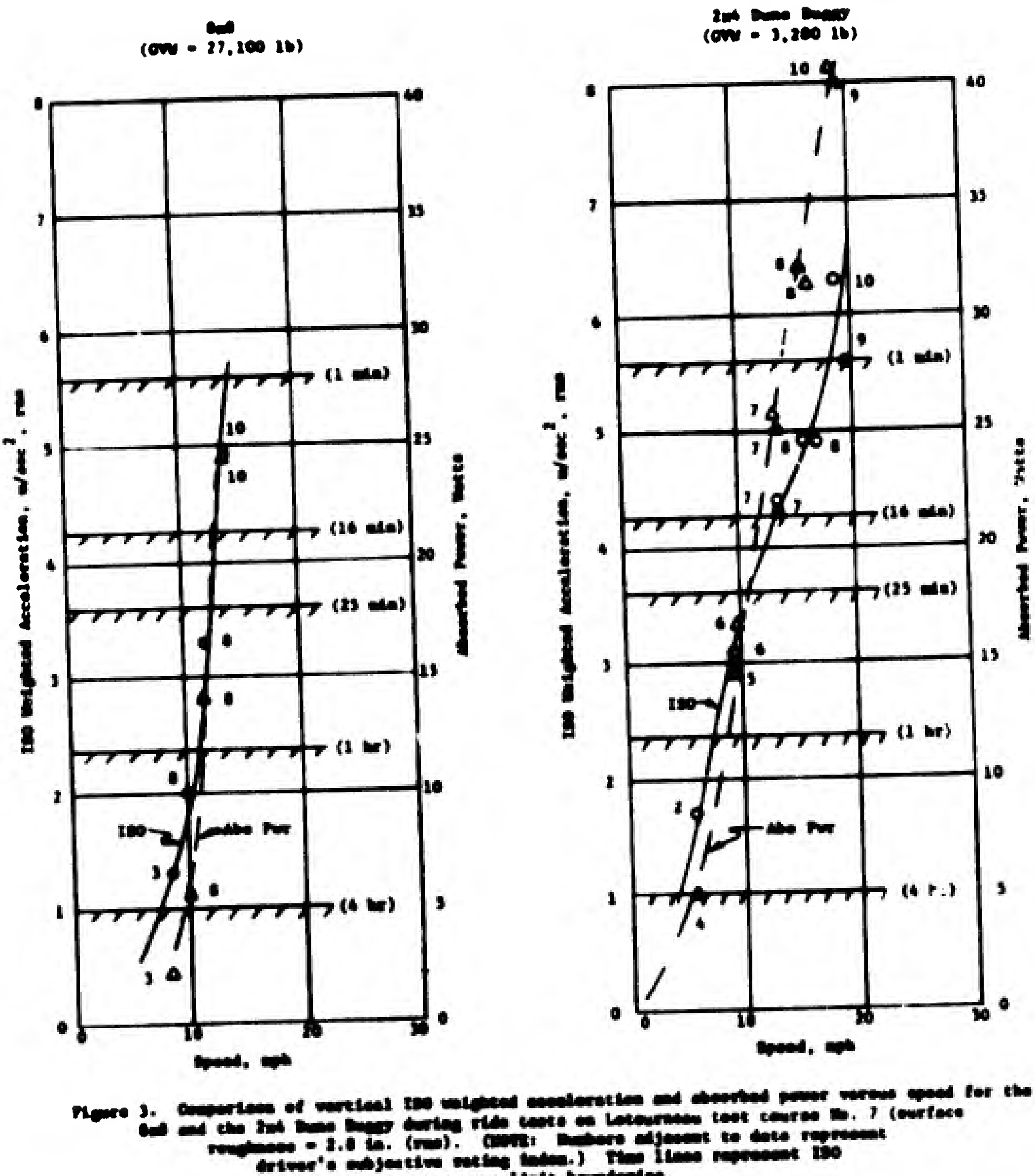


Figure 3. Comparison of vertical ISO weighted acceleration and absorbed power versus speed for the 8x8 and the 2x4 Dune Buggy during ride tests on Letourneau test course No. 7 (surface roughness = 2.8 in. (rms)). (NOTE: Numbers adjacent to data represent driver's subjective rating index.) Time lines represent ISO exposure limit boundaries.

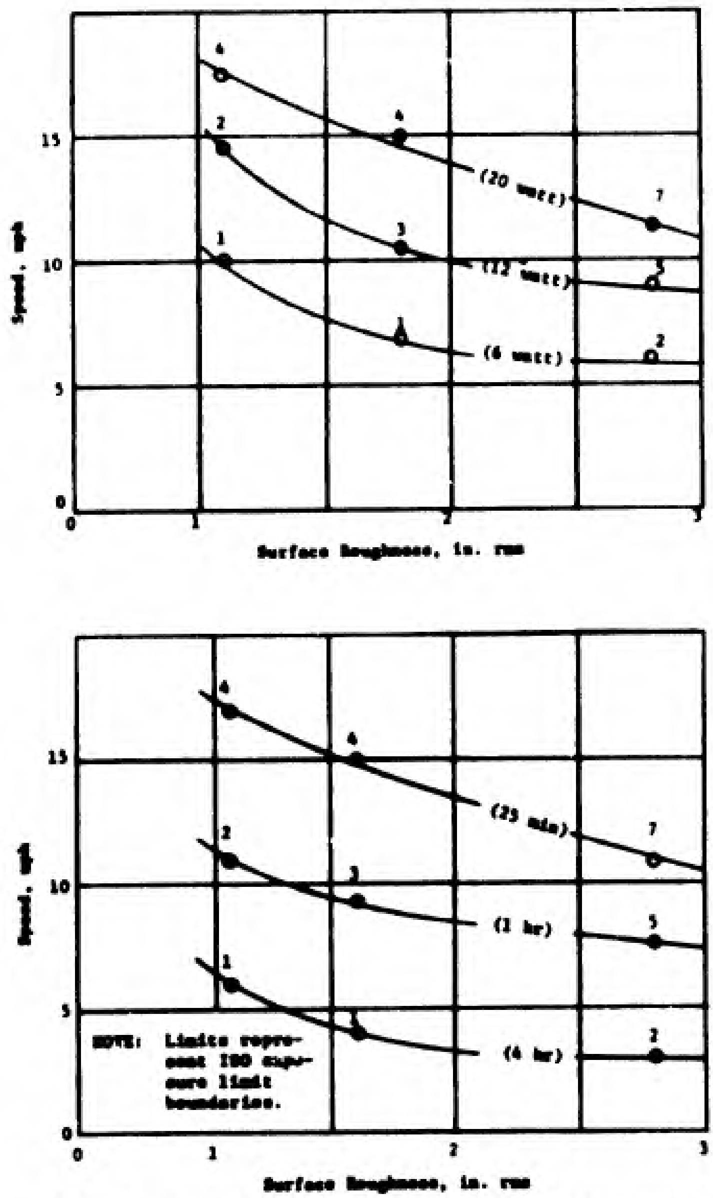


Figure 4. Comparison of absorbed power and ISO limiting-speed versus surface roughness relations for three selected levels of vertical vibrations (ride tests with the 2x4 Dune Buggy). (NOTE: Numbers above data denote driver's subjective rating index.)

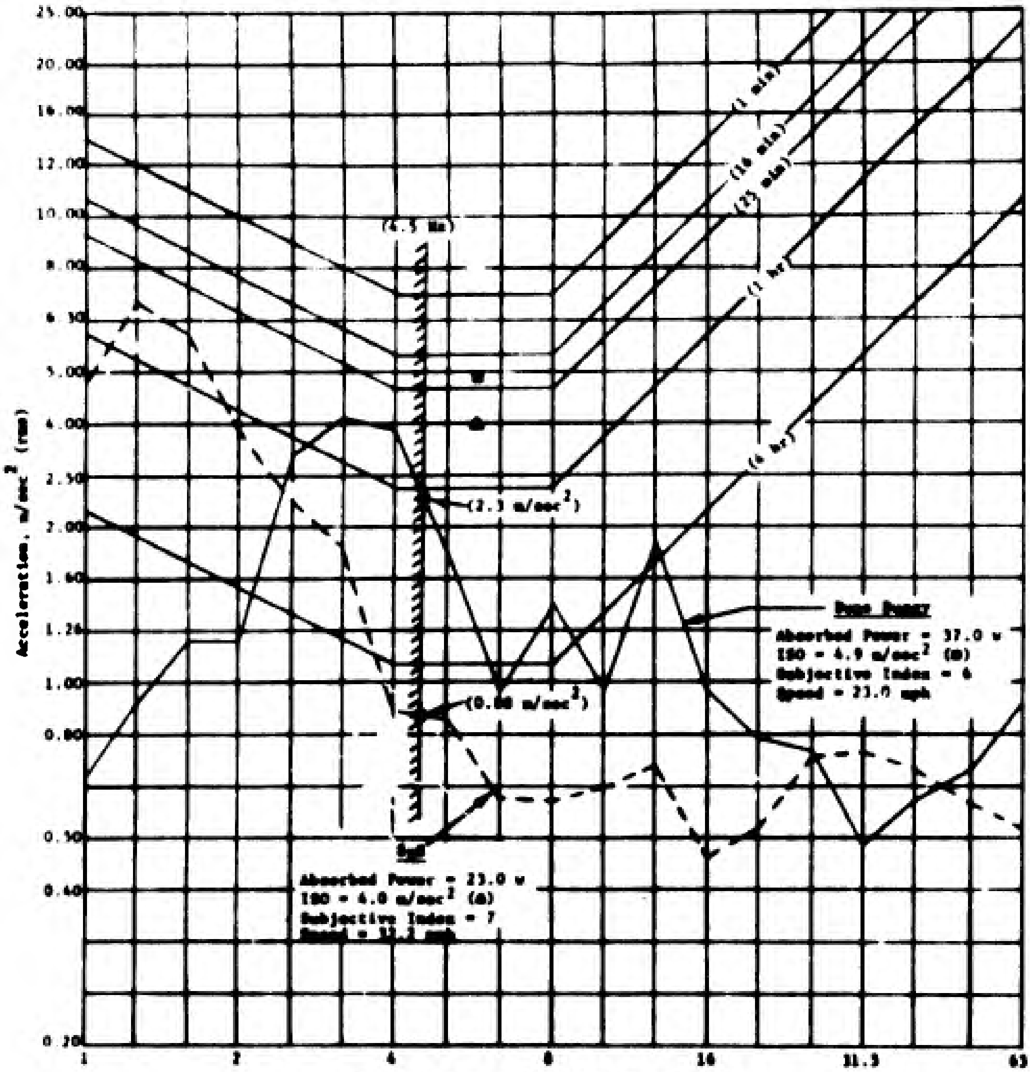
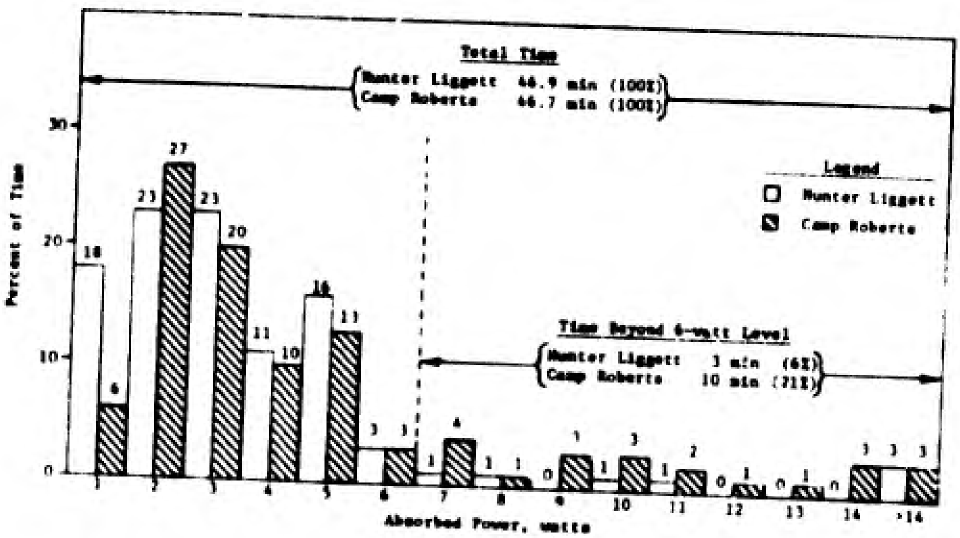
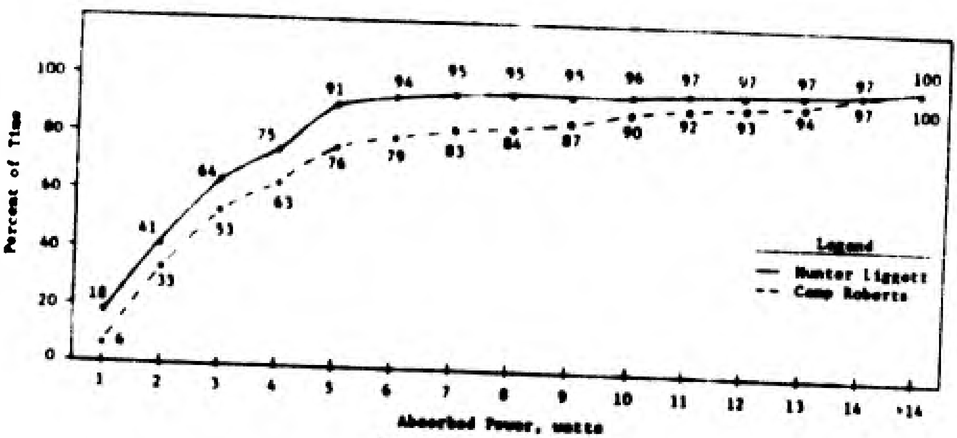


Figure 5. Comparison of ISO vertical acceleration exposure limits for [illegible] vehicle and Dune Buggy during ride tests on Letourneau test course No. 5 (surface roughness = 1.6 in., rms)



a. Relative frequency



b. Cumulative frequency

	Statistics	
	Hunter Liggett	Camp Roberts
Traverse length	22.4 mi	22.3 mi
Average speed	28.7 mph	28.6 mph
Total time	46.9 min	46.7 min

Figure 6. Relative and cumulative frequency distributions of vertical absorbed power measured at the driver's seat of a light wheeled vehicle on two mobility traverses

Table 1

Ride Data for 8x8 and 2x4 (Dune Buggy)

Vehicle	Test Course	Surface Roughness in., rms	Test No.	Time (sec)	Speed (mph)	Ride Meters: Absorbed Power watts	Ride Meters: ISO Acceleration m/sec^2 (rms)	Subjective Index
8x8	Lot 4	1.1	30	23.5	14.5	1.4	1.3	2
			31	12.5	27.3	10.2	3.0	4
			32	15.9	21.4	6.4	2.5	3
			33	15.5	22.0	6.8	2.5	4
			34	7.7	44.3	16.6	3.2	3
			35	6.9	49.4	20.0	3.6	3
	Lot 5	1.6	36	23.6	14.4	5.4	1.9	5
			37	22.5	15.1	5.0	1.9	5
			38	30.5	11.2	2.0	1.2	3
			39	17.1	20.0	12.6	3.3	6
			40	13.4	25.4	12.4	3.5	4
			41	10.6	32.2	23.0	4.0	7
	Lot 7	2.8	42	39.0	8.7	2.2	1.3	3
			43	29.4	11.6	14.0	3.3	8
			44	34.1	10.0	9.7	2.0	8
			45	24.1	14.1	24.5	4.9	10
2x4 (Dune Buggy)	Lot 4	1.1	76	66.0	5.2	1.3	0.9	1
			77	62.5	6.5	1.5	1.0	1
			78	36.8	9.3	6.1	1.9	1
			79	34.3	9.9	6.6	2.0	1
			80	23.4	14.6	14.8	3.0	2
			81	23.3	14.6	14.8	3.1	3
			82	17.8	19.2	22.1	3.8	4
			83	17.3	19.7	25.5	4.1	4
			84	12.5	27.3	33.4	4.6	5
			85	12.2	27.9	40.5	5.0	6
	Lot 5	1.6	150	60.3	5.7	3.5	1.4	1
			151	59.5	5.7	3.2	1.3	1
			152	33.8	10.0	11.5	2.6	3
			153	34.8	9.8	9.9	2.4	2
			154	23.7	14.4	18.7	3.5	4
			155	24.6	13.9	16.8	3.3	3
			156	18.5	18.4	25.5	4.2	4
			157	18.5	18.4	23.0	4.0	3
			158	14.8	23.0	37.0	4.9	6
			159	Void	Void	Void	Void	Void
			160	14.6	23.4	32.3	4.7	5
			161	12.5	27.3	42.2	5.3	6
			162	12.0	28.4	35.1	5.1	6
			163	8.8	38.8	41.4	5.9	6
			164	8.7	39.2	36.6	5.3	6
			165	7.6	44.9	38.7	5.9	6
			166	7.8	43.7	34.7	5.3	7
	Lot 7	2.8	179	58.5	5.8	5.0	1.7	2
			180	55.9	6.1	5.0	1.7	2
			181	36.1	9.7	16.8	3.3	6
			182	36.0	9.5	14.5	3.1	5
			183	25.4	13.2	25.8	4.4	7
			184	25.1	13.6	25.1	4.3	7
			185	22.0	15.5	32.1	4.9	8
			186	20.5	16.6	31.4	4.9	8
			187	17.3	19.7	41.2	5.6	9
			188	18.2	18.7	42.8	6.3	10

Table 2

Comparison of Limiting Speeds versus Surface Roughness for Selected Absorbed Power and ISO Vertical Vibration Levels

Absorbed Power Levels

Test Course	Surface Roughness in. (rms)	Limiting Speeds, mph 6-watt	12-watt	20-watt	40-watt
		2x4 Dune Buggy			
4	1.1	10.0 (1)	14.5 (2)	17.5 (4)	27.5 (6)
5	1.6	7.0 (1)	10.5 (3)	16.0 (4)	25.0 (6)
7	2.8	6.0 (2)	9.0 (5)	11.5 (7)	19.0 (10)
		8x8			
4	1.1	22.0 (3)	31.0 (4)	52.0 (3)	--
5	1.6	15.0 (5)	22.5 (5)	30.5 (7)	--
7	2.8	10.0 (8)	10.5 (8)	13.0 (10)	--

ISO Levels

Test Course	Surface Roughness in. (rms)	Limiting Speeds, mph (4-hr) 1.06 m/sec^2	(2-hr) 2.36 m/sec^2	(25-min) 3.60 m/sec^2	(1-min) 5.60 m/sec^2
		2x4 Dune Buggy			
4	1.1	6.0 (1)	11.0 (1)	17.0 (4)	40.0 (6)
5	1.6	4.0 (1)	9.5 (3)	15.0 (4)	38.0 (6)
7	2.8	3.0 (2)	7.5 (4)	11.0 (6)	18.0 (9)
		8x8			
4	1.1	14.0 (2)	20.5 (4)	50.0+ (3)	--
5	1.6	11.0 (3)	17.0 (6)	26.0 (4)	--
7	2.8	8.0 (3)	10.5 (8)	12.5 (8)	--

NOTE: Numbers in parentheses denote driver's subjective rating index (1 to 10). Dashes in columns denote levels could not be achieved due to vehicle control problems.